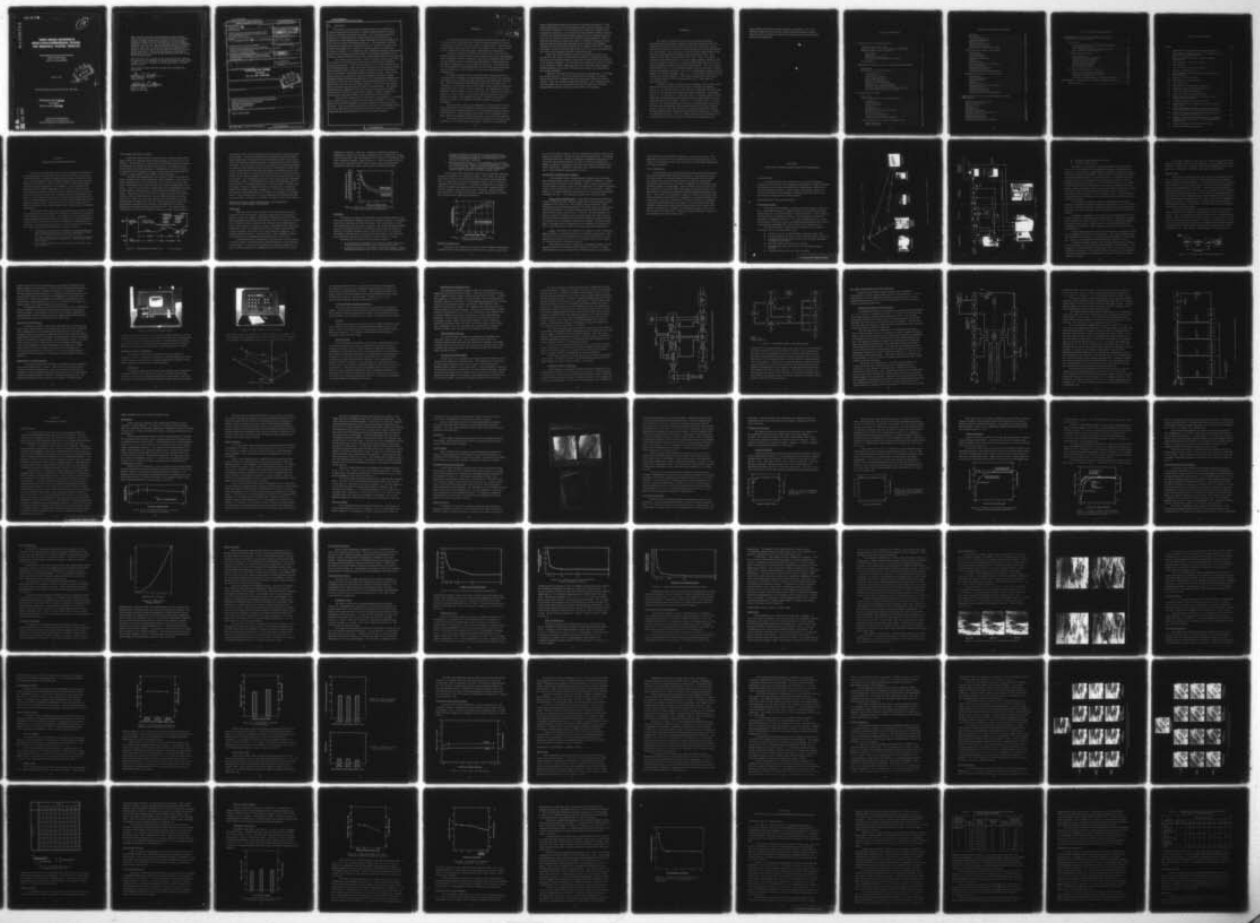
AD-A039 762 HUGHES AIRCRAFT CO CULVER CITY CALIF DISPLAY SYSTEMS--ETC F/G 17/2
VIDEO IMAGE BANDWIDTH REDUCTION/COMPRESSIONS STUDIES FOR REMOTE--ETC(U)
OCT 76 M L HERSHBERGER, R J VANDERKOLK PE64732F.
UNCLASSIFIED HAC-P76-243R ASD-TR-76-26 NL

1 OF 2
ADA039 762



AD A039762

ASD TR 76 25

(10)

VIDEO IMAGE BANDWIDTH REDUCTION/COMPRESSION STUDIES FOR REMOTELY PILOTED VEHICLES

Display Systems and Human Factors Department
Hughes Aircraft Company
Culver City, California 90230

DDC
RECEIVED
MAY 20 1977
C

October 1976

Final Technical Report for Period January 1975 – May 1976

APPROVED FOR PUBLIC
RELEASE
Distribution Unlimited

AIR FORCE SYSTEMS COMMAND
AERONAUTICAL SYSTEMS DIVISION
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

AD No.
DDC FILE COPY

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (IO) 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.

Gary C. Comfort

GARY C. COMFORT, MAJ, USAF
Program Manager

Richard E. Steere

RICHARD E. STEERE, COL, USAF
Director, RPV SPO
Deputy for RPV/ALSM

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: ASD-TR-76-26	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)*: VIDEO IMAGE BANDWIDTH REDUCTION/ COMPRESSION STUDIES FOR REMOTELY PILOTED VEHICLES,	5. TYPE OF REPORT & PERIOD COVERED: FINAL TECHNICAL REPORT, JANUARY 1975 - MAY 1976,
	6. PERFORMING ORG. REPORT NUMBER: D0470, P76-243R
7. AUTHOR(s): M. L. HERSHBERGER AND R. J. VANDERKOLK	8. CONTRACT OR GRANT NUMBER(s): F33657-75-C-0352
9. PERFORMING ORGANIZATION NAME AND ADDRESS: HUGHES AIRCRAFT COMPANY, DISPLAY SYSTEMS AND HUMAN FACTORS DEPARTMENT, CENTINELA AND TEALE STS. CULVER CITY, CALIFORNIA 90230	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 64732F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE SYSTEMS COMMAND, AERONAUTICAL SYSTEMS DIVISION, DEPUTY FOR REMOTELY PILOTED VEHICLES/ AIR LAUNCHED STRATEGIC MISSILES, WRIGHT-PATTERSON AFB, OHIO 45433	12. REPORT DATE: OCTOBER 1976 / 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*: HAC-P76-243R, HAC-D0470	15. SECURITY CLASS. *(of this report)*: UNCLASSIFIED / 15a. DECLASSIFICATION/ DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

APPROVED FOR PUBLIC RELEASE
Distribution Unlimited



17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

VIDEO BANDWIDTH REDUCTION/COMPRESSION
REMOTELY PILOTED VEHICLES
HUMAN PERFORMANCE
TARGET ACQUISITION
TELEVISION

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

(SEE OTHER SIDE)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 405 763

SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

20. ABSTRACT

A laboratory research and simulation program was conducted to evaluate and demonstrate methods of reducing video bandwidth to improve anti-jam capability of television data links. Four laboratory parametric studies were conducted using a remotely piloted vehicle simulator to establish the relationships between video bandwidth reduction techniques and RPV operator target acquisition performance. Nine bandwidth reduction/compression systems were selected based on the results of the parametric studies and compared to a standard TV baseline system in a laboratory systems simulation. A recommended video bandwidth reduction/compression system was selected based on the results of the systems simulation, and a hardware implementation analysis of the recommended system was performed.

The results of the parametric studies revealed that frame rate could be reduced to 3.75 frames per second using a standard 3-axis stabilized sensor pointing mode. With motion compensation or cursor designation control aiding techniques, frame rate could be reduced to 0.94 frame per second. It was found that video resolution could be reduced to 256 by 256 elements for the prebriefed, known target location mission simulated. Optical zoom did not improve the operators' ability to recognize and acquire targets. Minimal operator performance degradation was obtained with bandwidth compression ratios up to and including 1 bit per picture element (6:1 compression ratio). Bit error rate jamming as high as 10^{-2} bit errors per sample did not result in any reduction of operator task performance. The systems simulation was conducted to verify the results of the parametric studies using special Air Force provided target imagery. Without exception, the results of the parametric studies were confirmed by the simulation.

Based on the results of the five laboratory investigations, a 3.75 frame per second frame rate, 256 by 256 element video resolution, 1.0 bit per picture element RPV bandwidth reduction/compression system was recommended. This recommended system which provides a 192:1 bandwidth reduction ratio (246K bits per second data rate) was the subject of a hardware implementation analysis which was the final task in the program.



SUMMARY

In current and projected remotely piloted vehicle (RPV) systems, it is necessary for a human operator to effect terminal navigation of the RPV to a target by means of video from an electro-optical sensor. Transmission of useful video signal data from the RPV to the operator at a remote control center is difficult in hostile electronic countermeasure environments.

Anti-jam protection of wideband video data links is one of the most difficult problems confronting RPV system designers and can be best achieved by RF bandwidth reduction. Bandwidth reduction and bandwidth compression are the principle means of reducing video bandwidth by reducing temporal and spatial redundancies that exist within the video data. The implications of video bandwidth reduction/compression on RPV strike operator performance were addressed in this program via man-in-the-loop laboratory investigations.

A remotely piloted vehicle simulation facility was prepared for the investigations by modifying an existing Hughes RPV simulator and interfacing the simulator with a Hughes developed one-dimensional Hadamard transform unit. The RPV simulation facility provided control of video frame rate, resolution, sensor pointing control mode, optical zoom, Hadamard bandwidth compression ratio, and bit error rate jamming. The equipment also simulated RPV vehicle dynamics, sensor video, data link, ground-based processor, operator's control console, and provided automatic performance scoring and data recording. The simulator was used to conduct four parametric laboratory studies and a bandwidth reduction/compression systems simulation.

The parametric studies were conducted to obtain data which functionally relate operator target acquisition performance to bandwidth reduction/compression system design parameters. The parameters investigated were video frame rate, sensor pointing control mode, video resolution, optical zoom, Hadamard bandwidth compression ratio, and bit error rate jamming.

The results of the parametric studies revealed that frame rate could be reduced to 3.75 frames per second using a standard 3-axis stabilized

sensor pointing mode without any reduction in operator performance. With motion compensation or cursor designation control aiding techniques, frame rate could be reduced to 0.94 frame per second without any significant loss in operator performance. It was found that video resolution could be reduced to 256 by 256 elements without degrading operator target acquisition performance for the prebriefed, known target location mission simulated. Optical zoom did not improve the operators' ability to recognize and acquire targets. Minimal operator performance degradation was obtained with bandwidth compression ratios up to and including 1 bit per picture element (6:1 compression ratio). Bit error rate jamming as high as 10^{-2} bit errors per sample did not result in any reduction of operator task performance.

Nine video image bandwidth reduction/compression systems were derived from the results of the parametric studies and compared to a baseline 512 by 512 element resolution, 6-bit video, 30 frames per second system in the systems simulation. The simulation was conducted to verify the results of the parametric studies using special Air Force provided target imagery. Without exception, the results of the parametric studies were confirmed by the systems simulation.

Based on the results of the five laboratory investigations, a 3.75 frame per second frame rate, 256 by 256 element video resolution, 1.0 bit per picture element RPV bandwidth reduction/compression system was recommended. This recommended system which provides a 192:1 bandwidth reduction ratio (246K bits per second data rate) was the subject of a hardware implementation analysis which was the final task in the program.

PREFACE

This study was initiated by the Air Force Systems Command, Aeronautical Systems Division, Deputy for Remotely Piloted Vehicles/Air Launched Strategic Missiles, Wright-Patterson Air Force Base, Ohio to demonstrate methods of achieving a reduced/compressed baseband bandwidth for a video signal. The research was conducted by the Display Systems and Human Factors Department of Hughes Aircraft Company, Culver City, California under USAF contract F33657-75-C-0352. Cpt. P. G. Borop (formally of ASD/YMRC) was the Air Force Project Engineer during the first half of the program. Major G. C. Comfort (ASD/YMRC) was the Air Force Program Manager during the second half of the program. Cpt. R. A. Dysart (ASD/YMRH) and Dr. H. C. Self (AMRL/HER) served as Air Force technical advisors throughout the program. Mr. M. L. Hershberger of Hughes Aircraft Company was Project Manager, and Mr. R. J. VanderKolk of Hughes Aircraft Company was Project Engineer. The research sponsored by this contract was initiated January 1975 and completed May 1976. This report was submitted July 1976.

A number of people at Hughes Aircraft Company made valuable contributions to the study program which the authors gratefully acknowledge. Messrs. J. W. Wheeler and M. J. Parrish were responsible for the development of the one-dimensional Hadamard transform equipment. Additionally, Messrs. J. W. Wheeler, M. J. Parrish, and D. L. Nicponski performed the bandwidth reduction/compression system hardware implementation analysis which was part of this program. Messrs. C. E. Dickson and D. W. Craig and Ms. J. A. Herman conducted the laboratory investigations, analyzed the data from the investigations, and provided material for the final technical report. Messrs. R. L. Andrews and J. A. Schrunk modified and improved the existing Hughes RPV simulation facility which was necessary to conduct the laboratory research. Dr. L. A. Scanlan made major contributions to the research approaches used to conduct the laboratory investigations and

improvements in the RPV simulator hardware and software. Mr. D. J. Ketcham modified and improved his earlier developed computer software which performed a number of critical functions necessary to accomplish the laboratory investigations.

TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND 1

The Strike Operator's Tasks 2
Operator Tasks, Video Information, and Bandwidth Reduction/Compression Techniques 3

Frame Rate 3
Resolution 4
Bandwidth Compression 5
Performance Compensating Techniques 6

Study Approach 7

2. REMOTELY PILOTED VEHICLE SIMULATOR EQUIPMENT . . . 9

Introduction 9
Description of the RPV Simulator 9

Functional Overview 9
Video Sources 13
Vehicle Steering Mode 14
Sensor Pointing Mode 14
Digital Refresh Memory 14
Operator's Control Console 16
Experimenter's Control Console 16
Computer Functions and Software 17
RPV Data Link Simulation and Video Processor 24
RPV Simulator Parameters Variation 28

3. PARAMETRIC STUDIES 31

Introduction 31
Video Frame Rate and Control Mode Study 32

Introduction 32
Study Parameters 33
Research Design 34
Operators 35
Target Scenes 35
Briefing and Reference Materials 35
Study Procedures 35
Performance Measures 37
Results and Discussion 38
Conclusions and Recommendations 42

Video Frame Rate, Precision Designation Study 43

Study Parameter 44
Research Design 44

TABLE OF CONTENTS (Continued)

Operators 44
Target Scene 44
The Tracking Task 45
Laboratory Equipment 45
Study Procedure 47
Performance Measures 48
Results and Discussion 48
Conclusions and Recommendations 51

Video Resolution, Optical Zoom Study 52

Introduction 52
Study Parameters 54
Research Design 56
Laboratory Equipment 56
Operators 57
Target Scenes 57
Briefing and Reference Materials 57
Study Procedures 58
Performance Measures 59
Results and Discussion 59
Conclusions and Recommendations 63

Bandwidth Compression, Jamming Study 64

Introduction 64
Research Approach 67
Research Design 68
Operators 71
Target Scenes 71
Briefing and Reference Materials 71
Study Procedures 73
Performance Measure 74
Results and Discussion 74
Conclusions and Recommendations 77

4. BANDWIDTH REDUCTION/COMPRESSION SYSTEMS SIMULATION 81

Introduction and Background 81
Research Parameters 84
Research Design 85
Operators 85
Target Scenes 86
Laboratory Equipment 86
Briefing and Reference Materials 86
Simulation Procedures 87
Performance Measures 87
Results and Discussion 88
Conclusions and Recommendations 91

TABLE OF CONTENTS (Continued)

5. BANDWIDTH REDUCTION/COMPRESSION SYSTEM IMPLEMENTATION ANALYSIS 93

Introduction. 93

Video Bandwidth Reduction/Compression Signal Processing Function 93
Jam-Protection Signal Processing Function 95
Data Link System Performance 96

Partitioning of the System 98

Sensor Module 100
Bandwidth Compression Module 101
Frame Rate Buffer Module 102
Timing and Control Module 105
Spread Spectrum Modem 107
Scan Converter Module 108
Data Expansion Module 110

Hardware Implementation Technique 112

Applicable Component Technology 112
Airborne Processing Unit Hardware 115
Ground Unit Hardware. 117
Reliability, Maintainability and Safety Analysis. 118

APPENDIX A. ANALYSIS OF VARIANCE SUMMARY TABLES 121

REFERENCES. 133

LIST OF ILLUSTRATIONS

Figure		Page
1	Representative Profile of Strike Mission Segment	2
2	Mean Time to Acquire Targets as a Function of Frame Rate and Sensor Pointing Mode	4
3	Effect of Resolution on RPV Target Recognition Performance	5
4	RPV Simulator – Mission Capabilities	10
5	RPV Simulator	11
6	Tele-Cine Video Recording Apparatus	13
7	Hughes Television Scanner	14
8	Block Diagram of RPV Simulator Refresh Memory Mechanization	15
9	Operator's Control Console	17
10	Experimenter's Control Console	18
11	RPV Kinematics	18
12	Simulation of Image Motion Compensation	22
13	Simulation Software Functional Diagram	23
14	Video Data Link Block Diagram	25
15	Video Test Links Functional Diagram	27
16	Effect of Video Frame Rate on Operator Target Recognition Performance	32
17	Briefing and Reference Material Packet	36
18	Frame Rate Effects on Operator Target Recognition Performance	38
19	Frame Rate Effects on Operator Target Recognition Performance with Transmission Delay Taken Out	39
20	Effects of Frame Rate and Control Mode on Operator Target Acquisition Performance	40
21	Effects of Frame Rate and Control Mode on Combined Operator Target Recognition and Target Acquisition Performance	41
22	Research Design Used in Frame Rate Study	44
23	Hand Control Shaping Function	46

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
24	Effects of Frame Rate on Target Designation Time	49
25	Effects of Frame Rate on Precision Target Designation Accuracy	40
26	Frame Rate Effects on Target Tracking Accuracy	51
27	Examples of the Three Resolutions Investigated	54
28	Example Target Scene at 1X, 2X, 4X, and 8X Zoom	55
29	Effects of Video Resolution on Operator Target Acquisition Performance	60
30	Comparison of Zoom and No Zoom Conditions	61
31	Percent of Trials Zoom Used When Available	62
32	Amount of Zoom Used by RPV Operators	62
33	Zoom, Frame Rate Interaction	63
34	Example Bandwidth Compression Bit Error Rate Jamming Target Scene Used in the Study	69
35	Example Bandwidth Compression Bit Error Rate Jamming Target Scene Used in the Study	70
36	Experimental Design for Bandwidth Compression, Bit Error Rate Jamming Study	72
37	Experimental Design for Bandwidth Compression Study	73
38	Effects of Bit Error Rate Jamming on Operator Target Acquisition	75
39	Bandwidth Compression Effects on Operator Target Acquisition Performance	76
40	Comparison of Bandwidth Compression From 1:1 to 12:1	77
41	Effects of Bandwidth Compression on Operator Tactical Target Recognition	79
42	Range-to-Target Recognition Performance	88
43	Probability of Correct Target Recognition Performance	90
44	Data Compression Modules	98
45	Data Expansion Modules	99
46	Memory Architecture	104
47	Timing and Control Module of Airborne Unit	105
48	Expansion Module Block Diagram	111
49	Power-Delay Products of Component Technology	113
50	Airborne Processing Unit Hardware Diagram	116
51	Airborne Unit Packaging	117
52	Ground Processing Unit Hardware Diagram	117

LIST OF TABLES

Table		Page
1	Example Video Bandwidth Reduction/Compression Systems	83
2	Bandwidth Reduction/Compression Systems Evaluated in the Simulation	85
3	Video Signal Processing Functions	94
4	Data Link Performance Characteristics	97
5	Key Parameters for Interfacing the Sensor Module with the System	100
6	Characteristics of Single Chip CCD Memories	103
7	Scan Converter Process Breakdown	109
8	*Data Expansion Parameters*	111
9	Reliability Analysis	119

SECTION 1

INTRODUCTION AND BACKGROUND

It has been recognized for some time that to exploit the full potential of remotely piloted vehicles (RPVs) a new generation system is required. This system must be capable of planning and executing missions on a large scale, of controlling many RPVs in flight simultaneously, and of accommodating a mix of missions. One of the key missions, and the most difficult in terms of required equipment and technology, is air-to-ground strike, particularly in the defense suppression area. This is because practical RPV navigation techniques presently available cannot achieve the necessary accuracy to bring the vehicle into a sufficiently precise relationship to the target. It is therefore necessary for a remotely located human operator to effect terminal navigation of the RPV by means of transmitted imagery from an electro-optical sensor. Transmission of the imagery signal from the RPV to the operator at the remote control center is difficult in a hostile ECM environment.

The problem addressed by this study program was to derive a design for a video data link system such that satisfactory transmission of images in a jamming environment is possible. This implies that by the application of image bandwidth reduction/compression techniques, the signal bandwidth can be decreased to the point that, through the application of spread spectrum techniques, a measure of processing gain over the jammer can be achieved. The recommended design must satisfy the following criteria:

1. The quality of the sensor video displayed to the human operator must be high enough to allow detection, recognition and acquisition of the target within prescribed time constraints.
2. The operational implementation must be reasonable in terms of cost, size, weight, power consumption, cooling requirements, and reliability.
3. The resulting bandwidth must be no greater than 450 kHz, and preferably less.

THE STRIKE OPERATOR'S TASKS

During the strike segment of an RPV sortie, a single vehicle will be under control of a dedicated remote strike operator for an interval of 3 to 5 minutes. The functions of the strike operator during this period will include: 1) examination of briefing and reference materials, 2) monitoring of automatic vehicle and systems operation, 3) adjustment and control of sensors, 4) recognition and acquisition of targets, and 5) preparation and launch of a weapon. A representative strike profile is shown in Figure 1.

Video data link bandwidth will have the largest effect on the tasks of target recognition and sensor pointing for target acquisition. The process of target acquisition starts, for the operator, at the time he assembles, prepares, and annotates the briefing and reference materials appropriate to the target. These may include maps, oblique and vertical photographs, sketches, mission profiles, and anything he can put together to help him locate the target. This packet will be accessible to the strike operator at his console station. Prior to vehicle handover from an enroute controller or during run-in to the strike area, the strike operator will refresh his memory by consulting the briefing packet materials. During pop-up, the sensors will automatically be pointed in the direction of the target with an accuracy dependent on accrued navigation and pointing errors. The sensor field of view will be on the order of 20 degrees – enough to assure that the target is

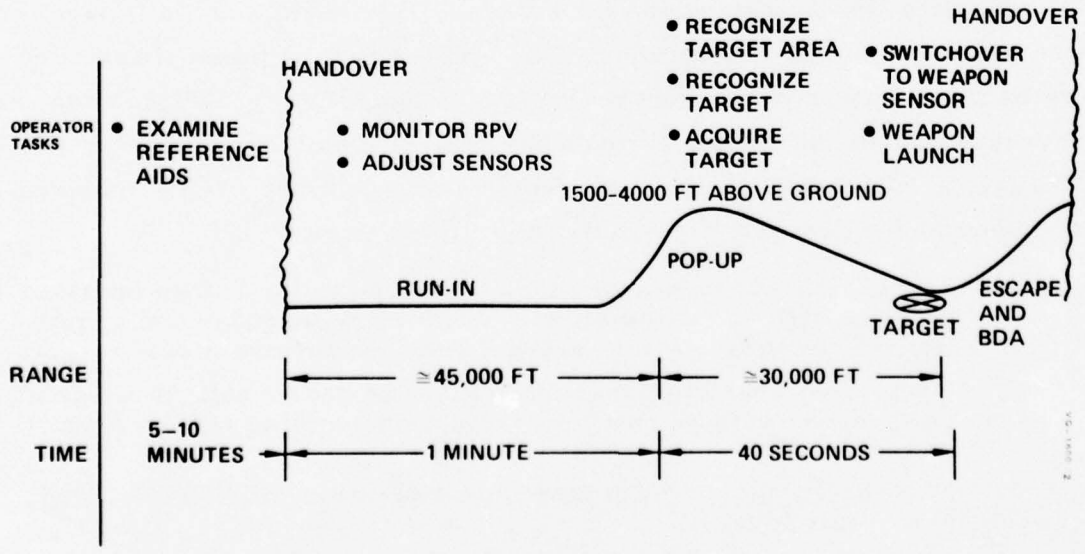


Figure 1. Representative profile of strike mission segment.

in the field of view and that sufficient context is provided at the initial stages of acquisition. The vehicle will pop-up to an altitude that will meet operational requirements and unmask the terrain between the RPV and the target. The strike operator's initial task will be to recognize the area that contains the target. His ability to do this will be a function of the video image quality, the adequacy of his briefing, and the presence of prominent and unique landmarks. If the operator knows where the target is in relation to these landmarks, he will then use a hand control to either slew the sensor line of sight to lock-on the target or designate the target to the system by placing a cursor on the target. The combination of closure on the target and zoom capability, if available, will serve simultaneously to increase the displayed target size and the number of resolution lines placed across the target. At some range the operator will have enough information to decide that he has found the target and is willing to commit a weapon to it. He will then re-designate the target for final weapon delivery or preparatory to handover to a weapon sensor. After weapon release, the strike operator will conduct battle damage assessment, if required, or handover the vehicle to the enroute operator.

OPERATOR TASKS, VIDEO INFORMATION, AND BANDWIDTH REDUCTION/COMPRESSION TECHNIQUES

Frame Rate

When video frame rate is reduced, the video frame may be reconstructed at the remote display using data storage and scan conversion to provide a flicker-free display. Bandwidth reduction as large as 30:1 has been contemplated by reducing the frame rate from 30 to 1 frame per second, but a transmission delay is incurred that is equal to one sampling period. Frame rates as low as 1 frame per second, as demonstrated by AMRL (Self and Heckart, 1973), are adequate for the task of target recognition where control of the RPV and sensor is made fully automatic through use of an onboard autopilot/navigator. For this reason, a 30:1 bandwidth reduction and possibly more is plausible during the performance of this task.

In subsequent manual control tasks requiring zoom, sensor slewing, or vehicle control, the control loop is closed through direct observation of the video picture. In most control applications involving sampled data systems, it has been found that a sampling rate at least 20 times the control

bandwidth is required. Thus, for a 5 RAD/sec bandwidth requirement (adequate for manual rate control) a sampling rate of 8 samples per second or more is desired. This was supported by the results of a preliminary RPV study conducted at Hughes, shown in Figure 2. These data indicate that for either sensor pointing or direct vehicle control, operator performance deteriorates rapidly for frame rates less than 8 frames per second.

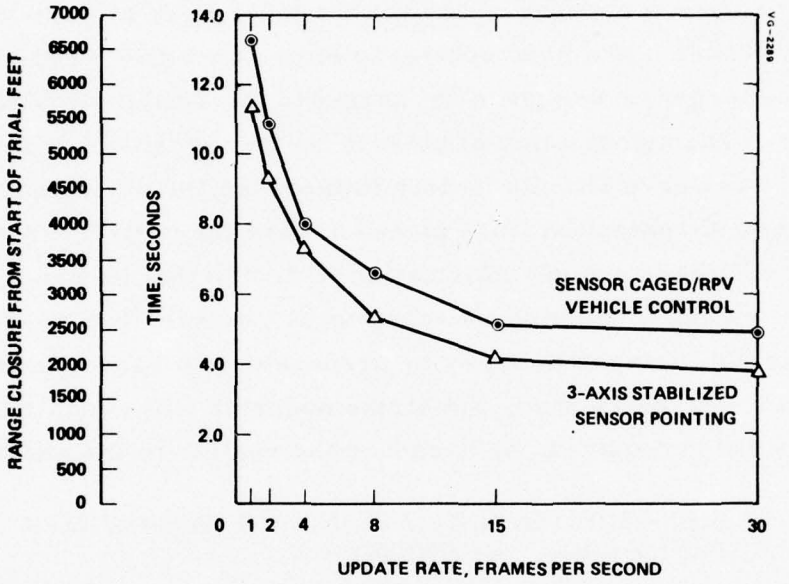


Figure 2. Mean time to acquire targets as a function of frame rate and sensor pointing mode.

Resolution

The operator's ability to discriminate targets and thus separate them from the background is dependent upon sensor display resolution. Accordingly, total system resolution will affect the range at which targets may be found and the probability that they may be acquired. The system should be designed to provide the operator with the resolution he needs to find the targets of interest at the longest possible range, as time in the "slot" is very short. The highest resolution will be required in the initial phase of the attack during and just after pop-up when the operator must recognize the target.

Resolution can be reduced by at least three methods:

1. Removing picture elements or scan lines in a manner that leaves resolution evenly distributed across elevation and azimuth.
2. Removing elements in a non-linear or anisotropic manner. Maintaining high resolution at the center of the scene and progressively

reducing resolution toward the edge of the presentation is an example of non-linear resolution. Providing higher resolution in the elevation dimension than the azimuth dimension is an example of anisotropic resolution.

3. Removing elements from the area surrounding a full resolution, moveable spot on the display. "Foveal Spot Scanning" is a special case of this technique. Moving the high resolution spot by means of a hand control, in a manner similar to cursor positioning, would be another means for achieving a similar result.

A preliminary RPV experiment on the effects of quantized resolution on target recognition was conducted at Hughes. In the study, the operator had to find a target for which he had been briefed using aerial photographs. Time to acquire the target was the dependent variable, and the results for resolution are shown in Figure 3. This figure indicates that a resolution of 480 lines asympotically approaches 100 percent target recognition while a 240 line resolution only allows 90 percent recognition. Analog bandpass filtering and other methods which provide a global degradation in resolution may be detrimental to operator performance.

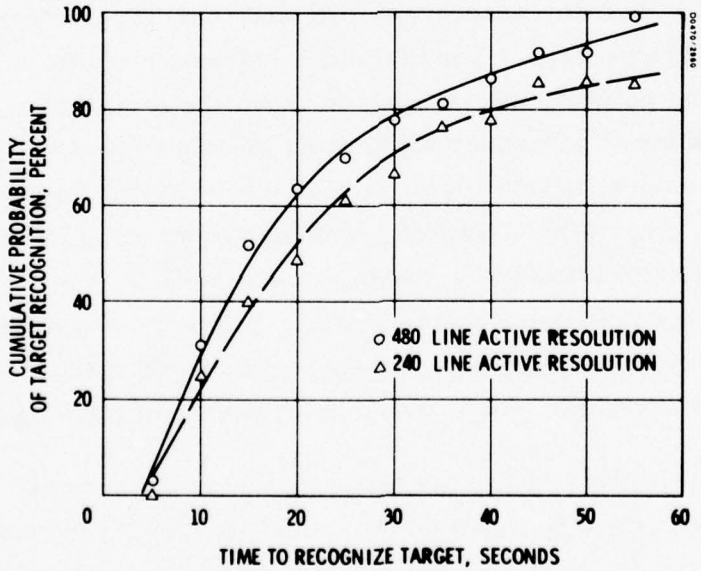


Figure 3. Effect of resolution on RPV target recognition performance.

Bandwidth Compression

Theoretical and computer simulations of video bandwidth compression techniques indicate that digital picture transmission is possible using as few

as 0.5 bit per picture element. Bit rate reduction does degrade video image quality and, therefore, can degrade operator task performance. Evaluations of images produced by computer simulations of bandwidth compression techniques have been largely qualitative in which an original uncompressed image is subjectively compared to the same image that has undergone bandwidth compression. Quantitative data which relate operator task performance to video bandwidth compression are scarce.

Performance Compensating Techniques

The bandwidth reduction/compression techniques described above, when pressed to their limits, will degrade the operator's ability to recognize the target and control RPV sensor pointing. This is primarily because of reduced display resolution caused by a S/N reduction, loss of spatial frequency content, and transmission delays caused by frame rate reduction. Greater degrees of bandwidth reduction/compression can be achieved if compensating techniques are used. Two promising techniques are described below.

Image Motion Compensation. Image Motion Compensation (IMC) is a method to enhance operator sensor pointing and tracking performance under conditions of low frame rate. The technique utilizes real-time vehicle attitude and sensor pointing information to move the image of a single frame of data on the display in a manner simulating the movement that would be observed if the frame rate was high. In this way, the image would be constantly in motion, providing a smooth transition from one frame of data to the next and thereby providing the information needed for operator control. IMC appears to be a promising compensation technique, because the equipment is incorporated in the ground processing equipment and requires the RPV to relay only vehicle attitude and sensor gimbal angle information.

Zoom. The ability of the operator to recognize a target is dependent upon the number of resolution elements overlaying the target image. This criterion can be met by providing sufficient sensor resolution for a target image of given sensor field of view or by reducing field of view to achieve the required number of resolution elements.

Zoom allows increased resolution for recognition purposes once the target area has been recognized and the operator is oriented. A single magnification may not be suitable for all situations because of the inability

of the operator to orient himself if limited to a narrow field of view. The questions concerning zoom are related to the field of view requirements for target area acquisition as well as the image size and resolution requirements for target recognition.

STUDY APPROACH

The principle focus of this program was strike operator task performance with video bandwidth reduction/compression. The program included four major tasks. An existing Hughes remotely piloted vehicle simulator was modified and integrated with a Hughes developed one-dimensional Hadamard transform system to provide the apparatus for conducting man-in-the-loop laboratory investigations. Four parametric research studies were then conducted to obtain data which functionally relate RPV operator task performance to video image bandwidth reduction/compression design parameters. The results of the parametric studies were used to derive nine bandwidth reduction systems which were compared to a baseline standard 512 by 512 element, 6-bit video, 30 frames per second TV system in a bandwidth reduction/compression systems simulation. A recommended video image bandwidth compression/reduction was selected based on the results of the systems simulation and a hardware implementation analysis of the recommended system was performed. These four program tasks are described in the following four sections of this report.

SECTION 2

REMOTELY PILOTED VEHICLE SIMULATOR EQUIPMENT

INTRODUCTION

A remotely piloted vehicle simulator and a real-time Hadamard transform video processor were designed and developed to provide an effective and efficient means to study and evaluate the terminal phase of RPV strike and reconnaissance missions. These facilities provided the capability to perform the required video bandwidth reduction/compression man-in-the-loop laboratory research and simulation studies.

DESCRIPTION OF THE RPV SIMULATOR

Functional Overview

The Hughes RPV Simulator consists of simulation software and hardware, including a XDS Sigma 5 digital computer, special high-speed input/output interfaces, an image generator, a symbol generator, a scan converter, and experimenter and operator consoles. The principal parts of the RPV simulator are depicted in Figure 4. The sensor simulation device is a television scanner (TVS) which scans rear-illuminated photographic film imagery to produce data simulating RPV video from an electro-optical sensor.

The RPV simulator is depicted in block diagram form in Figure 5. Its salient features are summarized below:

- Provides a source of simulated RPV television sensor video
- Provides dynamic operator control of vehicle, sensor, and cursor
- Provides a means of evaluating real-time transform bandwidth compression techniques
- Provides a means for frame rate variation
- Provides gray shade bits variation for simulation of digital data link
- Provides variation of sensor video resolution

PRECEDING PAGE BLANK-NOT FILMED

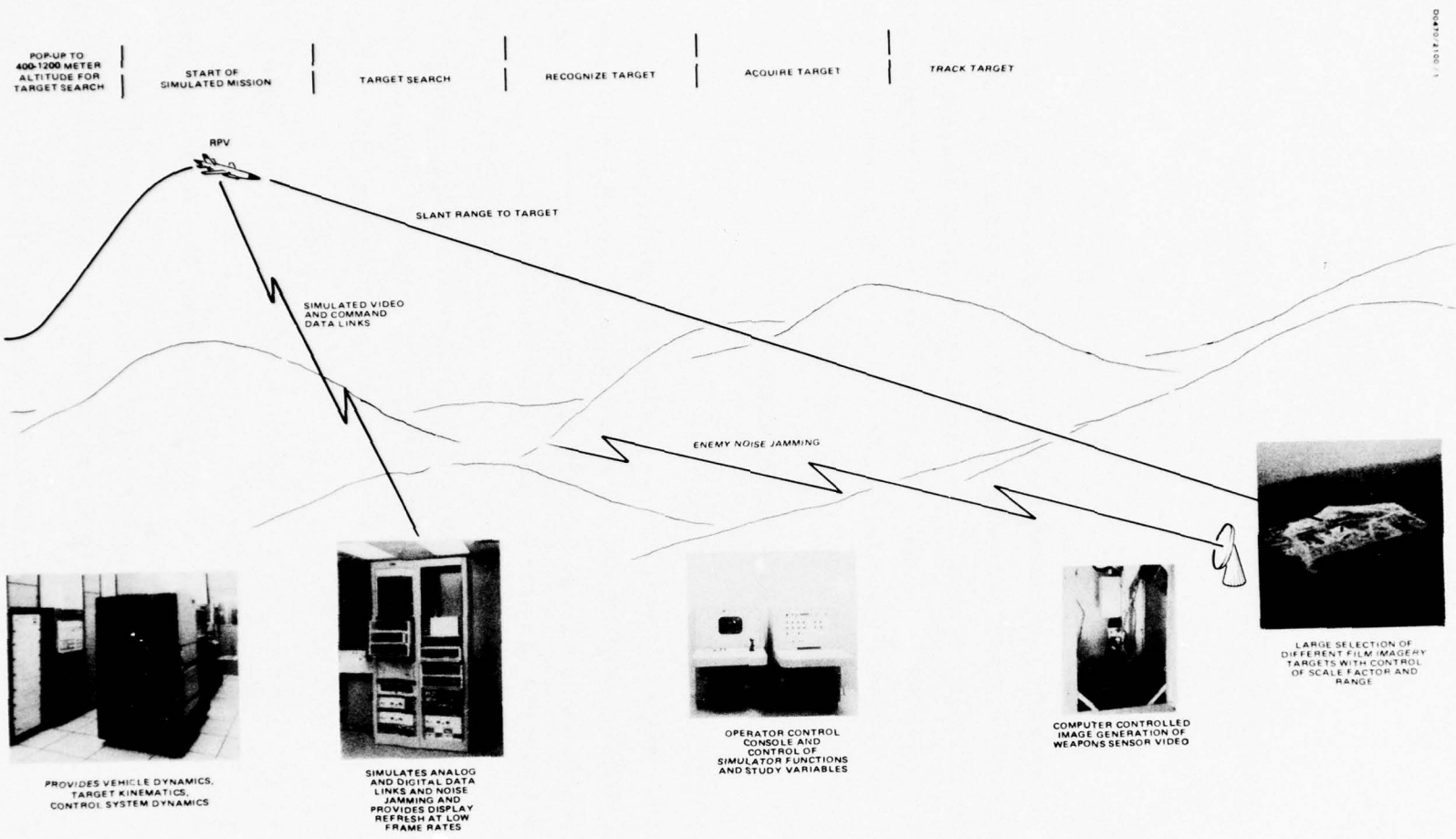


Figure 4. RPV simulator – mission capabilities.

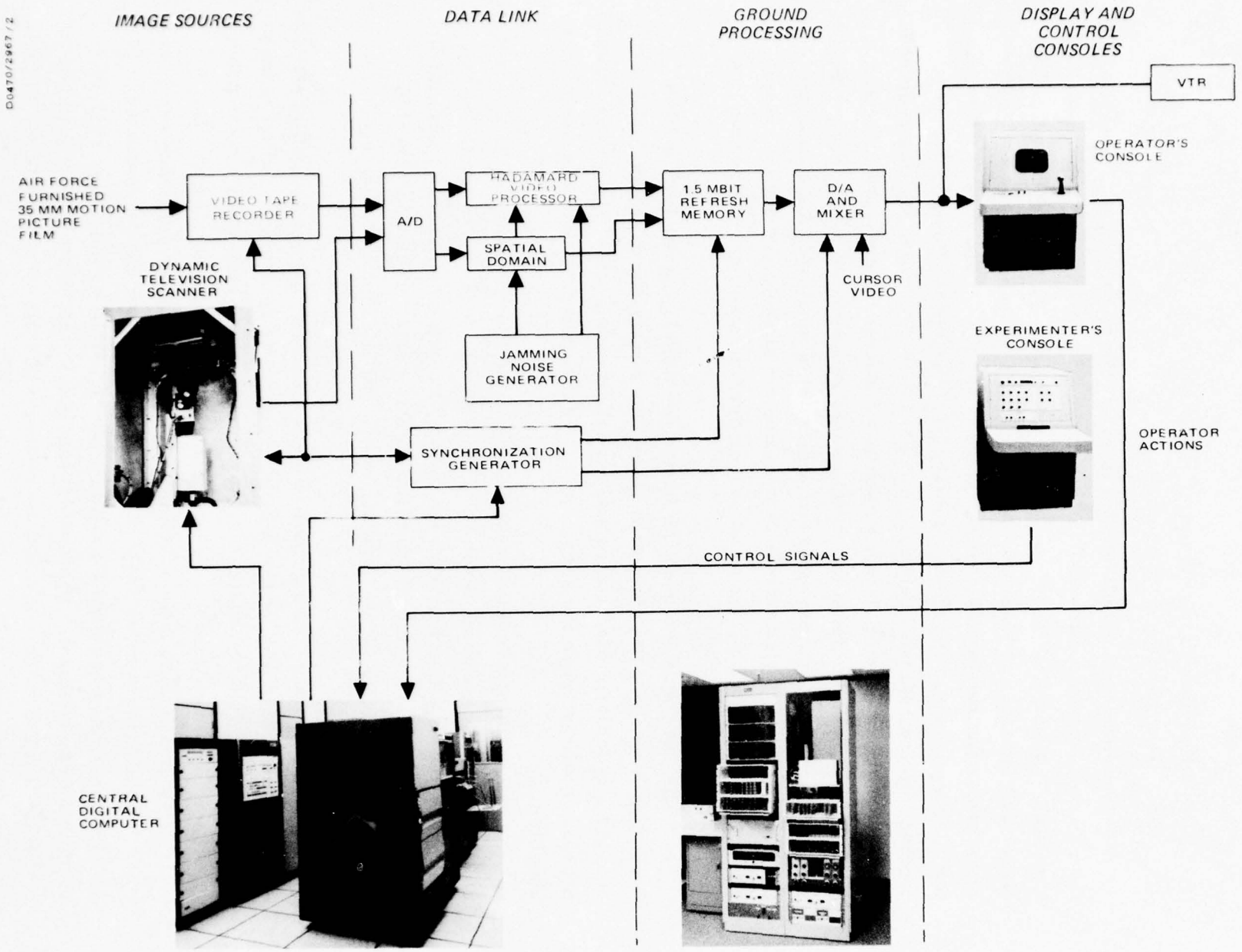


Figure 5. RPV simulator.

- Provides digital jamming noise source
- Provides variable zoom.

The video was simulated in a television-type format at a selected frame rate. It was digitized at the spatial and intensity resolution desired and either transmitted in the spatial-intensity domain or transformed to the Hadamard domain and transmitted. Jamming noise was introduced by pseudo-randomly changing the bits at the desired error rate. The digital video was then decoded back to the spatial domain, if initially transformed, prior to loading into the refresh memory. A 1.5M bit refresh memory was required to convert the low frame rate formats to a flicker-free standard television format. Output video from the memory was converted to analog form, mixed with cursor video, and presented on a television monitor. All necessary parameters were varied from a central control console. A digital computer was used to provide the flight and sensor dynamics and provided experimental control and scoring.

The simulator included the means for simulating the RPV vehicle dynamics, providing the simulated video, the simulation of the data link with real-time transform electronics and digital jamming noise, the ground based processor with refresh memory, and the experimenter's and RPV operator's consoles.

A computer controlled servo-driven zoom lens simulated RPV target closure as well as a zoom function in the RPV sensor. Atmospheric attenuation variation as a function of range to target could be simulated by computer variation of camera gain. Typical values for range simulation with this equipment are 30,000-foot range at pop-up with closure to 1,500 feet at the end of the run.

Sensor pointing was perceived by the RPV operator as dynamic attitude and translational motion of the sensor imagery. Two sensor pointing modes were included in the simulator: vehicle steering and stabilized sensor pointing. Both were controlled by a hand control on the operator's console.

Automatic simulator functions and vehicle/sensor dynamics computations for the RPV were performed by a Xerox Sigma 5 digital computer. The computer has been specifically configured for use in a multi-user real-time simulation environment. The system monitor in the Sigma 5 was designed to facilitate foreground/background operation to permit efficient utilization of computer resources.

The computer software written for the RPV simulation performed the following functions: vehicle/target kinematics, vehicle autopilot and sensor dynamics, scoring, data recording, experimental conditions set-up, atmospheric haze simulation, and motion compensation control aiding.

Video Sources

Two sources of simulated video were used, one originating from Air Force provided 35-mm film and the second originating from the Hughes dynamic flight simulation equipment. The Air Force provided 10 target runs on 35-mm film, which when projected at 24 frames per second simulated a target run of approximately 40 seconds. To perform the processing and desired simulation, this film was converted to a standard 525-line television format and recorded on video tape. This conversion was performed using the tele-cine film chain apparatus shown in block diagram form in Figure 6. The film was projected optically into the vidicon camera and recorded on the video tape recorder. By projecting at 24 frames per second, and using a special projector with a 60-Hz shutter rate, no flicker was recorded in the 30-frame per second video tapes.

The Air Force furnished target runs were "canned" runs which precluded evaluation of the operator actually flying the RPV or pointing the sensor. This was considered an essential aspect in the evaluation of frame rate as a means of bandwidth reduction. Also, the 10 target runs were not sufficient to conduct the four parametric laboratory investigations. Therefore, the existing television scanner in the Hughes RPV simulator was used in conjunction with existing film transparencies to augment the Air Force furnished scenes. This scanner, shown in Figure 7, consists of a high

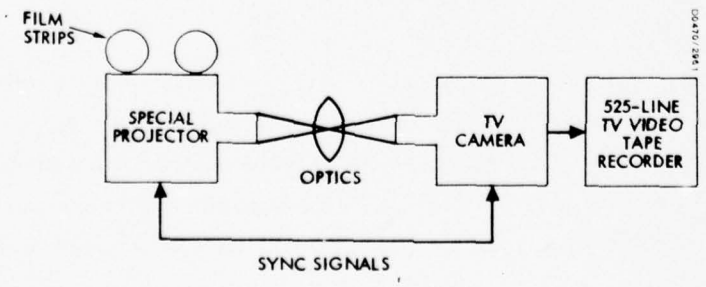


Figure 6. Tele-Cine video recording apparatus.

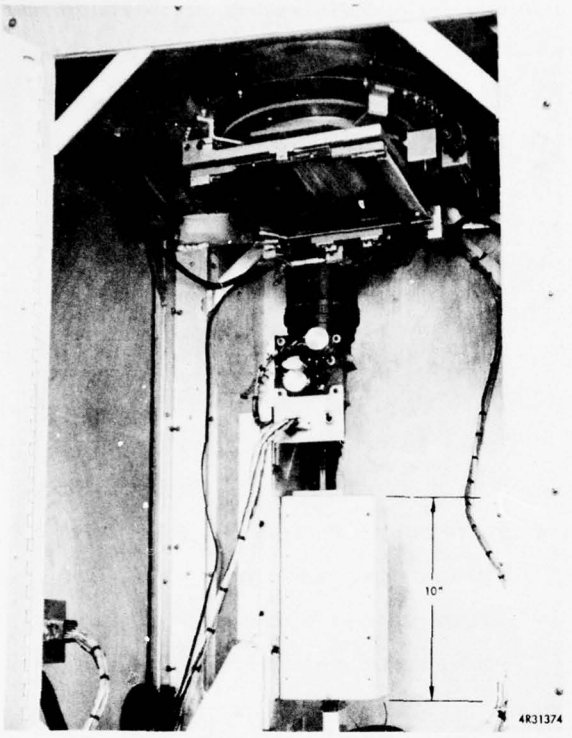


Figure 7. Hughes television scanner.

quality variable scan rate closed-circuit television camera, automated 20:1 zoom lens, and rotating/translating transport.

Vehicle Steering Mode

In this mode the simulated sensor was caged to the vehicle fuselage reference line. This is an aircraft or autopilot stabilized condition where the operator flies "through the autopilot". Hand control pitch rate commands appeared as vertical picture translation rates on the monitor and roll commands appeared as horizontal translations combined with picture roll. This was accomplished on the TV by computer control of the horizontal, vertical, and roll film transport servos. The desired flight dynamics were programmed in the computer.

Sensor Pointing Mode

The sensor was stabilized in pitch, roll, and yaw. The hand control was used to point the sensor independent of the attitude of the vehicle. Sensor motion was simulated using the film transport servos.

Digital Refresh Memory

In an actual RPV mechanization, low scan rate video would be received on the ground and displayed to the RPV operator. It is unacceptable to provide a display which is refreshed at a rate slower than 40-50 Hz, since the flicker would cause operator fatigue and degrade operator performance. Therefore, the input video must be stored to allow the display to be refreshed at a flicker-free rate. It is desirable to use a standard television rate

(30 frames per second, 60 field/sec), so standardized off-the-shelf display and recording equipment can be used.

There are two basic techniques for converting the slow scan video to a television format. One is to perform analog scan conversion using an analog scan converter tube. The other technique is digital scan conversion. The analog scan converter possesses an electron charge storage mesh upon which a charge pattern of the sensor scene is written at the slow scan rate and read off in the television format. Such tubes require many adjustments and require complex compensation circuitry to accommodate multiple writing rates. They also tend to provide non-uniform limited dynamic range displays, are unreliable, and expensive to replace. With digital scan conversion, the analog storage media function is accomplished with digital memory and associated digital logic which provides a crisp, uniform, and reliable display. Therefore, digital scan conversion is recommended for the actual RPV application and was the mechanization for this simulation.

The RPV simulator scanned the closed-circuit television camera at the desired frame rate (0.0625 to 30 Hz) and utilized a 1.5M-bit digital scan converter memory to provide the display refresh function. A block diagram of the refresh memory mechanization is shown in Figure 8. The refresh memory, implemented with MOS RAMS, consists of 32,768 words of 48 bits each. The digitized video was received from the simulated data link in

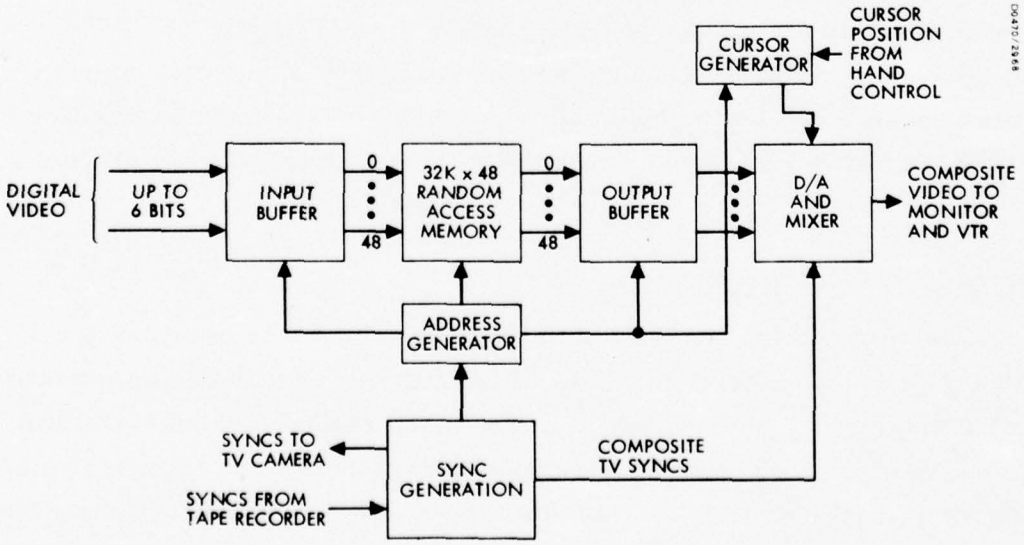


Figure 8. Block diagram of RPV simulator refresh memory mechanization.

groups of up to 6 bits each (depending on the gray shade encoding selected). Eight groups were accumulated in a 48-bit buffer and loaded simultaneously into the refresh memory. Readout was always in a 30 frame per second, 525-line format with 480 active lines. To provide 240 and 120 element vertical resolution modes, the same data were displayed on two and four lines, respectively. Horizontal resolution was controlled by utilizing low pass filters having cutoff frequencies of 4.2, 2.1, or 1.05 MHz in the input video channel prior to the analog to digital (A/D) conversion.

The digitized video was read out of the refresh memory, reformatted, digital to analog (D/A) converted, and mixed with composite sync pulses to drive the display. A positionable cursor was also provided, generated by comparing hand control position signals with display position addresses and generating video pulses to be mixed with the sensor video.

Operator's Control Console

The operator (subject) could control simulated RPV vehicle steering in the vehicle steering mode by introducing pitch rate and/or turn commands with a proportional, two-axis displacement hand control. In the ground stabilized sensor steering mode, displacement of the hand control introduced proportional vertical and/or horizontal rate commands to control the pointing angles of a simulated 3-axis gimballed, ground-stabilized sensor. The same hand control was used in other modes (cursor designation) to position a cursor on the display for various designation or tracking tasks. Manual zoom, lock-on, cursor activation, and image freeze commands were activated by switches on the hand control. A 14-inch television monitor was used for the video display. The operator's control console is shown in Figure 9.

Experimenter's Control Console

The controls for the RPV simulator not related to operator functions were on the experimenter's console. They provided mode and parameter selection and system adjustments. Some of the controls commanded the computer to initiate automatic operations and adjustments for formal studies. Others were used manually for informal studies or demonstrations. The functions performed by these controls are as follows: simulator mode

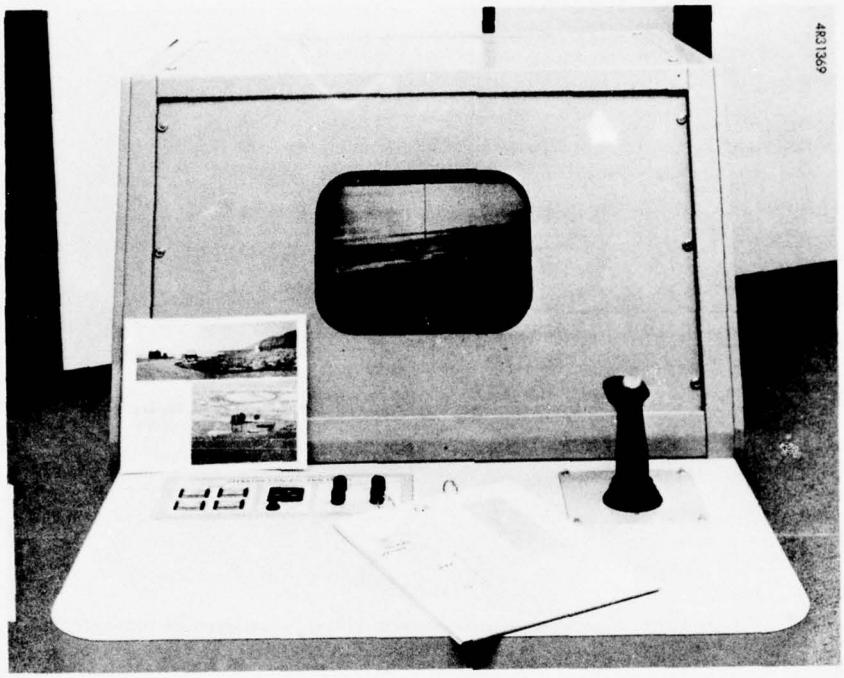


Figure 9. Operator's control console.

control, subject code insertion, test and initial condition selection, test run control, parameter selection in the manual mode, and cursor positioning and TV scanner adjustment in the manual mode. The experimenter's console, shown in Figure 10, was positioned near the operator's console so that the experimenter could monitor the display and the RPV operator's actions.

Computer Functions and Software

The software for the RPV simulation performed a number of important functions. Included were kinematics, vehicle/autopilot and sensor system dynamics, scoring, data recording, experimental condition set-up, initial condition set-up, and haze model simulation.

Kinematics

A fundamental function of the simulation software was to compute the location of the RPV with respect to the earth. To do this, the RPV was treated as a point mass in space that had velocity and direction. The direction was a result of vehicle attitude computed in another part of the program.

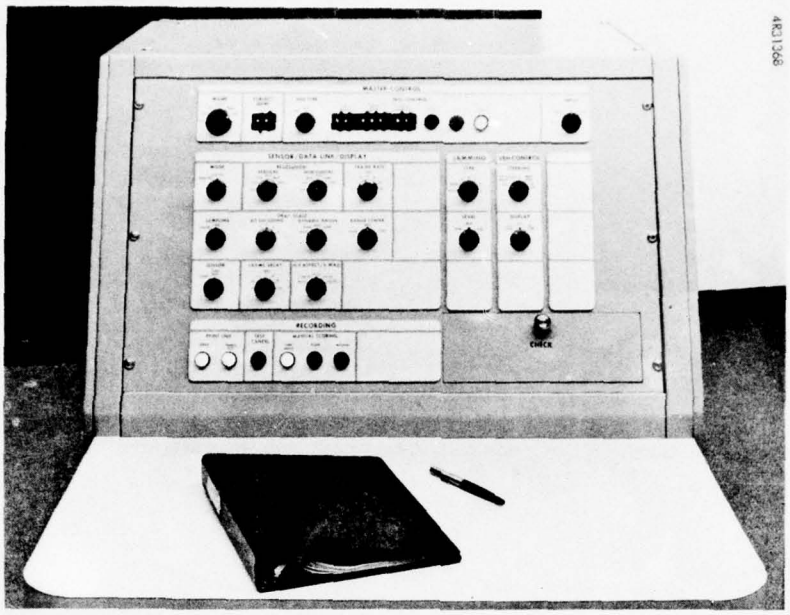


Figure 10. Experimenter's control console.

The vehicle velocity was assumed to be held constant by the autopilot. Figure 11 depicts the arrangement of the earth coordinate system with respect to the vehicle. The coordinate system was centered at the target, and the

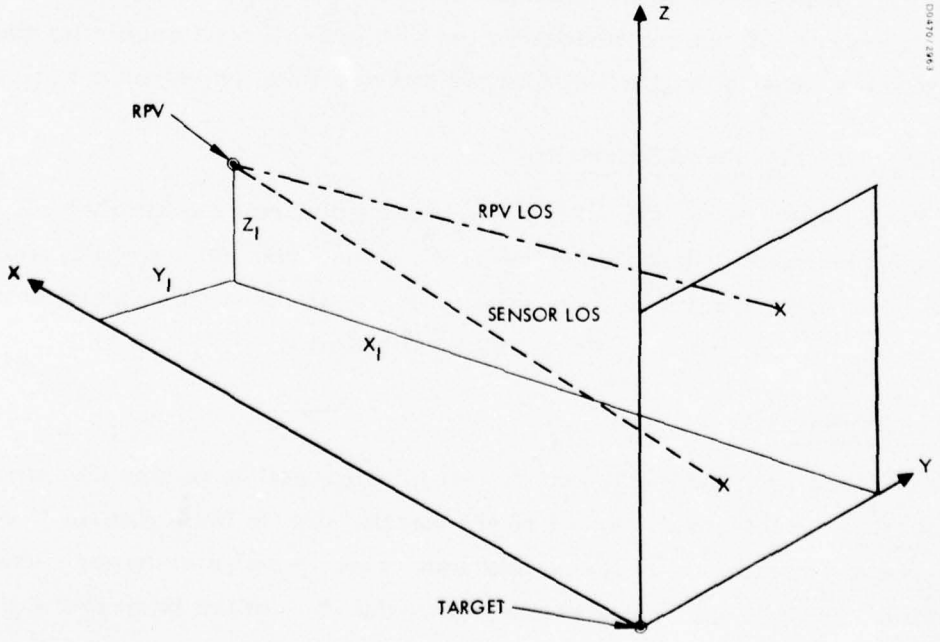


Figure 11. RPV kinematics.

Y-Z plane represented the area covered by the target film transparency. The kinematics software also computed the intersection of the vehicle or sensor line-of-sight within the Y-Z plane. These intersection points were used to position the film transparency servos to simulate the image motion resulting from vehicle or sensor motion. In Figure 11, X_I, Y_I, Z_I represent the initial RPV position at the start of a run.

Vehicle/Autopilot and Sensor Dynamics

The vehicle and autopilot dynamics were simulated as a combined system. This was done by using second-order short-period approximations with response characteristics typical of existing remotely piloted vehicles. Sensor dynamics were simulated as first-order, rate control characteristics.

Scoring

When the subjected centered the target on a reticle or placed a cursor over the target, the computer calculated the angular pointing error to the target. Time was measured from the beginning of the run until the lock-on button was depressed. The computer performed automatic scoring by recording all RPV operator actions.

Data Recording

Data recording was provided in several ways. All system data were recorded on magnetic tape at 0.2 second intervals to provide a complete history of each trial for later off-line reduction, tabulation, and analysis. In addition, instantaneous values of all system parameters were printed on the computer's high-speed line printer on command from the experimenter's console for a review of the simulator/experiment status. This provided verification of proper operation of the simulator to the experimenter. Finally, summary data (time, error, operator, etc.) were printed out at the end of each trial to provide immediate feedback of the trial results to the experimenter. The operator's target recognition and lock-on times were converted so the printout included slant range compensated downward to account for RPV forward translation that took place during any scene delay generated by the reduction/compression process. The automatic tabulations of results simplified subsequent data analysis.

Experimental Conditions Set Up

The experimenter had the ability to control a large number of experimental variables from his console. This same control was exercised by the computer when the master control mode was set to "AUTO". By using this capability, the experimenter could pre-define a series of experimental conditions which were selectable. As the experiment progressed, he selected each new set of parameter values by setting the "TEST SELECT" digi-switches to the next test number. The computer then automatically set all of the variables to the desired values. In this way, the experimenter greatly reduced the set-up time for each trial and could operate with confidence that he had not forgotten to set some key parameter, thereby enhancing data reliability. The parameters selected in this way were input source (TV, flying-spot scanner, tape), mode (analog, digital), vertical resolution, horizontal resolution, frame rate, gray scale bit encoding, sensor (continuous, snapshot), frame rate, jamming type, jamming level, display (no symbols, attitude, all), video filter, pre-amp gain, and camera gain.

Initial Conditions Set-Up

In a similar manner, initial test conditions were predefined and selected as sets for each trial. The computer read the value of the "INITIAL CONDITIONS" digi-switch and initialized the problem accordingly. The parameters so selected were cross range error, altitude error, range to target, RPV initial roll angle, RPV initial pitch angle, RPV initial yaw angle, and RPV velocity.

Image Motion Compensation

At low frame rates, the operator of an RPV has much difficulty in the control of the sensor for acquisition tasks. This difficulty can be overcome by dynamically moving the single frame image at the ground station in harmony with the motion of the vehicle sensor. This is possible, because the sensor gimbal angles are available over the low bandwidth data link. Because the ground scene represents a snapshot field of view for one instant in time, blank areas will appear on the monitor as the imagery moves. However, on the next frame update, the blank area should be filled by the new frame.

The RPV simulation modeled an image motion compensation system by using the Sigma 5 computer to command selective readout from the display refresh memory as a function of computed vehicle motion. Figure 12 illustrates the functional operation of the image motion compensation simulation. The digital refresh memory contained a complete snapshot video frame representing the world at the time of the last video update. Vehicle motion subsequent to that instant in time was computed and the information was used to determine a starting address and corresponding time delay for initiation of information readout from the refresh memory during each refresh TV field. If the sensor pointing angle had moved down and to the right, then memory readout was initiated "down" the appropriate number of TV lines in memory coordinates and "over to the right" the appropriate number of picture elements. During the latter part of each line and following the last line in memory, the display was blanked. The displayed image then appeared to have moved up and to the left of the TV monitor.

If the sensor pointing angle had moved up and to the left since the last video update, the displayed image should appear to move down and to the right with the upper and left portions of the display blanked. This was accomplished by delaying the initiation of memory readout during each refresh TV field the appropriate number of TV line periods and then delaying the start of each TV line readout by the appropriate amount.

When the sensor pointing angle had moved to either of the two quadrants not described, a combination of the two techniques just discussed was used to read out the image, i.e. starting memory address shift and time delay in readout initiation as appropriate for the given quadrant.

The image azimuth and elevation positions were updated continuously by the Sigma 5 computer to simulate the low bandwidth transmission of the sensor gimbal and vehicle position relative to the ground.

Simulation Software Operation

Taken together, the computer/software functional capabilities were implemented as shown in the block diagram of Figure 13. At the beginning of each series of trials, data describing initial conditions and test conditions were read from punched cards into a "Master Data Base" in the computer by a master control program. The master control program then controlled the

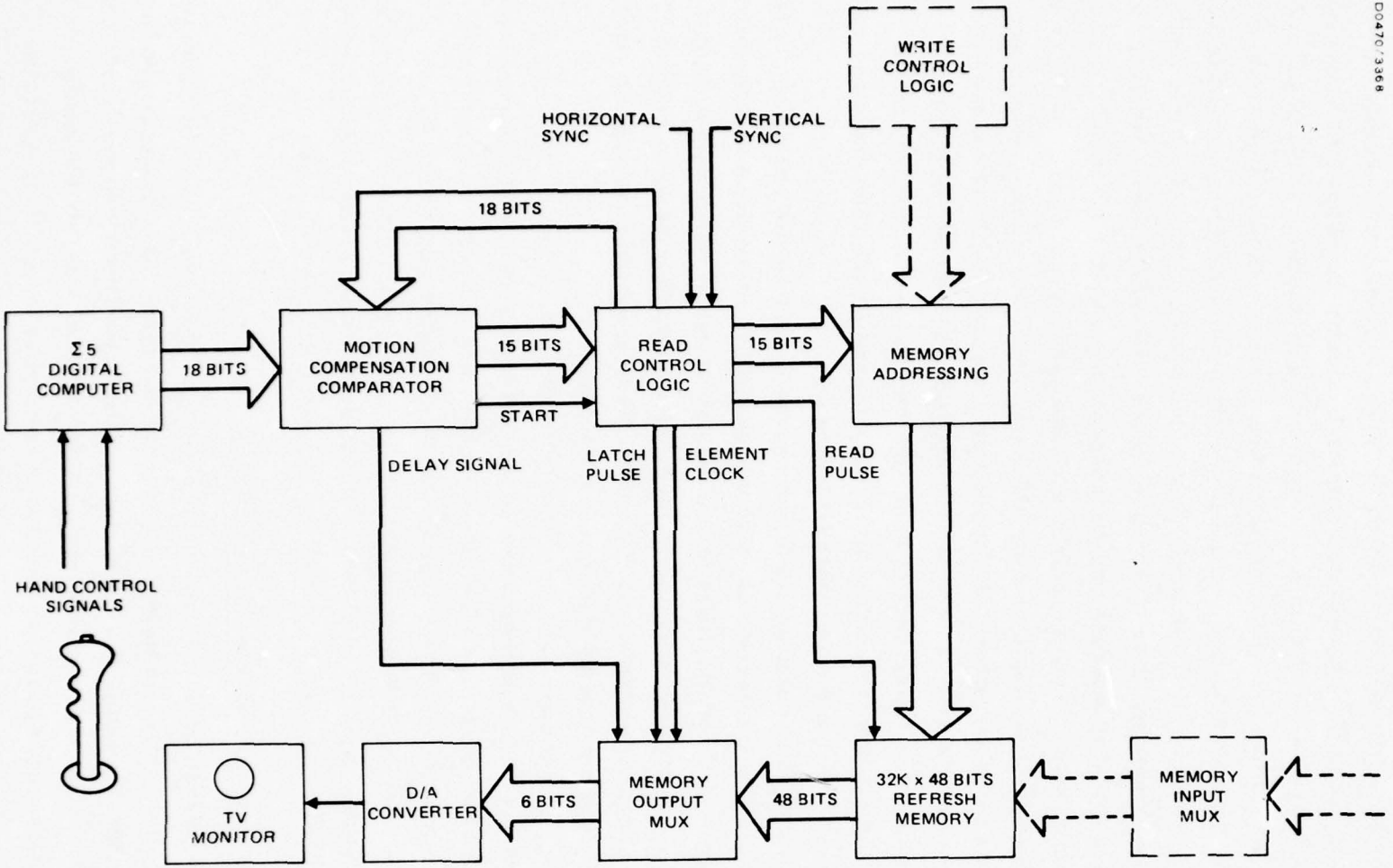


Figure 12. Simulation of image motion compensation.

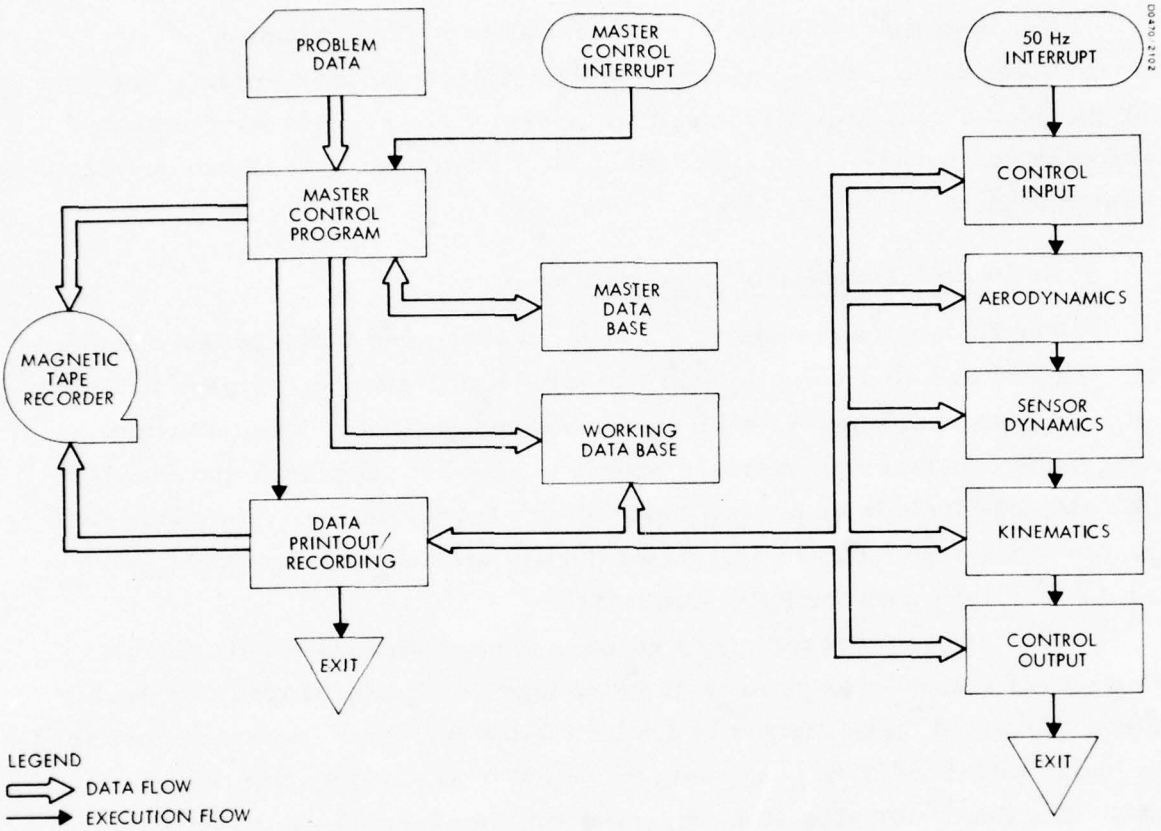


Figure 13. Simulation software functional diagram.

operation of the simulation (start, stop, reset, new trial, etc.) by monitoring the status of switches on the experimenter's console. At the beginning of each trial, data corresponding to that selected by the experimenter (initial conditions and experimental parameters) were transferred from the Master Data Base to the "Working Data Base", and the real-time computation processes were initiated. Then, once each 20 milliseconds, analog and discrete control signals were read from the consoles, vehicle/autopilot and sensor dynamics and kinematics were computed, and appropriate command values were output to the servos in the simulator. Trial data were output to the magnetic tape storage unit, and at the end of each trial an end-of-file mark was written on the magnetic tape, and control returned to the master control program until the next trial was begun.

RPV Data Link Simulation and Video Processor

The data link simulation equipment allowed the evaluation of transmission in both the spatial domain and the transform domain. The data link included a real time Hadamard transform video processor to achieve bandwidth compression up to 12:1 which is equivalent to 0.5 bit per picture element transmission data rate.

Hadamard Transform Video Processor

The Hadamard transform video processor used in the program allowed 3:1, 4:1, 6:1 and 12:1 compression ratios; 2:1, 4:1 and 8:1 low pass filtering; and a programmable variable window compression ratio. The following paragraphs describe the interface between the video processor and the RPV simulator and include an overall block diagram description. The video data link block diagram, Figure 14, shows the key elements of the video processor and the interface with the RPV simulator.

The video processor accepted EIA 525 standard television signals from the RPV simulator camera or video tape recorder, shaped this analog video, converted these signals to a 6 bit digital representation, accomplished the Hadamard transform of the data 96 bits at a time, and compressed the data. The expansion algorithm accepted the transformed and compressed video data (which could contain bit inversions) and estimated the original 10 bit Hadamard transform signal. This algorithm was implemented with a series of hardwired logic and programmable read only memories which were configured to achieve the various compression ratios of 3:1, 4:1, 6:1, 12:1, and variable window compression. The inverse Hadamard transform was then performed, and the resulting 6-bit digital video was sent to the refresh memory in the RPV simulator.

The bit inverter functioned as a test noise insertion point in the 12 MHz serial data link. Mechanization was accomplished using an "exclusive or" gate inserted in the serial link. Activation of the gate inverted the serial data bit. Thus, impulse noise effects were studied under precisely controlled conditions by driving the bit inverter with a programmable random error bit generator. Also built into the video processor was the capability of simulating error protection. It was found that protecting the most significant 2 bits of the 5 bits used to encode sequency zero in the Hadamard domain resulted in better video quality, and this scheme was used

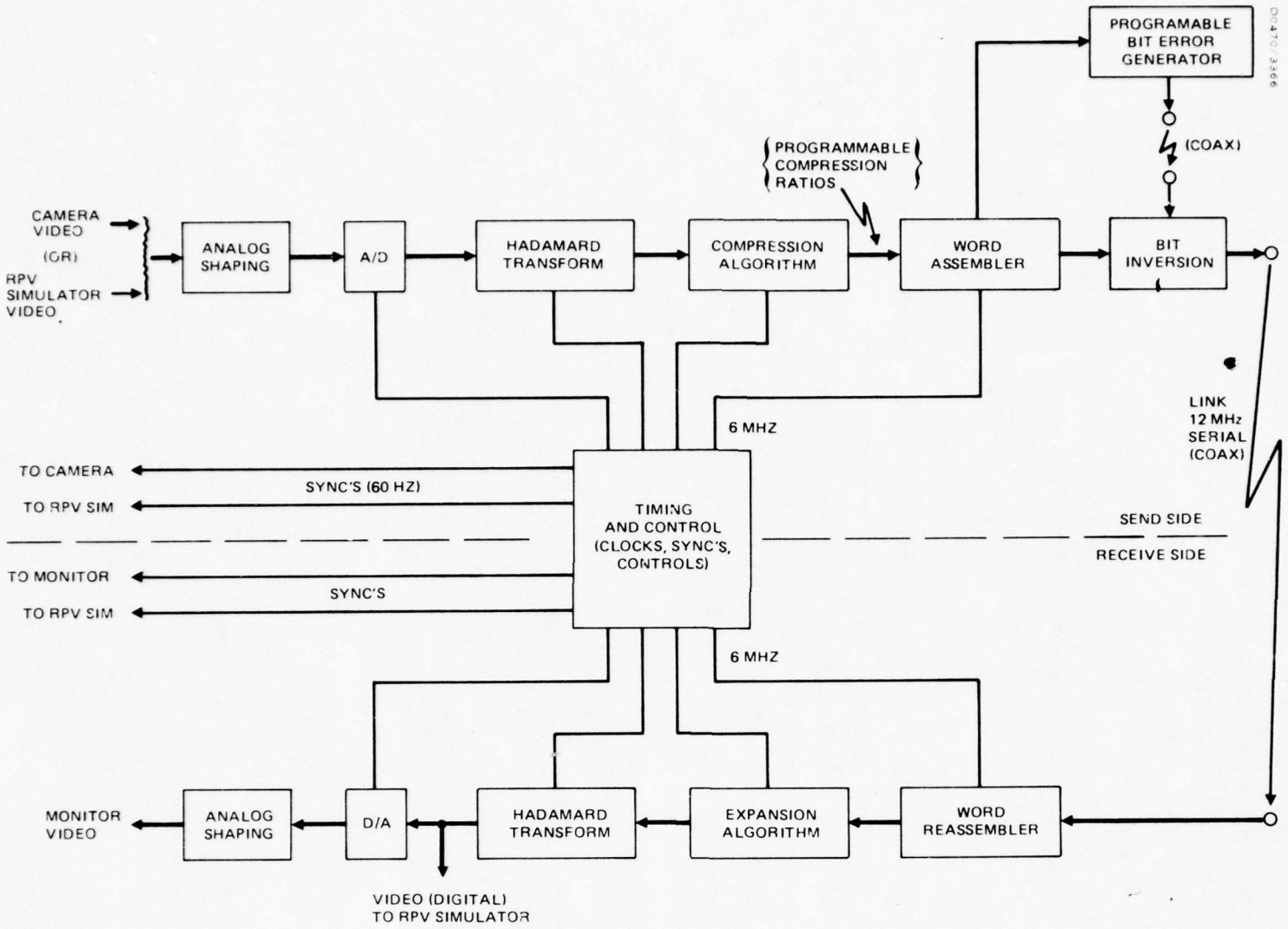


Figure 14. Video data link block diagram.

during the studies in this program. The overhead for the error protection was 8.6 percent. Thus, the actual compression ratios were reduced by 8.6 percent. For example, the 3:1 compression ratio was actually 2.74:1.

Timing and control circuitry generated all clocks required within the processor and provided both a field synchronization pulse and a line synchronization pulse to the RPV simulator camera or video tape recorder. Synchronization signals were also generated and sent to the RPV simulator for the transfer of digital video data to the refresh memory.

The variable window compression technique used a 4:1 compression ratio in the center half of the video image and 12:1 compression ratio in the outer periphery of the image. Thus 25 percent of the image area had 4:1 compression, and the peripheral 75 percent of the image area had 12:1 compression. The resulting average compression ratio was 10:1.

The video processor sampled the video data at either a 4, 5, 6, 7, or 8 MHz rate and quantized these data to 6 bits per sample. The video test links functional diagram in Figure 15 shows the possible configurations to which the video processor could be switched by front panel control. In the processor bypassed mode, the monitor displayed the analog video data as received from the video source. In the digital video mode, the 6 bit digital video was clocked in parallel at the 4, 5, 6, 7, or 8 MHz rate yielding an effective 24, 30, 36, 42, or 48 megabits per second video data rate. The transformed video mode connected the 10 bit video data (6 bits plus processing gain), in a parallel back-to-back configuration to ensure that the Hadamard transform equipment was not introducing computational errors. The compressed video mode was a 5-bit parallel back-to-back configuration that clocked data based on the compression algorithm. A sequency counter was used to determine the exact timing reference. The preceding back-to-back configurations were switched internal to the video processor and did not interface directly with an external communications link.

In the normal mode configuration, the word assembler accepted the compressed data and assembled these data into one 32-bit word every 16-clock periods (or picture elements) thereby providing a serial output data stream that averaged 2 bits per sample for a 3:1 compression ratio. This resulted in a serial data rate of 8, 10, 12, 14 or 16 Mbps, depending on the sampling rate. The normal configuration used a 6-MHz sample rate and a 12-Mbps data rate.

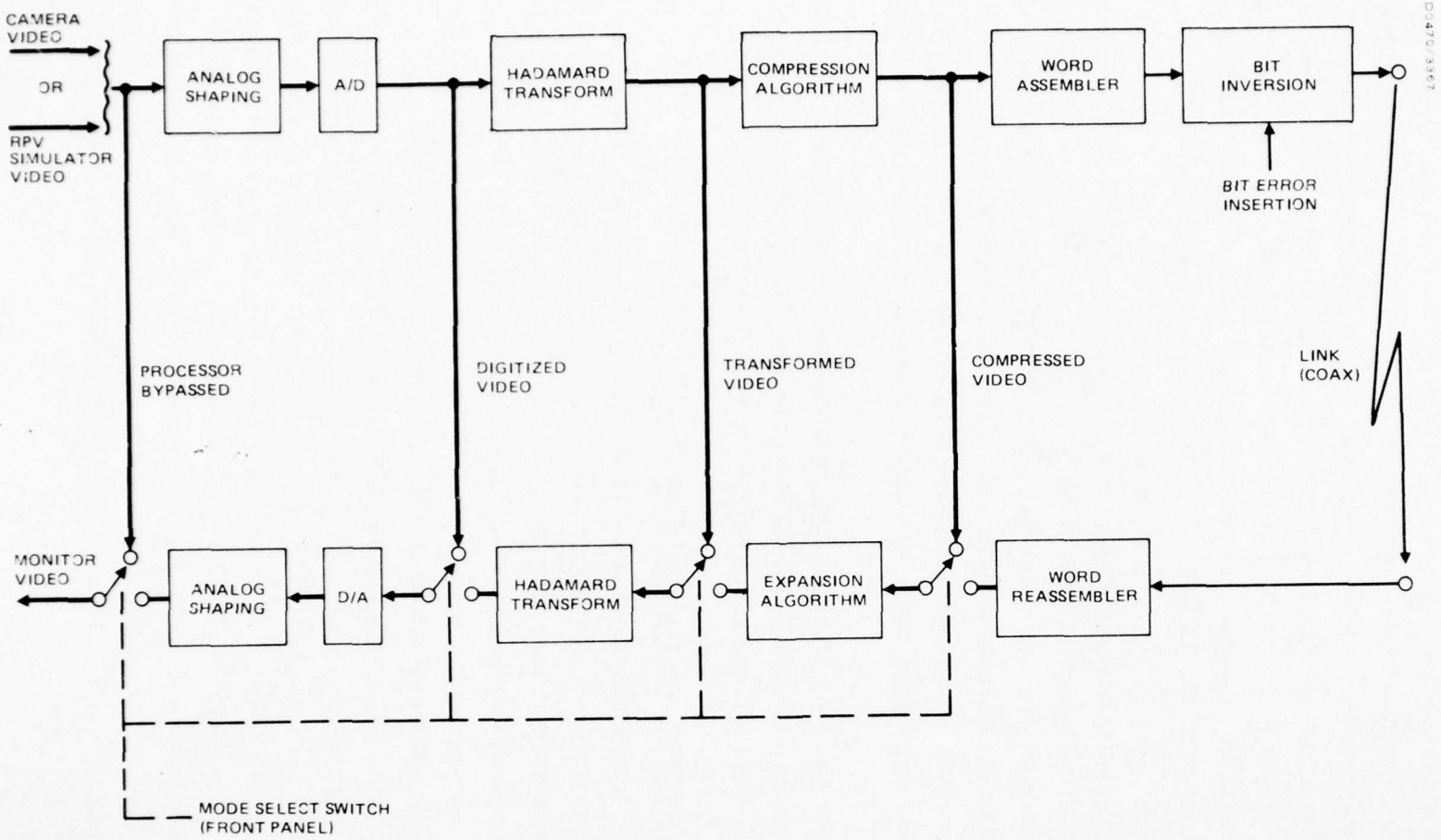


Figure 15. Video test links functional diagram.

The word reassembler converted the 32-bit word into the proper format for application to the expansion algorithm. The 32-bit word configuration was inherent in the video processor design and without the aid of a frame memory was impractical to change. Greater compression ratios were achieved (including the variable compression mode) by blanking out selected bit positions in the 32-bit word. For example, when a 4:1 compression was selected, only 24 of the 32 bits were addressed. The remaining 8 bits were ignored.

The video processor had an integral bit error generator that produced bit inversions in the serial data stream. The bit errors were inserted in a random fashion at average rates varying from 10^{-1} to 10^{-5} errors per data bit. Since the serial data stream was comprised of 32-bit words which could have some unused data positions (depending on the compression ratio), the bit error rate generator clock was gated to sequence only during active bit positions.

The serial data stream contained video data but no synchronization signals. The 60 Hz and 15,750 Hz sync signals were hardwired in the processor and did not interface with the communications link.

RPV Simulator Parameters Variation

The parameters that were varied during the man-in-the-loop laboratory studies and the means of controlling them are briefly summarized below. The first parametric study examined the effects of frame update rate and target designation techniques on operator target recognition and target acquisition performance. Frame update rate was varied by enabling the reading into the refresh memory of a single image frame at the appropriate time. This was coincident with the flash of a strobe light behind the film transparency to prevent image smearing effects. The three target designation techniques used were 3-axis stabilized sensor steering in which the target was moved under a fixed cursor, 3-axis stabilized sensor steering with motion compensation, and 3-axis stabilized sensor steering with cursor designation in which the RPV operator placed a movable cursor over the target. The steerable sensor was simulated by utilizing the Sigma 5 computer to drive the translatable film transport in elevation and azimuth coordinates

in harmony with the operator's hand control movements. The movable cursor technique was accomplished by having the hand control drive the cursor via the computer. Image motion compensation was accomplished by having the computer control the refresh memory addressing and/or readout time delays as described in the section on image motion compensation.

The second parametric study investigated the RPV operator's ability to precision designate and track targets for weapon delivery as a function of video frame update rate. A 3-axis stabilized sensor pointing system was simulated. Frame rate and stabilized sensor pointing were simulated in the same manner as the first parametric study.

The third parametric study was designed to evaluate the effects of operator controlled zoom, sensor resolution, and frame rate on target recognition. Resolution was degraded from the 525 line standard in the horizontal dimension by low pass filtering the analog video prior to A/D conversion. Vertical resolution was degraded by repeating a raster line one or more times in subsequent lines during display refresh and skipping down an equivalent number of lines in the refresh memory for the next new information to be displayed. Zoom was implemented by driving the servoed zoom lens upon operator command via a thumb operated control on the operator's hand control and the Sigma 5 digital computer. The computer also provided simulated range closure using the zoom lens.

The fourth parametric study examined the effects of bandwidth compression and jamming. The bandwidth compression, including variable window compression, was accomplished by means of the Hadamard transform video processor. A controlled level of bit error rate was implemented by means of a bit error generator and an exclusive or gate which inverted randomly selected bits in the serial data stream.

The final study was a systems simulation in which 10 combinations of Hadamard bandwidth compression, sensor resolution, and bit error rate jamming were evaluated. These parameters were varied as described above. For this study, the Air Force supplied 35-mm film imagery was converted to video tape using the tele-cine converter.

SECTION 3

PARAMETRIC STUDIES

INTRODUCTION

The primary task of this program was to investigate methods of reducing video bandwidth through man-in-the-loop simulation, thereby reducing the susceptibility of the video data link to jamming. Three bandwidth reduction/compression techniques were to be evaluated in the presence of noise jamming and compared to a baseline 4.5 MHz video data link.

A number of techniques exist to reduce video bandwidth. Among the more promising techniques are video frame rate reduction, sensor resolution reduction, and bandwidth compression. Although these techniques can provide the desired bandwidth reduction, they can also produce degraded operator target recognition and target acquisition (sensor pointing) performance. The problem is to know how much reduction/compression can be achieved without degrading operator performance below acceptable limits, or alternatively to know what performance compensating techniques might be used to maintain acceptable operator performance with large reductions of video bandwidth.

A large number of bandwidth reduction/compression systems can be postulated from various combinations of reduction/compression techniques and performance compensating techniques. Since only three systems were to be evaluated in the systems simulation, the problem was how to select the three systems. Very little quantitative data existed which described the relationship between RPV operator performance and bandwidth reduction/compression techniques. It was therefore not possible to utilize existing behavioral data to select the three bandwidth reduction/compression systems. It was also deemed undesirable to make best guesses based on opinion or casual observation. The solution employed in the program was to conduct parametric laboratory investigations to obtain the necessary behavioral data relating RPV operator performance to video bandwidth reduction/compression techniques and performance compensating techniques. To this end, four man-in-the-loop laboratory studies were conducted to provide the necessary data to configure the three bandwidth reduction/compression systems for evaluation in the systems simulation task. These four parametric studies are described in this section.

PRECEDING PAGE BLANK-NOT FILMED

VIDEO FRAME RATE AND CONTROL MODE STUDY

Introduction

Video frame rate reduction holds considerable promise for large reduction of video bandwidth. A 1-frame per second frame rate would provide a 30:1 reduction of bandwidth compared to a standard 30-frame per second TV frame rate. Frame rate reduction, however, may degrade the operator's performance.

There are two principle operator tasks in the strike phase of the RPV air-to-ground strike mission: target recognition and target acquisition (sensor pointing to lock-on to the target). Self and Heckart (1973) investigated the effects of 1-, 3-, 8-, and 24-frame per second frame rates on RPV operator target recognition performance. The results of the Self and Heckart (1973) study, shown in Figure 16, indicate a slight trend for operator performance (range-to-target at recognition) to improve as frame rate increased from 1 to 8 frames per second. The difference among the four frame rates were not, however, statistically reliable. It was therefore concluded that frame rates as low as 1 frame per second do not degrade RPV operator target recognition performance.

Hillman (1967) in a literature review of Human Factors Considerations in Real-Time Airborne Target Acquisition reviewed four papers which investigated the effects of frame rate on target designation performance. The findings of the four investigations indicated the lowest acceptable frame rate to be between 2 and 7.5 frames per second. These findings indicate a bandwidth reduction potential somewhere between 4:1 and 15:1.

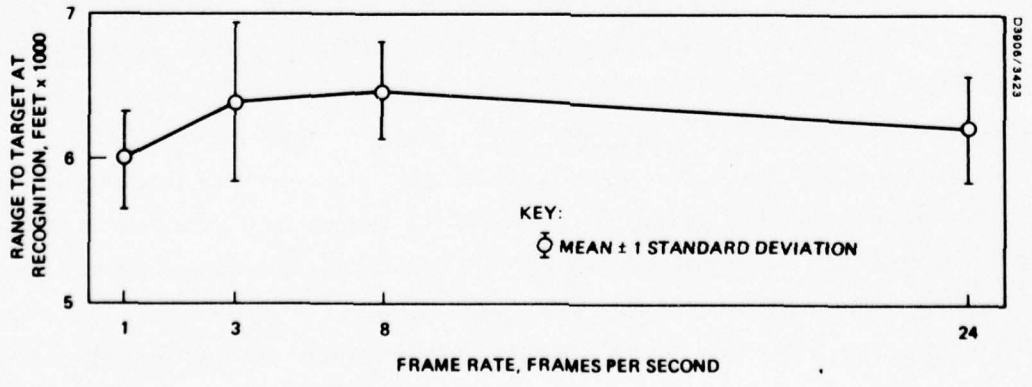


Figure 16. Effect of video frame rate on operator target recognition performance.

This past research indicates that frame rates as low as 1 frame per second have little effect on operator target recognition performance, but for target acquisition the lower bound for acceptable operator performance is between 2 and 7.5 frames per second. Since the past target acquisition research, other than Self and Heckart (1973), was not directed to the RPV mission and because of the discrepancies in the lowest acceptable frame rate among the different investigators, this study was conducted to determine the effects of frame rate and control modes on operator target acquisition performance for the RPV strike mission.

Study Parameters

Four video frame rates and three sensor pointing control modes were investigated in the study. The four frame rates were 0.23, 0.94, 3.75 and 7.5 frames per second. The three control modes were 3-axis stabilized sensor pointing, 3-axis stabilized with motion compensation, and cursor designation.

In the 3-axis stabilized mode, displacement of the operator's hand control introduced azimuth and/or elevation rate commands to control the pointing angles of a 3-axis gimballed, ground stabilized sensor. The operators observed the results of their control commands by observation of the video scene. Temporal sampling of the video produced effects analogous to transmission delay such that the results of control commands were not visible until the second update following the control command. Thus, the video frame rate determined the amount of time that elapsed between control input and the displayed image sensor response.

In the 3-axis stabilized with motion compensation mode, video transmission delay was compensated by encoding the stabilized sensor gimbal angles at the beginning and end of the video frame transmission and correcting the video presentation on the TV monitor by the progressive difference in gimbal angles. The effect was to produce continuous control of video image slewing, analogous to a 30-frame per second update rate. Between video frame updates, portions of the display where the video had been slewed from were blanked. For example, if an operator slewed the image up 2 degrees and to the left 2 degrees the bottom right-hand 2 degree portion of the display was blanked because no video in this area existed in the scan converter memory.

The cursor designation control mode had two sub-modes: 3-axis stabilized sensor pointing and image freeze with cursor positioning. This mode worked in the following manner. At the start of a trial run, operators slewed the stabilized sensor to get the target anywhere within the sensor field of view. When an operator recognized the target or target area and had the target in the sensor field of view, he depressed a trigger switch on the hand control which simultaneously froze the displayed scene and enabled a moveable cursor on the display. With the trigger depressed, the cursor responded to position commands from the hand control. The operator then placed the cursor over the target. If he was sure of his designation accuracy at this point he was free to command lock-on by depressing a button also located on the hand control. If he decided, however, that he desired more information (available with increased image scale factor zoom at each frame update) or wished to reposition the target, the operator released the trigger and returned the hand control to the center position. This caused the area under the cursor to move to the center of the display and returned the operator to the stabilized sensor mode. This process could be repeated until the operator was sure of his designation accuracy at which point he commanded sensor lock-on.

The three control modes were investigated in combination with the 0.23-, 0.94-, 3.75-, and 7.5-frames per second frame rates. The manner in which frame rate and control modes were implemented in the RPV simulation equipment was described in Section 2.0.

The vehicle/target mission geometry for this study was the computer model of a BGM-34 RPV with attitude hold autopilot flying at 680 feet per second with a 0.5 fuel load as described in Section 2.0. The RPV popped up at a 30,000-foot range to the target and closed to a minimum range of 1500 feet to the target. A 1 σ crosstrack navigation error of 1700 feet was simulated with a 20-degree TV sensor field of view. A 525-line TV sensor resolution with 6-bits gray level encoding was simulated. The 14-inch diagonal display was refreshed at 30 frames per second with 2:1 interlace.

Research Design

A 3 x 4 factorial design was used to present the 12 combinations of control mode and frame rate to 12 operators. A 12 x 12 latin square was used to assign the 12 combinations of frame rates and control modes to

12 operators and 12 targets, such that each operator received 12 trials — each of the 12 conditions with a different one of the 12 targets.

Sensor control mode served as a blocking dimension such that the four frame rate trials with a particular sensor control mode occurred together. The order of presentation of control modes and frame rates were balanced across operators.

Operators

Twelve Hughes engineering personnel served as operators (subjects) in the study. All the operators had served as subjects in previous sensor target acquisition studies at Hughes.

Target Scenes

High resolution forward oblique aerial photographic transparencies taken over the southwestern United States were used to select the twelve 20-degree field of view target scenes for the study. The targets were bridges, POL storage areas, storage buildings, refineries, factories, and dams.

Briefing and Reference Materials

In RPV strike missions, target locations will be known and briefing and reference materials will be available to the strike operators. Briefing and reference materials were prepared in individual target briefing packets as illustrated in Figure 17. Each packet contained two oblique aerial photographs representing viewing ranges to the target of 1 mile and 3 miles at a look angle similar to that expected at vehicle pop-up. Target locations were circled on the photographs and a pin hole on the 1 mile range photograph indicated the target aimpoint. Also included were short written descriptions of the target and surrounding area. The descriptions were patterned after standard Air Force briefing procedures. The operators studied the photographs prior to the start of a trial mission and retained the briefing photos for reference during the mission.

Study Procedures

The operators' task was to recognize and acquire the prebriefed targets as rapidly as possible. Each trial started at a range of 30,000 feet from the target, closing at 680 feet per second. At the start of each trial,



Figure 17. Briefing and reference material packet.

the display was blanked for two frame periods, simulating a maximum two frame period data link video transmission delay. Thus the simulated RPV had closed from 45 feet (7.5 frames per second frame rate) to 5440 feet (0.23 frame per second rate) before the operators saw the first video frame, depending on the frame rate. Prior to trial start, an operator was given the appropriate briefing packet and allowed to study it. When the operator indicated he was ready, the trial was started. The operator's first task was to recognize (locate) the target, point to the target, and say "there" to indicate he had found the target. At this point the experimenter pressed a pushbutton to stop a digital timer that was used to measure operator target recognition time. The operators were not required to be able to discriminate target detail before signaling target recognition. They merely had to locate the target on the basis of contextual cues.

After an operator had recognized (located) the target, he had to acquire the target by positioning the target within a fixed 1-degree radius circle in the center of the display (3-axis stabilized and 3-axis stabilized with motion compensation modes) or position the movable crosshair over the target (cursor designation mode). When the operator had acquired the target, he depressed a pushbutton on the hand control to command lock-on, ending the run.

Prior to formal data collection, the operators received extensive training. Standardized written instructions which described the RPV mission, the purpose of the study, and the general study procedures were read to the operators. The operators were then trained on the target acquisition task with the 12 different combinations of frame rate and control mode using a single example target scene. When the operators had mastered the target acquisition task, a series of six complete training trials was run. Formal data collection immediately followed the training trials.

Performance Measures

Operator target recognition and target acquisition performance were measured. Target recognition performance was measured with the digital timer. The time scores were later converted to range-to-target values. The experimenter recorded whether or not the operator had correctly recognized

the target. Target acquisition time and range at the instant the operator commanded lock-on were measured by the computer and printed out at the end of each trial.

Results and Discussion

The range-to-target at recognition and acquisition were analyzed for the reliability of frame rate and control mode effects with analyses of variance. In a small percentage of the trials, the operators either failed to correctly recognize the targets or failed to acquire the targets. In these instances a range of zero feet was assigned. Analysis of variance summary tables are presented in Appendix A of this report.

Target Recognition

Video frame rate had a highly statistically significant effect on operator target recognition performance. The probability that the differences obtained among the four frame rates could be due to chance was less than one out of 200 ($p < 0.005$). This effect of frame rate is shown in Figure 18. It is clear that the performance difference due to frame rate is attributable to the degraded performance at the 0.23-frame per second rate. The 0.94-, 3.75-, and 7.5-frame per second rates produced essentially equivalent performance.

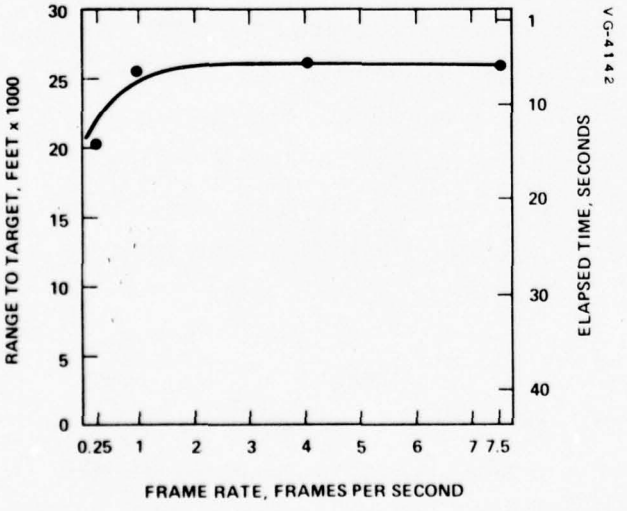


Figure 18. Frame rate effects on operator target recognition performance.

The two frames transmission delay before the operator's saw TV video simulated in the study, in effect, resulted in an initial range penalty. For the 0.23-frame per second rate, this penalty was 5,040 feet; the penalty was 45 feet with the 7.5-frames per second rate. When the operator target recognition performance data are corrected for differences in transmission delay with the four rates, the results shown in Figure 19 are obtained. Operator target recognition performance as a function of frame rate with transmission delay eliminated was a flat, straight line function. Analysis of variance for range-to-target at recognition without transmission delay showed there were no statistically reliable differences among the four frame rates ($p > 0.25$).

Frame rates from 0.23 to 7.5 frames per second, therefore, do not differently effect operator target recognition performance. These results are in agreement with Self and Heckarts' (1973) conclusion that frame rates from 1 to 24 frames per second produce equivalent target recognition performance. The only effect of frame rate on target recognition performance is due to transmission delay which can be from one to two frame periods. This transmission delay penalty may be operationally significant at very low frame rates as demonstrated in this study with the 0.23-frame per second frame rate.

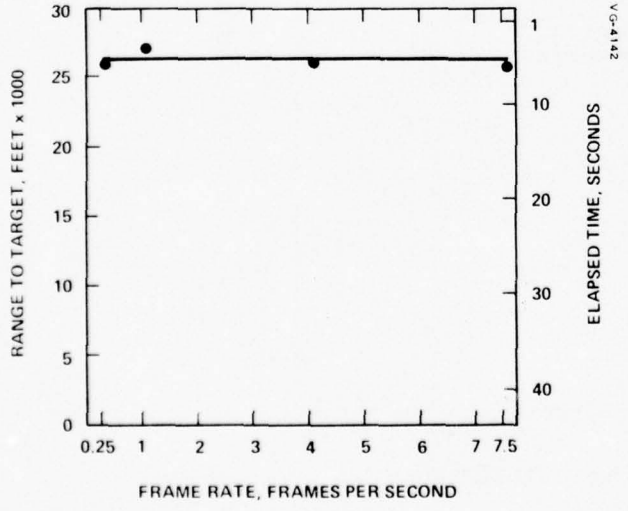


Figure 19. Frame rate effects on operator target recognition performance with transmission delay taken out.

Since only coarse or no sensor pointing was required prior to operator target recognition, sensor pointing control mode should have no effect on operator target recognition performance. The results of the study verified this prediction. There were no statistically reliable differences among the three control modes ($p > 0.25$).

Target Acquisition

Figure 20 shows the effect of frame rate and control mode on operator target acquisition performance. A fixed average target recognition range value was added to each of the range-from-target at lock-on scores to produce the curves shown in Figure 20.

Frame rate had no effect on operator target acquisition with the cursor designation and the 3-axis stabilized with motion compensation control modes. The cursor designation mode was slightly superior to the 3-axis stabilized with motion compensation mode. Apparently the operators found it easier to use the cursor designation mode and thus could acquire targets slightly faster

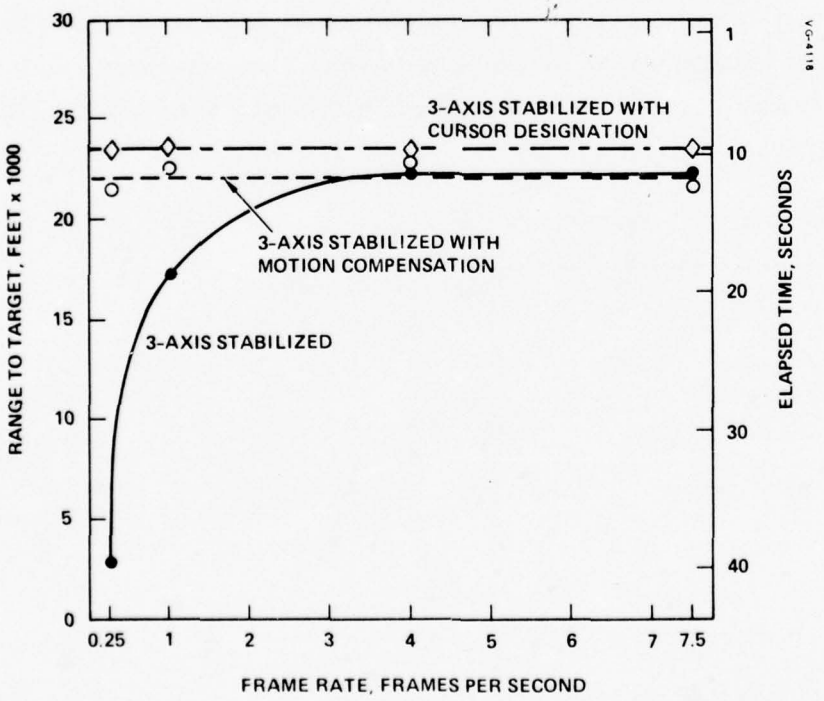


Figure 20. Effects of frame rate and control mode on operator target acquisition performance.

(a longer range-to-target). The average difference between the two modes was 2,058 feet.

With the 3-axis stabilized mode, operator target acquisition performance degraded rapidly as frame rate was reduced below 3.75 frames per second. Between 3.75- and 0.94-frame per second rates, range-to-target at acquisition went from 21,703 feet to 15,205 feet – a difference of 6,498 feet. At 0.23 frame per second, mean acquisition range was 5,279 feet. Performance was constant between 3.75 and 7.5 frames per second with the 3-axis stabilized mode.

The study results indicate that operators can acquire targets (control sensor pointing) with frame rates as low as 0.23 frame per second using either the cursor designation or 3-axis stabilized with motion compensation control modes without any degradation of their performance. If an unaided 3-axis stabilized system is used, performance degradation can be expected with video frame rates below 3.75 frames per second.

Combined target recognition and target acquisition operator/system performance is shown in Figure 21. The data are for trial start to target

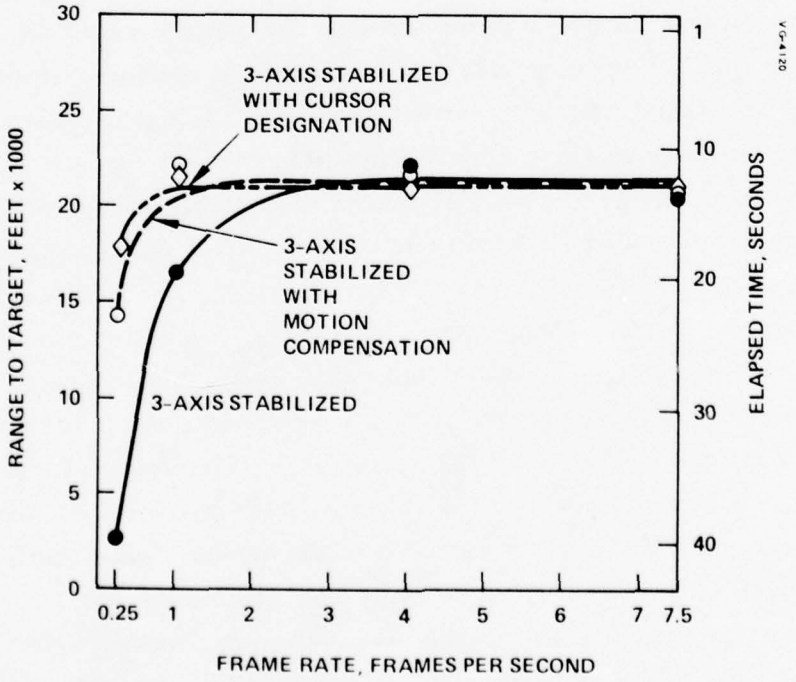


Figure 21. Effects of frame rate and control mode on combined operator target recognition and target acquisition performance.

lock-on, including the initial two frames transmission delay. An analysis of variance was performed on the data; frame rate, control mode, and the interaction between frame rate and control mode were all statistically significant (p's < 0.001, 0.02, and 0.005, respectively).

The combined performance curves show no differences among the six combinations of 3.75- and 7.5-frames per second frame rates and the three sensor control modes. For frame rates of 3.75 frames per second or higher, aided sensor pointing control techniques such as investigated in this study will not improve performance over an unaided 3-axis stabilized mode. Below 3.75 frames per second, aided control mode techniques can be expected to produce substantial performance improvement.

With any control mode, a transmission delay penalty of one to two frame periods will be incurred. The lower the frame rate, the greater will be the penalty. Frame rates below 0.94 frame per second can be expected to produce substantial penalties as reflected in reduced range-to-target at lock-on.

Conclusions and Recommendations

The results of the study demonstrated that frame rates as low as 0.94 frame per second using a cursor designation or motion compensation control aiding technique will not result in any degradation of operator target recognition/acquisition performance. Thus a bandwidth reduction of 30:1 can be achieved without any performance penalty if control aiding techniques of the type investigated are implemented in RPVs. Although operator target recognition and target acquisition performance at the 0.23-frame per second frame rate with the cursor designation and motion compensation modes was not degraded, a reduction of range-to-target at lock-on will occur because of the long transmission delay. Assuming a one frame period transmission delay, the range penalty would be 2720 feet for a RPV flying at 680 feet per second with a 0.23-frame per second video frame rate. If RPV system planners can tolerate a 2700-foot range penalty, a 120:1 bandwidth reduction could be realized with an aided 0.23-frame per second system.

If the cost, complexity, weight, and volume allowances for RPVs will not permit control aiding techniques, then a standard unaided 3-axis stabilized sensor or caged sensor pointing system will have to be implemented.

With this implementation, a 32 percent reduction in range-to-target at lock-on (6,620 feet) occurred as frame rate was decreased from 3.75 to 0.94 frame per second. Frame rates of 0.94 frame per second and less can be expected to result in significant performance degradation. The visually fit curve for the 3-axis stabilized mode in Figure 21 indicates that no substantial performance degradation will occur at a 3-frame per second rate. The visually fitted curve also indicates that at a 2-frames per second frame rate, a 640-foot reduction in range-to-target at acquisition would occur compared to the 3.75-frame per second frame rate. This 640 feet reduction represents a 3 percent performance loss. It therefore appears that RPV operators can accomplish target acquisition within a 1-degree radius gate with minimal performance degradation using an unaided 3-axis stabilized, 2-frames per second frame rate system. Such a system would provide a 15:1 bandwidth reduction compared to the standard 30 frames per second system.

VIDEO FRAME RATE, PRECISION DESIGNATION STUDY

The previously described study investigated the effects of video frame rate and sensor pointing control mode on RPV operators' ability to recognize and position target aimpoints within a 1-degree diameter gate. Sensor pointing to position target aimpoints within a 1-degree error circle is adequate to: 1) accomplish handover from a large field of view vehicle sensor on an RPV to a narrow field of view weapon sensor such as a Maverick or Stubby Hobo missile and 2) satisfy most non-strike RPV missions where sensor pointing is required (e.g., real-time reconnaissance). Strike missions with conventional weapons will, however, require greater than 1-degree pointing accuracy for target kill. This study was therefore concerned with the effects of video frame rate on precision target designation for weapon delivery.

The study was largely funded by the Naval Undersea Center, San Diego, California under contract N66001-75-C-0228. The Air Force and Naval Undersea Center agreed in the early stages of both programs to share information that would result from the two allied programs. Since both Air Force and Navy programs required an investigation of video frame rate for precision sensor pointing, a single expanded scope study was conducted. The original Naval Undersea Center study was expanded to include measurement of single precision target designation (the Navy study required continuous target

tracking) and a larger sample of video frame rates. The data resulting from this single expanded study was provided to both the Air Force and the Navy.

Study Parameter

Video frame rate was the single parameter investigated in this study. Six values of frame rate — 0.94, 1.88, 3.75, 7.5, 15.0, and 30.0 frames per second — were investigated.

Research Design

A within-subjects design was used in which six subjects (operators) each received all six frame rates. The presentation order of the frame rates was counterbalanced across operators using a latin-square technique. Five replications of each frame rate/operator combination were run. The first replication served as a practice/warm-up trial and was not used in the data analyses. Thus, each operator received six blocks (frame rates) of five trials (replications) in which the last four replications in each block provided the data to determine the effects of frame rate on target designation and target tracking performance. Figure 22 shows the research design used in the study.

Operators

The six operators used in the study were engineering personnel within the Display Systems and Human Factors Department of Hughes Aircraft Company. These personnel were selected based on their past experience and demonstrated performance in target designation and tracking tasks.

OPERATORS	FRAME RATE, FRAMES PER SECOND					
1	0.94*	30	1.88	15	3.75	7.5
2	1.88	0.94	3.75	30	7.5	15
3	3.75	1.88	7.5	0.94	15	30
4	7.5	3.75	15	1.88	30	0.94
5	15	7.5	30	3.75	0.94	1.88
6	30	15	0.94	7.5	1.88	3.75

*Each cell represents a block of five trials.

Figure 22. Research design used in frame rate study.

Target Scene

A single target scene, consisting of a Stalin tank in a plain background, was used in the study. The tank was scaled to represent a 9,843-foot slant range with a 2-degree sensor field of view. The tracking point was the centroid of the tank. The physical location of the tank centroid was pointed out to the six operators.

The Tracking Task

At the start of each trial, the tank target was positioned 125 feet from the center of the display in a random direction and drifting at 164 feet per second. The drift rate was due to the simulated vehicle/target geometry in which the RPV was flying at a 2500-foot altitude, a speed of 164 feet per second, and a ground range-to-target of 9,843 feet. The sensor field of view was 2 degrees.

At the start of a trial, the 2-degree field of view represented a ground coverage of 354 feet. The 125-foot initial target offset position represented 38 percent of the field of view or a displacement of 3.8 inches from the center of the 14-inch diagonal display. The forcing function the operators were required to track was a tangent function in which target motion rate increased with time (as range-to-target decreased).

The operator's task was to position the target aimpoint on a set of fixed crosshairs on the display as quickly as possible, depress a pushbutton (for measurement of designation accuracy), and track the target (maintain minimum displacement between the target aimpoint and the crosshairs) for 35 seconds.

A two-axis position displacement hand control was used by the operators to input sensor rate commands to a simulated 3-axis stabilized sensor. Vertical stick deflection commanded sensor elevation rate slewing; horizontal stick deflection commanded sensor azimuth rate slewing. Hand control pitch rate commands appeared as vertical picture translation rates on the TV monitor, and hand control azimuth rate commands appeared as horizontal picture translation rates. Figure 23 shows sensor slew rate per amount of hand control deflection. This X^2 function was the same for all four quadrants of hand control deflection.

Laboratory Equipment

The Hughes RPV simulation facility, described in Section 2, was used in conjunction with a general purpose RPV simulation computer program. This facility consists of a Xerox Sigma 5 digital computer and associated software, a television scanner and transport mechanism, a digital refresh memory, an experimenter's control console, an operator's console, and associated interface electronics. This system provided realistic control of

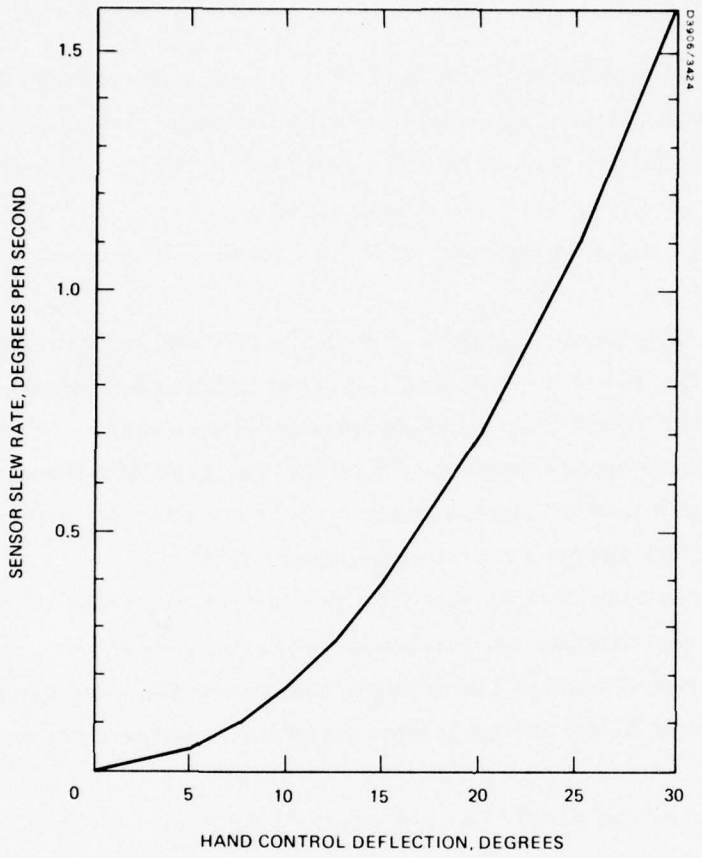


Figure 23. Hand control shaping function.

flight dynamics within the limits of the programmable vehicle characteristics and the means of varying frame rates and other transmission variables. The reduced frame rates were produced by updating the digital refresh memory at the reduced rate while flicker free television was provided by reading out of the memory at a standard 60 Hz rate. The desired experimental conditions were selected from the experimenter's control console and then computer generated. The target was displayed through use of the television scanner and was driven by the transform platform servos. The target motion drive signals were from the computer. The operator's control actions were relayed by the computer to the transport platform. The target aimpoint location was stored in the computer so that it could determine operator target designation and tracking error and print them out at the end of each trial.

Study Procedure

When each operator entered the laboratory, he was given a set of standardized written instructions to read. Any requested clarifications to the instructions were then given. Prior to formal data collection, extended training was given to familiarize the operators with the tracking task using the various frame rates. Each operator received training on all frame rates. Initially the operators received the 30-frame per second frame rate and were allowed to learn the sense of the hand control (relationship between hand control displacement and picture motion). The operators could choose between a fly-to sense (move hand control towards the target) and a conventional flight control sense (move hand control toward target in azimuth and away from target in elevation to bring target towards the center of the display). After the operators had selected and learned the hand control sense, extensive training was given at each of the six frame rates.

Each trial started with the display blanked. When the test conductor had selected the appropriate test conditions, he depressed the computer "RUN" pushbutton. The computer selected the required conditions, unblanked the display, and started the trial. The operator saw the target displayed 125 feet (3.8 inches) from the crosshair in the center of the display. The operator positioned the target aimpoint (slewed the sensor) until the target aimpoint was positioned on the crosshair and depressed a pushbutton on the hand control. During this part of the trial, the target moved at a fixed 164 feet per second. When the operator depressed the pushbutton, designation error was measured by the computer and the simulation of range closure to the target was initiated, resulting in the tangent function tracking rate. The operator was then required to track the target aimpoint for 35 seconds. At the end of 35 seconds, the trial was terminated and RMS error over the last 30 seconds of the trial was computed.

The use of the 164 feet per second fixed rate at the beginning of each trial and the introduction of range closure with increased tracking rate in the latter part of each trial allowed a measure of both single target designation error and target tracking error. It was not feasible to initiate range closure at the start of the trials, because the time required to make the single designation at the low frame rates would have resulted in the tracking rate going to infinity before the 35 second tracking task started.

Performance Measures

Time to target designation, designation error, and RMS tracking error were measured on each trial. Time, in seconds, was measured from the start of a trial until the operator positioned the target aimpoint on the display crosshair and depressed the designation pushbutton on the hand control. Radial designation error in milliradians was measured at the time the operators depressed the pushbutton on the hand control. Radial RMS tracking error in milliradians was measured during the last 30 seconds of the 35 second tracking run. The tracking run started as soon as the operators had made their designation and depressed the pushbutton on the hand control.

Results and Discussion

The time and error data resulting from the study were plotted as a function of frame rate and subjected to analyses of variance to test for the reliability of the effects of frame rate on the performance measures. The probability that the obtained differences among frame rates could have occurred by chance was less than 0.001 for designation time and designation accuracy and less than 0.01 for RMS tracking error. Thus, both results were statistically significant.

Designation Time

The effect of frame rate on target designation time is shown in Figure 24. Designation time ranged from 16 seconds at the 30-frames per second frame rate to 61 seconds at the 0.94-frame per second frame rate — nearly a four times increase in the time required to make a single precision designation of the tank target. The largest reduction in time as frame rate increased was between 0.94 and 3.75 frames per second (33 seconds). Between 3.75 and 15 frames per second, the reduction in designation time was more gradual (13 seconds). There was no difference between 15- and 30-frames per second frame rates.

This study was principally concerned with the effects of frame rate on precision target designation and tracking. The instructions to the operators stressed accuracy — not time. Therefore the time data are not necessarily indicative of the time it would take an operator to make a precision target designation in the real-world situation. The time data are indicative of the

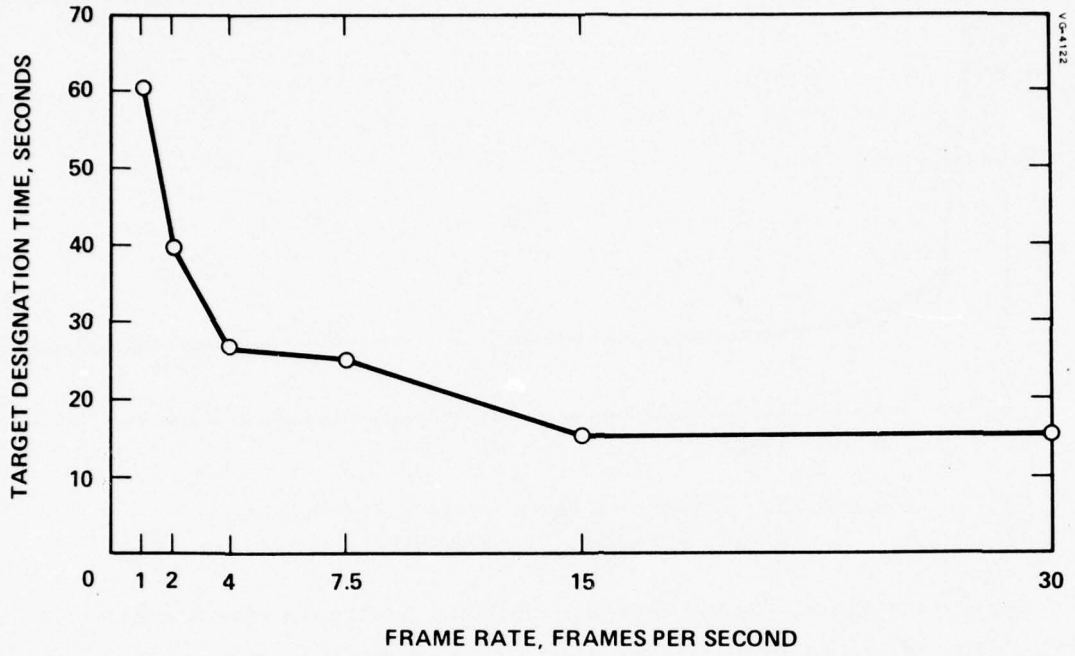


Figure 24. Effects of frame rate on target designation time.

task difficulty with the various frame rates and thus provide an index of the relative time required to make a precision target designation for frame rates from 0.94 to 30 frames per second. Clearly, 0.94 and 1.88 frames per second are extremely difficult to use, 3.75 and 7.5 frames per second are of moderate difficulty, and 15 and 30 frames per second can be used with relative ease.

Designation Error

Figure 25 shows the effect of frame rate on radial designation error. Designation error ranged from 4.46 milliradians at the 0.94-frame per second frame rate to 0.82 milliradian at the 30-frames per second rate — a greater than 5 to 1 difference. It is obvious from Figure 25 that the largest improvement in designation error occurred as frame rate increased from 0.94 to 1.88 frames per second (from 4.56 to 1.56 milliradians designation error). There was a more gradual improvement in designation error as frame rate increased from 1.88 to 7.5 frames per second (1.56 to 0.88 milliradians designation error). Target designation error was essentially constant from 7.5 to 30 frames per second (0.88 to 0.82 milliradian designation error).

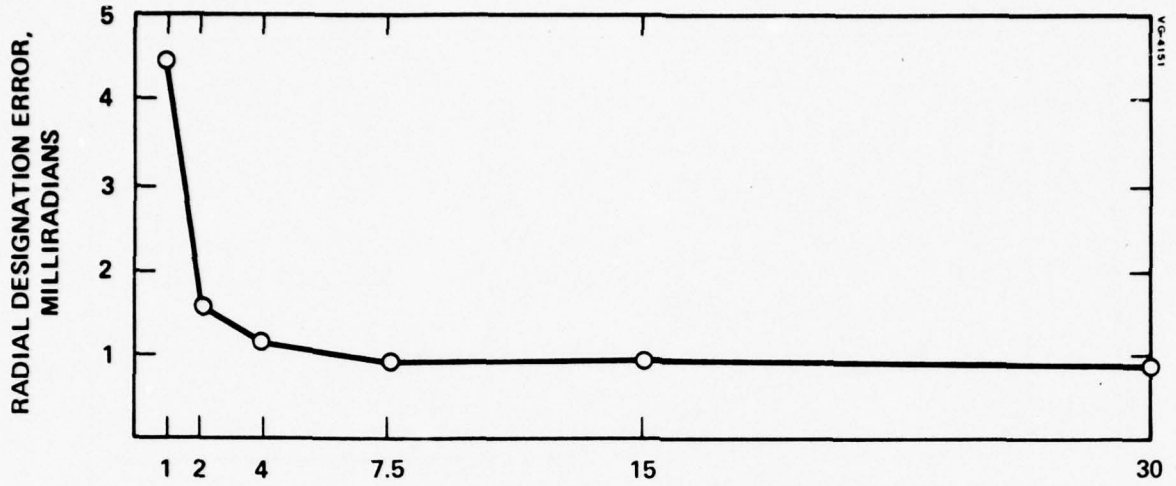


Figure 25. Effects of frame rate on precision target designation accuracy.

A Newman-Keuls simultaneous test for multiple contrasts was used to test for the reliability of differences among each of the pairs of frame rates. The results of this test showed that the 0.94-frame per second frame rate produced significantly ($p < 0.01$) greater designation error than the other five frame rates. Differences among the 1.88-, 3.75-, 7.5-, 15-, and 30-frames per second frame rates, however, were not statistically reliable. One can therefore conclude that any frame rate of 1.88 frames per second or greater will result in equivalent operator precision target designation performance. With a larger data sample and more operator training, it would be possible to determine reliable differences between frame rates from 1.88 to 7.5 frames per second. The performance differences, however, would be small, as shown in Figure 25.

RMS Tracking Error

The effect of frame rate on RMS tracking error, as shown in Figure 26, reveals the same general results that were obtained for designation error. Tracking error decreased rapidly as frame rate increased from 0.94 to 3.75 frames per second (10.4 to 1.5 milliradians), a small decrease in tracking error was observed as frame rate increased from 3.75 to 15 frames per second (1.5 to 0.77 milliradians), and tracking error remained essentially constant between 15 and 30 frames per second (0.77 to 0.70 milliradian).

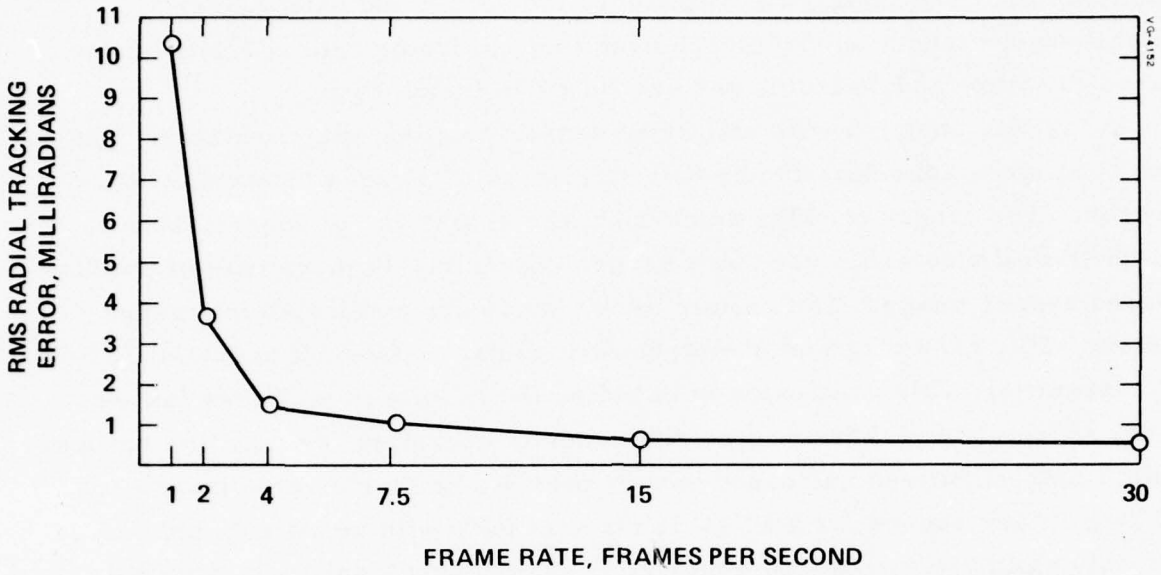


Figure 26. Frame rate effects on target tracking accuracy.

Although there was a two-to-one decrease in tracking error as frame rate increased from 3.75 to 15 frames per second, this difference was not statistically significant ($p > 0.05$). Thus a major improvement in tracking accuracy occurred as frame rate increased from 0.94 to 3.75 frames per second; increasing frame rate beyond 3.75 frames per second resulted in minimal improvement in operator tracking performance.

Conclusions and Recommendations

The three performance measures; designation time, designation error, and tracking error; all showed the same general effect of frame rate on operator performance. Performance improved rapidly as frame rate increased from 0.94 to 3.75 frames per second. Increasing frame rate from 3.75 to 15 frames per second provided a slight improvement in operator performance. Increasing frame rate beyond 15 frames per second did not improve the operator's performance for the RPV targeting task.

Based on the small performance differences among the 3.75-, 7.5-, 15-, and 30-frames per second rates and the lack of statistical reliability, it can be concluded that there is little, if any, performance advantage to recommend a frame rate greater than 3.75 frames per second for RPV

applications. The findings of this study, therefore, indicate than an 8:1 bandwidth reduction can be achieved through frame rate reduction compared to a standard 30-frame per second video frame rate.

In this study, 3-axis stabilized sensor pointing was simulated. There has been some consideration by RPV designers of a caged (unstabilized) sensor. The danger of using an unstabilized sensor is, of course, atmospheric turbulence which can cause large, unpredictable movement of the displayed sensor image. The results of this study are applicable to a caged sensor RPV, assuming that atmospheric turbulence does not cause large RPV disturbances. This conclusion is based on the results of a Hughes funded study which showed there was no difference in operators' designation accuracy with 3-axis stabilized and caged sensor modes with frame rates from 1 to 30 frames per second for a BGM-34 class of RPV with an attitude hold autopilot flying in low turbulence weather. The operator's ability to designate and track targets with a caged sensor in moderate and large turbulent weather has not, to our knowledge, been investigated at any frame rate. The issue of caged sensor and reduced frame rate in a turbulent environment should be investigated before RPV designers select a caged sensor, reduced frame rate design. We would not recommend generalizing from the results of the present study or the Hughes funded study for a caged sensor design, because turbulence was not considered.

VIDEO RESOLUTION, OPTICAL ZOOM STUDY

Introduction

Video bandwidth can be reduced by reducing video resolution. A 256 by 256 element resolution sensor would provide a 4:1 bandwidth reduction compared to a standard 512 by 512 element resolution TV sensor system. The prebriefed location known target recognition task required by the strike mission simulated in this program allows operators to "locate" targets by correlating features on the briefing material and the video display. The features operators typically chose from the briefing material are large man-made or natural terrain features. These large features can usually be discerned at long range with reduced sensor resolution. In a Hughes Internal Research and Development study, a preliminary evaluation of 256 by 256 and

512 by 512 TV sensor resolutions was conducted. The results of the study, although tentative due to the small data sample collected, indicated a slight advantage for the higher sensor resolution.

A technique to compensate for reduced sensor resolution is the use of optical zoom. Optical zoom provides a means by which effective resolution (resolution lines on the target) can be increased and effective range can possibly be decreased (target size increased) at the expense of the effective field of view (amount of instantaneous displayed ground coverage). Zoom could be used by the operator to increase resolution and target size at his option as soon as he recognized the target area. It is hypothesized that with zoom capability, the operator could perform the recognition task at a lower video resolution as well as he could with a higher video resolution without zoom. Hence, the lower video resolution/zoom approach would result in reduced bandwidth. This hypothesis is supported by considerable basic research data on static displays which show that operator target recognition performance improves as target definition and target size are increased. The potential benefits of optical zoom for RPV operator target recognition remain to be tested in the context of a laboratory study or simulation with sensor dynamics.

Optical zoom might interact with video frame rate because 1) zoom causes a change in image scale factor and 2) frame rate reduction causes a time delay in the displayed effects of zooming. At low frame rates, this delay may cause the operator to become disoriented when the next frame with the stepped increase in zoom (increased scale factor) is displayed. It is also the case that with continuous zoom at low frame rates, the operator has no immediate visual feedback on the amount of zoom commanded. If he zooms around the wrong area, the target may be out of the sensor field of view on the next frame. At high frame rates, the operator will see a near continuous change in scale factor as he zooms. If he sees he is zooming around the wrong area, he can rapidly correct. Thus zoom may improve operator performance at high frame rates and degrade operator performance at low frame rates.

This study was conducted to : 1) determine the effects of TV sensor resolution on the RPV target acquisition task, 2) determine if optical zoom will compensate for reduced sensor resolution, and 3) determine if optical zoom interacts with video frame rate.

Study Parameters

Sensor video resolution, optical zoom, and video frame rate were investigated in the study. The digital TV sensor resolutions were 512 by 512, 512 by 256, and 256 by 256 resolution elements (horizontal by vertical). Actual measured resolution using a Buckbee-Mears USAF resolution chart was 480 resolution elements for the 512-element resolution system and 240 resolution elements for the 256-element resolution system. Figure 27 shows an example target scene at the three resolutions investigated.

Two optical zoom conditions were investigated: 1) no zoom and 2) up to 8X zoom. In those trials where 8X zoom was available, the operator could zoom up to 8X at his discretion. The operators were not forced to use zoom even though it was available. An example target scene at 1X, 2X, 4X, and 8X zoom is shown in Figure 28.

Video frame rates of 0.23, 0.94, and 7.5 frames per second were investigated to determine if frame rate interacted with optical zoom. The 0.23-frame per second frame rate provided a long (4 seconds) delay that should cause operator disorientation if such a problem exists. The 0.94-frame per second frame rate provided a short (approximately 1 second) time delay, and the 7.5-frames per second frame rate provided nearly instantaneous zoom feedback to the operators in which no disorientation should occur.



256 BY 256 256 BY 512 512 BY 512

Figure 27. Examples of the three resolutions investigated.



1X



2X



4X



8X

Figure 28. Example target scene at 1X, 2X, 4X, and 8X zoom.

The vehicle/target mission geometry for this study was the computer model of a BGM-34 RPV with attitude hold autopilot flying at 680 feet per second with an 0.5 fuel load as described in Section 2.0. The RPV popped up at a 30,000-foot range to the target and closed to a minimum range of 1500 feet to the target. A 1σ crosstrack navigation error of 1700 feet was simulated with a 20-degree TV sensor field of view. The 14-inch diagonal display was refreshed at 30 frames per second with 2:1 interlace, and 6-bits gray level encoding was used.

The 3-axis stabilized with motion compensation control mode was used for operator sensor slewing. One objective of the study was to test the interaction between zoom and frame rate due to transmission delay. Inclusion of the control aspects of frame transmission delay would have confounded the results. Since the Video Frame Rate and Control Mode Study showed no performance differences among frame rates from 0.23 to 7.5 frames per second with the 3-axis stabilized with motion compensation control mode, this mode was used.

Research Design

A 3 x 3 x 2 factorial design was used to present the 18 combinations of resolution, frame rate, and zoom to 18 operators. An 18 x 18 latin square was used to assign the 18 combinations of resolution, frame rate, and zoom conditions to 18 operators and 18 targets. Each operator received 18 trials — each of the 18 conditions with a different one of the 18 targets.

Each operator received two blocks of nine trials for the zoom and no zoom conditions. Presentation order of zoom conditions was counterbalanced across the 18 operators. The nine combinations of resolution and frame rate conditions were randomized across the 36 combinations of operators and zoom conditions.

Laboratory Equipment

The Hughes RPV simulation facility, described in Section 2, was used to effect this study. The facility includes a Xerox Sigma 5 digital computer with a general purpose RPV simulation computer program, a television scanner and film transport mechanism, a digital refresh memory, an experimenter's control console, an operator's console, and associated

interface electronics. This system provided realistic control of RPV flight and sensor control dynamics and the means of varying sensor resolution, frame rate, optical zoom, and other RPV system variables.

Resolution was reduced from the 512 line standard in the horizontal dimension by low pass filtering the analog video prior to A/D conversion. Vertical resolution was reduced by repeating a raster line one time in the subsequent line during display refresh and skipping down an equivalent number of lines in the refresh memory for the next new information to be displayed. The reduced frame rates were produced by updating the digital refresh memory at the reduced rate while flicker free video was provided by reading out of the memory at a standard 30 Hz frame rate. Optical zoom was implemented by driving the servoed zoom lens via a thumb operated control on the operator's hand control and the Sigma 5 digital computer.

The desired study conditions were selected from the experimenter's control console and then computer generated. The target scene was displayed through use of the television scanner and was driven by the transform platform servoes. The target scene drive signals were from the computer. The operator's control actions were relayed by the computer to the transport platform. Operator performance data were printed out at the end of each run by the computer.

Operators

Eighteen Hughes engineering personnel served as operators (subjects) in the study. All the operators had served as subjects in previous sensor target acquisition studies at Hughes.

Target Scenes

High resolution forward oblique aerial photographic transparencies taken over the southwestern United States were used to select eighteen 20-degree field of view target scenes for the study. The targets were bridges, POL storage areas, storage buildings, refineries, factories and dams.

Briefing and Reference Materials

Briefing and reference materials were prepared in individual target briefing packets. Each packet contained two oblique aerial photographs,

representing viewing ranges to the target of 1 mile and 3 miles at a look angle similar to that expected at vehicle pop-up. Target locations were circled on the photographs, and a pin hole on the 1-mile range photograph indicated the target aimpoint. Also included were short written descriptions of the target and surrounding area. The operators studied the photographs prior to the start of a trial mission and retained the briefing photos for reference during the mission.

Study Procedures

The operator's task was to recognize and acquire the prebriefed targets as rapidly as possible. Each trial started at a range of 30,000 feet from the target, closing at 680 feet per second. Initial frame transmission delay was not simulated. At trial start (30,000 feet from the target), the display was unblanked and an operator immediately began searching for the target. Prior to trial start, an operator was told the resolution, frame rate, and zoom condition he would receive, given the appropriate briefing packet, and allowed to study the briefing packet. When the operator indicated he was ready, the trial was started. The operator's task was to recognize (locate) and acquire the target by positioning the target within a fixed 1-degree radius circle in the center of the display using the 3-axis stabilized with motion compensation control mode. When the operator had acquired the target, he depressed a pushbutton on the hand control to command lock-on, ending the run.

In those trials where optical zoom was available, the operators could command up to 8X zoom anytime between trial start and lock-on. The decisions to zoom, when to zoom, and how much to zoom were left up to the operators. The operators could zoom-in and zoom-out. For example, if an operator zoomed-in a full 8X and found he had lost his orientation to the target scene, he could zoom-out as much as he wanted. The operators were not forced to use zoom.

Prior to formal data collection, the operators were trained on the study procedures and the study conditions they would be experiencing. Standardized written instructions which described the RPV mission, the purpose of the study, and the general study procedures were read to the operators. The operators were then trained on the study procedures using

a single target scene. When the operators had learned the task sequence, a series of six complete training trials was run. Formal data collection immediately followed the six training trials.

Performance Measures

Range-to-target at acquisition and zoom utilization were measured. Range-to-target was measured to the nearest foot at the instant the operators commanded lock-on. The amount of zoom used was measured to the nearest 0.1X. The final amount of zoom commanded was the measured zoom. For example, if an operator had commanded 8X zoom, reduced zoom to 2X, and then commanded an additional 2X zoom, the final value of 4X zoom was recorded and used as the measure. Both range-to-target and zoom were measured by the computer and printed out at the end of each trial.

Results and Discussion

The effects of video resolution, zoom, and frame rate on range-to-target at acquisition were analyzed using analysis of variance to test for the reliability of the effects of these parameters on operator target acquisition performance. The results of the analysis (see Appendix A for analysis of variance tables) revealed that only optical zoom had statistically reliable effects on operator performance. These results are discussed below.

Video Resolution

As shown in Figure 29, the differences among the three resolutions tested were extremely small. The difference in range-to-target at acquisition between the two extremes of resolution was less than 200 feet. This small difference was not statistically significant ($p > 0.25$).

For the prebriefed target strike mission, it appears that 256 by 256 element resolution is sufficient resolution for RPV operators to rapidly locate and acquire targets. A higher resolution system with greater bandwidth would not be expected to result in any improvement of operator performance for the task and type of targets employed in this study.

Optical Zoom

Mean range-to-target at acquisition was shorter (poorer performance) when zoom was available than when zoom was not available. This finding is

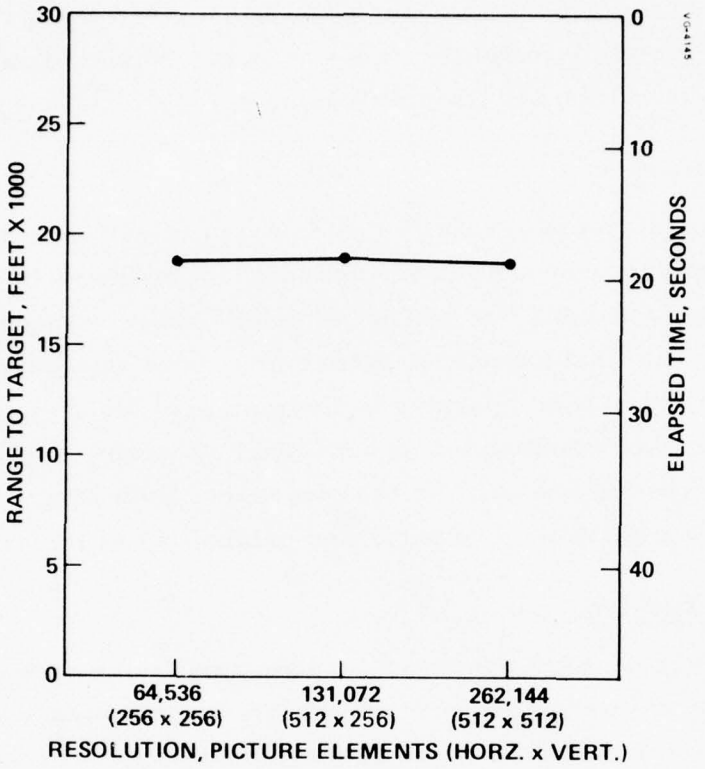


Figure 29. Effects of video resolution on operator target acquisition performance.

shown in Figure 30. On average, the operators acquired the targets at an 1,800-foot shorter range-to-target when zoom was available than when zoom was not available. This 1,800-foot difference was statistically reliable between the 0.01 and 0.05 probability levels.

Although the effect of optical zoom was statistically reliable, the use of optical zoom degraded operator performance. The hypothesis to be tested in the study was that optical zoom would improve performance due to increased resolution (lines on target) and increased target size, particularly at the reduced (256 by 256) sensor resolution. Because no degradation of performance was found with a reduced 256 by 256 element resolution system and zoom did not interact with resolution, one would not expect zoom to improve performance. It takes time to use zoom, and increased time means reduced range-to-target. Thus, the poorer performance with zoom is not surprising, considering that the 256 by 256 element resolution provided undegraded operator performance.

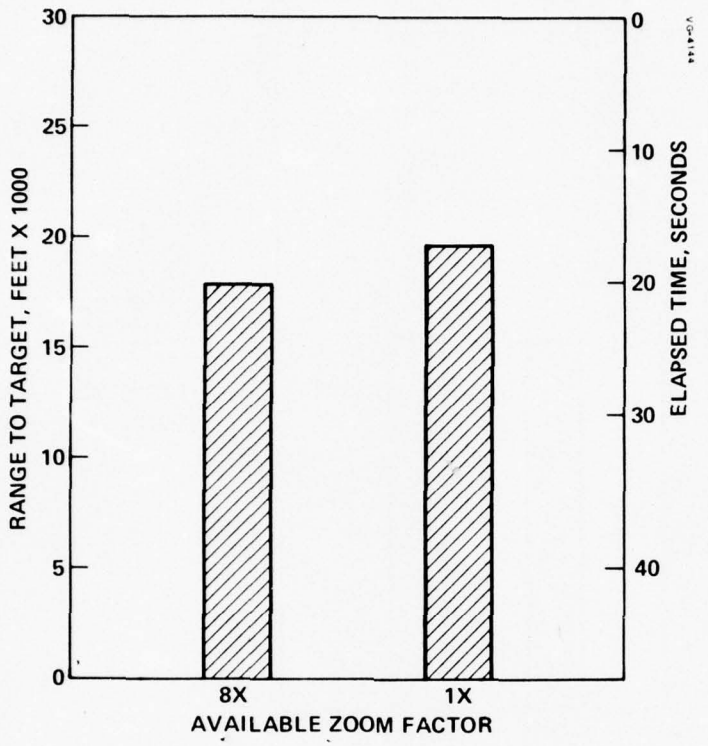


Figure 30. Comparison of zoom and no zoom conditions.

In those trials where zoom was available, the operators chose to use zoom about 55 percent of the time. This percent zoom usage is shown in Figure 31 for the three resolutions evaluated. It can be seen that there was little difference in the percent of trials zoom was used at the three resolutions. The amount of zoom used, when the operators choose to use zoom, is shown in Figure 32. On average, the operators used about 2X zoom. Slightly more zoom (0.2X) was used with the 256 by 256 and 512 by 256 system resolutions than with the 512 by 512 system resolution.

Video Frame Rate

The effects of video frame rate and the interaction between video frame rate and optical zoom were not statistically significant (p's > 0.25). No performance differences were expected due to frame rate because the 3-axis stabilized with motion compensation control mode was used in the study, and the Video Frame Rate and Control Mode Study had shown no effect of frame rate on operator target recognition or target acquisition performance using this mode.

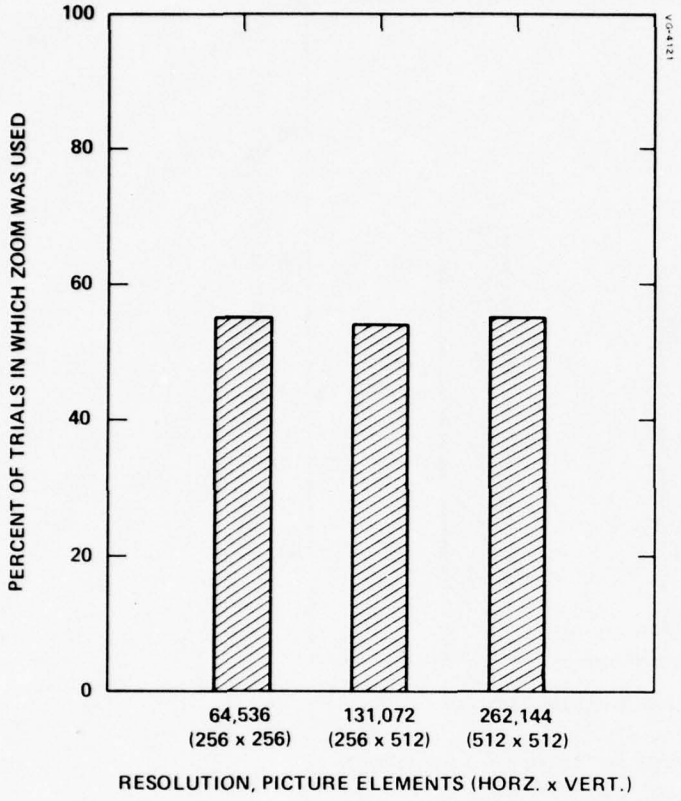


Figure 31. Percent of trials zoom used when available.

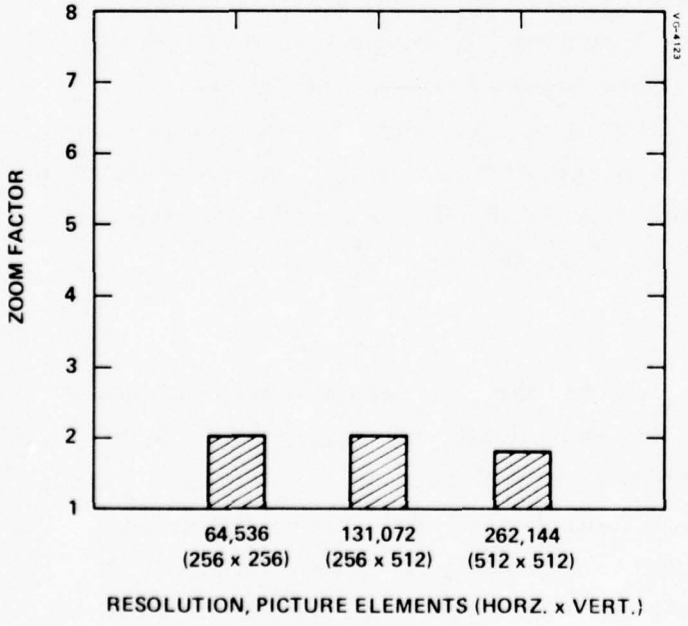


Figure 32. Amount of zoom used by RPV operators.

The lack of an interaction between frame rate and zoom, illustrated in Figure 33, indicates that when zoom was used at the 0.23 frame per second frame rate (the operators used zoom on 52 percent of the trials with the 0.23 frame per second frame rate) the operators did not experience any reorientation problem. Although the operators did poorer with zoom than without zoom, the range-to-target degradation caused by using zoom was no greater for the 0.23 frame per second frame rate than the 7.5 frames per second frame rate.

Conclusions and Recommendations

Based on the results of this study, a 256 by 256 element TV video resolution system is recommended for the prebriefed target strike mission investigated. Such a 256 by 256 resolution system would provide a 4:1 bandwidth reduction compared to a standard 512 by 512 line resolution TV sensor system.

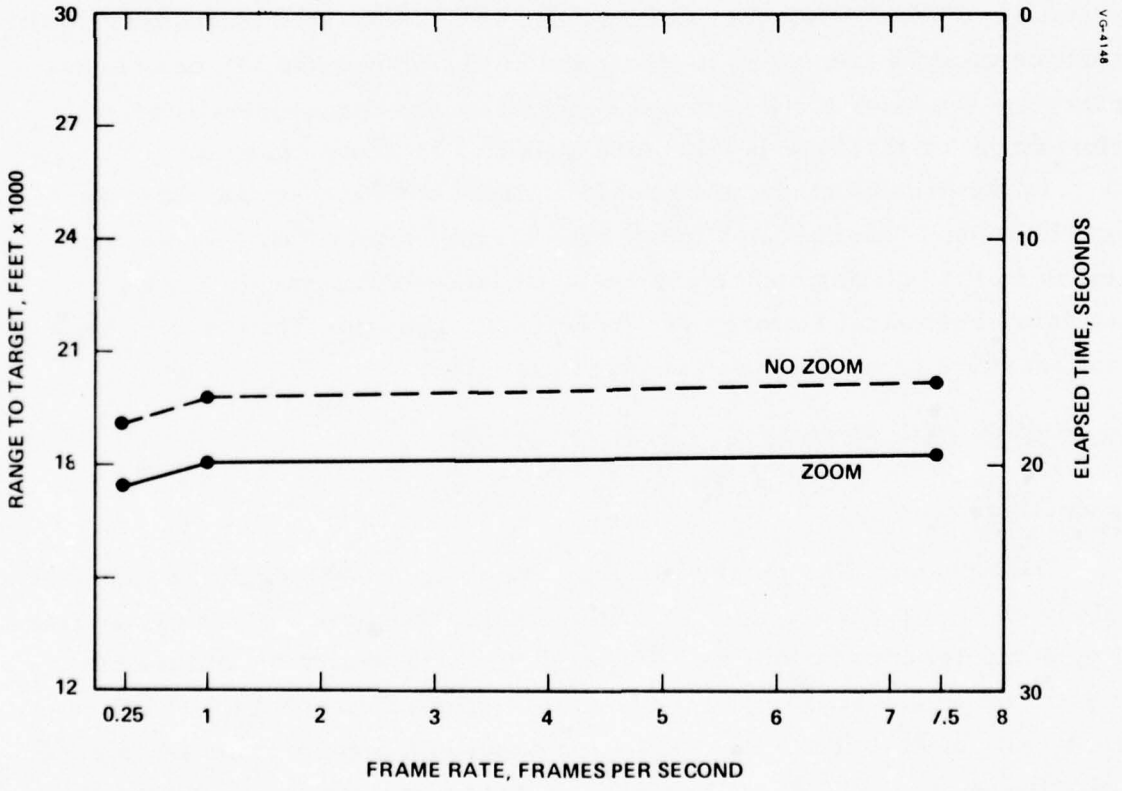


Figure 33. Zoom, frame rate interaction.

Because there was no degradation at the 256 by 256 element resolution, one can speculate on even lower resolution systems. Prior to conducting this study, a pilot study was conducted. In the pilot study, a 128 by 128 element sensor resolution was evaluated and found to be too poor to consider including in this study. A 200- to 256-element resolution sensor system is probably the best choice for the prebriefed, target location known RPV strike mission.

Optical zoom did not improve the operators' ability to recognize and acquire targets. Using zoom resulted in decreased range-to-target at acquisition due to the time spent using zoom. Therefore, optical zoom is not recommended for the prebriefed, target location known RPV strike mission.

Previous research which has shown performance benefits of high resolution are not necessarily in conflict with the findings of the present study. Most past research concerned with sensor resolution has been for the task of recognizing and/or identifying tactical vehicle-sized targets when the location of the targets was not precisely known. For that type of task, some minimum number of resolution elements must be on a target before recognition or identification can occur. As range-to-target increases, sensor resolution must be increased to obtain the criterion number of lines across the target. Operator tactical target recognition and target identification performance for that task is therefore sensitive to sensor resolution.

In the present study, the operator's task can be best described as target location. The operator locates the target by correlating contextual features on the briefing and reference materials with the target scene. Since large contextual features are typically chosen, operator performance is not sensitive to variations in sensor resolution.

BANDWIDTH COMPRESSION, JAMMING STUDY

Introduction

Video bandwidth compression techniques have been explored extensively over the past few years. It has been shown in both theoretical studies and by computer simulations that digital picture transmission is possible using as few as 0.5 bit per picture element. Studies directed toward hardware development indicate that real-time bandwidth compression techniques yield between 30 and 40 dB peak signal-to-RMS noise ratios using 1 to 2 bits per picture element and therefore approach the Pulse Code Modulation (PCM) quantization noise limits for 6 and 8 bit quantization.

Bandwidth compression techniques differ in the mathematical operations required to compress the data and in the domain (mathematical space) to which the compressed data are transformed. The mathematical operations to be performed impact hardware cost, size, and weight, while the compressed data domain determines the compression ratio, susceptibility to channel errors, and the usefulness of the transform domain data.

Delta Modulation and Differential Pulse Code Modulation (DPCM) techniques have the simplest mathematical operations in that only a comparison operation or an interpolation operation is needed. The difference between the actual value and the predicted value is transmitted. Such spatial domain compression techniques usually result in encoding with between 2.0 and 3.0 bits per pixel and are characterized by many picture errors (usually a streak) whenever a single channel error occurs. Because the RPV operating environment is likely to be hostile, the implementation simplicity does not outweigh its susceptibility to noise jamming. However, these techniques have been effective when used in conjunction with transform coding.

In transform coding, a one- or two-dimensional mathematical transform of an image line segment or block is performed. A bit rate reduction or bandwidth compression is obtained by requantization of the transform coefficients. Transform coding is effective, because the process transforms a set of spatial domain picture element intensity levels through a one-to-one mapping into a related set of nearly independent transform coefficients. The statistics of the transform coefficients are such that they can be described by their mean and variance and that the channel capacity required to transmit the set of sequency coefficients is less than that required to transmit the original picture elements. Since the transform process yields a set of nearly independent transform coefficients, each coefficient can be assigned a unique quantization and reconstruction rule.

The challenge in achieving bit rate reduction without seriously degrading the quality of the reconstructed picture is in the derivation of the transform domain quantization and reconstruction algorithms. In general, the mean squared error criterion and the related rate distortion and information theory provide the required mathematical tools to define the theoretical performance limitations. Encoding schemes developed at the universities provide an initial estimate for the algorithms.

Theoretical and empirical data are available to show that most transforms exhibit nearly the same bandwidth compression capabilities for a fixed mean squared error performance. However, the mathematical operations involved in various transforms are vastly different. The distinguishing feature of the various transforms is the structure of the basis vector set against which the set of picture statistics are compared.

The simplest transforms to implement are the Haar and the Hadamard, since they involve only simple (no imaginary components) arithmetic operations. The Hadamard transform requires about twice as many operations as the Haar, but the Hadamard operations involve only simple addition and subtraction, while the Haar requires either addition of non-integer values or multiplication, depending on the implementation. The most difficult transform to implement is the Fourier, since it requires complex arithmetic operations. The Hadamard and the Haar result in comparable hardware cost, size, and weight.

Two-dimensional transforms are generally assumed capable of achieving about 0.5 bit per picture element improvement over one-dimensional transforms of the same length basis vector. This increased bit rate reduction has not yet been practical, since frame storage is required in the implementation. Within the next several years, frame storage costs will be sufficiently low to make a reevaluation of the two-dimensional implementation necessary.

An important transform domain technique evaluation criterion is the usefulness of the spatial domain to transform domain mapping. The composition of the transform basis vector set determines this mapping. It is well known that the Fourier transform maps the spatial time domain into the spatial frequency content of the picture. The Hadamard transform maps spatial time domain samples to spatial sequences (rectangular wave signals analogous to Fourier domain sine wave frequencies). The Haar transform accomplishes either a local or global spatial domain mapping, and it is difficult to relate the transform coefficients to picture content.

Another important feature of transform coding is that while the mapping from the spatial domain to the transform domain results in compaction of the picture detail, the inverse mapping back into the spatial domain spreads (or averages) the detail over the length of the transform. This spreading factor results in increased noise immunity to noise received in the transform domain. One-dimensional Fourier and Hadamard transforms

achieve a reconstructed picture comparable to a PCM bit error rate of 10^{-5} when the channel error rate is really 10^{-2}. The Haar transform averages over only a few of the spatial domain samples and does not achieve an appreciable amount of noise immunity.

Of the compression techniques which could be employed, Hughes selected the one-dimensional Hadamard transform as the one most suitable for RPV application. This was based upon considerations of implementation complexity and cost, noise immunity of the compressed signal, risk, and exploitation potential of the signal for bandwidth reduction and system non-linearity compensation purposes.

Under Hughes company-funded efforts, real-time Hadamard transform equipment was designed and constructed. The equipment, designed to vary bandwidth compression ratio and simulate and vary bit error rate jamming, was interfaced with the Hughes RPV simulator to investigate the effects of bandwidth compression and bit error rate jamming on RPV operator target acquisition performance.

Research Approach

It was deemed desirable to investigate bandwidth compression from 1:1 (6 bits per picture element, no compression) to 12:1 (0.5 bit per picture element) in combination with bit error rate jamming from zero (no jamming) to 10^{-2} bit errors per sample. However, it was not possible to simulate bit error rate jamming in combination with the 1:1 uncompressed spatial domain condition. Also as part of this study, a special variable window compression technique was to be evaluated.

To most efficiently accommodate these two special conditions, two separate studies were conducted. The first study was a two-factor investigation of one-dimensional Hadamard bandwidth compression and bit error rate jamming in which 2, 1, and 0.5 bits per picture element compressions and 0, 10^{-3}, and 10^{-2} bit error rate jamming levels were investigated. The second study was a single factor investigation of one-dimensional Hadamard bandwidth compression without jamming. Five levels of bandwidth compression were evaluated in this second study. These five levels were 6, 2, 1, 0.6, and 0.5 bits per picture element (1:1, 3:1, 10:1, and 12:1 compression ratios, respectively). As previously stated, the overhead for the error protection on the two most significant bits was 8.6 percent. Thus the 3:1

compression ratio was actually 3-[3 x 0.086] or 2.74:1. Similarly, the 12:1 compression ratio was actually 12-[12 x 0.086] or 10.97:1.

The 0.6 bit per picture element (10:1 compression ratio) condition was the special variable window compression technique. The variable window compression technique used 1.5 bits per picture element in the center half of the video image and 0.5 bit per picture element in the outer periphery. Thus the center 25 percent of the image area was compressed 4:1 and the peripheral 75 percent of the image area was compressed 12:1. The resulting average compression ratio was 10:1.

The rationale behind the variable window compression technique is that an operator needs high quality video only in the center portion of the target scene to see high spatial frequency target detail. To perceive lower spatial frequency local area cues and contextual information in the peripheral portions of the target scene, reduced quality video will suffice. Since the operator has control of sensor pointing, he can position the target area in the high quality center portion of the image. The low quality peripheral portion of the image should be adequate to locate the target area and allow the operator to slew the sensor to position the target in the center portion of the display.

The manner in which bandwidth compression and bit error rate jamming were implemented in the Hadamard transform equipment and the interface between the Hadamard equipment and the RPV simulator were described in Section 2.0. Figures 34 and 35 show two example target scenes with bandwidth compression and bit error rate jamming. The vehicle/target mission geometry for this study was the computer model of a BGM-34 RPV with attitude hold autopilot flying at 680 feet per second with an 0.5 fuel load as described in Section 2.0. The RPV popped-up at a 30,000-foot range to the target and closed to a minimum range of 1500 feet to the target. A 1σ crosstrack navigation error of 1700 feet was simulated with a 20-degree TV sensor field of view. A 525-line TV sensor resolution was simulated. The 14-inch diagonal display was refreshed at 30 frames per second with 2:1 interlace. The 3-axis stabilized sensor pointing mode with 3.75 frames per second frame rate was used in the study.

Research Design

A 3 x 3 within-subjects factorial design was used to present all combinations of 3:1, 6:1, and 12:1 Hadamard compression ratio and 0, 10^{-3}, and 10^{-2} bit error rate (BER) jamming to 12 operators (subjects) in the first



NO COMPRESSION,
NO JAMMING

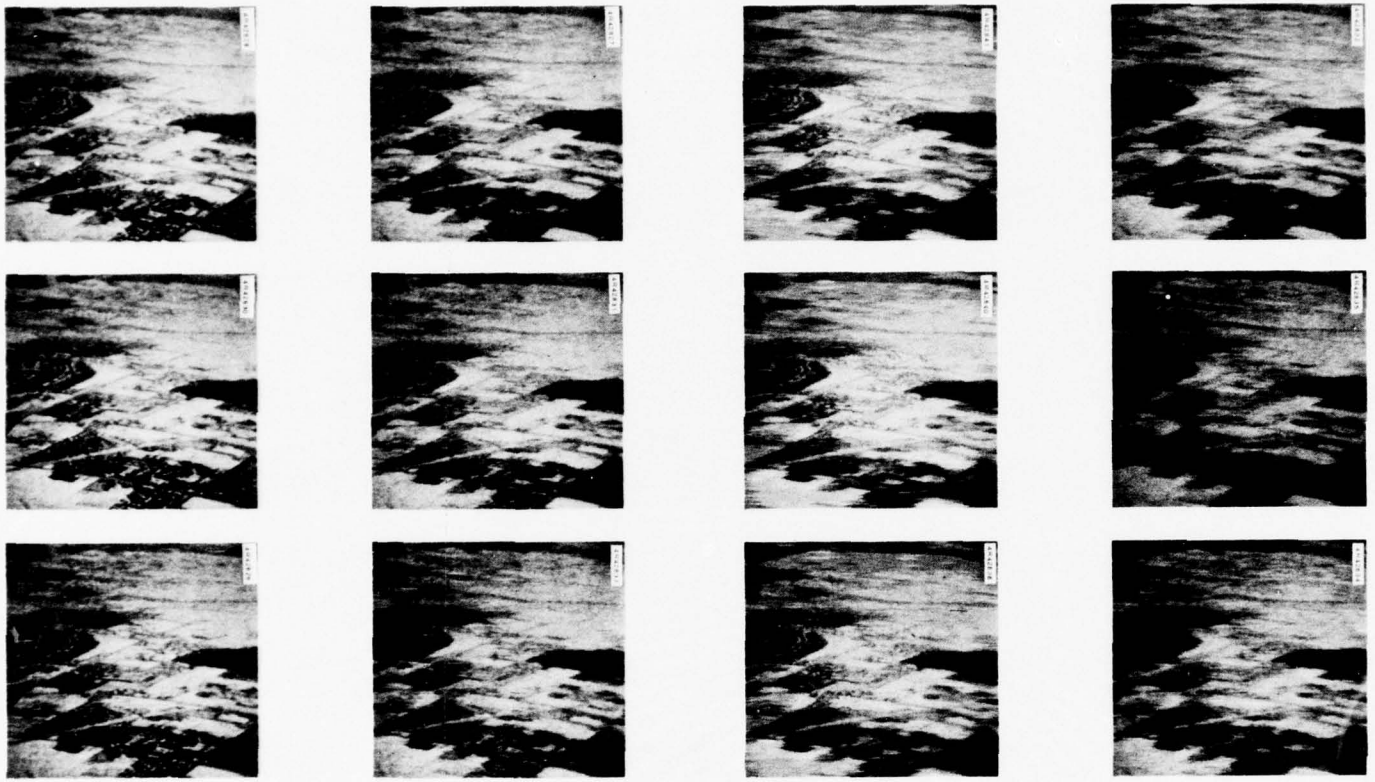


Figure 34. Example bandwidth compression bit error rate jamming target scene used in the study.

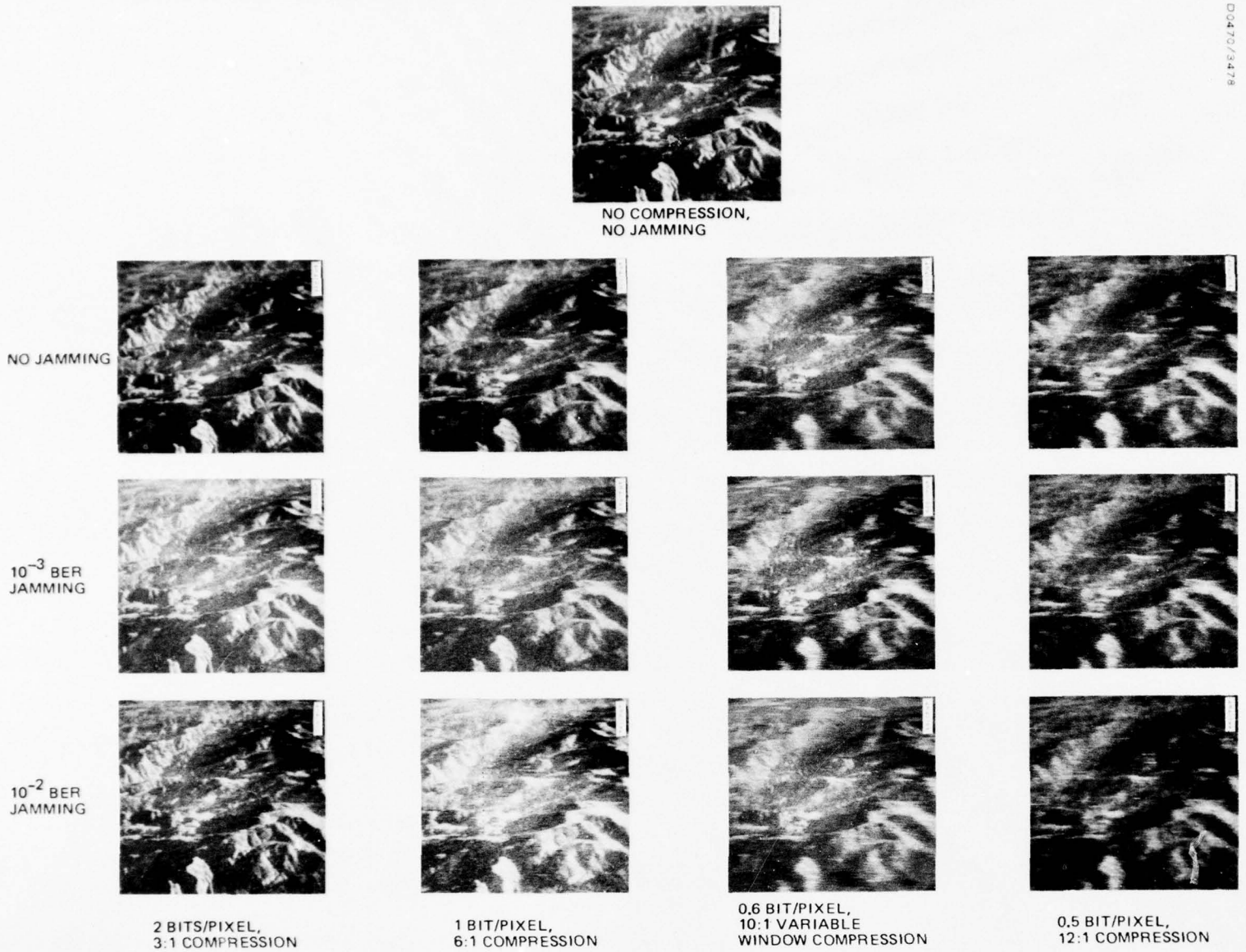


Figure 35. Example bandwidth compression bit error rate jamming target scene used in the study.

portion of the study. For each operator, Hadamard compression ratio was blocked into three groups of six trials each. The order of block presentation was counterbalanced across the 12 operators. Within a block of six trials at a particular compression ratio, each BER occurred twice, and across the 18 trials (18 targets) that each operator received, all six possible orders of the three BER's were presented. Across the entire design each target occurred equally often in each of the nine combinations of conditions which completely balanced targets, operators, and conditions. The resulting design is shown in Figure 36.

A within-subjects single factor design with five levels of bandwidth compression and 10 operators was used in the second portion of the study. For each operator, compression ratio was blocked into five groups of two trials each. The order of block presentation was counterbalanced across the 10 operators. Across the entire design, each of the 10 targets occurred equally often in each of the five compression ratios which completely balanced targets, operators, and compression ratios. The design for this study is illustrated in Figure 37.

Operators

Hughes engineering personnel who had served as operators (subjects) in previous sensor target acquisition studies at Hughes participated as operators in the study. Twelve operators were used in the first study; 10 operators were used in the second study.

Target Scenes

High resolution forward oblique aerial photographic transparencies taken over the southwestern United States were used to select eighteen 20-degree field of view target scenes for the first study and 10 target scenes for the second study. The targets were bridges, POL storage areas, storage buildings, refineries, factories, and dams.

Briefing and Reference Materials

Briefing and reference materials were prepared in individual target briefing packets. Each packet contained two oblique aerial photographs representing viewing ranges to the target of 1 and 3 nautical miles. Target

		TARGETS																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
OPERATORS	1	A3	A2	A0	A2	A3	A0	B2	B0	B3	B0	B2	B3	C0	C3	C2	C3	C0	C2
	2	A2	A0	A3	A0	A2	A3	C0	C3	C2	C3	C0	C2	B3	B2	B0	B2	B3	B0
	3	B0	B3	B2	B3	B0	B2	C2	C0	C3	C0	C2	C3	A0	A3	A2	A2	A3	A0
	4	B0	B3	B2	B3	B0	B2	A3	A2	A0	A2	A3	A0	C2	C0	C3	C0	C2	C3
	5	C2	C0	C3	C0	C2	C3	B3	B2	B0	B2	B3	B0	A0	A3	A2	A3	A0	A2
	6	C3	C2	C0	C2	C3	C0	A0	A3	A2	A3	A0	A2	B2	B0	B3	B0	B2	B3
	7	A0	A3	A2	A0	A2	A3	B3	B2	B0	B3	B0	B2	C2	C0	C3	C2	C3	C0
	8	A3	A2	A0	A3	A0	A2	C2	C0	C3	C2	C3	C0	B0	B3	B2	B0	B2	B3
	9	B2	B0	B3	B2	B3	B0	C3	C2	C0	C3	C0	C2	A0	A3	A2	A0	A2	A3
	10	B2	B0	B3	B2	B3	B0	A0	A3	A2	A0	A2	A3	C3	C2	C0	C3	C0	C2
	11	C3	C2	C0	C3	C0	C2	B0	B3	B2	B0	B2	B3	A2	A0	A3	A2	A3	A0
	12	C0	C3	C2	C0	C2	C3	A2	A0	A3	A2	A3	A0	B3	B2	B0	B3	B0	B2

D0470/3479

KEY:

HADAMARD BANDWIDTH COMPRESSION RATIO

- A) 3:1
- B) 6:1
- C) 12:1

BIT ERROR RATE JAMMING

- 0) 0
- 2) 10^{-2}
- 3) 10^{-3}

Figure 36. Experimental design for bandwidth compression, bit error rate jamming study.

OPERATORS	TARGETS									
	1	2	3	4	5	6	7	8	9	10
1	A	A	B	B	C	C	D	D	E	E
2	B	B	A	A	E	E	C	C	D	D
3	C	C	D	D	A	A	E	E	B	B
4	D	D	E	E	B	B	A	A	C	C
5	E	E	C	C	D	D	B	B	A	A
6	A	A	B	B	C	C	D	D	E	E
7	B	B	A	A	E	E	C	C	D	D
8	C	C	D	D	A	A	E	E	B	B
9	D	D	E	E	B	B	A	A	C	C
10	E	E	C	C	D	D	B	B	A	A

D0470/3480

KEY:

HADAMARD BANDWIDTH COMPRESSION RATIO

A) 1:1, NO COMPRESSION
B) 3:1
C) 6:1
D) 10:1, VARIABLE WINDOW
E) 12:1

Figure 37. Experimental design for bandwidth compression study.

locations were circled on the photographs and a pin hole on the 1-mile range photograph indicated the target aimpoint. Also included were short written descriptions of the target and surrounding area. The operators studied the photographs prior to the start of a trial mission and retained the briefing photos for reference during the mission.

Study Procedures

For both studies the operators' task was to recognize and acquire the prebriefed targets as rapidly as possible. Each trial started at a range of

30,000 feet from the target, closing at 680 feet per second. Prior to trial start, an operator was given the appropriate briefing packet and allowed to study it. When the operator indicated he was ready, the display was unblanked and the trial was started. The operator's task was to recognize (locate) and acquire the target by positioning the target within a fixed 1-degree radius circle in the center of the display using the 3-axis stabilized sensor pointing mode. When the operator had acquired the target, he depressed a pushbutton on the hand control to command lock-on, ending the run.

Prior to formal data collection, the operators received extensive training. Standardized written instructions which described the RPV mission, the purpose of the study, and the general study procedures were read to the operators. The operators were then trained on the target acquisition task procedures with a single example target scene. When the operators had mastered the target acquisition task, the study conditions were demonstrated. A series of six complete training trials was then run. Formal data collection immediately followed the six training trials.

Performance Measure

Range-to-target at acquisition (lock-on) was used to assess the effects of bandwidth compression and BER jamming on operator target acquisition performance. Range-to-target at the instant the operators commanded lock-on was measured to the nearest foot by the computer and printed out at the end of each trial. The experimenter recorded whether or not the operators had acquired the correct target.

Results and Discussion

The range-to-target at acquisition data were analyzed for the reliability of bandwidth compression and bit error rate jamming effects with analysis of variance for the two studies. On the few trials where the operators failed to acquire targets, a range of zero feet was assigned. Analysis of variance summary tables are contained in Appendix A of this report. Analysis of the data indicates that bit error rate jamming as high as 10^{-2} bit errors per sample does not degrade operator target acquisition performance and that a large bandwidth compression will result in reduced operator performance. These results are discussed below.

Bit Error Rate Jamming

Figure 38 depicts the small, non-reliable ($p > 0.25$) differences obtained among the three BER jamming levels. The slightly superior performance obtained with 10^{-3} BER jamming compared to zero and 10^{-2} BER jamming is due to sampling variability in the study. Thus BER jamming, as manifested in horizontal lines 16 elements long in the transform domain video, did not interfere with operator target acquisition performance.

Bandwidth Compression

Bandwidth compression ratios of 3:1, 6:1, and 12:1 were evaluated in the first study. A statistically significant effect ($p < 0.05$) was obtained. As shown in Figure 39, there was little performance difference (492 feet) between the 3:1 and 6:1 compression ratios. However, a large degradation of operator performance (3,919 feet) occurred as compression increased from 6:1 to 12:1. This large (20 percent) reduction of performance between 6:1 and 12:1 compression ratios accounts for the statistically significant effect obtained.

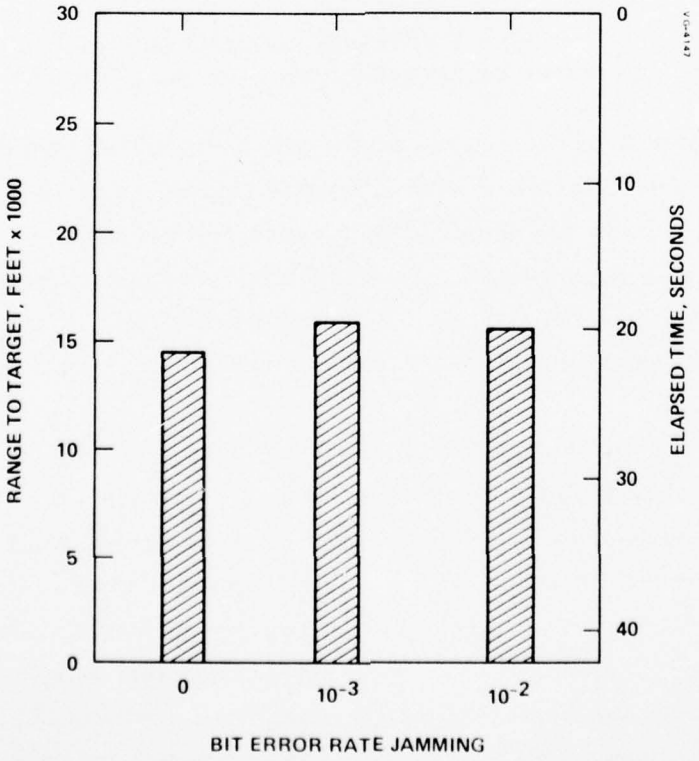


Figure 38. Effects of bit error rate jamming on operator target acquisition.

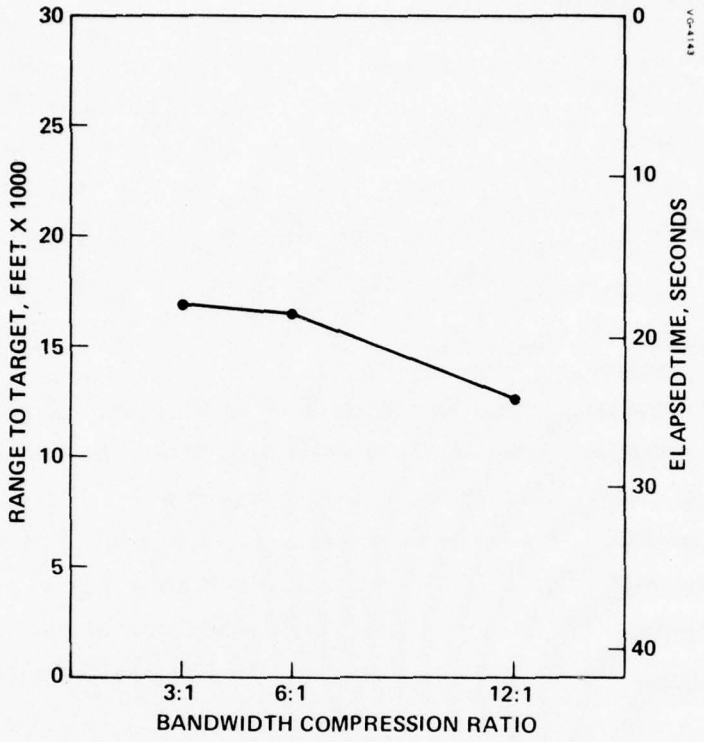


Figure 39. Bandwidth compression effects on operator target acquisition performance.

The results of the second study which evaluated compression ratios of 1:1, 3:1, 6:1, 10:1 (variable window compression), and 12:1 are shown in Figure 40. Although the effect of bandwidth compression in this smaller sample study was not statistically significant, the performance obtained was very similar to the first study. Operator performance degradation between 1:1 and 6:1 was small (659 feet) and large between 6:1 and 12:1 compression (2,995 feet).

Performance obtained with the 10:1, variable window compression condition was only slightly better than the 12:1 compression ratio condition. It had been predicted that the variable window compression technique would permit greater compression than a single window compression approach. The nearly linear curve between 6:1 and 12:1 compression indicates the 10:1 variable window compression would be no better than 10:1 single window compression. Apparently the need to slew the sensor to position desired portions of the scene in the center window resulted in increased task time and hence, reduced range-to-target acquisition. A larger center window might eliminate

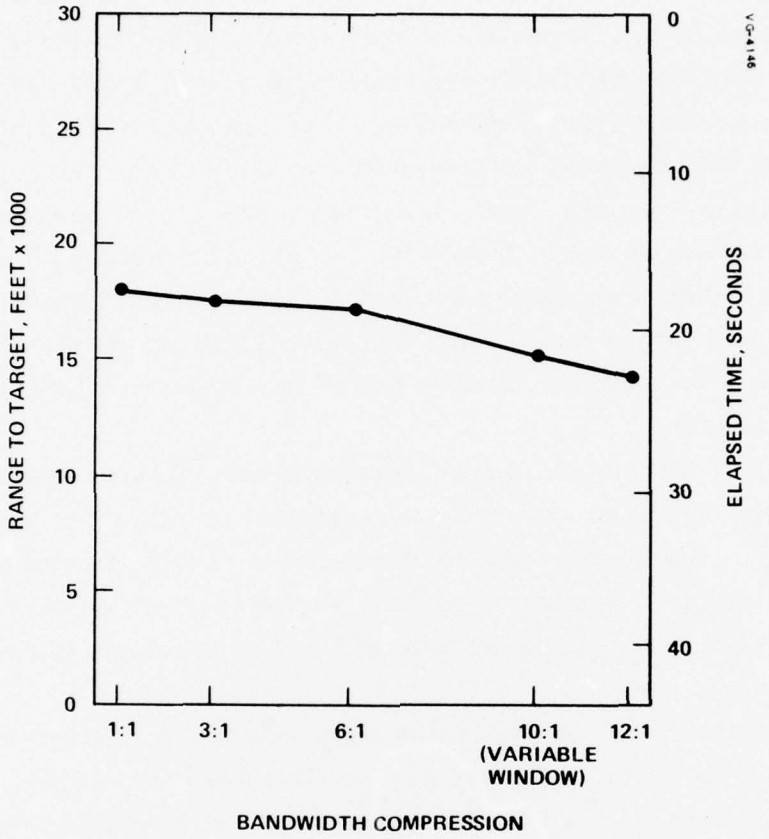


Figure 40. Comparison of bandwidth compression from 1:1 to 12:1.

the need to slew the sensor, thereby obtaining greater performance with a moderate reduction of bandwidth over single window compression. Further research will be necessary to determine the utility of the variable window compression technique.

Taken together the results of the two studies indicate that minimal operator target acquisition performance degradation will occur with bandwidth compressions up to 6:1 (1 bit per picture element). With compression ratios greater than 6:1, substantial performance degradation can be expected.

Conclusion and Recommendations

The key findings of this study were 1) bit error rate jamming as high as 10^{-2} bit errors per sample did not degrade operator target acquisition performance and 2) acceptable operator target acquisition performance

degradation occurred with 1-bit per picture element, one-dimensional Hadamard transform, bandwidth compression. Based on these two findings, a 1-bit one-dimensional Hadamard transform system can be recommended to achieve a 6:1 bandwidth compression that will operate in a high jamming environment without compromising RPV operator performance.

The above recommendation applies to the prebriefed, target location known mission simulated in the study. A 1-bit per picture element transform system may not be acceptable for other RPV missions, such as tactical vehicular-sized target strike. A 1-bit per picture element compression does result in some degradation of video image quality as was illustrated in Figures 34 and 35.

For the prebriefed, target location known mission where the targets are relatively large and where large contextual features can be used to locate the target, the video image quality degradation resulting from compressions up to 6:1 is not large enough to produce degraded operator performance. For small tactical targets whose location will not be precisely known, this may not be the case.

Some evidence to support this supposition comes from a recent study conducted for the Naval Undersea Center (Hershberger, 1976). In that study, a hybrid discrete cosine transform system with differential pulse code modulation developed by the Navy was evaluated. Bit encoding levels of 1, 2, and 5 bits per picture element and bit error rate jamming levels of 0, 10^{-3}, and 10^{-2} bit errors per sample were investigated and compared with an uncompressed 6 bit per picture element baseline. The operators' task was recognition of tactical vehicle targets (tank, jeep, staff car, half-truck, open truck, tow truck, APC, 5-ton truck and crane). The results of the study, presented in Figure 41, showed considerable degradation of operator performance, compared to the baseline uncompressed baseline condition, at 1-bit per picture element compression (6:1 compression ratio). Bit error rate jamming had no effect on operator tactical target recognition performance.

It, therefore, appears that the amount of compression that can be achieved without appreciable operator performance degradation is dependent upon the mission/task requirements. For a tactical target, location not precisely known mission, a 3:1 to 4:1 compression ratio appears to be acceptable. For the target location known mission investigated in this program, a 6:1 and possibly 8:1 compression ratio appears to be the limit.

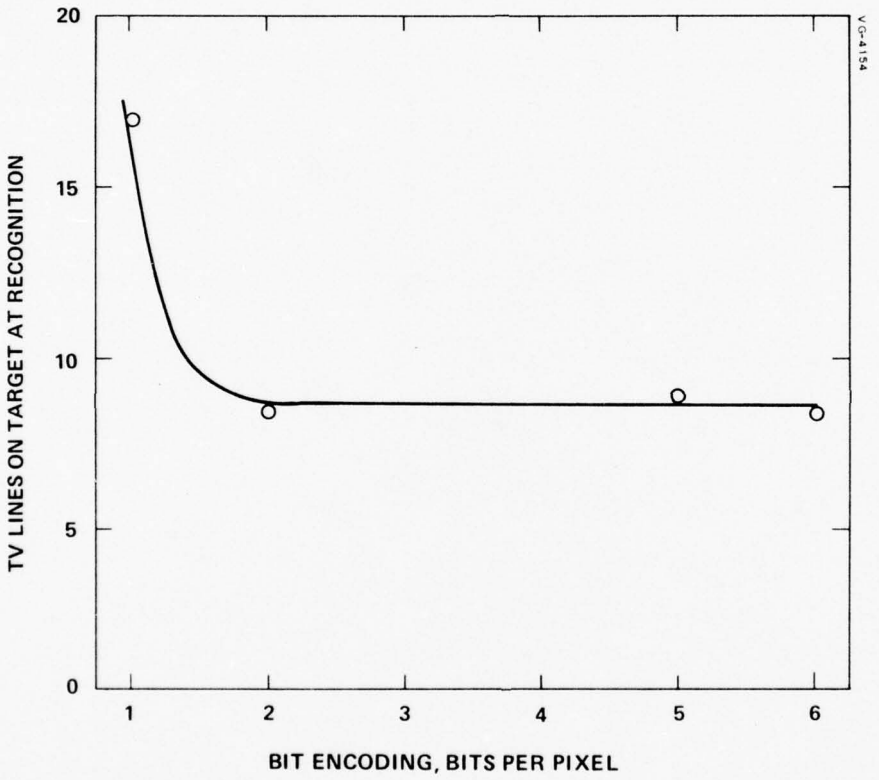


Figure 41. Effects of cosine/DPCM bandwidth compression on operator tactical target recognition.

SECTION 4

BANDWIDTH REDUCTION/COMPRESSION SYSTEMS SIMULATION

INTRODUCTION AND BACKGROUND

The objective of this program was to demonstrate methods of achieving a reduced/compressed video bandwidth to facilitate efforts for incorporating anti-jam techniques on a television video data link. The demonstration was to be in the form of a man-in-the-loop simulation. A minimum of three bandwidth reduction/compression systems in the presence of noise jamming were to be simulated and compared to a baseline 4.5 MHz video data link.

The parametric laboratory studies, described in Section 3, were conducted to obtain the necessary data so that the three or more bandwidth reduction/compression systems to be simulated could be realistically configured. Bandwidth reduction techniques in the temporal, spatial, and transform domains and techniques to compensate for bandwidth reduction and thereby maintain acceptable operator performance were investigated in the parametric studies.

Frame rate reduction was investigated as a means of reducing video bandwidth in the temporal domain. The results of the two studies which investigated frame rate reduction showed that a 3.75 frames per second frame rate with a 3-axis stabilized sensor pointing system would result in no degradation of operator target recognition or target acquisition (sensor pointing) performance. A 1.88 frames per second frame rate would result in a 3 percent range-to-target performance loss for sensor pointing within a 1-degree radius gate. For precision target designation, a 1.88 frames per second rate would result in a 0.4 milliradian increase in designation error compared to a 3.75 frames per second rate. The use of a 3.75 or 1.88 frames per second rate with the consequent 8:1 and 16:1 bandwidth reduction, respectively, relative to a standard 30 frames per second TV rate will depend on the mission requirements.

Image motion compensation and cursor designation control aiding techniques would allow frame rate to be reduced to 0.94 frame per second

PRECEDING PAGE BLANK-NOT FILMED

without reduction of operator/system performance. With such sensor pointing performance compensating techniques, frame rates as low as 0.23 frame per second can be used without any degradation of operator performance. There is, however, an initial transmission delay penalty that translates into a sizeable range penalty with the very low frame rates. Assuming a one frame period transmission delay with a 0.23-frame per second frame rate and an RPV flying at 680 feet per second, a 2,720 foot range penalty would be incurred.

With the type of sensor pointing control mode compensating techniques investigated in this program, a 32:1 bandwidth reduction (a 0.94-frame per second frame rate) can be achieved without performance loss. Bandwidth reduction as great as 128:1 (0.23 frame per second frame rate) can be obtained if one is willing to accept the initial range penalty caused by transmission delay.

Sensor video resolution reduction was investigated as a means of reducing video bandwidth in the spatial domain. A 256 by 256 element sensor resolution was found to produce operator target recognition and acquisition equivalent to a standard 512 by 512 element sensor resolution. A system resolution of about 200 by 200 elements is estimated to be the limit of resolution reduction before operator performance degradation occurs for the prebriefed target location known mission. A bandwidth reduction between 4:1 and 6.5:1 can thus be achieved with TV sensor resolution reduction.

The one-dimensional Hadamard transform bandwidth compression equipment developed by Hughes was used to investigate bandwidth compression effects on RPV operator performance. That laboratory study revealed that 1-bit per picture element compression could be achieved without degradation of operator target acquisition performance. Operator performance was considerably degraded at 0.6- and 0.5-bit per picture element compressions. It, therefore, appears that compression ratios of 6:1 and possibly 8:1 can be employed while retaining acceptable RPV operator performance.

The results obtained from the parametric studies can be used to configure a number of bandwidth reduction/compression systems. Table 1 identifies the baseline and eight potential systems. The eight systems range from a conservative 24:1, 2M bits per second data rate system to a 6656:1, 7K bits per second bandwidth reduction/compression system. Based on the

TABLE 1. EXAMPLE VIDEO BANDWIDTH REDUCTION/ COMPRESSION SYSTEMS

Bandwidth Reduction/ Compression System	Frame Rate	Resolution, digital elements	Compression, bits per pixel	Control Aiding	Amount of Bandwidth Reduction/ Compression
BASELINE	30	512 x 512	6	No	1:1
1	3.75	512 x 512	2.0	No	24:1
2	3.75	512 x 512	1.0	No	48:1
3	3.75	256 x 256	2.0	No	96:1
4	3.75	256 x 256	1.0	No	192:1
5	1.88	256 x 256	1.0	No	384:1
6	0.94	256 x 256	1.0	Yes	768:1
7	0.23	256 x 256	1.0	Yes	3072:1
8	0.23	200 x 200	0.75	Yes	6656:1

findings of the parametric studies, a 3.75 frames per second frame rate, 256 by 256 resolution, 1 bit per picture element system would be recommended. This system would provide a 192:1 bandwidth reduction/compression ratio, 246K bits per second data rate. It is within the current state-of-the-art and would be a low risk design which would not degrade operator task performance compared to a standard 47M bits per second TV system.

The objective of the bandwidth reduction/compression systems simulation was to evaluate three or more selected systems, such as identified in Table 1, in the presence of jamming. A total of 10 conditions (three systems combined with three levels of jamming plus the baseline) were to be evaluated in the systems simulation.

The simulation was to utilize 35-mm motion picture film supplied by the Air Force as the source target imagery. The film was collected using a Flight Research IV 35-mm camera with a 3-inch focal length lens mounted on a T-33 aircraft. The camera was hard-mounted to the aircraft and had a 20.5-degree field of view.

The weather during some of the target runs was fairly turbulent which produced large aircraft disturbances which in turn produced large, rapid

displacements in the target scenes. This image motion coupled with the limited 20.5-degree field of view target imagery precluded simulation of sensor pointing. Hence, video frame rate could not be a variable in the systems simulation. The simulation was, therefore, constrained to an evaluation of operator target recognition performance with video sensor resolution, bandwidth compression, and bit error rate jamming as variables.

Because of these limitations it was decided that the systems simulation should be a verification study of the results obtained in the parametric studies. To this end, 10 combinations of sensor resolution (256 by 256 and 512 by 512 elements), one-dimensional Hadamard bandwidth compression (1:1, 3:1, 4:1, 6:1, and 12:1 compression), and bit error rate jamming (0.0 and 10^{-2} bit errors per sample) were selected by the Air Force and Hughes for evaluation in the bandwidth reduction/compression systems simulation.

RESEARCH PARAMETERS

Operator target recognition performance under nine combinations of reduced system bandwidth and bit error rate jamming were compared with performance on a standard 512 by 512 element resolution, 6 bit video, 30 frames per second television system which served as a baseline. System bandwidth reduction was varied from 3:1 to 24:1 by manipulating sensor resolution and Hadamard transform compression ratio. Two resolution conditions were employed: standard 512 by 512 element television sensor video and a 256 by 256 element system. The reduced resolution condition provided a 4:1 system bandwidth reduction ratio. Hadamard transform compression ratios of 3:1, 4:1, 6:1, and 12:1 provided additional system bandwidth reduction. Jamming was simulated in selected conditions with a bit error rate of 10^{-2} errors per sample. Table 2 details the nine combinations of resolution, Hadamard transform compression ratio, and bit error rate (BER) examined in the simulation. Also tabled are the total system bandwidth reduction ratios due to resolution and compression.

The nine selected systems permitted validation of the parametric study results for resolution, bandwidth compression, and bit error rate jamming. Comparisons between systems 1 and 5, and 2 and 8 permitted evaluation of 256 by 256 and 512 by 512 element sensor resolutions at 3:1 and

TABLE 2. BANDWIDTH REDUCTION/COMPRESSION SYSTEMS EVALUATED IN THE SIMULATION

System Parameters	Systems Evaluated									
	Baseline	1	2	3	4	5	6	7	8	9
Sensor Resolution	512	512	512	512	512	256	256	256	256	256
Hadamard Compression Ratio	1:1	3:1	6:1	6:1	12:1	3:1	3:1	4:1	6:1	6:1
Bit Error Rate Jamming	0	0	0	10^{-2}	10^{-2}	0	10^{-2}	10^{-2}	0	10^{-2}
System Bandwidth Reduction Ratio	1:1	3:1	6:1	6:1	12:1	12:1	12:1	16:1	24:1	24:1

6:1 bandwidth compression ratios. Comparisons between systems 1 and 2; 3 and 4; 5 and 8; and 6, 7, and 9 permitted evaluation of bandwidth compression ratios from 3:1 to 12:1. Performance obtained with systems 2 and 3, and 8 and 9 permitted evaluation of 0.0 and 10^{-2} BER jamming. Each of the nine systems could, of course, be compared with the baseline standard TV system.

RESEARCH DESIGN

A between-subjects design was used with eight subjects (operators) in the baseline and each of the nine bandwidth reduction/compression systems given in Table 2. Each operator received 10 target trials with one of the nine systems or the baseline. The presentation order of the 10 conditions was blocked to control for possible video tape degradation or other changes that might occur over time. Thus, each block of 10 subjects tested, represented one complete sample of the 10 conditions.

OPERATORS

Eighty Hughes Engineering personnel participated as operators (test subjects) in the simulation. All the operators had some previous experience in sensor video target recognition.

AD-A039 762 HUGHES AIRCRAFT CO CULVER CITY CALIF DISPLAY SYSTEMS--ETC F/G 17/2
VIDEO IMAGE BANDWIDTH REDUCTION/COMPRESSIONS STUDIES FOR REMOTE--ETC(U)
OCT 76 M L HERSHBERGER, R J VANDERKOLK PE64732F.

UNCLASSIFIED HAC-P76-243R ASD-TR-76-26 NL

2 OF 2
ADA039 762



END

DATE
FILMED
6-77

TARGET SCENES

Ten test and four training scenes were used in the simulation. The target scenes were approximately 1500-foot altitude oblique motion pictures of rural and urban areas in the southwest United States. The scenes simulated a RPV closing on a target at a rate of 400 knots with an initial range-to-target of 3.3 to 6.4 nautical miles. The targets were industrial complexes, highway and railroad bridges, a dam, Surface to Air Missile sites, and isolated buildings.

The original imagery was Air Force supplied 35-mm motion picture film. This film was transferred to video tape using a tele-cine converter which consisted of a 35-mm movie projector and a synchronized television camera focused on the film plane. In a subsequent step, the video tapes were processed through the Hughes RPV simulation equipment, including the Hadamard transform hardware. This step allowed the desired parameters for each of the 10 conditions to be controlled and a new set of video tapes to be made. These final tapes with the 10 target scenes and four training target scenes for each of the nine bandwidth reduction/compression conditions and the baseline condition were used to present the target scenes to the operators.

LABORATORY EQUIPMENT

A television video tape unit and an 8.6-inch (diagonally measured) television monitor were used to present the imagery to the operators. A switching relay was placed in series with the video signal to allow the television monitor to be blanked by the test conductor between trials. A digital timer was used to time operator target recognition time.

Resolution measurements of the display monitor and video tape unit showed that the 512 by 512 element television resolution produced 420 active resolution elements measured with a Buckbee Mears resolution chart. The 256 by 256 element resolution produced 210 active resolution elements.

BRIEFING AND REFERENCE MATERIALS

Briefing and reference materials used in the simulation were prepared in individual briefing packets containing two oblique aerial photographs and a written description of the target and local area cues. The aerial photographs depicted slightly different aspect angle views of the target as seen from ranges

of 1 and 3 nautical miles with the target position circled. The photographs provided the operators contextual information to aid them in recognizing (locating) the target. The written description informed the operators of the target type, the specific aimpoint they were to designate, and contextual cues present in the scene. Prior to beginning a trial, an operator had time to study the briefing packet which was available to him for reference during the trial.

SIMULATION PROCEDURES

The operators' task was to find and point out the location of the prebriefed targets. The operators were instructed to make a designation (point to the target with a stylus) as soon as possible even if target recognition was based on contextual cues. Prior to a trial, the operator studied the briefing packet, and the test conductor summarized the salient features in the scene and answered any questions. When the operator was ready, the display was unblanked and the timer started. The operator searched the display to locate the target as the vehicle closed on the target. When the target was located the operator used a pointer to designate its position and said "there". The test conductor stopped the timer and checked to see if the operator had correctly located the target.

Standardized written instructions were read by the operators and four training trials were given to familiarize the operators with the simulation procedures, target types, and the bandwidth reduction/compression condition they would experience. Following training, the 10 target scene trials were conducted. The entire session, including training, lasted approximately 30 minutes.

PERFORMANCE MEASURES

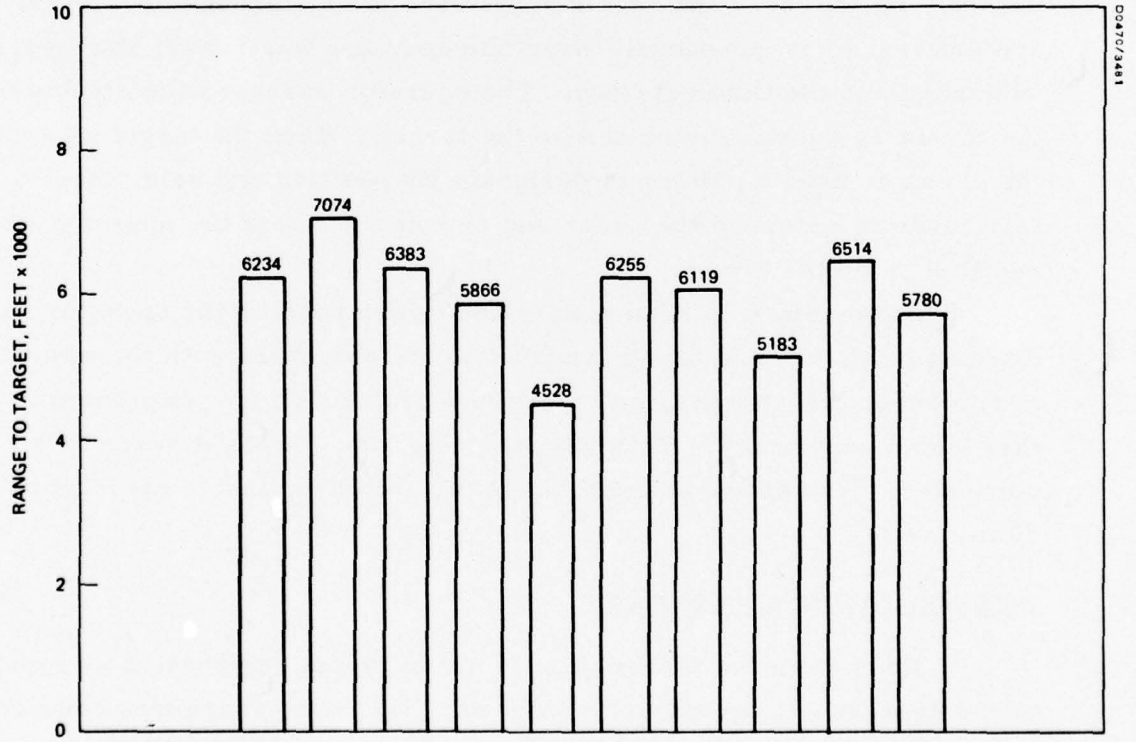
Time from the start of each trial to target designation was measured to the nearest 0.1 second and recorded. This time score was converted to time-to-target at designation by subtracting the time score from the total trial length. When an operator did not find the target, the total trial length was used as the time score. Assuming a constant 400 knots speed, the range-to-target at designation was computed. Probability of correct target

recognition/designation was derived from the number of correct target recognition/designation trials for each of the ten conditions.

RESULTS AND DISCUSSION

The range-to-target at recognition and probability of correct target recognition data were analyzed for statistical significance of performance differences among the baseline and the nine bandwidth reduction/compression systems using analysis of variance. The analyses of variance revealed there were no reliable differences among the ten conditions for range-to-target at recognition ($p > 0.25$) and that there were reliable differences among the ten conditions for probability of correct target recognition ($p < 0.01$).

Figure 42 gives the average range-to-target at recognition results for the baseline and the nine bandwidth reduction/compression systems. It is clear from Figure 42 that differences were obtained among the ten conditions.



SYSTEMS:	BASELINE	1	2	3	4	5	6	7	8	9
RESOLUTION:	512	512	512	512	512	256	256	256	256	256
HADAMARD COMPRESSION (BITS/PIXEL):	6	2	1	1	0.5	2	2	1.5	1	1
SYSTEM BANDWIDTH REDUCTION:	1:1	3:1	6:1	6:1	12:1	12:1	12:1	16:1	24:1	24:1
BIT ERROR RATE JAMMING:	0	0	0	10^{-2}	10^{-2}	0	10^{-2}	10^{-2}	0	10^{-2}

Figure 42. Range-to-target recognition performance.

The obtained performance differences, however, were not large enough to be statistically reliable. It is also apparent that many of the differences among the ten conditions are not logical. For example, System 1 with 3:1 bandwidth compression was superior to the baseline system; System 8 with 256 by 256 element resolution and 6:1 compression was superior to System 7 with 256 by 256 element resolution and 4:1 compression. These and the other non-statistically reliable differences are apparently due to sampling error caused by differences among the operators assigned to the ten conditions. The 12:1 compression (0.5 bit per picture element) 512 by 512 element resolution system produced the poorest performance which agrees with the parametric study results.

Probability of correct target recognition for the baseline and the nine bandwidth reduction/compression systems is shown in Figure 43. The analysis of variance of the probability data revealed statistically reliable differences among the ten conditions. A post hoc Newman-Keuls simultaneous test for multiple contrasts revealed that System 4 with 512 by 512 element resolution and 12:1 compression (0.5 bit per picture element) was significantly poorer the other nine conditions ($p < 0.01$) and that there were no reliable differences among the other nine conditions. Twenty-nine percent fewer targets were correctly recognized with System 4 than the baseline, and 28 percent fewer targets were correctly recognized with System 4 than with System 8 (256 by 256 element resolution and 6:1 compression). A 12:1 (0.5 bit per picture element) compression system definitely results in degraded operator target recognition performance.

The fact that there were no reliable differences among any of the nine systems and the baseline, except for the 12:1 compression system, means that there was no operator performance degradation due to: 1) 256 by 256 element resolution, 2) bandwidth compression up to and including 6:1 (1 bit per picture element) compression, and 3) 10^{-2} bits per sample bit error rate jamming. Although the poor range-to-target recognition performance obtained with System 4 at 12:1 compression was not reliably different from the other nine conditions, the results agree with the probability data. Apparently, the larger variability of the range data prevented the 12:1 compression system from being reliably different from the other nine conditions with the relatively small number of observers used in the study.

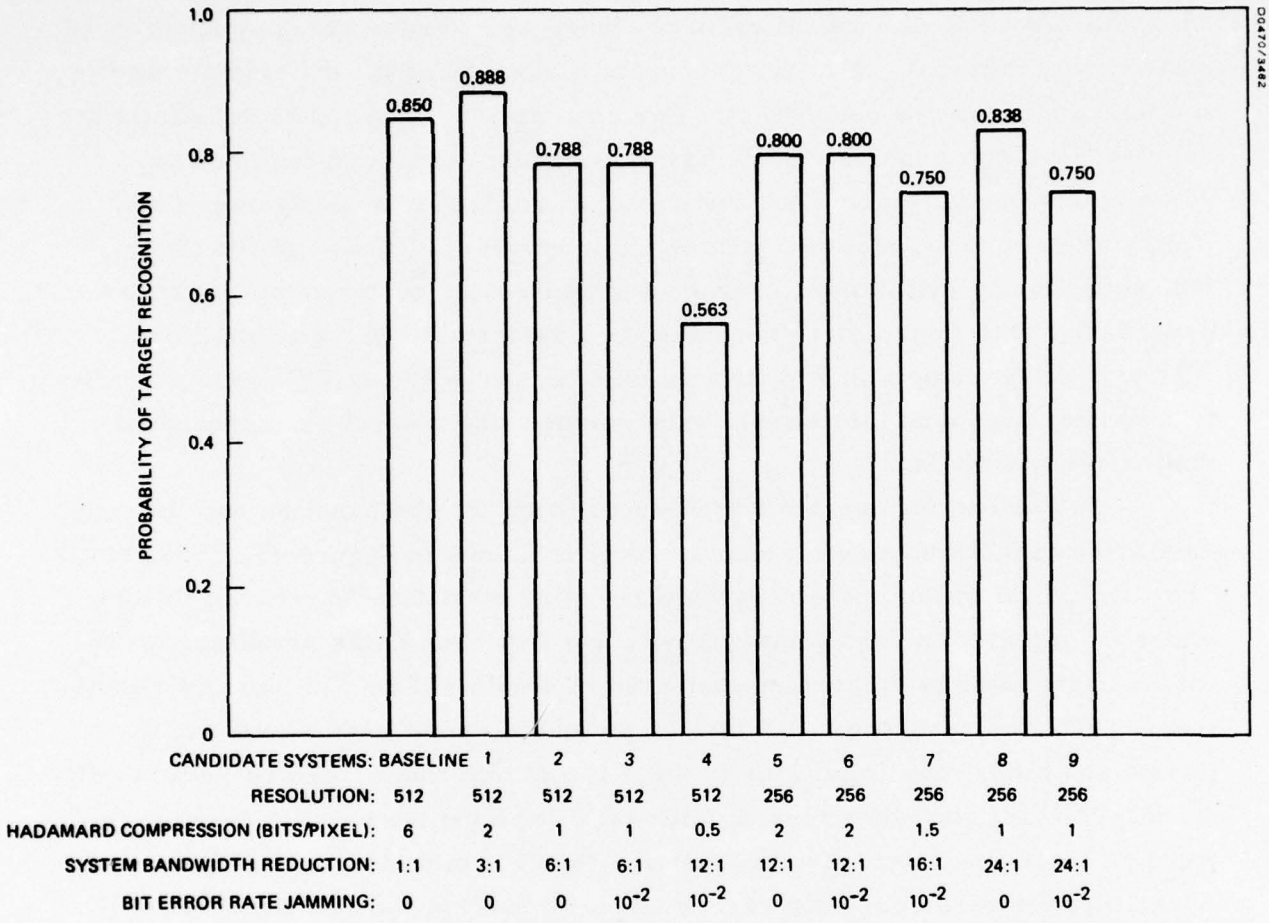


Figure 43. Probability of correct target recognition performance.

The results of the simulation indicate that operator performance is not a simple function of the amount of bandwidth reduction/compression. It is how much reduction or compression is obtained for a given reduction/compression technique. For example, System 8 (256 by 256 element resolution and 6:1 compression) which provided a 24:1 bandwidth reduction/compression was far superior to System 4 (512 by 512 element resolution and 12:1 compression) which provided only half as much (12:1) bandwidth reduction/compression. It appears that bandwidth reduction/compression can be achieved with resolution reduction and bandwidth compression without loss of operator performance but only within certain limits. For the prebriefed target location

known mission simulated, approximately 6:1 compression and 256 by 256 element resolution are the limits.

CONCLUSIONS AND RECOMMENDATIONS

The bandwidth reduction/compression systems simulation was conducted to verify the resolution, compression, and bit error rate jamming results of the parametric studies. The parametric studies showed that 256 by 256 element resolution, 6:1 (1 bit per picture element) one-dimensional Hadamard compression, and 10^{-2} bits per sample bit error rate jamming would not degrade RPV operator target recognition performance. These results were, without exception, verified by the systems simulation. The Bandwidth Compression, Bit Error Rate Jamming parametric study showed that operator performance degraded with compression ratios greater than 6:1; the same result was obtained in the systems simulation.

From the review of the parametric study results provided in the introduction to this section, a 3.75 frames per second frame rate, 256 by 256 element resolution, 1 bit per picture element one-dimensional Hadamard bandwidth reduction/compression system with a 192:1 bandwidth reduction/compression ratio (246K bits per second data rate) was the recommended Hughes system. This recommendation still holds and is the subject of the bandwidth reduction/compression implementation analysis presented in the following section of this report.

SECTION 5

BANDWIDTH REDUCTION/COMPRESSION SYSTEM IMPLEMENTATION ANALYSIS

INTRODUCTION

An analysis of how the selected Hadamard transform reduction/compression technique can be implemented as part of a drone control system was the final task in this program. The selected Hughes digital approach to video data bandwidth compression allows the data compression and communications link to be treated separately. Although this analysis is primarily concerned with the implementation of the data compression portion of the video data link, a complete jam-resistant video data link capable of being compatible with many mission types is postulated. Appropriate modularization of the data link and prudent use of new component and signal processing technologies makes such a data link achievable.

Development of a jam-resistant video data link to be compatible with many mission types and accepted by many military user agencies is a formidable task. Before one can confront such a task, the requirements for the video data link must be established. It does not appear feasible to satisfy the many unique mission requirements with one universally acceptable set of data link requirements. As a result, a modular approach to the video data link has been taken. The modular approach allows functional elements (modules) to be changed such that the video data link can satisfy various mission requirements and user needs. The implementation analysis has therefore been conducted to establish the "best" partitioning of the video data link such that the link can be modified with minimal cost and hardware impact. The following analysis addresses the functional partitioning of the video data link and the data compression implementation aspects of the selected bandwidth reduction/compression system.

Video Bandwidth Reduction/Compression Signal Processing Function

The video signal processing function has been divided into airborne video processing to minimize the baseband video data rate and ground

PRECEDING PAGE BLANK-NOT FILMED

processing to maximize the quality of the display video. Since the airborne equipment is to be expendable, the signal processing function must be implementable with advanced component technologies. Less restriction is placed on ground processing, since there is more space available and the units can be reused for many missions.

The airborne signal processor will accept an analog signal from the aircraft sensor module and convert this waveform into a digital signal for transmission to the ground. The objective of the video processing function is to minimize the demands on the communications channel while preserving the essential video information. Table 3 identifies the key signal processing functions.

The source encoder works on the video waveform from the sensor and uses a priori information to reduce the data rate of the digitally encoded data. This processor includes: 1) the Hadamard transform unit to convert the video into a domain where the use of a priori information is maximized, 2) the A/D

TABLE 3. VIDEO SIGNAL PROCESSING FUNCTIONS

Airborne Video Processing	
• Source Encoding	– Encodes the video for efficient transmission. (Includes bandwidth compression and A/D conversion.)
• Frame Rate Reduction	– Removes interframe correlation to reduce the required data rate.
• Resolution Reduction	– Removes some of the spatial correlation to reduce the data rate.
• Channel Encoding	– Encodes the sync. signals and adds error protection to selected data bits.
Ground Video Processing	
• Image Enhancement	– Uses knowledge of transform domain coefficients to enhance the contrast, brightness and edges.
• Image Motion Compensation	– Reduces the operator image registration task when frame rates are reduced below 4 per second.
• Display Refresh	– Eliminates flicker.
• Inverse Transform and Image Estimation	– This function converts the digital data into a best estimate of the original image for display.

converter to encode this information, and 3) any special processing required to encode the sensor synchronization signals. The above partitioning is from a functional viewpoint and is accomplished in a bandwidth compression module.

Frame rate reduction and resolution reduction are done in a frame rate buffer module. This processing is used to exploit the excessive time and spatial correlation that is in the sensor data. The man-in-the-loop video image bandwidth reduction/compression laboratory studies showed that frame rate reduction ratios of 8:1 and resolution (both vertical and horizontal) reduction of 4:1 have no significant impact on the RPV operator's recognition and acquisition tasks. This bandwidth reduction combination gives a data rate reduction ratio of 32:1. These results are not necessarily universally acceptable for all missions but indicate the significance of this processing.

Channel encoding on the compressed data is used to condition the digital data so that the impact of a channel error is minimized. This function will add error protection to selected data bits and interleave the sync signals with the video data to decrease the effectiveness of a jammer.

The ground-based video signal processing will invert the encoding process that was done in the airborne unit and condition the video for display. Most of the processing will be done while the data are in the transform domain where the data quantity is minimized and the transform coefficients represent a spatial dimension of the video signal. Image enhancement processing can be done on the transform domain data. Image motion compensation and refreshing for display would be implemented in the ground processing equipment to reduce the operator target acquisition control problem if frame rate is reduced below 4 frames per second and to provide a 30 frame per second display refresh rate.

Jam-Protection Signal Processing Function

Jam-resistance is provided through spread spectrum processing where the processing gain is defined as the ratio between the transmitted data rate (chip rate) and the actual baseband signal or video data rate. In general, the objective is to minimize the video data rate (by bandwidth compression and frame rate reduction) and transmit at the maximum data rate that can be supported by the communication channel. The improvement in communications efficiency achieved by this signal processing provides anti-jam (AJ) margin.

Spread-spectrum signal processing results in encoding the video such that the simultaneous time-frequency-amplitude volume available in the communications channel is occupied in a manner that minimizes the jammer's effectiveness. This is best done, for a wide class of jammers, by making the transmitted signal appear as noise in each observable dimension (time, frequency, amplitude). Usually the maximum available amplitude is transmitted and the signal in time and frequency is randomized. The standard spread spectrum techniques are pseudorandom direct sequence modulation, time hopping, and frequency hopping.

There is currently no specified communications link for future RPV and guided weapon systems missions, but studies indicate that a 20 MHz bandwidth is about the maximum sole use allocation that can be expected. This limits the maximum frequency spreading that can be done and indirectly limits the maximum digital signaliing rate. In a direct sequence spread spectrum system, this limits the chip (spread spectrum signalling element) rate to 32 MHz (assuming QPSK modulation). The ratio of this chip rate to the video data rate establishes the spread spectrum processing gain.

The communications channel (transmitter and receiver) will set the maximum signal-to-noise ratio (S/N) at the modem and will cause this to be a time-varying function. The result will be bit errors in the video data. The bit error rate is determined by the modulation type and the input S/N.

Data Link System Performance

Table 4 presents the selected data link system performance characteristics. The sensor is assumed to be a standard 525-line TV camera with a 4.2 MHz bandwidth and is capable of outputting 32 shades of grey. A resolution of 32 shades of grey requires that the output peak signal to rms noise ratio be at least 30 dB. Based on this bandwidth-S/N combination, the communications channel must be able to support a carrier-to-noise power density (C/N_o) ratio of at least 96.2 dB. Jam-resistance is provided by reducing this C/N_o requirement. The specified 30 dB of AJ protection is achieved by reducing the C/N_o requirement to 66.2 dB.

Assuming a 4 ϕ modulation type and a 10^{-2} BER requirement, 5 dB of the 66.2 dB is allocated to S/N and the remaining 61.2 dB is allocated to allowable bandwidth. This translates to a maximum allowable video data rate of 2.2 megabits per second. The laboratory studies indicated that data rates

TABLE 4. DATA LINK PERFORMANCE CHARACTERISTICS

Video Parameters	525 Line Analog TV	Compressed Digital TV	
		Without IMC*	With IMC
Bandwidth	4.2 MHz	–	–
Frame Rate	30	3.75	0.25
Video S/N	30 dB	–	–
Video Resolution	240 x 267 line Pr	256 x 256 pixels	256 x 256 pixels
Digital Quantization (Hadamard Transformed)	–	1.0 bit per pixel	1.0 bit per pixel
Digital Data Rate	–	246 Kbps	16.4 Kbps
Required Bandwidth (assumes 4 ϕ digital)	4.2 MHz	148 KHz	9.9 KHz
Required Bit Error Rate	–	10^{-2}	10^{-3}
Required S/N (assumes 4 ϕ digital)	30 dB	5.0 dB	7.0 dB
Required Carrier-to-Noise Power Density Ratio	96.2 dB	57.2 dB	47.0 dB
Resultant Jam-Resistance	Refererence	39.0 dB	49.2 dB

*IMC Image Motion Compensation

considerably less than 2.2 Mbps could be achieved by a combination of frame rate reduction, transform domain encoding, and resolution reduction.

The Video Frame Rate and Control Modes study showed that when frame rate is reduced below 3.75 frames per second, some type of control aiding such as image motion compensation is required for the operator to achieve rapid, accurate target acquisition. When this compensation is done, frame rates as low as 0.25 frame/sec (1 frame every 4 seconds) were found to be acceptable. Table 4 shows that with resolution reduction quantization, frame rate reduction, and image motion compensation, jam-resistance improvements of up to 49 dB can be achieved.

PARTITIONING OF THE SYSTEM

Appropriate system partitioning will result in a cost-effective data link that can easily be adapted to many varied user requirements. Hughes' approach to the reduction/compression of the video bandwidth provides a natural partitioning of the video data link. The isolation of the data compression/expansion functions is possible since the recommended design does not achieve bandwidth reduction by use of channel encoding or partial response filtering. Accordingly, the conventional MIL-188-C interface can be met without additional processing in the relay. Multiple relays would only contribute to increased errors in the selected digital approach, rather than introduce additive noise as in an analog system.

The top level functions of the data compression and expansion groups, shown in Figures 44 and 45, have been assigned a group of key functional variables which have been identified for consideration in the development of an optimum hardware arrangement. Exceptions are the image motion compensation and the image enhancement modules, which may be integrated into either the frame rate buffer (scan converter) or the data expansion (transform) module functions. At present, these functions are not part of the data

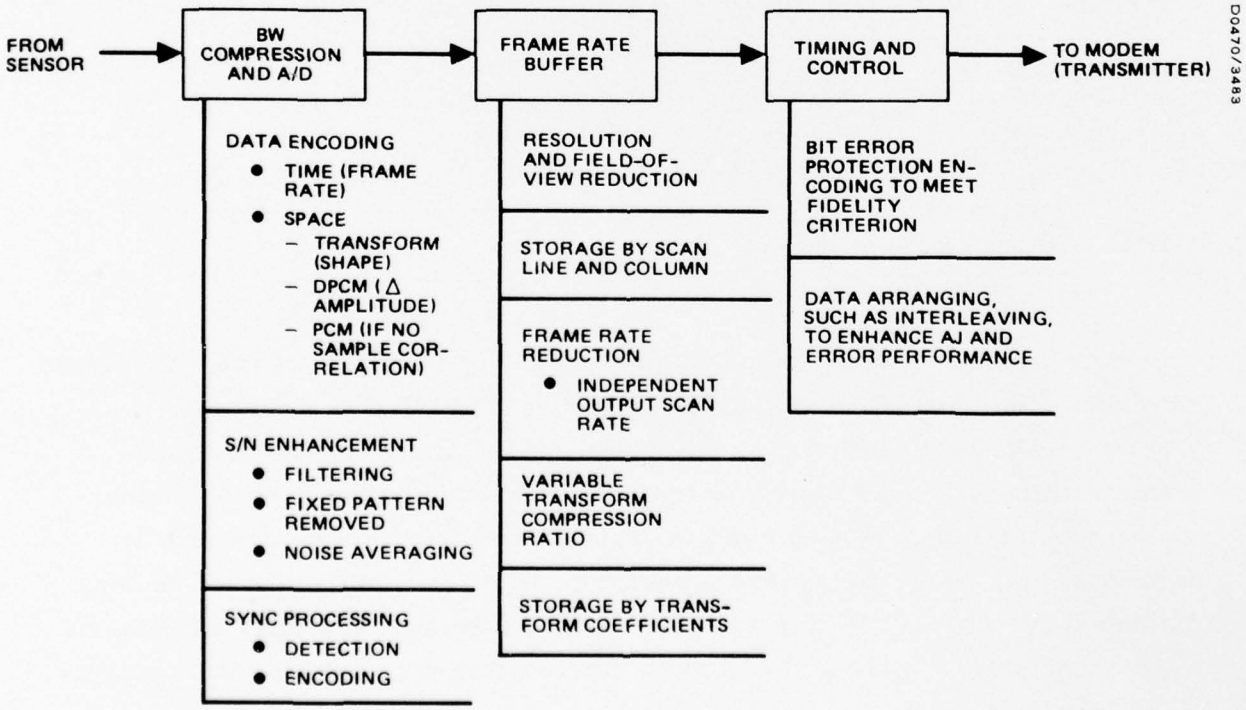


Figure 44. Data compression modules.

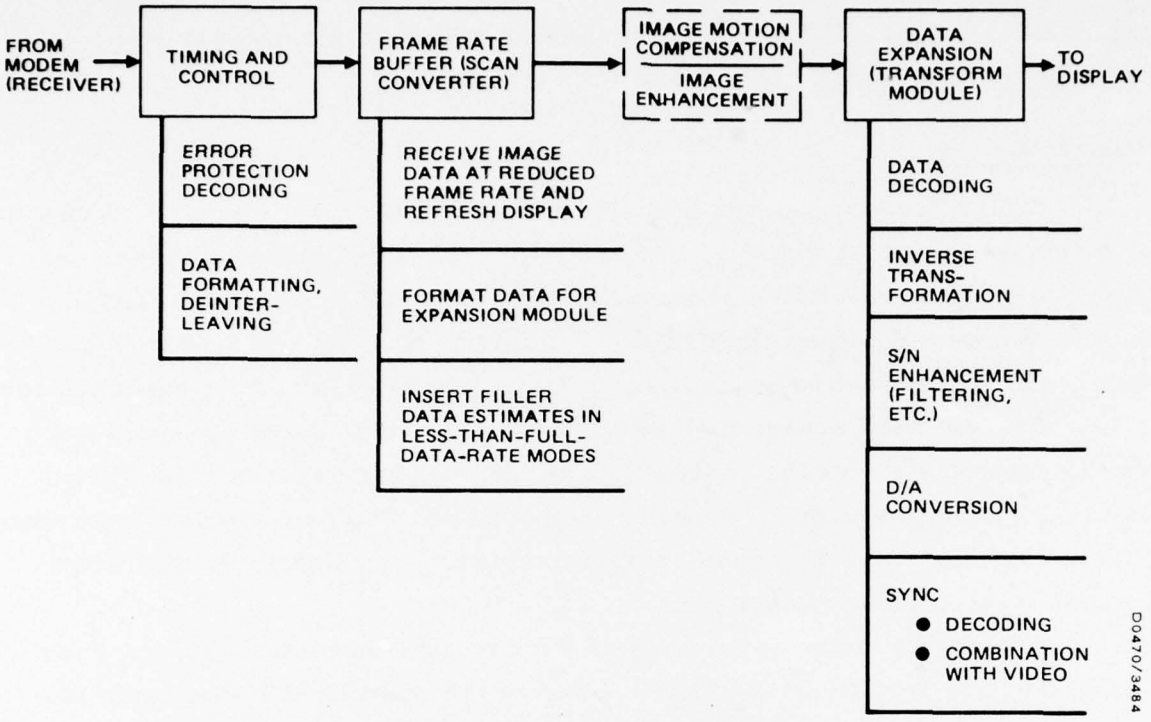


Figure 45. Data expansion modules.

expansion group. These added features will enhance the performance of the data link but are not believed to be of sufficient importance to be incorporated at this time. This functional design approach allows the prime variables of each function to be isolated such that maximum flexibility can be obtained. The functional design approaches can then be considered as a group to determine the most reasonable overall physical configuration. In light of recent technology advances, numerous compact packaging schemes can be envisioned – to the point of incorporating most of the airborne data link functions with the sensor unit. In addition to making expendable processing hardware possible, the benefits of small package size, weight, and power are inherent. Because of this, certain mechanical considerations and flexibility for varied user requirements become more important issues. Partitioning the system solely for small size and weight can result in a configuration which is difficult to repair and maintain and costly to manufacture.

The following discussion addresses the items to be considered in the selection of the various data link modules. The objective was to make each module a stand-alone unit from the functional and interface viewpoint but to enable incorporation of the modules into the data link on a card or unit

replaceable basis. The primary emphasis was directed toward minimizing the size, power, weight and cost of the airborne unit.

Sensor Module

There are several types of electro-optical sensors presently available or under development that may be used to provide the dynamic imagery data required for use with RPVs and electro-optically guided weapons. These include Forward Looking IR (FLIR), television, and low light level TV (LLTV). New technologies such as detector arrays are being developed for these sensors.

The primary sensor module problem is to ensure that the video data link is compatible with the sensor capabilities and that the essential sensor output data are preserved for use by the operator. Table 5 shows the primary parameters that must be considered in interfacing any sensor to the rest of the jam-resistant video data link.

The output video signal will, in general, be characterized by a time-function whose amplitude is either related to the input light intensity or the

TABLE 5. KEY PARAMETERS FOR INTERFACING THE SENSOR MODULE WITH THE SYSTEM

Input Prime Parameters	Sensor Process Variables	Output Prime Parameters
Energy Type Light IR Radar freq Energy Level Areas of Interest Target Parameters Size, Contrast, Shape Vehicle Dynamics Velocity Acceleration (stability) Sensor Location Automatic focus control or other camera control signals Sync Signals	Aperture size, time Detector Type Noise, Temp Lens Characteristics Size, Focal Length Zoom Scan Format Focus Control Signal Bandwidth Stabilization Mounting Conf.	Signal (voltage) dynamic range noise level linearity bandwidth Resolution Field of View Scanning Format Sync Signals Fixed pattern distortion or noise

log of intensity. A knowledge of the amplitude behavior is necessary to determine signal distortion as amplitude non-linearity, fixed pattern noise, and random noise. Knowledge of these amplitude oriented parameters is necessary to develop the signal processing techniques required to: (1) optimally band-limit the video, (2) encode the video, (3) invert any fixed pattern distortion, and (4) filter uncorrelated noise.

The output voltage will be output in some relatively standard scanning format. The scanning process impacts the correlation function of the video signal. For example, if Maverick E1A 525 line, 30 frame per second format is used, the video data must be blocked in 63 μsec intervals where each interval represents a scan line. Each 63 μsec interval can be processed to exploit the spatial correlation within the scene. However, if the processing is done over too long a period, the data will become uncorrelated. This implies the need to force the signal processing to be synchronous with the sensor to maximize the available information.

The sensor dynamic range, ambient noise level, and modulation transfer function provide much of the information required to interface the sensor with the Hadamard transform. This information also allows the prediction of the maximum achievable performance available from the sensor.

The optimum strategy for a jammer is to jam the synchronization signals of the standard video link. Consequently, special processing must be done to protect the sync signals. Sensor mounting is also important in the drone control system because the sensor platform (aircraft or weapon) is inherently unstable with respect to the ground field-of-view.

Bandwidth Compression Module

The bandwidth compression module is one of the main signal processing elements in the jam resistant video data link. This module processes the analog video based on a priori knowledge of the sensor output characteristics and encodes the video based on this knowledge.

The Hadamard transform domain signal processing approach offers efficient encoding because: (1) the amplitude probability density function of the transform domain coefficients except DC are zero mean and Gaussian in nature, (2) each coefficient occurs at a rate of 1/N times the sampling frequency, and (3) each coefficient can be quantized according to a unique rule. Hughes

has studied the quantization problem and has concluded that: (1) a length-16 Hadamard transform is nearly optimal for video processing, (2) quantizing to more than an average of 3 bits per sample will rarely be required and in some applications an average of 0.5 bit may be sufficient, and (3) the transform process should be analog and quantization should be done in the transform domain to simplify the A/D converter requirements.

Frame Rate Buffer Module

To achieve video bandwidth compression such that a high degree of jam-resistance can be provided, data rate reduction is required. The redundancy of the video data from frame to frame makes possible frame rate reduction. To accommodate such a scheme, a frame of video data must be accepted at a high rate in real-time and then output at a slower rate over a duration of several frames. The frame rate buffer module will perform this task. Within the video data link, the frame rate buffer will be provided with compressed digital data. As a result, the data rate into the frame rate buffer will be lower; consequently, the storage requirements will be reduced considerably from the standard PCM reference. For example, instead of requiring 1.5M bits to store a full frame at 6 bits per pixel, an input of data compressed 3:1 would require approximately 500K bits of storage.

To meet the constraint of cost on the complete data link, memory devices are required to have an ultra-low cost. Cost in conjunction with storage time, ruggedization, data rate flexibility, and potentially low overhead suggest that either NMOS RAM or digital CCD is the best approach for such a memory. To achieve the lowest possible module cost, the design should be based upon commercially available memory devices.

The primary advantages of the CCD memory compared to conventional digital shift registers or other digital memory devices are its low power dissipation, high bit density, small element size, and potential low cost per bit. In addition, the serial structure of the CCD lends itself to first-in/first-out memory requirements. The practicality and usefulness of the CCD digital memories have become apparent. Several companies are now offering as stock items memory chips with 10 kilobit capacity as shown in Table 6. An example of more advanced technology is the Hughes 2069 memory chip which has a 32 kilobit capacity. A new version of this memory is being built with

TABLE 6. CHARACTERISTICS OF SINGLE CHIP CCD MEMORIES

	Technology	Bits	Clock Speed	Power, mW		Access Time, μs	
				Operate	Standby-Recirculate	Nom	Max
*Fairchild CCD 450 (1975)	n Channel	9 x 1024	50 kHz - 3 MHz	250	30	168	340
*Bell Northern (1974)		8 x 1024	1 MHz			128	256
*Intel 2416 (1975)		16 x 1024	1.3 - 2 MHz				200
*Fairchild (1975)	n Channel	16 x 1024	5 MHz	200			
+Westinghouse (1975)		2048	Non volatile memory		50	12.8	25.6
+Fairchild (1075-76)		32K					
+Hughes 2068 Low Power Memory Chip	n Channel	32K	1.7 MHz - 20 MHz	10			

*Offered for sale as stock items, 1975
+Experimental or proprietary devices

smaller basic cell size and a 64 kilobit capacity. Future expectation of a single chip with 1 MHz clock rate and 10^6 bit capacity organized in very long registers is realistic.

As a baseline approach, the memory architecture shown in Figure 46 indicates a high degree of adaptability to a wide range of memory requirements. It utilizes several of the Hughes type 2069 32-kilobit chips arranged to form an array in which the data are accessed on a line-by-line (scan-to-scan) basis. The memory chip is entered with high speed serial shift registers. When the registers are fully loaded with a line of transform coefficients, all of the cells are transferred simultaneously downward. Because of the parallel transfer, the downward shift occurs only once for each row as a whole, thus the row gates operate at 1/n times the frequency of the input register, where n is the number of storage cells in a line. This reduces the power requirements of the interior rows. In addition, the n-fold increase in time allowed for the parallel-downward transfer helps to achieve a high charge transfer efficiency. Upon removal of the data, selected lines can be deleted or further compressed on a line-to-line basis.

For an increase in line length or number of lines, memory can be added in the appropriate direction, thereby maintaining the data flow described above. The availability of larger memory devices would allow a proportional reduction in the number of memory devices and similarly lead to minimizing the peripheral circuitry.

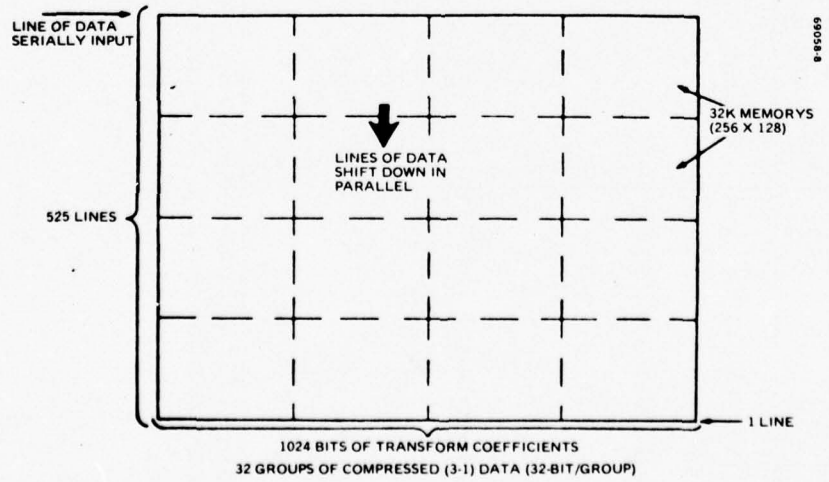


Figure 46. Memory architecture.

Timing and Control Module

The timing and control modules of the airborne and ground units provide a common point to institute data link control and thereby provide synchronization of data flow. In addition, the modules are a focal point for the key data rate compression variables and consequently provide a node at which video quality can be optimized for a given degree of jam resistance. Figure 47 depicts the envisioned timing and control module of the airborne unit. The module commands the transfer of selected data from the frame rate buffer, adds error protection to selected data, encodes the sync, and formats the data for transmission. In addition, it supplies a clock to the other modules and generates the pseudo-random (PN) sequence for spread spectrum modulation. The timing and control module of the ground unit performs functions similar to those in an airborne unit.

Hughes' Hadamard transform work has shown that if a selected few of the transform domain data bits are received erroneously due to channel errors, the picture is severely degraded. Digital error encoding is added to these data bits (about 4) to make every data bit equally important to picture reconstruction. These benefits, however, cannot be obtained without trade-offs in the form of reduced data rate and additional equipment needed for encoding and decoding.

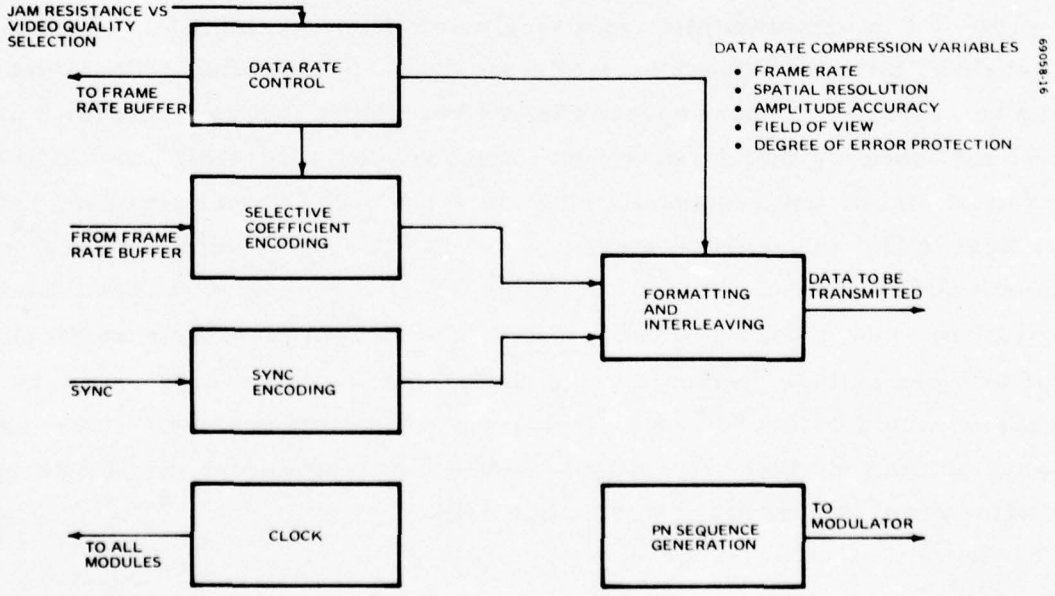


Figure 47. Timing and control module of airborne unit.

Different coding techniques, codes, and decoding algorithms are used, depending upon the expected error types, data rate requirements, and cost constraints. For the video data link, the types of channel to be accommodated can vary from system to system. Specific channel parameters must be known before an intelligent code selection can be made. The optimum technique for a specific link would be to provide error-free communication with minimum added redundancy and cost. Nearly any code can be used for random or burst detection or correction, depending upon the decoding algorithm. However, the efficiency and consequent success of a coding scheme depends strongly on proper usage.

The bandwidth compression scheme used in the recommended video data link separately processes the sync and video waveforms. This separate processing allows the use of a digital approach to sync generation and thereby provide an extra margin of jam protection to the sync signal. By spreading and interleaving the sync signal within the video data, a fixed spread spectrum processing gain of the sync signal can be achieved.

Work at Hughes has indicated that protection of the two most significant bits of sequency zero yields sufficient picture quality at bit error rates up to 10^{-2}. However, providing error correction for only two bits is not as efficient a providing protection for larger numbers. The Hamming sphere packing bound can be used to show that three redundant symbols are required to protect 2 information bits via a single error correcting code. By adding the 3 overhead bits and using a perfectly packed (7, 4) Hamming code, 4 data bits may be protected. This approach is recommended, because it allows protection of not only the two most significant sequency zero bits, but also the two most significant sequency 1 bits. The most significant sequency 1 bits are next in line in terms of sensitivity from both the standpoint of energy content and perceived degradation. The 3 bits of redundancy added for error control increases the video data rate by 9.4 percent (assuming an average rate of 2 bits per picture element). The implication is that 8.6 percent less compression would be possible with this error protection scheme. However, for many applications three of the higher single-bit sequencies may be dropped to allow room for the error correcting bits.

In the Hughes' approach to an anti-jam video data link, all the necessary video sync signals would be integrated into the pseudo-random (PN) sequence timing. By deriving all the camera sync signals from the PN generator after obtaining PN sync (which is required to demodulate the spread waveform), the ground terminal could then regenerate the required sync signals for the monitor. Consequently, the video sync signals can be integrated into the spread waveform without affecting the compression ratio.

The selection of a PN sequence for use in a spread spectrum modem involves several systems aspects. Pattern dependent parameters such as autocorrelation and cross-correlation determine signal acquisition, data, and interference performance. The apparent randomness and balance of the code affects system interceptability and compromise. Privacy is best achieved through the use of varied codes for different transceivers. Good autocorrelation properties are desirable to prevent spurious receiver response at high signal-to-noise ratios, and good cross-correlation properties are required to maintain privacy when two or more sets of users are on the same RF energy.

Spread Spectrum Modem

To enhance acceptance of the video data link, it is recommended that the airborne interface with the communications channel be at an intermediate frequency so the individual user can select his own bandwidth, carrier frequency, transmitter and antenna. The airborne module (modulator) and the ground module (demodulator) together maximize the degree of jam-resistance via a communications link within the constraints imposed by the communication channel, the information data rate, and the need to minimize airborne unit complexity.

The communications channel typically has a limited bandwidth over which the data can be transmitted and exhibits some type of fading and ducting. The insensitivity of the transformed data in conjunction with error protection encoding results in the data being less sensitive to the bit error rate. This insensitivity to the bit error rate relaxes the requirements of the modem such that multipath and ducting become insignificant. At present,

there is no specific communications link for RPV or guided weapon missions. However, studies indicate that a sole use allocation of about 20 MHz maximum is expected. This limits the maximum frequency spreading that can be used to achieve jam-resistance. To achieve the desired jam resistance within the system constraints, an appropriate set of modem variables must be chosen.

In choosing a modulation technique, performance in terms of detection and signal tracking and compatibility with the channel characteristics such as multipath, inter-symbol interference, and channel coherence must be considered. For the three commonly employed generic waveforms for spread spectrum; frequency hop, time hop, and phase shift keying (PSK); several general comparisons can be made. When a wideband limiting amplifier is used, the time hop waveform will suffer less limiter suppression loss than either frequency hop or PSK. The suppression of one signal by others of the same class is significantly less for time hop. However, this advantage of time hop does not exist for linear repeaters and may even be reversed for systems using automatic level control. From the intercept viewpoint, the PSK waveform is the most noiselike and, as a result, less susceptible to casual intercept. Experience, however, has indicated that the largest single factor in interceptibility is radiated power density.

The PSK technique appears to offer the simplest implementation, because it doesn't require the multiple frequency generation as in frequency hop or the peak power as in time hop. The various modulation techniques (PSK, QPSK, CPSM) differ in their spectral sidelobe characteristics. These characteristics determine the signal bandwidth and dynamic range limitations. From a susceptibility standpoint alone, modulation implementation, low detectability, code tracking capability, and minimum sidelobe level considerations must be included in the selection process.

Scan Converter Module

The scan converter module performs the inverse process of the airborne frame rate buffer module. Digital video data which has been received and error-corrected in the timing and control module is stored. The scan converter then acts as a refresh memory to supply data to be displayed at a 30-frame per second frame rate. Depending on mission requirements, the

scan converter will receive data at rates from 30 frames per second down to as little as a frame every few seconds. Other methods of data rate reduction such as scan line skipping and transmission of partial areas of the frame may also have to be accommodated. The scan converter will be required to "fill-in" the missing data in such a way as to present a constant format to the data expansion module. These requirements are summarized in Table 7.

A number of secondary requirements will also impact the design of the scan converter. These include: 1) considerations of commonality with the airborne frame rate buffer components, 2) variable resolution on an intra-frame basis, and 3) image motion compensation to reduce the effects of large incremental scene changes during low frame rate transmission.

Image motion compensation is the primary driver of the scan converter design. By incorporating two identical memories, the distorted "painting" of a new image over the old is eliminated. One memory receives data while the other refreshes the display. Also, with two memories, the possibility of interframe processing is not excluded.

TABLE 7. SCAN CONVERTER PROCESS BREAKDOWN

Prime Input Parameters	Process Variable	Prime Output Parameters
Data Format Scanning Format Sync Field-of-View Resolution Frame Rate Bits/Coefficient	Receive Image Data at Reduced Frame Rate and Refresh Display Format Data for Expansion Module Insert Filler Data Estimates in Less-Than-Full-Data-Rate Modes	Display Compatible Frame Rate (30 Frames/Sec Nominal) Transform Block Formatted Data Output Frame Data Quantity Sufficient for Full Resolution 512 x 512 Pixel Display

Past cost tradeoff studies have indicated that digital disk memories had a competitive edge over solid-state memories in terms of initial system costs for frame-store applications. In terms of maintenance requirements and with recent reductions in solid-state memory pricing, digital disk memory does not now appear to be the best choice for an RPV system. To preserve the flexibility needed to incorporate the various options discussed, a solid-state memory should be used. As stated previously, some consideration should be given to hardware commonality with the airborne frame rate buffer function. However, functional requirements should be given priority. If the design requirements are more efficiently met by using a random access memory (RAM) structure (or other alternate) instead of a shift register approach, then RAMs should be selected as the design approach.

Other important items to be considered in designing the scan converter memory architecture are

1) Storage capacity: A 256 x 256 pixel format using a 6:1 compression ratio would require approximately 65K bits per frame.
2) Impact of algorithm modifications: Design to minimize the difficulty of revising bit allocations for individual coefficients in the data.
3) Impact of scan format modifications: Design to miminize the difficulty of revising the memory row and column arrangements and the associated timing when a sensor with a scan format other than 525 lines, 30 frames per second is used.

Based on the preceding considerations, the scan converter will consist of two solid-state memories which will alternately switch between data reception and display refresh functions. The switching will be at the incoming data frame rate. The size of each of the memories will be approximately 65K bits. Random access memory chips currently available on the market are expected to be used, because package size is less of a constraint on the ground and flexibility is a prime requirement.

Data Expansion Module

The data expansion module accepts digitally encoded data from the scan converter module (frame rate buffer and digital refresh memory), does a digital-to-analog conversion, and then inverse transforms the data into analog video for display. To a large extent this function is the mathematical

inverse of the bandwidth compression function. Table 8 lists the parameters associated with the data expansion module.

The expansion module, illustrated in Figure 48, should be located between the frame store buffer and the display to reduce the size of the frame store buffer and to enable incorporation of the D/A into the expansion module. This requires that the expansion unit be capable of operating on the 30 frames per second digital data but does not significantly impact the hardware since the bandwidth compression module will operate at this rate.

The expansion module drives the display, and consequently, to minimize requirements on the display, must provide a standard EIA compatible interface. This interface includes such functions as impedance matching, adding the video to the required 1.0 volt pedestal, incorporating the sync

TABLE 8. DATA EXPANSION PARAMETERS

Prime Input Parameters	Process Variables	Prime Output Parameters
Frame Rate (Sync)	Inverse Transform	Analog Video Signal
Encoded Transform Coefficients	Data Decoding	Video Bandwidth
Zero Mean Gaussian	S/N Enhancement Filtering	S/N Ratio
μ_i, σ_i	Sync Separate Combined	Sync Signal
S_o Is Uniform	D/A Conversion	

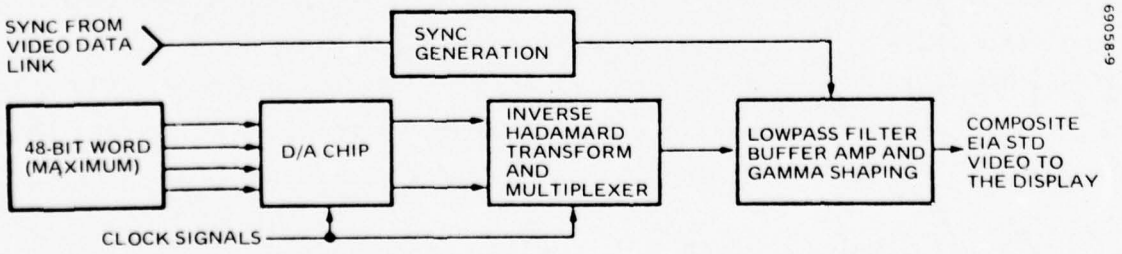


Figure 48. Expansion module block diagram.

signal with the proper timing delay, and providing sufficient signal amplitude to be within the AGC range of standard sets.

The expansion module could also include a gamma shaping function which can be adjusted by the operator to make the display output a uniform grey scale step wedge. This function will provide the adjustment required to match the display to the sensor and would allow a limited amount of image enhancement.

HARDWARE IMPLEMENTATION TECHNIQUE

The implementation approach for the airborne and ground bandwidth reduction/compression hardware has been selected to satisfy the requirements of most users. The objective was to make each module of the video data link a stand-alone unit from a functional and interface viewpoint, thereby allowing incorporation of user dependent features on a card or unit replaceable basis. The sensor, modems, transmitter/receiver, antenna, and display have been excluded from the hardware implementation study, because they are independent of the reduction/compression hardware.

The selected implementation allows for the demonstration of an advanced video data link in the near future and lays a foundation upon which refinements and the definition of special interfaces and components can be made to extend this implementation.

Applicable Component Technology

The processing capability, size, power, and cost of the video data link are dependent upon the capability of the digital technology available in the near future. The following survey and review cover the generic field of logic devices suitable for large scale integration (LSI) and eliminates all except the principal contenders for low cost, low power-delay product, and high density capability within the next 5 to 10 years. The three digital LSI technologies that show the greatest potential are I^2L, CMOS and DMOS. Figure 49 shows the current and projected power-delay products of the various technologies.

Charge Coupled Devices

CCDs have enjoyed tremendous growth since their introduction in 1970. Although CCDs have been actively developed for imaging, analog signal

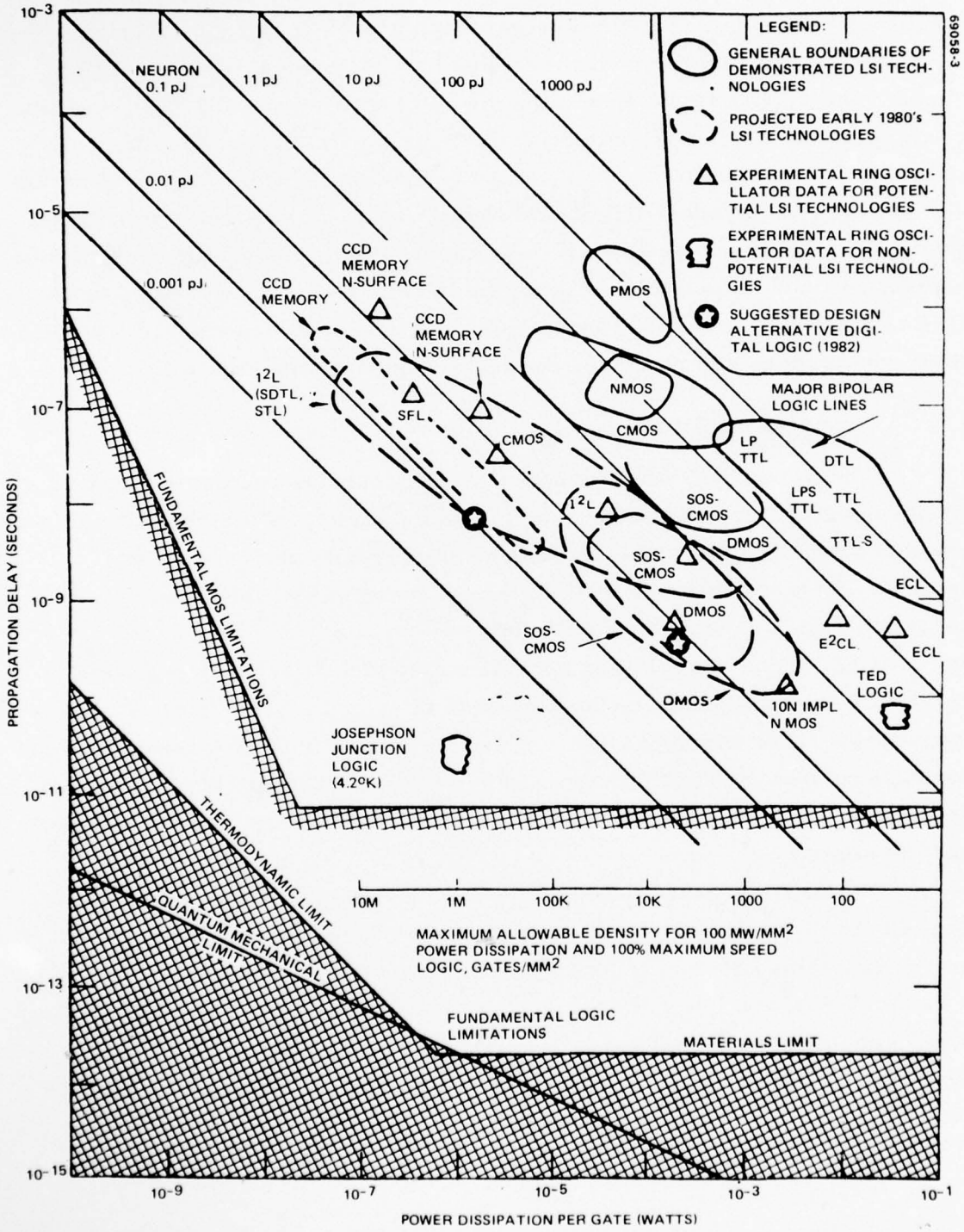


Figure 49. Power-delay products of component technology.

processing, and digital memories, relatively little effort has been devoted to CCD digital logic. The very low power, high density, and relatively high frequency possible with CCDs suggests that useful CCD logic structures may be possible. Low power CCD memories have been steadily advancing in speed, power, and size. However, the complexities of CCD logic in terms of clock generation, bias and control voltage inputs, interconnects, and regeneration and output circuitry indicate that competition for the ultimate low power-delay product LSI digital system will be a difficult uphill battle for CCDs. Their competition (I^2L, CMOS, DMOS) are continuously reducing capacitance and output voltage swing to achieve better power-delay products. CCD technology, however, has a unique place in shift register-like applications where there are no competing technologies on the horizon.

Transversal Filters

The advent and development of CCD recursive and non-recursive (transversal) filters opens the door to a wide variety of matched filtering and analog correlation signal processing previously not available for analog design. These devices are well suited for many of the video and spread-spectrum signal processing functions.

CCD cross-correlators provide a convolution between input and reference analog signals. A special case of such a circuit is the CCD transversal filter which has a set of approximately weighted reference coefficients that multiply incrementally delayed signal samples. The sum of the weighted time samples provides the convolution of the reference function and the signal.

Hughes is presently developing a chip (Hughes CRC101 Hadamard Transform Chip) that contains a set of 16 orthogonal transverse filters having weightings of plus and minus 1. This chip will perform the Hadamard transform of 16 samples of analog video and output 16 sequence coefficients which contain the original video data in a more compact form. The unit is designed for operation at a 20 MHz clock rate and includes the required sample and hold circuitry.

CCD Signal Processing Chip

Another development is the CRC100 signal processing CCD Chip. The devices on this chip are specifically tailored to A/D, D/A, and digital

logic requirements similar to those of the video data link. The chip contains four A/D converters, two comparators, logic elements, D/A converters, sample and hold/peak detection units, and CMOS drivers. For each A/D system, the anticipated resolution is 8 bits with an operating speed of about 1 M bit per second while dissipating 10 m watts or less (including clock power).

These devices can be used to encode the analog transform coefficients from the transversal filters in the compression function and decode the coefficients for use by the transversal filters in the expansion function. The transform coefficients would output from the Hadamard transform chip at 1/16th the clock frequency, which is expected to be about 10 to 12 MHz. Consequently, the 1.0 MHz limitation would not limit system performance. Also, each transform coefficient could be quantized separately and would require resolutions between 1 and 6 bits. Thus, 16 separate simple A/D converters could be put on one chip.

CCD Memory

The video data link frame store memory is expected to require about 65K bits of storage which does not need to be accessed randomly. By appropriate structuring of the memory and appropriate recirculation and cooling, the CCD memory is a prime candidate to achieve low power and maximum bit density (to reduce weight). For ground-based equipment, power, size, and weight are of lesser importance.

The most efficient CCD digital memory organization, measured by a criterion of bit density on a chip, is a "serpentine" arrangement of long chains of serially connected shift registers. This configuration requires a minimum of peripheral circuits but increases the clock rate. To reduce access time (clock rate), the CCDs can be organized in a serial-parallel-serial arrangement for line addressable memories. It appears to be practical to increase the bit capacity to 10^6 bits at 1.0 MHz operation.

Airborne Processing Unit Hardware

Figure 50 shows the implementation of the airborne hardware. The arrows indicate the signal flow path. The sensor and modulator are shown for completeness; although, they are not included in the size, power, weight,

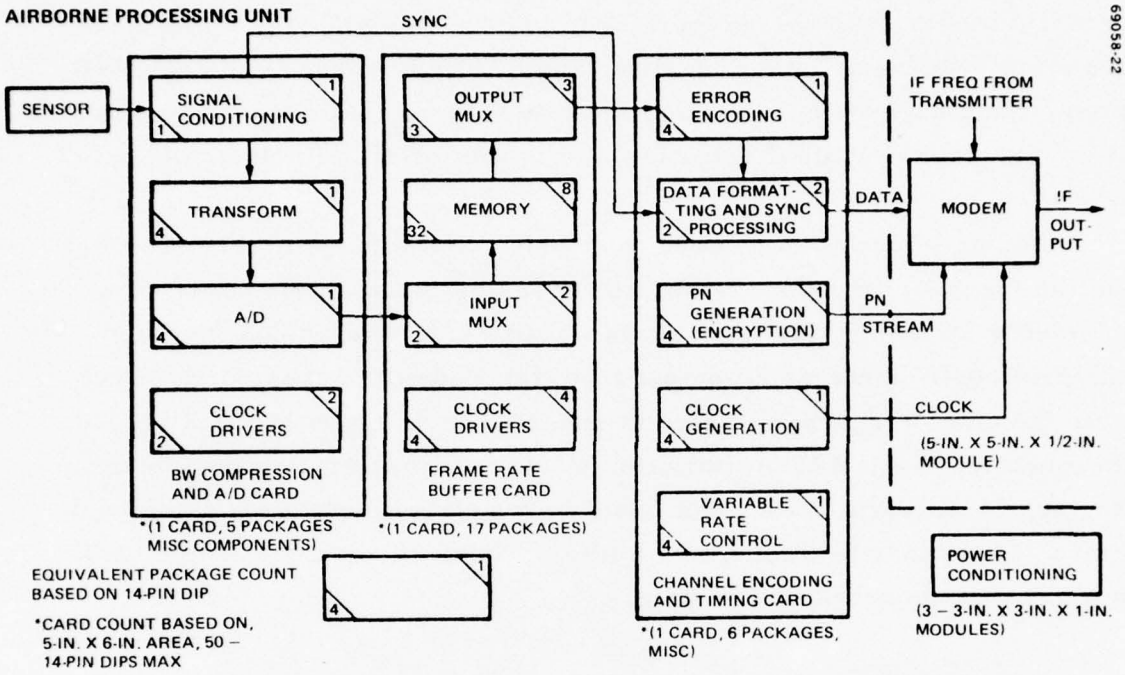


Figure 50. Airborne processing unit hardware diagram.

and cost estimates. The unit is partitioned into three modules. The bandwidth compression module, frame rate buffer module, and channel encoding and timing module are expected to be implemented on three 5 inch by 6 inch cards. It is estimated that 28 chips, which require the area of about 60 equivalent 16-pin dual inline packages (DIPs), are required to implement the airborne hardware.

Assuming an average cost of $50 per chip and $200 per card, the three completed cards will have a material cost of about $2000. Considering the power conditioning requirement, connectors, and overall module enclosure, a reasonable material cost for the airborne unit (excluding sensor, modulator, transmitter, and antenna) is $2500. In production quantities of 1000, a sell price of about $4500 appears reasonable.

The three cards plus power conditioning are expected to be capable of being contained in a 1/5 ATR package, as shown in Figure 51, and will require about 300 cubic inches of space. The preliminary weight estimate is 5 pounds. Not more than 5.6 watts (0.2 amps at 28 volts) is expected for power consumption.

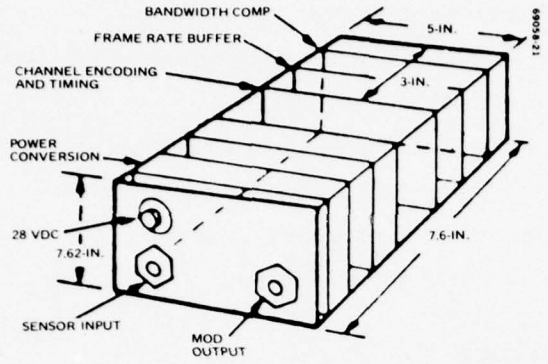


Figure 51. Airborne unit packaging.

Ground Unit Hardware

The hardware requirements for the ground unit are essentially the same as the airborne unit except for the additional memory requirements for the scan converter and that slightly lower grade components may be used due to the less stressful environment. The extra memory impacts the size, power, weight, and cost in that an additional card with 17 chips is required. Therefore, 45 chips are required to implement the ground unit. Figure 52 diagrams the ground processing unit hardware.

Again assuming an average cost of $50 per chip and $200 per card, the four completed cards will have a material cost of about $3050. Considering the power conditioning requirement, connectors, and overall module

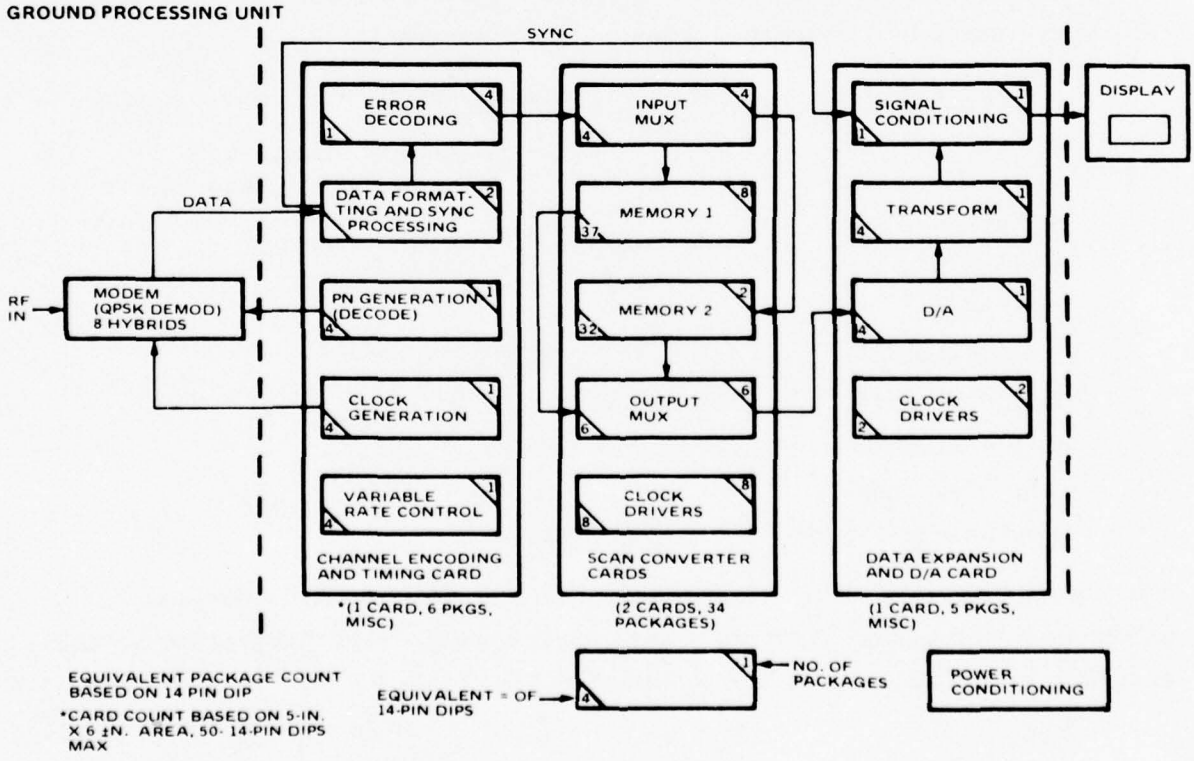


Figure 52. Ground processing unit hardware diagram.

enclosure, a reasonable material cost for the ground unit (excluding demodulator receiver and antenna) is $3600. A sell price of about $6000 would probably be adequate for production quantities of 100.

The four cards plus power conditioning are expected to be capable of being contained in 1/4 ATR package and will require about 350 cubic inches of space. The weight estimate is 6 pounds. Approximately 7 watts (0.25 amps at 28 volts) are expected to be adequate for power.

Reliability, Maintainability and Safety Analysis

An R/M/S analysis was performed on the recommended equipment implementation. For purposes of the analysis, the equipment was divided into the airborne unit and the master unit (contained in ground or airborne control center).

Reliability

A reliability analysis using failure rates computed according to MIL-HDBK-217B, 25°C ambient with 10°C rise to part ambient on the following Component/Quality Grades was performed:

Component	Quality Grade
IC/SSI	B-2 (Vendor Equivalent MIL-STD-883 Class B)
IC/MSI	B-2
IC/LSI	B-2
IC/Linear	B-2
Transistor	JANTX
Diode (Zener)	JANTX
Cap (Tantalum)	ER(M)
Cap (Ceramic)	ER(M)
Resistor (Carbon)	ER(M).

The master unit MTBF was computed for three environments because it might have to function in an airborne, mobile ground, or fixed ground station environment. The results are summarized in Table 9.

TABLE 9. RELIABILITY ANALYSIS

	Environment	MTBF, hours
Airborne Unit	Airborne Uninhabited	27,484
Master Unit	Airborne Inhabited	35,476
Master Unit	Ground Mobile	35,442
Master Unit	Ground Fixed	116,231

Maintainability

A preliminary maintainability analysis was performed, and it is estimated that 12 minutes will be required to interchange either the airborne unit or the master unit in the RPV. The units are established as Primary Replaceable Units (PRU). The PRU interchange estimate does not include the time required to gain access, since the particulars of the installation are not available. When maintenance is performed on the PRU, it will be accomplished by sequential replacement of assemblies, designated as Secondary Replaceable Units (SRU). The estimated Mean-Time-To-Repair for the PRU by SRU replacement is 19 minutes.

Safety

A preliminary hazard analysis was performed, and no Class III or Class IV equipment hazards were identified. No operating safety analysis has been performed, and operating safety hazards have not been considered.

APPENDIX A

ANALYSIS OF VARIANCE SUMMARY TABLES

PRECEDING PAGE BLANK-NOT FILMED

TABLE A-1. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE, CONTROL MODE STUDY – RANGE-TO-TARGET AT RECOGNITION

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	5.28	7.11×10^8	3	2.37×10^8	<0.005
Control Mode (C)	CS	0.46	3.36×10^7	2	1.68×10^7	>0.25
Subjects (S)			7.59×10^8	11	6.90×10^7	
FC	FCS	0.96	4.01×10^8	6	6.69×10^7	>0.25
FS			1.48×10^9	33	4.49×10^7	
CS			8.04×10^8	22	3.66×10^7	
FCS			4.63×10^9	66	7.01×10^7	

PRECEDING PAGE BLANK-NOT FILMED

TABLE A-2. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE, CONTROL MODE STUDY – RANGE-TO-TARGET AT RECOGNITION CORRECTED FOR TRANSMISSION DELAY

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	1.13	1.53×10^8	3	5.09×10^7	>0.25
Control Mode (C)	CS	0.46	3.37×10^7	2	1.68×10^7	>0.25
Subject(s)			7.59×10^8	11	6.90×10^7	
FC	FCS	0.95	4.02×10^8	6	6.69×10^7	>0.25
FS			1.48×10^9	33	4.49×10^7	
CS			8.04×10^8	22	3.66×10^7	
FCS			4.63×10^9	66	7.01×10^7	

TABLE A-3. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE, CONTROL MODE STUDY – RANGE-TO-TARGET AT ACQUISITION

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	11.52	1.19×10^9	3	3.97×10^8	<0.001
Control Mode (C)	CS	4.71	4.14×10^8	2	2.07×10^8	0.01 < 0.02
Subjects (S)			5.32×10^8	11	4.83×10^7	
FC	FCS	3.63	1.14×10^9	6	1.91×10^8	0.001 < 0.005
FS			1.14×10^9	33	3.44×10^7	
CS			9.68×10^8	22	4.40×10^7	
FCS			3.46×10^9	66	5.25×10^7	

TABLE A-4. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE PRECISION DESIGNATION STUDY – TARGET DESIGNATION TIME

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	7.8664	36309.71	5	7261.941	<0.001
Subjects (S)			34720.56	5	6944.109	
Trials (T)	ST	1.4417	1184.975	3	394.9917	>0.25
FS			23078.85	25	923.1538	
FT	FST	0.7467	4588.121	15	305.8745	>0.25
ST			4109.543	15	273.9695	
FST			30720.95	75	409.6125	

TABLE A-5. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE, PRECISION DESIGNATION STUDY – TARGET DESIGNATION ERROR

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	11.1612	239.0675	5	47.81351	<0.001
Subject(S)			58.14612	5	11.62922	
Trials (T)	ST	1.6736	14.80952	3	4.936505	>0.25
FS			107.0974	25	4.283895	
FT	FST	0.8604	42.16078	15	2.810719	>0.25
ST			44.24409	15	2.949606	
FST			245.0066	75	3.266755	

TABLE A-6. ANALYSIS OF VARIANCE FOR VIDEO FRAME RATE, PRECISION DESIGNATION STUDY – RMS TARGET TRACKING ERROR

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Frame Rate (F)	FS	5.3103	1718.426	5	343.6851	0.001 < 0.01
Subjects (S)			516.5952	5	103.3190	
Trials (T)	ST	1.9787	189.6862	3	63.22873	0.10 < 0.20
FS			1618.020	25	64.72079	
FT	FST	2.4076	920.5735	15	61.37155	0.001 < 0.01
ST			479.3291	15	31.95526	
FST			1911.796	75	25.49060	

TABLE A-7. ANALYSIS OF VARIANCE FOR VIDEO RESOLUTION, OPTICAL ZOOM STUDY – RANGE-TO-TARGET AT ACQUISITION

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Zoom (Z)	ZS	7.07	2.61×10^8	1	2.61×10^8	$0.01 < 0.05$
Resolution (R)	RS	0.63	3.41×10^6	2	1.71×10^6	>0.25
Frame Rate (F)	FS	1.33	5.08×10^7	2	2.54×10^7	>0.25
Subjects (S)			1.19×10^9	17	7.00×10^7	
ZR	ZRS	1.71	2.85×10^7	2	1.43×10^7	$0.10 < 0.25$
ZF	ZFS	0.01	6.58×10^5	2	3.29×10^5	>0.25
FR	FRS	0.61	5.90×10^7	4	1.48×10^7	>0.25
ZS			6.29×10^8	17	3.71×10^7	
FS			6.51×10^8	34	1.91×10^7	
RS			9.18×10^8	34	2.70×10^7	
ZRF	ZRFS	0.37	3.27×10^7	4	8.17×10^6	>0.25
ZFS			7.82×10^8	34	2.30×10^7	
ZRS			2.83×10^8	34	8.33×10^6	
FRS			1.64×10^9	68	2.41×10^7	
ZRFS			1.50×10^9	68	2.20×10^7	

TABLE A-8. ANALYSIS OF VARIANCE FOR BANDWIDTH COMPRESSION, JAMMING STUDY – RANGE-TO-TARGET AT ACQUISITION (STUDY NO. 1)

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Compression (C)	CS	3.61	8.42×10^8	2	4.21×10^8	$0.01 < 0.05$
Jamming (J)	JS	0.68	7.42×10^7	2	3.71×10^7	>0.25
Trials (T)	TS	3.71	2.06×10^8	1	2.06×10^8	$0.05 < 0.10$
Subjects (S)			2.12×10^9	11	1.93×10^8	
CJ	CJS	0.94	1.55×10^8	4	3.87×10^7	>0.25
CT	CTS	0.29	3.62×10^7	2	1.81×10^7	>0.25
JT	JTS	0.92	9.26×10^7	2	4.63×10^7	>0.25
CS			2.57×10^9	22	1.17×10^8	
JS			1.20×10^9	22	5.47×10^7	
TS			6.10×10^8	11	5.54×10^7	
CJT	CJTS	0.58	8.77×10^7	4	2.19×10^7	>0.25
CJS			1.80×10^9	44	4.09×10^7	
CTS			1.36×10^9	22	6.20×10^7	
JTS			1.13×10^9	22	5.13×10^7	
CJTS			1.66×10^9	44	3.77×10^7	

TABLE A-9. ANALYSIS OF VARIANCE FOR BANDWIDTH COMPRESSION, JAMMING STUDY – RANGE-TO-TARGET AT ACQUISITION (STUDY NO. 2)

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Compression (C)	CS	0.81	2.07×10^8	4	5.19×10^7	>0.25
Subjects (S)			9.73×10^8	9	1.08×10^8	
Trials (T)	TS	31.17	8.37×10^8	1	8.37×10^8	<0.001
CS			2.29×10^9	36	6.37×10^7	
CT	CST	1.56	3.27×10^8	4	8.16×10^7	0.10 < 0.25
TS			2.42×10^8	9	2.68×10^7	
CST			1.89×10^9	36	5.24×10^7	

TABLE A-10. ANALYSIS OF VARIANCE FOR SYSTEMS SIMULATION – RANGE-TO-TARGET AT RECOGNITION

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Bandwidth reduction/ compression systems (B)	S/B	1.25	3.68×10^8	9	4.09×10^7	>0.25
Targets (T)	ST/B	43.38	5.86×10^9	9	6.51×10^8	<0.001
Subjects within Systems (S/B)			2.29×10^9	70	3.26×10^7	
BT	ST/B	1.23	1.50×10^9	81	1.85×10^7	0.10 < 0.25
ST within Systems (ST/B)			9.46×10^9	630	1.50×10^7	

TABLE A-11. ANALYSIS OF VARIANCE FOR SYSTEMS SIMULATION – TARGET RECOGNITION PROBABILITY

SOURCE OF VARIANCE	ERROR TERM	F-RATIO	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE	PROBABILITY
Bandwidth reduction/ compression systems (B)	S/B	4.32	5.581	9	0.620	<0.01
Targets(T)	ST/B	21.22	24.356	9	2.706	<0.001
Subjects within Systems (S/B)			10.038	70	0.143	
BT	ST/B	1.59	16.406	81	0.203	<0.01
ST within Systems (ST/B)			80.336	630	0.128	

REFERENCES

Hershberger, M. L. Operator Performance Evaluation of Mini-RPV Video Image Bandwidth Reduction/Compression Techniques. Hughes Technical Report TP76-125, Hughes Aircraft Company, Culver City, California, June 1976.

Hillman, B. Human Factors Considerations in Real-Time Target Acquisition, in Air-to-Surface Missile Technology, 1975-1980, Vol. IV. Supplementary Reports, Institute for Defense Analyses, Science and Technology Division, IDA Log. No. HQ 67-7197, December 1967.

Self, H. C. and Heckart, S. A. TV Target Acquisition at Various Frame Rates. Technical Report AMRL-TR-73-111, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, September 1973.