AD-786 697

ARTILLERY-LAUNCHED CHARGE-COUPLED DEVICE (CCD)

Edward Willett, et al

Fairchild Space and Defense Systems

Prepared for:

Army Land Warfare Laboratory

June 1974

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AD786 697

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TECHNICAL REPORT LWL74-69	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): ARTILLERY LAUNCHED CHARGE COUPLED DEVICE (CCD) TV RECONNAISSANCE SYSTEM	5. TYPE OF REPORT & PERIOD COVERED: Final Report 12/3/73 - 4/15/74
	6. PERFORMING ORG. REPORT NUMBER: ED-AX-41
7. AUTHOR(s): Edward Willett, Fairchild Corp; Harold Forst, US Army Land Warfare Laboratory	8. CONTRACT OR GRANT NUMBER(s): DAAD05-74-C-0732
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Fairchild Camera and Instrument Corp, Space and Defense Systems Division, Syosset, NY 11791	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Land Warfare Laboratory, Aberdeen Proving Ground, MD 21005	12. REPORT DATE: June 1974
	13. NUMBER OF PAGES: ~~75~~ 78
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	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)

Surveillance
Target Acquisition
T. V.
Artillery
Charge Coupled Devices
Solid State Imagery System
Equipment Test

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

This report discusses the test, evaluation, and analysis of a charged coupled device (CCD) imagery system as might be deployed in artillery launched, parachute dropped, aerial reconnaissance system. An existing 100 x 100 element CCD camera was evaluated for image usefulness when deployed from a parachute. A system analysis was performed on how future 488 x 390 element CCD sensors might be used and the expected performance. It was concluded that the existing 100 x 100 element sensor provided useful information and

(cont'd on reverse)

block 20. ABSTRACT CON'T

that the 488 x 390 would do even better. An artillery launched TV system is easily within the state of the art. Winds over the target area would increase camera coverage but must be taken into account when it is desired to deploy the system over specific target coordinates.

DISCLAIMERS

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

TABLE OF CONTENTS

Preceding page blank

LIST OF ILLUSTRATIONS

SECTION 1

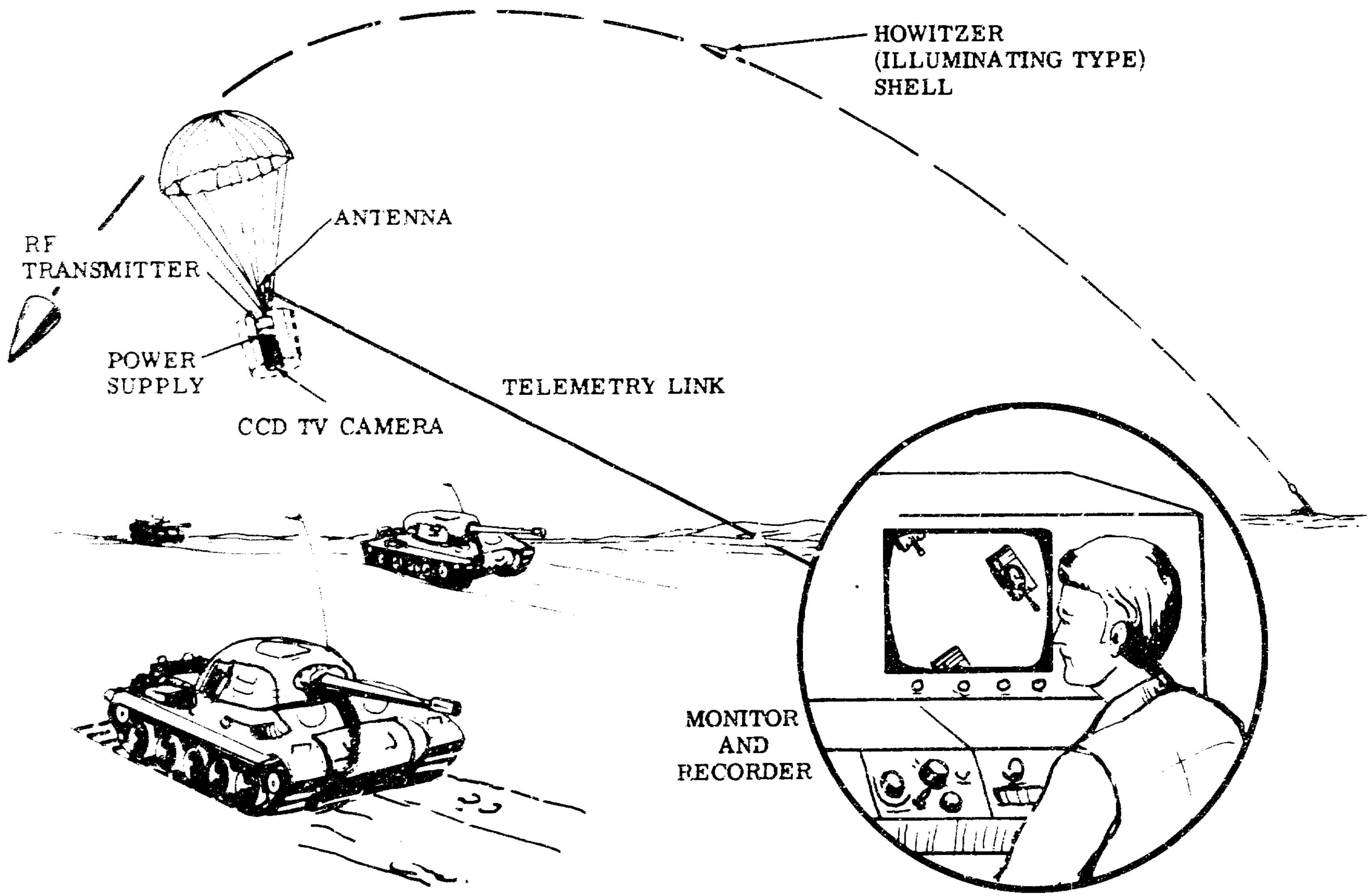
INTRODUCTION

This work was conducted under the US Army Land Warfare Laboratory Task 04-E-74 titled "Artillery Launched TV". The objective of the effort was to demonstrate some of the capabilities and limitations of a charge coupled device (CCD) television camera as it might be used in an artillery-launched, parachute-dropped, aerial reconnaissance system.

At the request of the Office of the Chief of Research & Development, the USALWL has undertaken a program to utilize existing hardware and demonstrate some of the advantages and limitations of such an artillery-launched TV system. The program consisted of two portions: the actual demonstration of existing hardware and a first-order analysis of how future systems might perform. A 4-month contract for the fabrication of the hardware and the analysis was awarded to Fairchild Space and Defense Systems, a division of Fairchild Camera and Instrument Corporation, Syosset, New York, under Contract No. DAAD05-74-C-0732.

Section 2 of this report, reporting on the hardware tests, was prepared by USALWL. Section 3, presenting the system analysis, was prepared by Fairchild.

ARTILLERY LAUNCHED TV CONCEPT



74-414

FIGURE 1.

SECTION 2

CAMERA HARDWARE AND FIELD TESTS

2.1 SYSTEM CONCEPT

The concept as displayed in Figure 1 is to use a TV camera in a fashion similar to the conventional artillery illuminating round. However, instead of having an illuminant which burns and emits light, this illuminant would be replaced with a CCD TV camera, a battery, a transmitter and an antenna. The artillery, from its normal position, would fire this artillery-launched TV round over enemy territory. At the proper time, as determined by the fuze on the projectile, the TV package and its parachute would be deployed from the rear of the projectile and float to earth. The now empty projectile would continue on its trajectory. The TV camera, pointed downwards, would transmit pictures of the ground via a suitable telemetry link, back to a base station. Upon striking the ground or at a given time after deploying, the TV unit would self-destruct in order to free the airways and to prevent enemy utilization of the system. At the base station, the received signals would be monitored on a real time TV display and recorded on a video tape recorder having stop-action capability for later play back, photography and analysis. The telemetry link requires near line of sight conditions but this should not adversely affect system capability and performance.

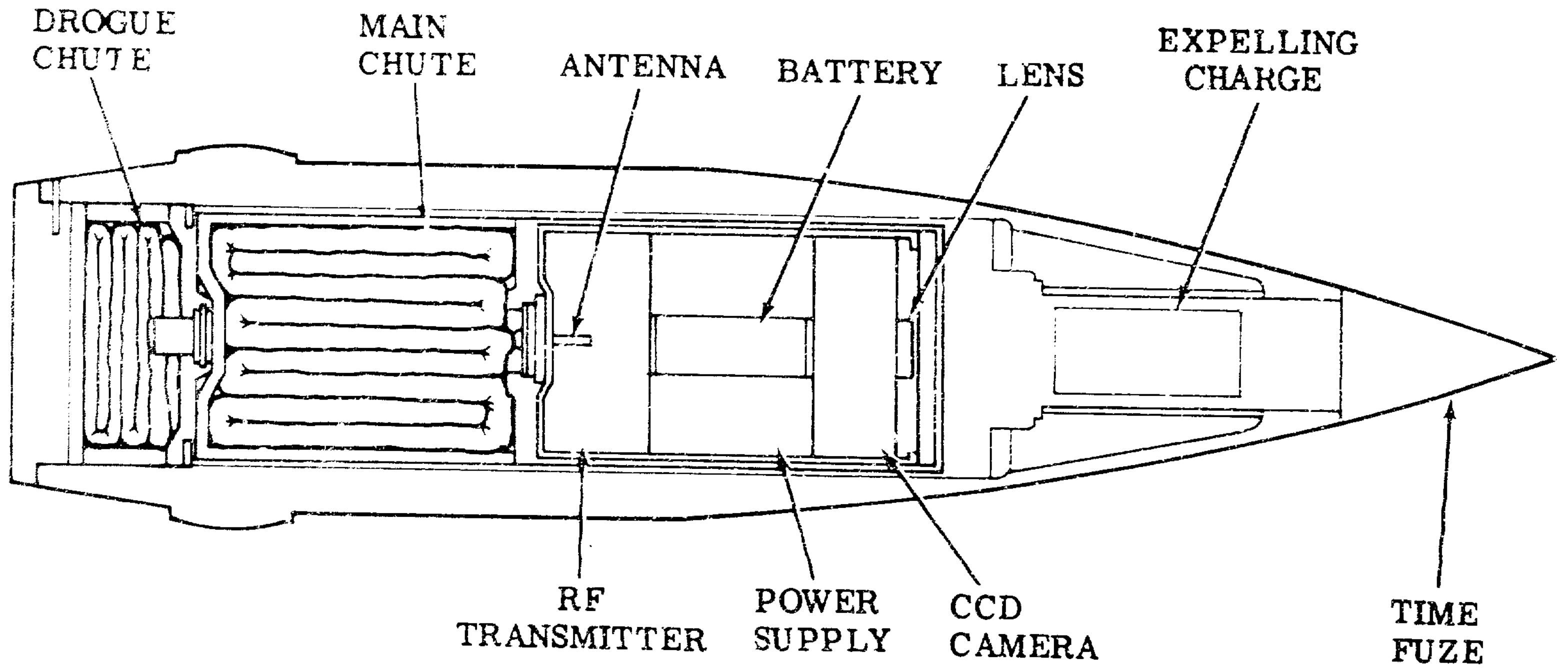
It is proposed that this system can be deployed in the M485E2, 155 millimeter illuminating round. Figure 2 shows how the system could be packaged in this round. The illuminant canister would be replaced with a CCD TV camera, battery, and RF transmitter canister which is 4-1/4" in diameter x 7-5/8" long. A photograph of a mock up of the proposed package is shown in Figure 3.

2.2 DESCRIPTION OF HARDWARE

The hardware portion of the program was fabricated by Fairchild using their existing 100 element by 100 element Model MV-100 CCD TV camera and circuits. The existing circuit boards were repackaged into the smallest convenient container (see Figure 4A), provided with AGC and power circuits, and used to drive an existing Government-furnished Delstar Model DS-500FC television transmitter. The whole unit was powered by 24 volts from a battery (4 each 6-volt Gel-cells in series) and was then packaged in a form suitable for both mounting on a helicopter and/or dropping by parachute (Figure 5 A & B).

The CCD element used in this program is a 100 element x 100 element CCD sensor more fully described in a later section. The light-sensitive elements are laid out in a standard 3 x 4 television format with each sensor occupying

ARTILLERY LAUNCHED TV PACKAGING



STANDARD 155 MM, M485 PROJECTILE W/M565 FUZE

ILLUMINANT REPLACED WITH CCD CAMERA, POWER SUPPLY, RF TRANSMITTER, AND DESTRUCTING CHARGE.

FIGURE 2. PROPOSED REPACKAGING OF A CONVERTED M-485 PROJECTILE TO HOLD THE CCD CANISTER

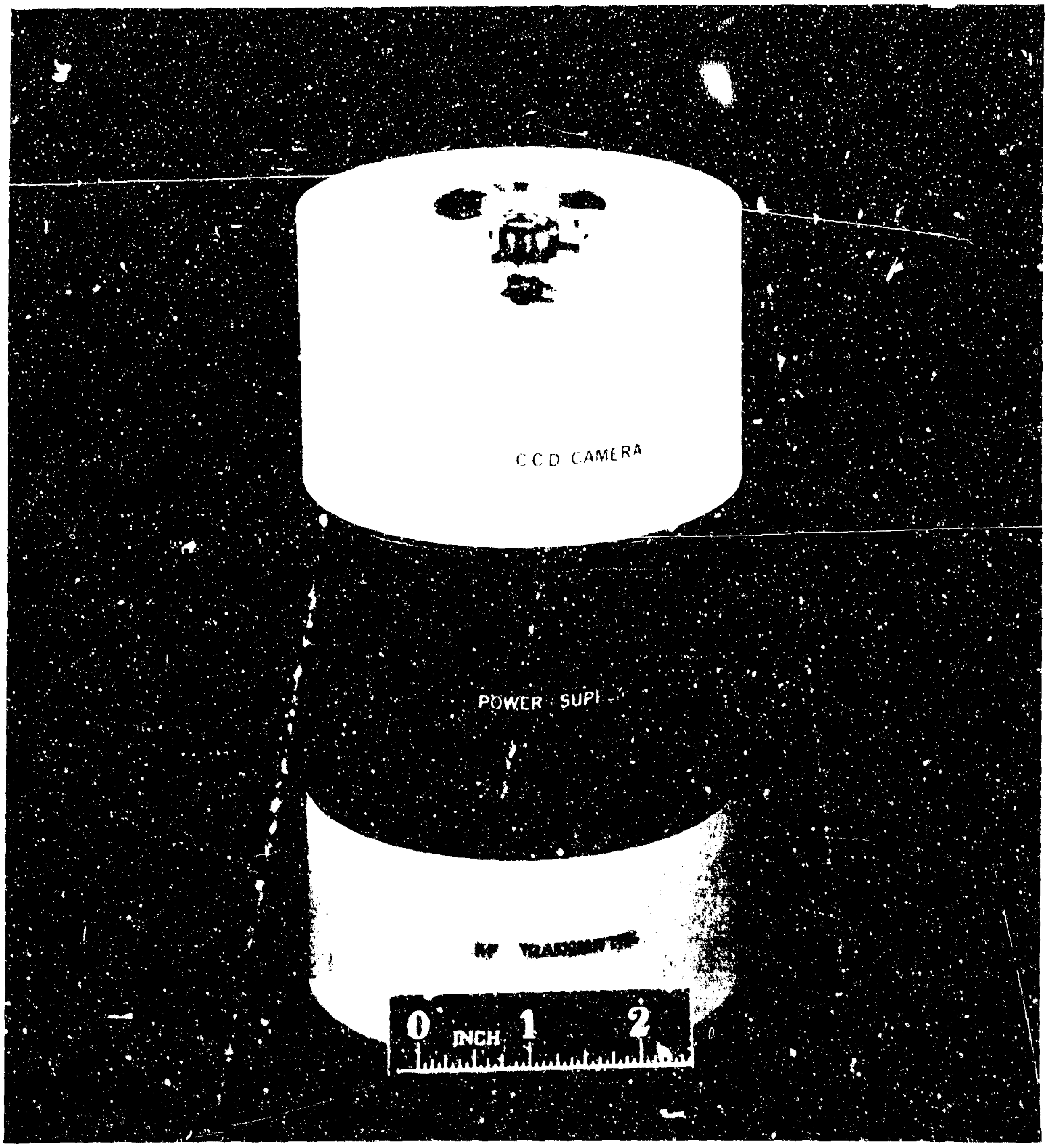


FIGURE 3. CUTAWAY MOCK-UP OF THE CCD CAMERA SYSTEM TO FIT INTO AN M 485 E2 ILLUMINATING ROUND

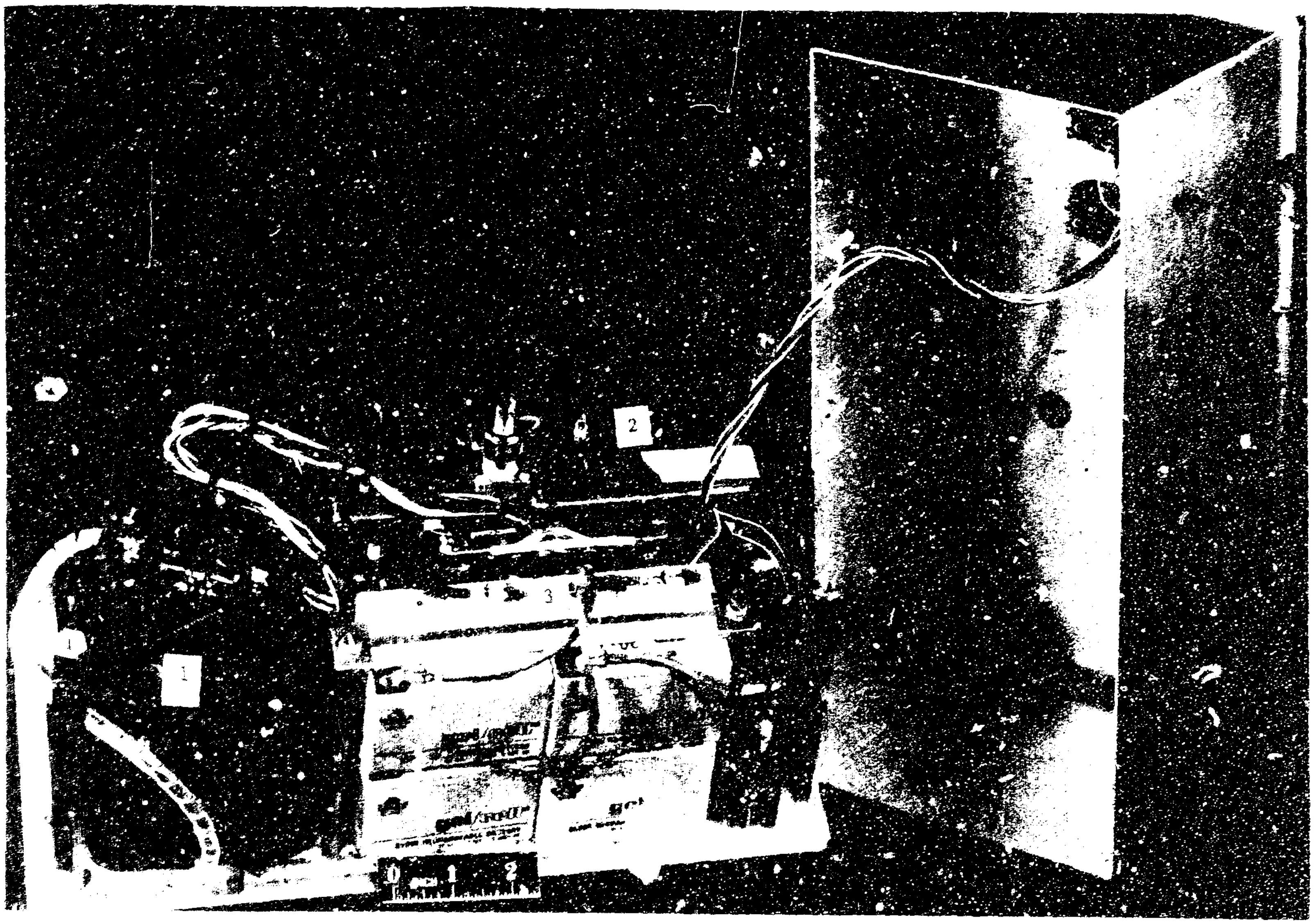


FIGURE 4A. INTERNAL VIEW OF CCD CAMERA PACKAGE
(1. CCD CAMERA, 2. RF TRANSMITTER, 3. BATTERY STACK WITH POWER REGULATORS)

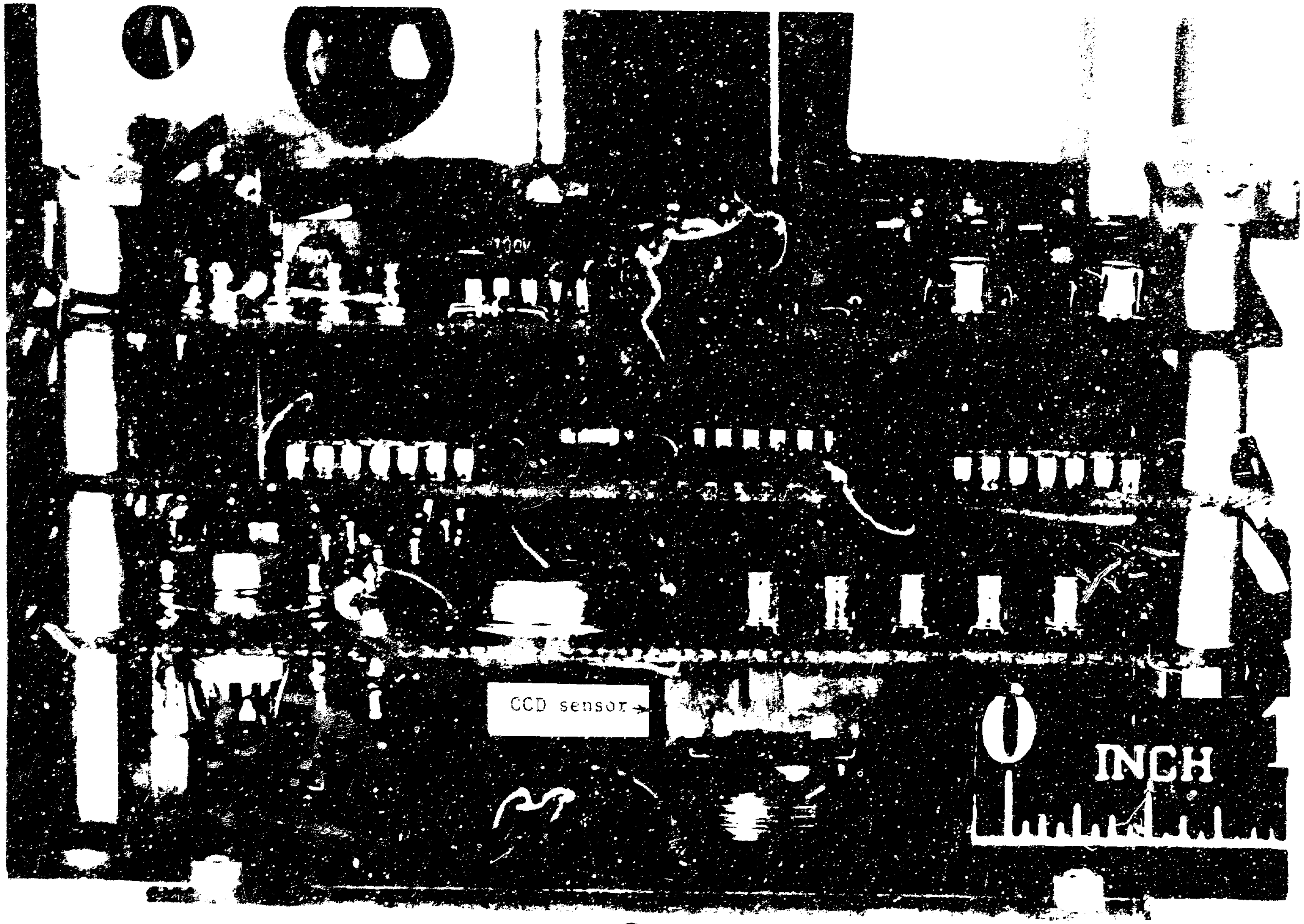


FIGURE 4B. CIRCUIT CARDS USED IN THE CCD CAMERA

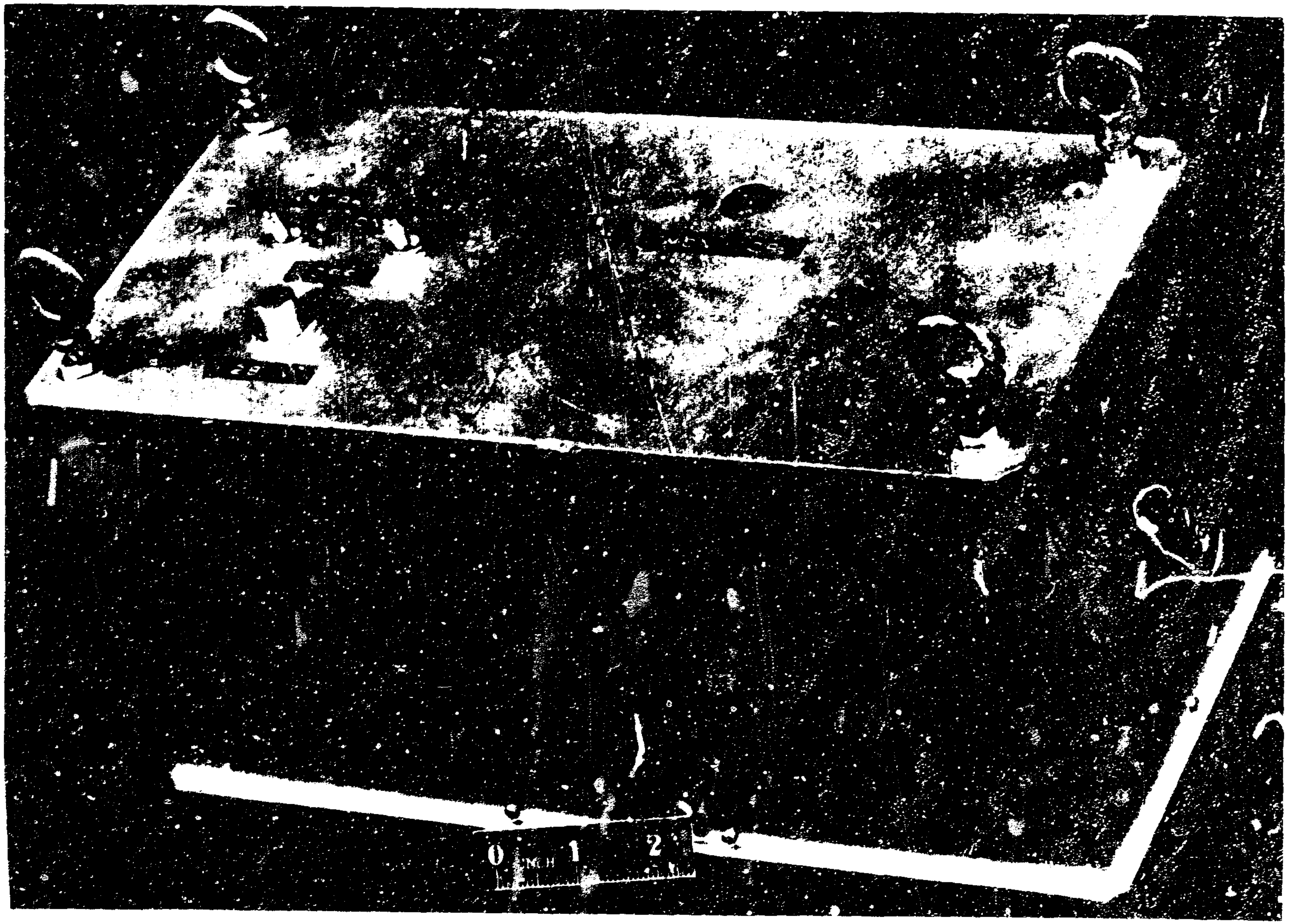


FIGURE 5A. TOP VIEW OF CCD CAMERA PACKAGE (SHOWING CHARGING POWER INPUT, SWITCHES AND TWO OUTPUTS)

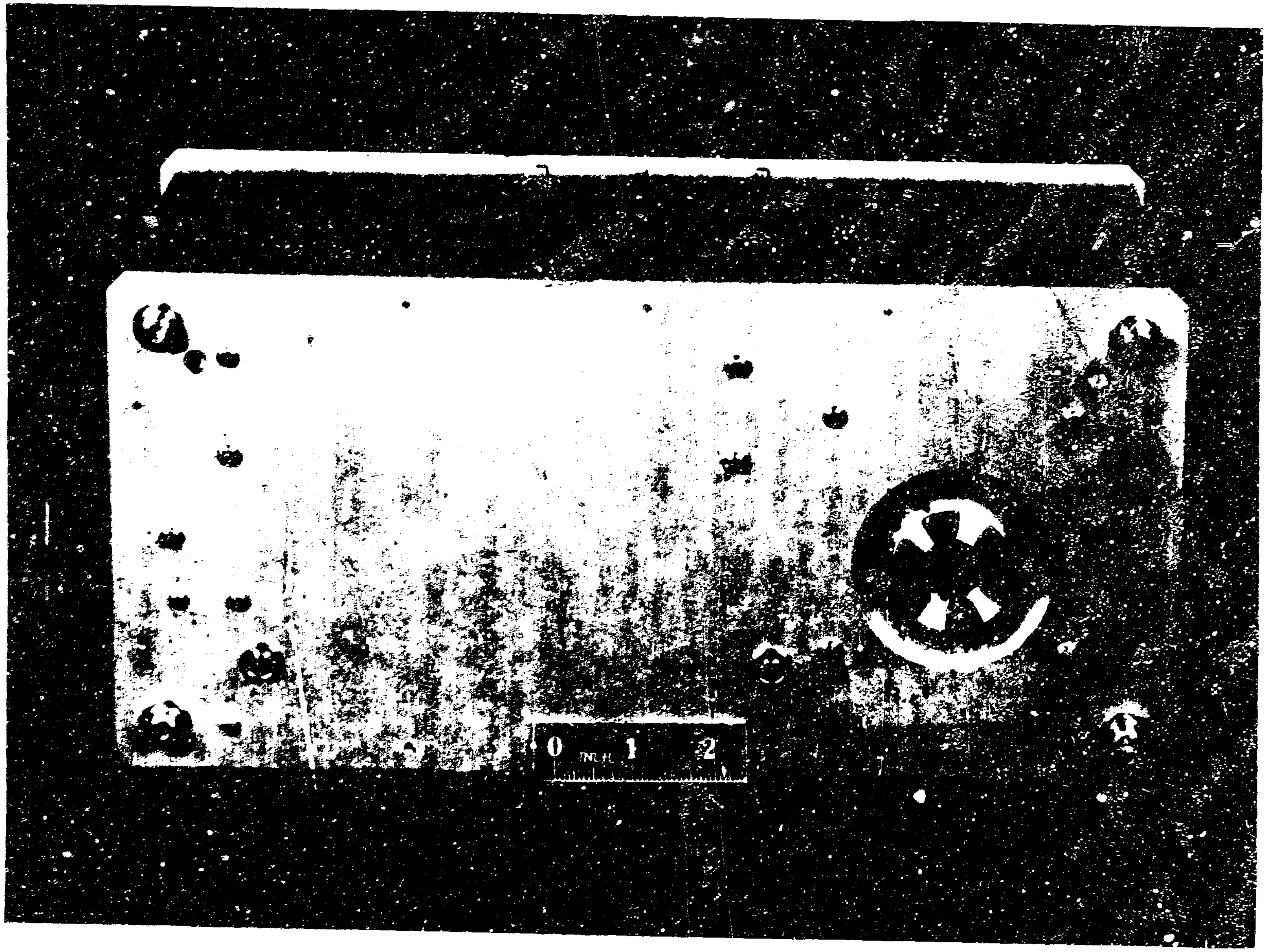


FIGURE 5B. BOTTOM VIEW OF CCD CAMERA PACKAGE
(SHOWING 10MM LENS WITH IRIS ADJUSTMENT)

1.2 mils in a vertical direction x 1.6 mils horizontally. Half of the horizontal distance (.8 mil) of the element is utilized for charge storing. This leaves an active light-sensitive area of 1.2 mils x .8 mil. The overall CCD sensor array has dimensions of approximately 3 millimeters x 4 millimeters and is scanned to yield a TV-compatible output; i.e., the 100 horizontal elements are read out in about 53 microseconds, the time needed to read out a horizontal line in the standard 525-line TV system. The vertical scan consists of a 2 to 1 interlace with a field (half of an interlaced frame) rate of 240 per second and a frame rate of 120 per second.

The image is focused on the CCD chip by means of either a 10-millimeter variable aperture lens or a 12.5-mm to 75-mm zoom lens. The output of the CCD chip is then fed through a video automatic gain control (AGC) circuit before being combined with the required synchronization pulses. The resulting TV-compatible (with the exception of the 4 times faster vertical framing rate) signal is available for output as the video input signal to a TV monitor or the modulation input of a television transmitter. The transmitter used was a commercially available, channel 14, Delstar Corporation Model DS500FC. The RF output from the transmitter is fed into a quarter wave stub antenna. The transmitter-antenna system provides a 475-megahertz, double side-band, amplitude-modulated output with about 1-1/2 watts into the antenna. The signal is presented on a standard Sony TV monitor slightly modified to accommodate 120 frames per second. For a hard wire connection between the TV transmitter package and the TV monitor, the video signal was used and fed directly to the video amplifier of the monitor. For telemetry applications, the transmitted RF was received on a log-periodic antenna and was fed, by way of a matching transformer, into the UHF terminals of the receiver. In either case, the processed video signals from the TV set were fed to a Sony Model AV-3400 video tape recorder. Vocie comments for the tape recorder were obtained either from a microphone connected to the recorder or from the audio output of a separate radio channel.

2.3 LABORATORY TESTS AND RESULTS

One set of laboratory tests, conducted with the cooperation of the Visionics Laboratory of the Night Vision Laboratory at Fort Belvoir, Va, consisted of observing a 1951 Air Force resolution chart with the CCD camera while the background illumination of the chart was varied in intensity. These tests were performed with an f/2.0 lens opening. The results indicated that the image is completely washed out at brightness levels of 11.4 ft-lamberts on the high end and .076 ft-lambert on the low end. For the same lens opening, usable resolution was obtained with background intensities ranging from about 7.7 ft lamberts on the high side down to .23 ft-lambert on the low side. This provides a 33 to 1 usable dynamic range for the CCD system. According to the manufacturer, the dynamic range is limited not by the sensors but by the on-chip output amplifier, which amplifies the composite video signal. Future CCD chips will have an improved amplifier that should offer a dynamic range between 350 and 1,000 to 1.

The data obtained from the resolution charts did not produce consistently smooth plots. In some cases, the expected smooth graph was obtained (i.e., poorer resolution at the saturated and low light level conditions with better resolution between). In other cases, the resolution was flat across the entire spectrum from saturation to low light level conditions. In the vertical scanning direction, the CCD's sensitive element has a physical size corresponding to a limiting resolution of 60 microns/line pair. The limiting resolution obtained from the laboratory data varied from 118 microns/line pair up to 51 microns/line pair. In the horizontal scan direction, the light sensitive element is 20 microns wide (0.8 milli-inch) spaced on 40 micron centers, which should provide a resolution of 80 microns/line pair. The measured resolution in this direction varied from a low of 100 microns per line pair to a high of 64 microns per line pair. These values for both the horizontal and vertical resolution correspond fairly well with the resolution limit as determined by the physical size of the individual detectors. Notice that a line pair requires two detectors: a black dot on one detector and a white dot on the adjacent detector.

An attempt was made to determine the spectral response of the CCD detector using a series of available high pass and low pass optical filters. Unfortunately the response of the filters is not known in the infrared region where the CCD device is still sensitive. It was concluded, however, that the CCD is responsive to near infrared radiation. This was proven by observing the infrared radiation reflected from grass and trees both before and after placing a visual band-pass filter in front of the camera lens. According to the manufacturer, the sensor's peak sensitivity occurs at about .75 micron. The observers must be trained in the use of this equipment in that the resulting pictures are formed in large part, from invisible, near infrared radiation. The TV images will not, in general, conform to the scene as viewed by human eyes.

Several laboratory measurements were made on the composite video signal. The horizontal sync pulses were the standard 64 microseconds apart with 11 microseconds utilized for the pulses and pedestal. This leaves approximately 53 microseconds for the horizontal video information. This information was obtained by sampling, in sequence, the 100 silicon detectors on a horizontal line. The vertical sync pulses occurred at a rate of 1 every 4.3 milliseconds with about 3.2 milliseconds of this time used to sample the 50 interlaced vertical TV lines. During a portion of the test where the CCD camera was originally attached to the helicopter (as discussed below), the ratio of video amplitude to sync pulse amplitude was too low and resulted in a lower-than-optimum contrast as displayed on the TV set. This was corrected for in subsequent tests and much improved pictures were received.

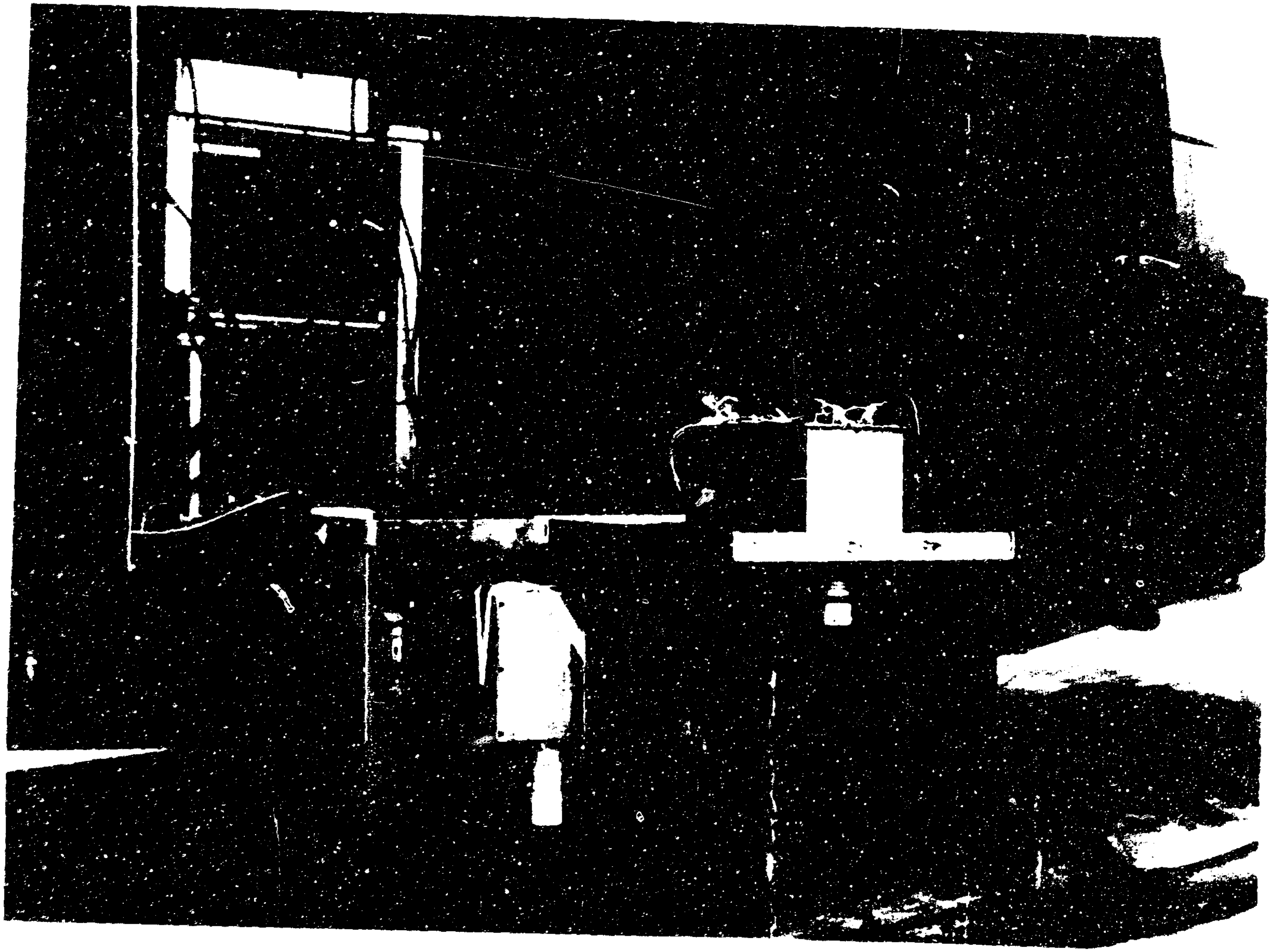


FIGURE 6. CCD CAMERA WITH CONVENTIONAL TV CAMERA AND LIGHT METER MOUNTED ON A UH-1H HELICOPTER

2.4 FLIGHT TESTS

The CCD camera was operationally tested in two modes: hard mounted to a UH-1H helicopter, and free-falling either on its own parachute or attached to a parajumper.

The helicopter portion of the test involved rigidly mounting the CCD camera, Sony TV camera, and a Tektronix light meter on the aircraft so that all units looked at the ground below the helicopter, as shown in Figure 6.

Video signals from both the CCD and standard TV camera were recorded on separate video recorders in the aircraft. During the first day of testing, the video signals from the CCD camera were also transmitted over an LWL developed airborne television system. These signals were recorded on the ground on a third video tape recorder. Voice information was recorded on all three tape recorders via a separate radio channel. During the helicopter tests, the CCD camera used a zoom lens with a focal length set mostly at 12-1/2 millimeters focal length.

The procedure for the aircraft-mounted test consisted of flying over selected target areas at seven altitudes so as to provide ground resolution (in the vertical direction on the picture), which varied from 10 feet to 1/10 of a foot. The two major target areas chosen were the aircraft "boneyard" at the Phillips Army Air Field at Aberdeen Proving Ground and the vehicle "boneyard" on Spesutie Island at Aberdeen Proving Ground. The aircraft area is shown in Figure 7 and contains various types of Air Force and Army aircraft along with engine packing crates. The vehicle target area (Figure 8) contained a series of trucks, tanks, jeeps and 105-mm weapons in various states of disrepair.

The light intensity reflected from the terrain below the aircraft was measured with a Tektronix J16 photometer using the J6503 illuminance probe. This probe measured the target luminance in foot-lamberts in an 8-degree field of view directly below the aircraft. The reflected intensity as read on this meter varied from a low of 200 ft-lamberts to as high as 700 ft-lamberts. The CCD's lens opening was f/16 for all of the helicopter-mounted tests.

Next, the CCD camera was dropped from the helicopter with a paratrooper. The unit was encased in styrofoam and attached to the parachute harness of the paratrooper. The unit survived these jumps and telemetered to a ground station uninteresting pictures of the grass and the airfield runways at Aberdeen Proving Ground.

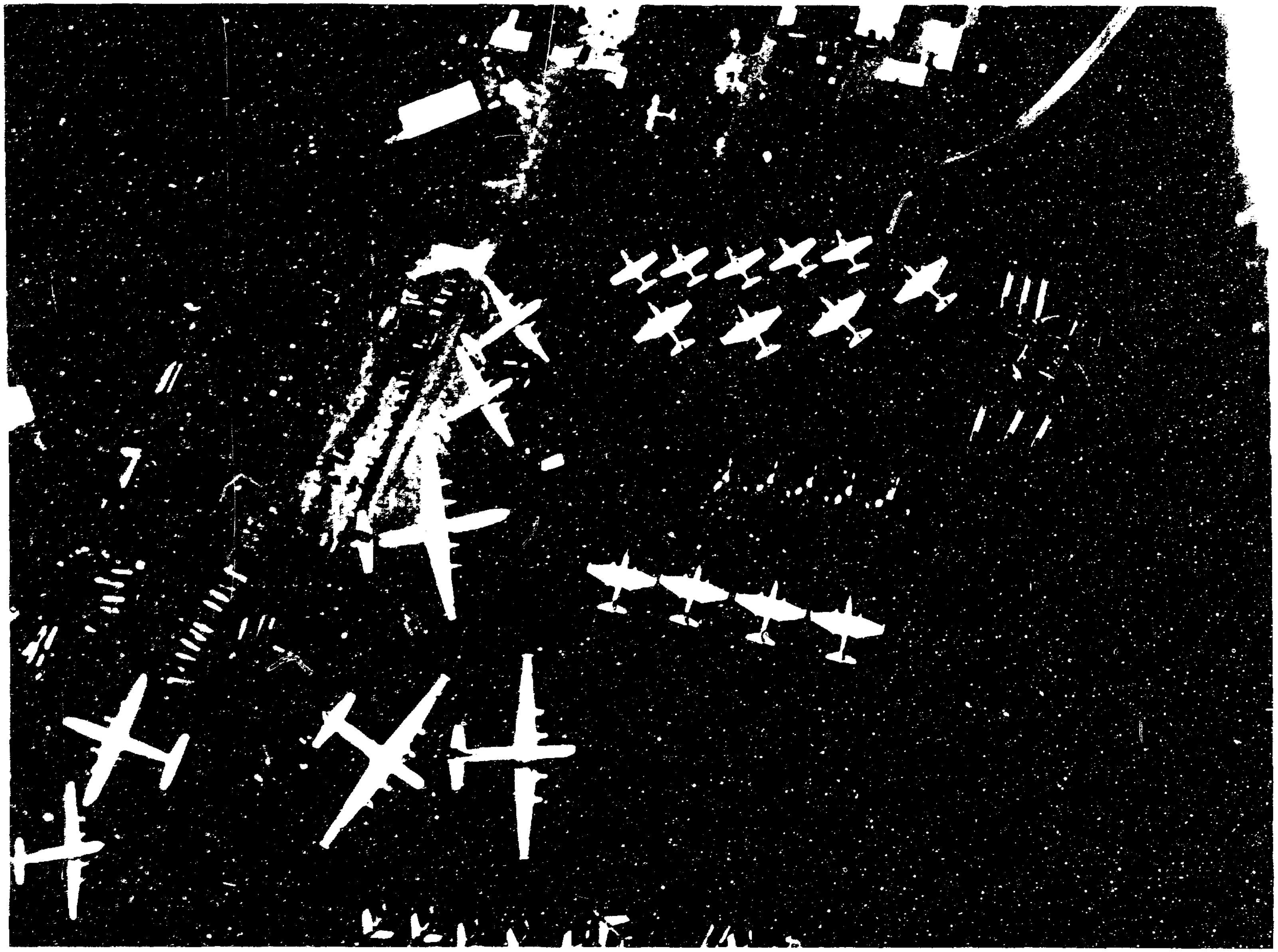


FIGURE 7. AIRCRAFT BONEYARD TARGET AREA FOR THE PARADROPS

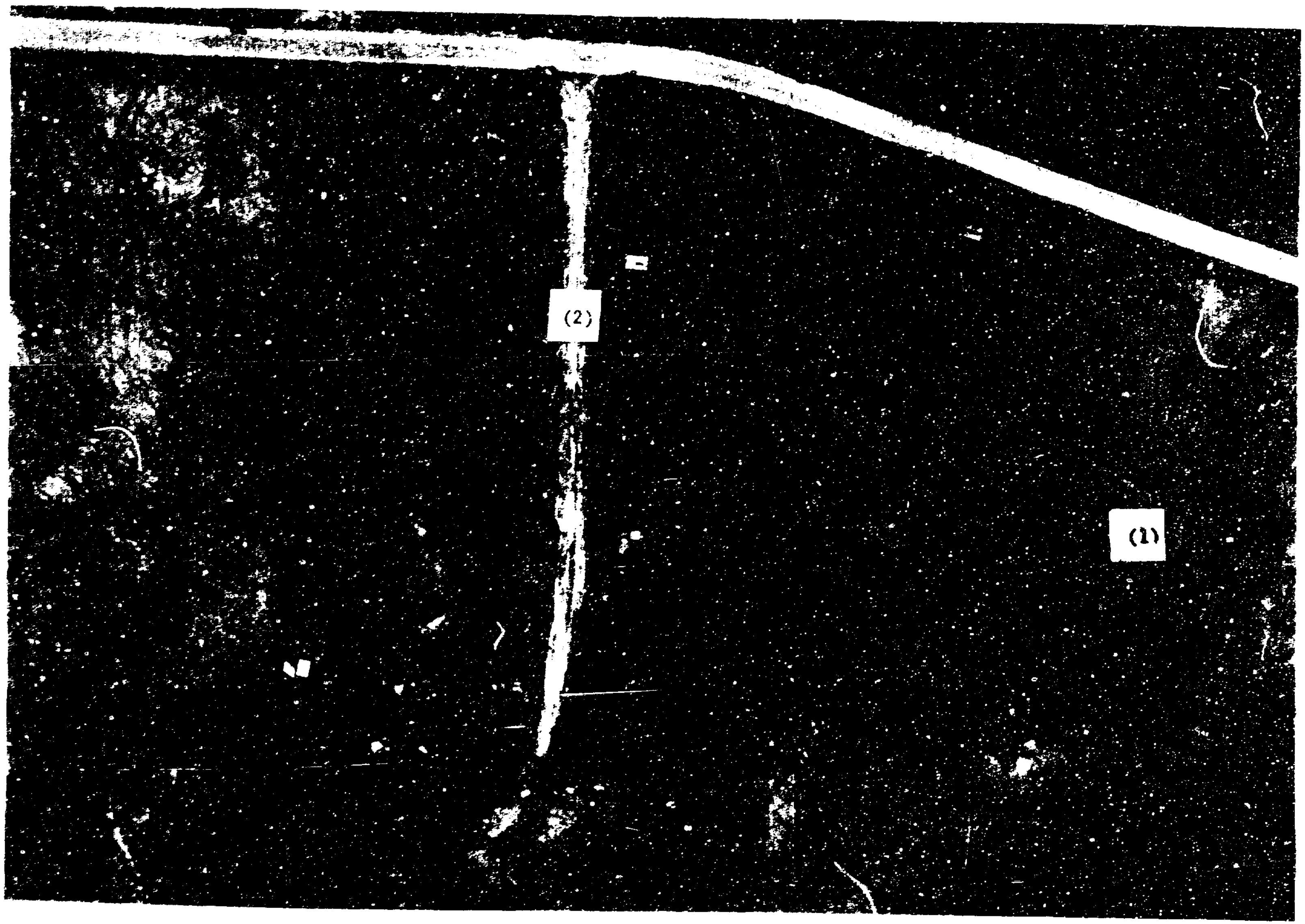


FIGURE 8. VEHICLE BONEYARD TARGET AREA FOR THE HELICOPTER TESTS (AREA PHOTOGRAPHED FOR FIGURE 10C, E, AND F, IS SHOWN AS (1). FIGURE 10D AS (2)).

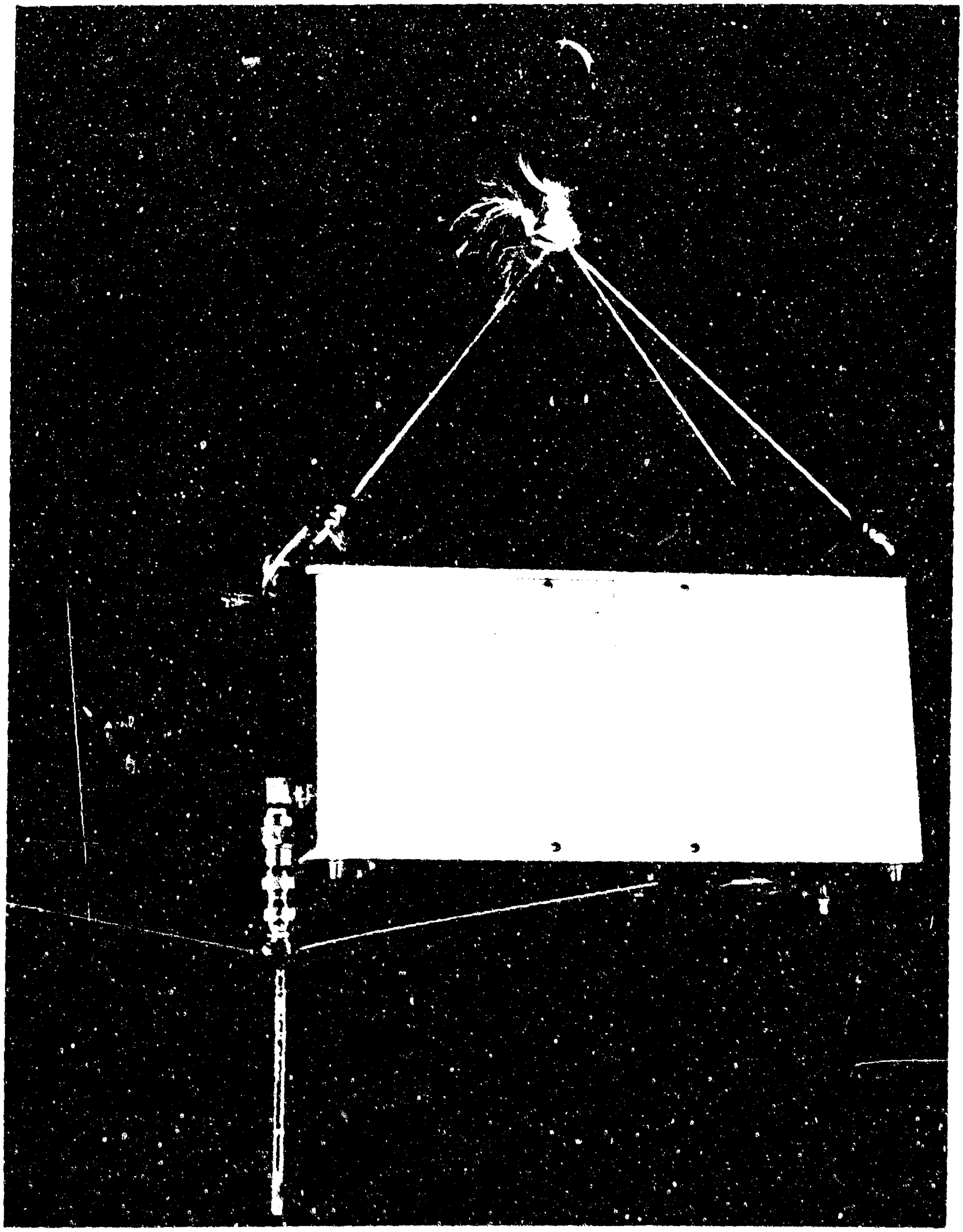


FIGURE 9. CCD CAMERA PACKAGE SHOWN SUSPENDED FOR PARACHUTE TESTS

Having gained confidence in the survivability of the CCD package, the unit was then free-dropped from the helicopter. For the free-drop situation, the 17-pound CCD camera package was rigged as shown in Figure 9 (except that styrofoam was added and a flexible cable was connected between the antenna and transmitter). The 10-millimeter flush-mounted lens was used for this test and two 100-inch diameter M485 illuminating round parachutes were attached to the package. The unit was carried to either a 1000-or 2000 ft altitude above the ground and dropped from the helicopter. The camera then floated to the earth with a drop rate of 15 ft/sec transmitting its pictures via TV channel 14. On the ground, the TV receiver monitored these received signals and the video was recorded. Paradrops were made over the aircraft boneyard at Aberdeen Proving Ground and over an Engineering Battalion training area at Fort Sill, Oklahoma. The CCD camera system survived 4 parachute jumps with paratroopers and 9 drops on its own without any ill effects (other than bending and breaking several antenna ground plane radials).

2.5 FLIGHT TEST RESULTS AND DISCUSSION

Before discussing the results, it is appropriate to describe some instrumentation problems that affected the quality of the pictures on the video tape. During the testing, the picture quality as displayed on the monitor was excellent; however, upon playback, it was found that the recording technique produced usable but not the same quality pictures. During playback of the recorded tapes, the TV set would lose synchronization every few seconds causing the pictures to "tear" horizontally. On stop-action playback, unsynchronized lines would interfere with picture quality. The cause of this trouble appears to be the non-synchronization of the 120 frame-per-second video being recorded on the video recorder designed for 30 frames-per-second. The solution to this problem was not investigated.

A second problem occurred in attempting to photograph the played-back images from the monitor using conventional, still, film cameras. The tearing problems mentioned above during stop-action prevented single video frame photography from being made. When the TV monitor was viewed visually, the eye integration reduces the effect of noise and increases resolution. The subjective impression when viewing moving scenes is of very good quality imagery. Photographs were finally produced using a still camera and 3000 ASA Polaroid film at 1/50 second.

The effect of the two problems mentioned above, plus the difficulty of matching gray scales on the TV and Polaroid film, results in the pictures for this report depicting a lesser quality of image than received on the TV monitor. The reader should bear in mind that the displayed image is far superior to those shown in this report. For the purpose of presenting an approximation of better image quality to the readers of this report, a 100 by 100 CCD camera was used to scan the photographs presented in

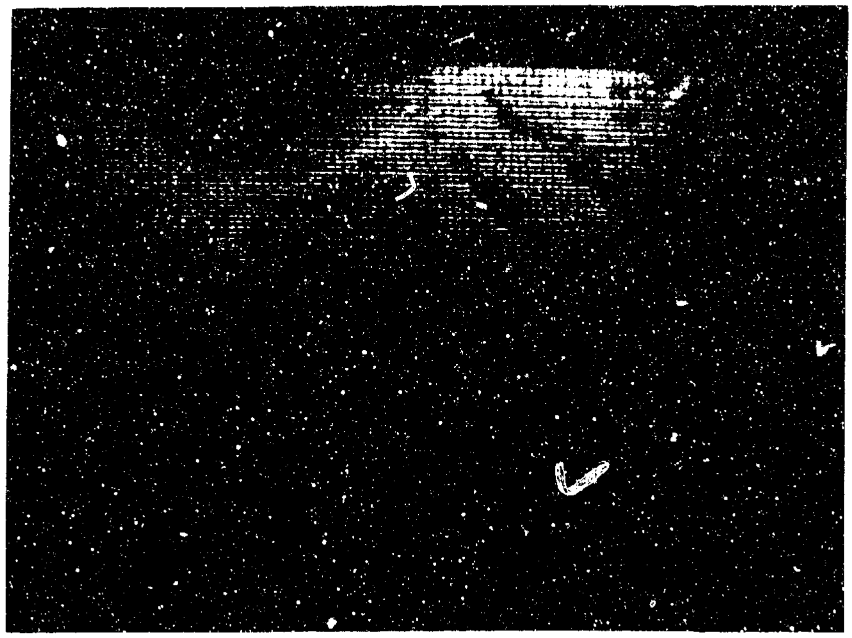
Figures 7 and 8. Polaroid photographs were then made directly from the TV monitor (i.e., without the tape recorder) of this "simulated" data. The subjects chosen and the fields of view used correspond to the actual video tape imagery obtained during the field tests.

Polaroid photographs of some of the tape-recorded video signals and the simulated data are shown in Figures 10 and 11. Figure 10 shows a sequence of photographs as the vehicle area of Figure 8 was overflown at various altitudes with the CCD package attached to the helicopter. Calculated ground resolutions (in the vertical direction on the photograph) of 10', 5', 2', 1', 0.5' and 0.25' are shown. The first four images were produced with the 12.5 mm focal length lens set at f/16 to provide 12.3° vertical field-of-view. The last two images were recorded with a 20mm focal-length lens (8.3° field-of-view) also at f/16. This series of photographs show how the image definition improves as the ground resolution improves. The vehicles are detectable in Figure 10 with a 10-foot resolution, begin to be recognized with a 2-foot resolution (much more so in viewing the TV monitor rather than the photograph), and start to become identifiable with 1/2 foot resolution.

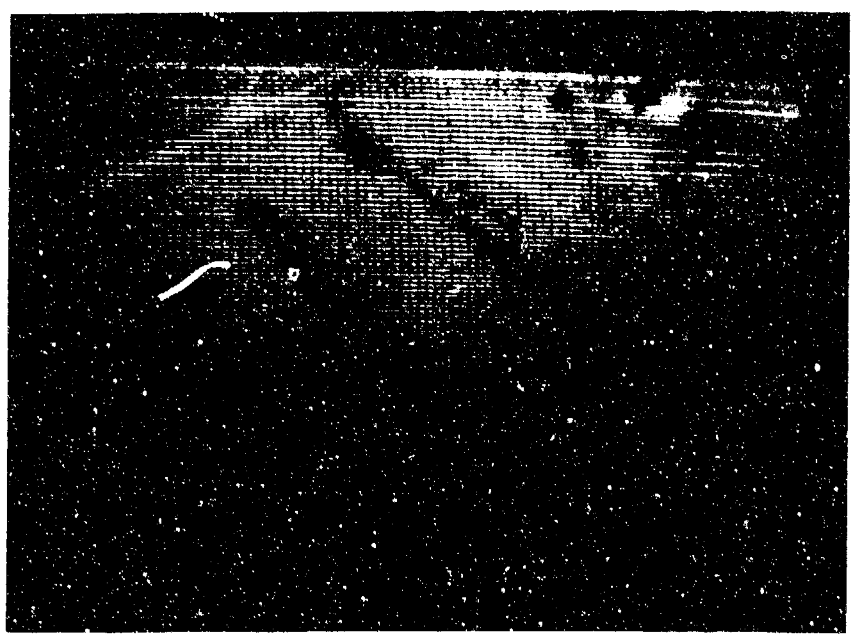
It should be pointed out that the total field of view for this 100 x 100 element sensor is related to the resolution quoted by a factor of 100 in the vertical direction and 133 in the horizontal direction. Thus, the 1 foot resolution provides a 100-foot x 133-foot total field of view.

Figure 11 shows sample views obtained when the CCD camera package was para-dropped over the aircraft boneyard area of Figure 7. The two photographs were taken from the monitor a few seconds apart corresponding to a CCD camera altitude of about 1500 feet above the ground. The camera used a 10 mm, f/22 lens which provided vertical resolution of 4.5 feet. The aircraft of Figure 11A were directly below the parachute and are clearly distinguishable from the buildings. Figure 11B was taken while the CCD camera package was swinging about the view of Figure 11A. This demonstrates the increased field-of-view obtained from the oscillation of the camera under the parachute.

The swinging and rotation of the parachute did not produce objectionable pictures. The maximum side-to-side swing obtained during these tests was in the order of 20 degrees with a peak-to-peak period of several seconds. This swinging provided an increased field of view for the sensor without significant smearing. The CCD camera rotations obtained during these tests resulted from the aerodynamic spin of the camera when dropped from the aircraft and before the parachute deployed. The worst remaining rotation rates were about 1/2 revolution per second and were the only annoying portion of the resulting imagery. These fast oscillations occurred on only one or two of the parachute drops and then for only a small portion of the descent.

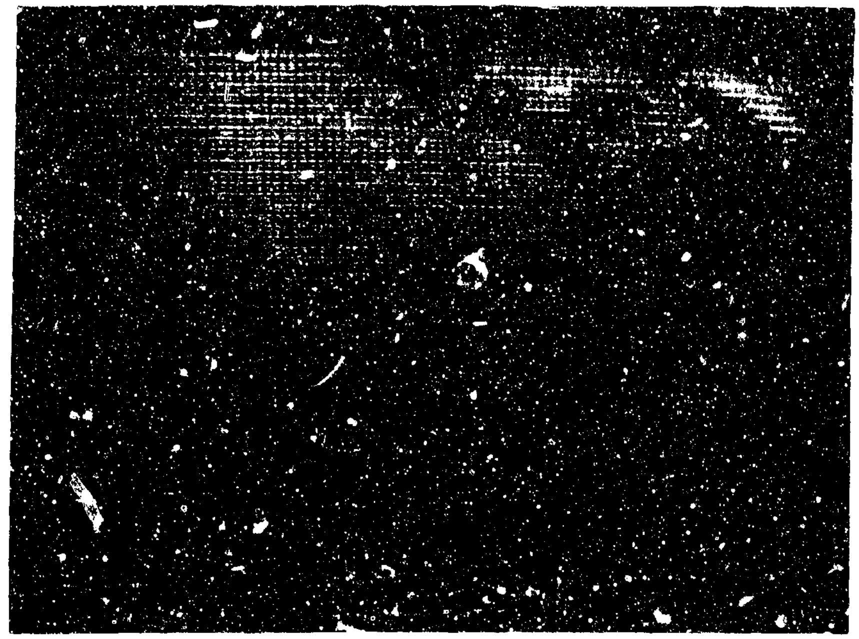


10 A. Vehicle boneyard with a 10 foot verticle ground resolution

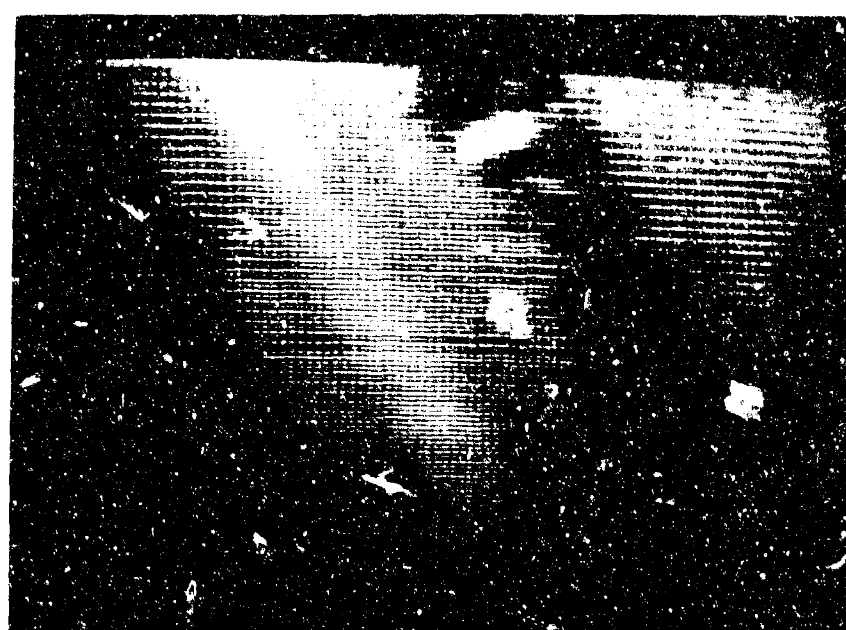


10 B. Vehicle boneyard with a 5 foot verticle ground resolution

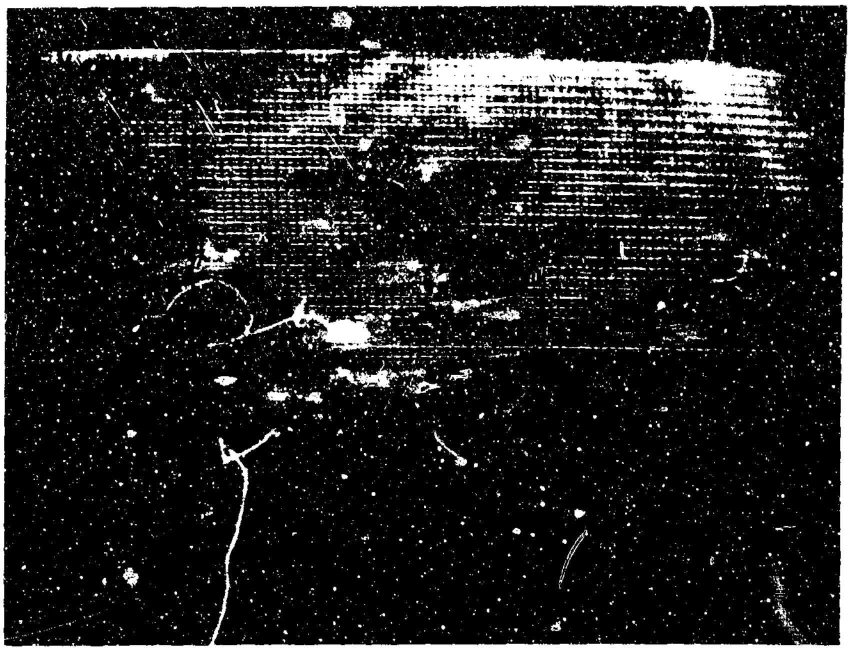
FIGURE 10. CCD imagry of the vehicle target area of Figure 8. Pictures A through F are degraded images photographed from viedo tapes made during the actual test. Pictures G, H and I are simulated data



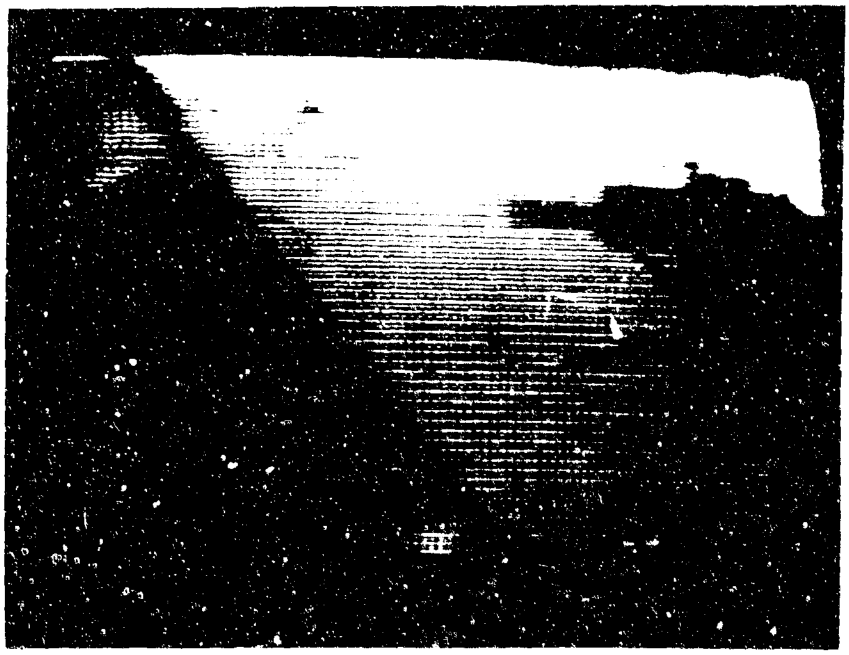
10 C. Vehicle boneyard with a 2 foot verticle ground resolution



10 D. Vehicle boneyard with a 1 foot verticle ground resolution

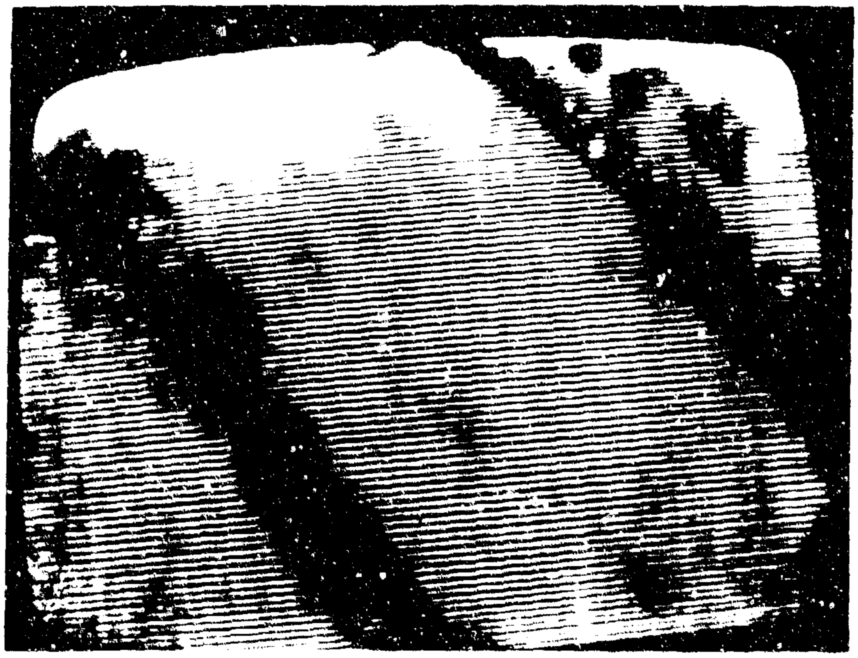


10 E. Vehicle boneyard with a 1/2 foot verticle ground resolution

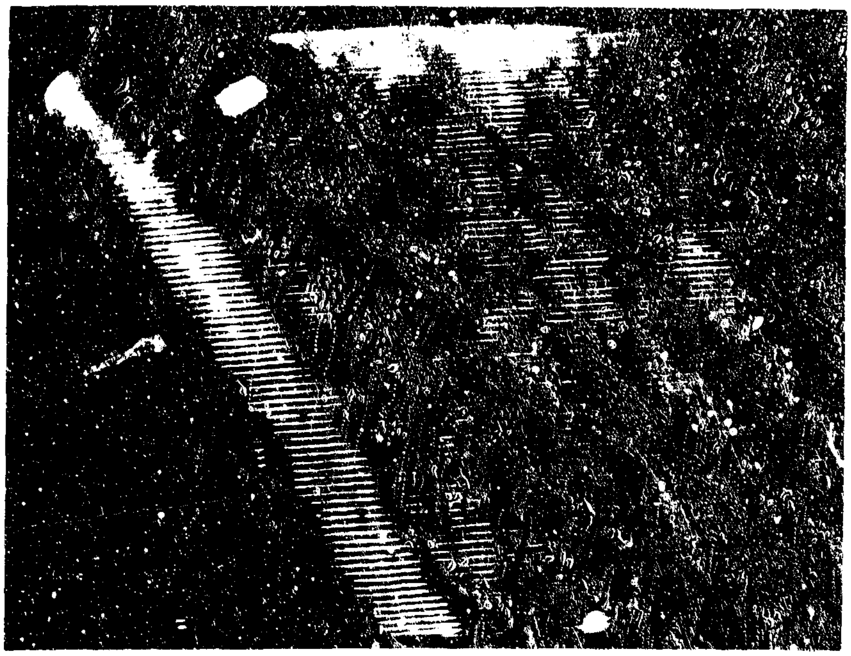


10 F. Vehicle boneyard with a 1/4 foot verticle ground resolution

10 G. Simulated data. vehicle boneyard with a 4 foot verticle ground resolution

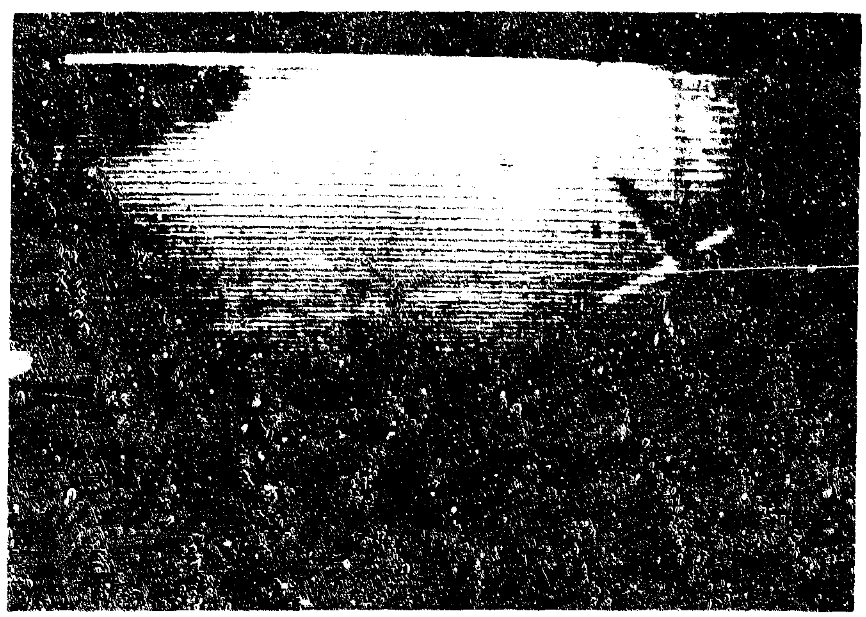


10 H. Simulated data. Vehicle boneyard with a 2 foot verticle ground resolution.



10 I. Simulated data. Vehicle boneyard with a 1 foot verticle ground resolution.

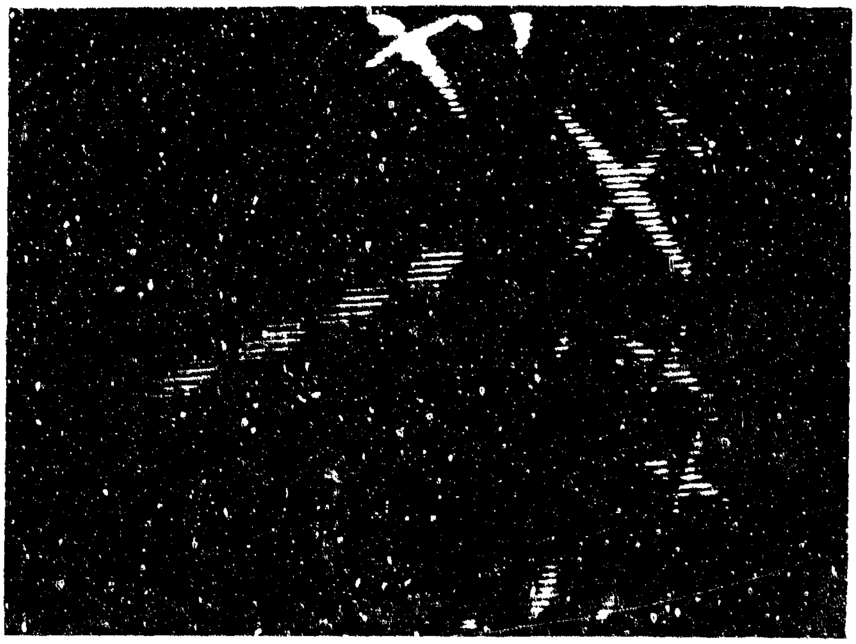
11 A. Telemeterd data with the camera looking straight down.



11 B. Telemetered data about 2 seconds after the picture in Figure 11 A above. This "extra" view results from the swinging of the camera below the parachute.

FIGURE 11. CCD imagry during a paradrop of the aircraft target area of Figure 7. Picutres A & B are degraded images made from video tapes recorded during the actual test. Pictures C & D are simulated data.

11 C. Simulated image of Figure 11 A



11 D. Simulated image of Figure 11 B

These tests demonstrated the improved picture resolution as the CCD camera comes closer to earth. The fixed field of view at higher altitudes allows a larger area of terrain to be seen but with poor resolution. This larger area contains a large number of terrain features which increase the chances of locating the position of the imagery. As the camera falls, the resolution improves but the total area of view becomes smaller. The better resolution allows better detection, recognition and identification of targets.

Deploying the CCD camera over a selected target area was a difficult task. For the nine helicopter drops in two different locations on two different days, there appeared to be a great difference between the wind at ground level and the wind aloft. The helicopter pilots were not able to position the helicopter and/or predict the wind accurately enough to allow two successive paradrops over the same path. The result was that a good survey of the area under the helicopter was obtained, but it would have been impossible to obtain a second drop to provide greater detail of some picture taken on a previous drop. It required approximately 10 to 20 minutes between paradrops for the helicopter to pick up the camera package and regain altitude for the next drop. For the weapon deployed system, a faster deployment rate could be utilized and the initial precision of deploying the CCD camera would be more closely controlled than could the helicopter-deployed camera used in this test series. This may improve the ability of the second shot to retrace the path of the first shot.

Position determination of the imagery can be performed utilizing a good map of the area or an Analytical Photometric Positioning System (APPS). Trials were run using a simulated paradrop with the CCD camera mounted on a helicopter and replayed for an APPS system operated by personnel from the Engineering Topographic Laboratories. Starting from an altitude which provided 10 foot ground resolution and utilizing the stop-action capability of the tape recorder, the APPS operators were able to determine the position of the CCD sensor (helicopter descending at a rate of about 15 feet per second and advancing forward at about 20 knots). Using this technique, the APPS operators were able to track the CCD sensor and to locate simulated targets with respect to known terrain features such as road junctions and buildings. This same technique could be utilized with the final system; however, it is vital to have a recording capability that provides the stop-action (single frame) so that the APPS operator will have sufficient time to locate his position on the APPS system.

The ultimate CCD system should provide a wide field of view to allow the detection of terrain features, and should also provide good resolution to allow early target detection and identification. This could be accomplished with the 100 x 100 element sensor evaluated for this test. The future 488 x 390 element sensor should provide improved capabilities.

2.6 CONCLUSIONS

From the data and subjective evaluation of the CCD system several conclusions can be drawn:

2.6.1 The 100 element x 100 element CCD camera can provide useful imagery for many military applications. Detection, recognition and identification of ground vehicle, aircraft and artillery weapon targets can be accomplished from the pictures transmitted back by the 100 element x 100 element CCD sensor.

2.6.2 The total field view for the transmitted picture is 100 times the resolution in the vertical direction by 133 times the resolution in the horizontal direction. This results in a rather narrow total field-of-view and requires that the CCD camera be placed accurately over the target.

2.6.3 An artillery-launched, parachute-deployed aerial reconnaissance system using the CCD technology is feasible and can be fabricated using existing technology.

2.6.4. The swinging and rotation of the CCD system as it parachutes to earth does not produce objectionable picture quality.

2.6.5. Improved resolution is obtained as the CCD camera falls toward the earth.

2.6.6. Deploying the CCD camera over a selected target area was a difficult task.

2.6.7. Position determination of the imagery from the Artillery TV can be performed utilizing either a good map or an APPS system.

2.6.8. The ultimate CCD system should provide as wide a field of view as possible.

2.6.9. The concept of the artillery launched, parachute dropped, aerial reconnaissance CCD TV system has several desirable advantages:

a. It can be packaged in existing 155mm illuminating shells (M-485), which should reduce the development time and cost.

b. It can be produced cheaply thus allowing deployment and operational control at the battalion level.

c. It can provide surveillance and target acquisition under hostile conditions when more sophisticated techniques might not be deployed.

d. It can provide observation on the "far side of the hill" which cannot be seen from the friendly territory. Line-of-sight to the target is not required. It is only necessary to have radio line-of-site to the CCD's transmitter, and the visual line-of-site from the CCD camera to the target.

e. It has the ability to go to the enemy's area. This provides a closer look, with "straight down" angles and imagery which may complement other viewing methods and intelligence devices.

2.6.10. The limitations of the concept include the following:

a. Unobscured line-of-sight from sensor to target is required from altitudes at which radio line-of-sight exists with the ground station. The system will not be able to see through clouds, heavy ground fog, smoke, etc. However, there are times when ground haze limits ground-to-ground vision, but vertical vision is adequate for Artillery-launched TV use.

b. The deployment range is limited to the range of the weapon. The M-485 round has a maximum range of 14 kilometers at Zone 7.

c. Positional accuracy of deployment will be limited by gun error and wind. The 155mm howitzer has a CEP of about 200 meters for the M-485 illuminating round. The nonpredictability of the winds vs altitude over the target area may cause an equally large error. (It is possible that this parachute TV technique could be combined with an APPS's data base and used to determine wind-vs-altitude).

SECTION 3

SYSTEM ANALYSIS

3.1 INTRODUCTION AND SUMMARY OF THE SYSTEM ANALYSIS EFFORT

In many military situations, reconnaissance of enemy-controlled areas is desired to permit more effective use of weapon systems. Because of the need, many devices have been and are being developed within the Army to assist in remote detection, identification, and location of targets in enemy territory. One such technique, which would be more cost-effective than drones and RPV's for limited reconnaissance applications, is to use an artillery shell to launch a parachute-carried TV system. The TV camera would point down at the ground while suspended under the parachute (similar to the standard artillery illuminating round), and would telemeter back the scene that it sees as it floats downward. The telemetered results would be displayed in a safe friendly area, both on a TV set and recorded for later playback and analysis on a standard TV recorder. The implementation of this idea and technique has been prevented by the lack of available TV camera tubes that would withstand the shock of being launched from an artillery weapon. Recent developments in charge coupled devices (CCD) have now made it feasible to fabricate a television-type sensor that has potential for withstanding the 12 to 20,000G's of acceleration encountered when launching a 155-mm artillery shell.

Under Contract No. DAAD05-74-C-0732, Fairchild Space and Defense Systems, a Division of the Fairchild Camera and Instrument Corporation, conducted a study program to establish the capabilities and limitations of artillery-launched, parachute-carried TV reconnaissance systems, based on Fairchild-developed CCD area photosensor arrays. The potential of such systems was demonstrated in actual field tests of a CCD TV camera system, using the Fairchild CCD-201, a 100 by 100 CCD area array of photosensors. The work under this contract was performed from 3 December 1973 to 15 April 1974. This section of the report presents the results of the system analysis efforts carried out during this period.

The parameter analysis of the TV Reconnaissance System is given in paragraph 3.2 of this report. It was determined that a resolution of 1 to 2 feet was required for target identification and 2 to 5 feet for target detection. The TV Reconnaissance System would be deployed in the same manner as the 155-mm M485 illuminating projectile and would have about the same delivery accuracy, 200 meters or 600 feet. A camera system using the Fairchild CCAID-488A sensor array and a 0.5-inch focal length f/2 lens would have the following ground coverages and limiting resolutions:

At 2,000 feet altitude

Ground Coverage	1,380' vertical by 1,840 horizontal	
Resolution	2.8' vertical	These terms
	4.7' horizontal	refer to the TV
	5.5' diagonal	frame format

At 1,000 feet altitude

Ground Coverage	690' vertical by 920' horizontal
Resolution	1.4' vertical
	2.35' horizontal
	2.8' diagonal

At lower altitudes, coverage would be restricted although resolution improves. Terrain obstacles and multi-path propagation, however, present more problems to radio communications at lower altitudes. To avoid operating at low altitudes, increased resolution could be achieved by a multi-focal length system (either a lens turret or a zoom lens) programmed to switch continuously from a 0.5-inch focal length lens to a 1.0-inch focal length to a 2.0-inch focal length and back to the 0.5-inch focal length, etc. This system, although it is more complex and requires mechanical motion, would provide the same diagonal resolution (0.7 foot) from an altitude of 1,000 feet that a 0.5-inch lens would give from 250 feet. Furthermore, by virtue of wind-induced drifts, ground coverage would be much increased.

Dawn to dusk performance is easily achieved by the system configured above. It is estimated that such a CCD TV Reconnaissance System could operate at ambient illumination levels of 0.01 foot-candles, an illumination level about half that produced by a full moon under clear sky conditions. The illumination levels corresponding to moonless night time conditions range from 10^{-4} to 10^{-5} foot-candles. Consequently, although the CCD TV camera sensitivity could be improved to allow operation at illumination levels as low as 0.001 foot-candles, night reconnaissance is best carried out with an auxiliary illumination source, such as the 155-mm M485 illuminating projectile.

Analysis showed that a carrier frequency of about 2,000 MHz was optimum for radio communication from the parachute-borne TV camera. At this frequency, a four-foot diameter parabolic dish receiving antenna and a 2-watt FM transmitter provide excellent communications over the maximum 10-mile range of the TV Reconnaissance System. A multipath fading margin of 26db is achieved and the 9° beamwidth of the receiving antenna requires no elaborate aiming procedures. When the receiving antenna is at the launch gun position, antenna azimuth and launch gun azimuth are, for all practical purposes, identical and two mounts can be slaved to one another. The antenna beam is narrow enough, however, to discriminate between the signals from several CCD TV cameras when multiple systems are deployed at the same time.

The CCD TV Reconnaissance System described in paragraph 3.3 consists of the gun-launched parachute-borne CCD TV camera-transmitter unit and a ground receiving station. The airborne unit is an exact duplicate, as to external dimensions, of the illuminant package in the standard 155-mm M485 illuminating projectile and would be used in a similar manner. Eight seconds after the primary expelling charge deploys the canister assembly and drogue parachute, the secondary expelling charge would deploy the CCD TV camera-transmitter unit and the main parachute. The camera lens is protected from the blast of the secondary expelling charge by a protective plate, which falls away after the camera-transmitter unit is expelled.

The camera-transmitter unit would be 4-1/4 inches in diameter by about 8 inches long. It has five major assemblies. The order given below represents the axial position of the various assemblies in the camera-transmitter unit.

1. Housing and lens assembly
2. CCD TV camera and power supply assembly
3. Battery
4. Timer and destruct charge assembly
5. RF transmitter

The battery would be energized on setback and provide power to the CCD TV camera, the timer and destruct charge assembly, and the RF transmitter. The system is operative as soon as the battery is energized. The transmitting antenna, which is a 1-1/2 inch quarter wave stub, is deployed with the main parachute.

The ground receiving station would consist of a four-foot parabolic dish antenna that would be positioned in azimuth over 360° but have only limited coverage in elevation. The antenna feeds an FM receiver that provides a video signal to a standard video tape recorder. The read after write output of the video tape recorder is displayed on a standard TV monitor. The video tape recorder and TV monitor can be remotely located from the FM receiver when a suitable communication link is provided.

It is estimated in paragraph 3.4 that the cost of the CCD camera-transmitter package for large production quantities would range from $600.00 to $1,200.00. This price includes a preliminary estimate of the CCD array cost and assumes that the Government will furnish materials, such as the battery and the destruct charge. A preliminary estimate of the CCAID-488A cost was included because, until the first one of these devices is made, it is not possible to reliably predict the production costs of what, in semiconductor terms, represents a huge device; much larger than any commercial semiconductor device being made today.

The CCD camera round is identical to the standard M485 illuminating round except that the illuminant package is replaced by the CCD camera-transmitter package. The final cost of a camera round is then equal to the cost of an M485 round plus the differential in cost between the camera-transmitter and illuminant packages.

The proposed follow-on program described in paragraph 3.5 presents the design and development of a CCD camera system that can survive the launch environment. The CCD camera will feature a 0.5-inch focal length lens and the CCAID-244A. The CCAID-244A is an area imaging device that has 244 rows of photosensors, each row consisting of 190 photoelements. This device is now in the early stages of fabrication.

All of the operational characteristics of the final system can be proven out in this proposed follow-on program, since the CCAID-244A is equivalent, except in size, to the CCAID-488A. Most importantly, the proposed program will have demonstrated that a CCD camera-transmitter system can be packaged inside the canister of the M485 illuminating projectile; that it can survive launch; that it can gather useful reconnaissance data and that it can transmit these data to a safely located command post.

3.2 TV RECONNAISSANCE SYSTEM PARAMETER ANALYSIS

3.2.1 Reconnaissance Target Characteristics

The military force having cognizance over the TV reconnaissance system has a need for both broad area and limited area reconnaissance coverage. There is a general need to assess the enemy held territory behind the FEBA as to the determination of the general topography, the location of identification points and the deployment of the enemy forces. These is also a particular need to monitor known key coordinates such as crossroads, strong points and railroad yards. The general need requires wide coverage at moderate resolution, whereas the particular need requires high resolution but usually at narrow fields of view and, in addition, accurate placement of the camera. Moderate resolution allows for target detection and high resolution for target identification.

The resolution required for damage assessment and surveillance for a wide range of military targets is given in Table 1. This tabulation indicates that, for the local battlefield conditions, a resolution of 2-5 feet is desirable and that the worst resolution should not exceed 20 feet, and preferably, 10 feet.

The required coverage for a particular target will vary widely. For example, examining a crossroad junction for military truck traffic requires a resolution ranging from 1-2 feet for identification to 10 feet for detection. Even a

TABLE 1

RESOLUTION REQUIRED FOR DAMAGE ASSESSMENT AND SURVEILLANCE

ITEM	MINIMUM KEY	REQUIRED RESOLUTION (Ft.)
Major Cities	Structures; buildings	200
General Area	Large Structures	100
Major mfg. buildings	Buildings	50
Supply Dumps-Depot	Pattern	20
Power Plants	Buildings	20
Helicopter Landing Pads	Pad	20
Military Vehicles	Truck	20
Mil. Water Traffic	Ships/Barges	20
Mil. Air Traffic	Parked Aircraft	20
RR Tracks, Yards	Area Pattern	10
Missile Launch Sites	Pattern	10
Aircraft Type	Aircraft	10
Assault Guns	Gun	10
Command Vehicles	Trucks	10
Missile Launches	Launcher	5
Combat OPS (Pers)	Small Groups	5
Mortars	Gun	5
Arm. Pers. Carriers	Truck	5
Tank	Turret, Gun Details	2
Power Lines	Wire & Poles	2
Launch Site Details	Pattern	2
Missile Component	Pattern	2
Recoilless Rifle	Rifle	
105mm Howitzer	Barrel, Wheels	0.5 - 1.0
Radar/Comm. Inst.	Antenna Shape & Pattern	0.5 - 1.0
Air Defense Missile	Launch Details & Nose Shape	0.25 - 0.50
Personnel	Individual	0.25 - 0.50
Aircraft (Details)	Engines, Weapons Racks	0.25 - 0.50

major crossroad junction would not cover as much as 200 feet in either direction. On the other hand, a major supply dump or depot can extend 2,000-5,000 feet in both directions. Furthermore, typical South Vietnamese strongpoints had a 3,000-foot diameter. This gives the approximate range of coverage required for targets of interest. Since the military force having cognizance over the TV reconnaissance system will be concerned with all of the enemy territory within the range of its artillery, reconnaissance over a much larger area is needed and a single gun-launched TV camera round would not be able to cover all of this area at adequate resolution. Multiple rounds will probably be needed. The coverage provided by a single round versus the ground resolution desired comes down eventually to a question of cost effectiveness and operational use.

The gun-launched CCD TV camera has sufficient sensitivity to operate from dawn to dusk (illumination levels in excess of 100 foot-candles) with very good picture quality. Daylight reconnaissance provides intelligence as to the deployment of the enemy forces and gives data as to the general terrain topography. However, night reconnaissance is required to get timely information on enemy movements as the enemy will generally move under the cover of darkness. The CCD TV camera can operate under full moonlight conditions (0.02 foot-candles) and somewhat less if lens and array performance is improved but the camera will not be able to work under moonless conditions (10^{-4} to 10^{-5} foot-candles of illumination). For complete night reconnaissance capability, the CCD camera system will require auxiliary illumination such as could be provided by the standard 155-mm illuminating projectile.

3.2.2 TV Reconnaissance System Delivery

The accuracy with which the reconnaissance system can be placed on target depends on, in addition to other factors, the type of surveillance to be carried out. Two cases can be considered; (1) general surveillance applications wherein intelligence information is obtained by means of a programmed search patternand (2) surveillance of locations at preselected map coordinates.

When a programmed search pattern is initiated, the first TV camera round will have errors in both plan position and deployment altitude. These errors would also apply to surveillance of locations at preselected map coordinates. From the observed scale in the telemetered imagery, the actual deployment altitude can be determined and the appropriate adjustments made to achieve the desired deployment altitude on the second round. In a programmed search pattern surveillance mode, the plan position errors obtained with the first TV camera round and the subsequent altitude correction round are not significant. Subsequent TV camera rounds would be offset accurately from the initial rounds by incremental adjustments to Fuze Setting (FS), Quadrant Elevation (QE) and Chart Deflection (CD). The entire search pattern might be shifted somewhat from the desired search pattern but surveillance of the region of interest would be essentially complete.

Surveillance of target locations at preselected map coordinates is much more demanding inasmuch as camera position as well as camera altitude must be established. The errors in the deployment of the first TV camera round can be determined by examining the telemetered imagery just as the errors in the delivery or ordinary artillery rounds are determined by a forward observer. The Analytical Photogrammetric Position Location System can be used in this context to track the location and orientation of the camera if the field of view contains recognizable features.

The CCD TV camera will be deployed in exactly the same way as is the illuminant in the M485 illuminating projectile. At a fixed time delay after launch, which depends on the fuze setting, the primary expelling charge is ignited. The explosion forces the drag parachute and canister assembly against the base plate, shearing the pins that hold the plate in place and expelling the parachute and canister. When the parachute and canister assemblies hit the airstream, the drag parachute deploys, and the anti-rotation fins unfold to slow the spin of the canister. The parachute and fins act together to reduce the canister velocity and spin to much smaller values than those at initial expulsion and this action takes place very quickly. After about 8 seconds, the delay element in the base of the canister, which was ignited by the primary expelling charge, burns through and ignites the secondary expelling charge, which then ejects the main parachute and the CCD TV camera from the canister assembly. The main parachute then deploys, suspending the CCD TV camera below it with an average descent rate of 15 feet per second. The orientation of the CCD TV camera in azimuth is a random variable and cannot be predetermined. The camera's line of sight will be essentially vertical. Under the influence of the winds, the camera will drift horizontally and its line of sight may deviate from the vertical. Swaying with an amplitude of 10° to 30° may occur. The camera's altitude and plan position at deployment are determined by the gun and target coordinates, the gun settings of FS, QE and CD, and the effects of air temperature, air density, wind, earth rotation, propellant temperature, and gun barrel wear and temperature. The introduction to the firing tables for the M485 illuminating projectile states that adjustments to the deployment position are rarely made to greater accuracy than 200 meters of the desired location. This can reduce the effectiveness of the TV Reconnaissance System or necessitate use of a second round. For example, at a resolution of 2 feet per TV line, a 500-element TV sensor would cover a 1,000-foot wide area on the ground but with a 600-foot (200 meter) error in deployment position, only 400 feet of this coverage would be in the desired target area. Improving deployment accuracy is very desirable but the difficulty of accomplishing this under battlefield conditions must be determined. Both camera swaying and horizontal drift serve to increase camera coverage and minimize the need for improved deployment accuracy.

The maximum charge that can be used with the M485 illuminating projectile is Charge 6W, which consists of propelling charge M4A1, base section 3 and increments 4, 5 and 6. For this maximum charge, the muzzle velocity is 472 meters/second. The maximum range to the target, for the nominal 600-meter illuminant ignition height, is 11,400 meters.

The M565 fuze used with the M485 illuminating projectile can be set to 0.1-second increments. At the maximum muzzle velocity of 472 meters/second, the projectile travels 47.2 meters in 0.1 second. At the 45° trajectory angle corresponding to the maximum range, the horizontal (and vertical) displacement for a 0.1-second increment is 33.3 meters or about 100 feet. This is a worst case value, since maximum range was used and no allowance was made for the decrease in projectile velocity due to ballistic drag.

Fuze setting changes must also be made to compensate for changes in muzzle velocity, range wind, air temperature, air density and projectile weight. The maximum values for each of these fuze setting changes are about:

Muzzle Velocity	0.06 second per 1 meter/second change
Range Wind...........	0.02 second per 1 knot
Air Temperature	0.04 second per 1% change (59°F std.)
Air Density	0.06 second per 1% change
Projectile Weight.....	0.06 second per 1.1 pound change

Unless these corrections are carefully made, the fuze settings may be in error by many times the 0.1-second increments. For example, every 1000 rounds the muzzle velocity decreases by about 2 meters/second. Furthermore, at either 10°F or 130°F, the muzzle velocity change due to the change in propellant temperature from the standard 70°F value is about 9 meters/second. The maximum fuze setting change is about 0.5 second for this variation alone.

Under battlefield conditions, it is debatable how many of these corrections will be properly applied. The 200-meter delivery accuracy mentioned previously is probably a very good value for unobserved artillery fire. Consequently, in a given situation, the TV Reconnaissance System could require two or more rounds to achieve effective reconnaissance. The first rounds, as previously stated, would be used as forward observers and the information obtained from them used to correct the gun settings.

In a given observation situation, the desired surveillance coverage could range from 200 feet to 5,000 feet. Because of deployment inaccuracies, the camera coverage must be somewhat larger.

For the purposes of determining camera coverage, the deployment error for both altitude and plan coordinates is assumed to be 200 meters (~600 feet). The required camera coverage is then equal to the desired surveillance coverage plus 2 x 600 feet at the nominal 600-meter deployment altitude. At a burst height of 400 meters corresponding to a 200-meter error in deployment altitude, the camera coverage is 2/3rds of this value. Consequently, the nominal camera coverage must be 150% of the value given by the formula cited above. At narrow angles of view camera swaying increases coverage twofold with somewhat smaller increases at wider angles of view (1.4x). This consideration is reflected in the following table:

Desired Surveillance Area	Required Camera Coverage
200' x 200'	1,050' x 1,050'
400' x 400'	1,320' x 1,320'
800' x 800'	1,800' x 1,800'
1,600' x 1,600'	2,730' x 2,730'
3,200' x 3,200'	4,620' x 4,620'

3.2.3 CCD TV Camera Performance

3.2.3.1 CCD Sensor Characteristics

There are five CCD area photosensor arrays currently being produced or under development by Fairchild. These are the following:

1. CCAID-100 (CCD-201)
2. CCAID-244A
3. CCAID-244B
4. CCAID-488A
5. CCAID-488B

The CCAID-100 (CCD-201) is the device used in the flight tests performed under this contract. It is a 100 by 100 element array of photosensors with a cell size that is 1.2 mils by 1.6 mils. The photosensor area is approximately 0.6 mil by 1.2 mils, the rest of the cell consisting of opaqued transfer and storage electrodes. The on-chip amplifier is a dual differential amplifier that has demonstrated a noise equivalent exposure in the laboratory of about 160 electrons at 25°C and a video frequency of 1 MHz.

The CCAID-244A, currently being fabricated, features a 244 by 190 matrix of photosensors. It has column anti-blooming and three output amplifiers. These are a dual differential amplifier (DDA), a floating gate amplifier(FGA) and a distributed floating gate amplifier (DFGA). A noise equivalent exposure of 10-40 electrons is expected for the FGA and DFGA structures when the array is cooled to -50°C to eliminate dark current noise. The cell size is 0.71 mil by 1.18 mils with a photosensor size of 0.4 mil by 0.71 mil.

The CCAID-244B is identical to the CCAID-244A except that it employs a gateless, self-aligned structure for the CCD storage registers. The cell size is the same but the photosensor size is increased to 0.55 mil by 0.71 mil. This makes for increased sensitivity. This device is under development.

The CCAID-488A is a larger version of the CCAID-244B. It features a 488 by 380 matrix of photosensors and is directly equivalent in performance to a standard 525-line TV camera tube. The image diagonal is 0.5".

The CCAID-488B is a very large chip designed for low light level applications. The 488 by 380 matrix of photosensors features a 1.18-mil by 2.09-mil cell size with a photosensor size of 1.18 mils by 1.46 mils. The photosensitive area is four times larger than that of the CCAID-488A and, therefore, the CCAID-488B will be four times more sensitive. The pohtosensor diagonal is 1". This device is currently in the design stage. Because of its very large chip size, the CCAID-488 will be a very expensive device and should be used only in those applications where its performance justifies the increased cost.

3.2.3.2 Camera Lens

The major factors bearing on the design of the camera lens are:

1. The lens must survive the projectile launch.
2. The lens field of view must meet the system requirements.
3. The lens should have aperture for maximum camera sensitivity.
4. The lens should have good modulation transfer at the spatial frequencies corresponding to the CCD arrays used. This good response must be obtained in the silicon spectral band ranging from 0.4 to 1.0 micron.

The strength of optical glass is influenced far more by configurational and, in particular, surface features than by composition and basic modulus of elasticity. Although the "ultimate" strength of glass under ideal conditions can be as high as 1,000,000 pounds per square inch, the engineering tensile strength of conventional glasses is frequently given as 1,000-2,000 pounds per square inch. Impact loading over small areas causes glass to crack at areas where surface flaws or stress concentrations exist. Conventional lens constructions wherein the lens elements are supported rigidly by metal rings at their edges would not survive launch. At some sacrifice to aperture, the lens elements could be elastically supported over a large area using silastic or similar material. This technique would avoid stress concentrations and allow lenses made in this manner to survive launch.

Reducing lens dimensions is another method that can be used to insure launch survivability. Mass decreases as the cube of the lens dimensions, whereas shear areas can be made to decrease directly with the lens dimensions. The lens dimensions are subject somewhat to system requirements; focal length is determined by the CCD array element size and the desired ground resolution and deployment altitude. The lens size is most easily decreased by decreasing lens aperture. This, of course, decreases system sensitivity, but it will be shown that the CCD camera system has adequate sensitivity even at reduced apertures.

Wide angle lenses of a given focal length are much larger than lenses of the same focal length, which have normal or narrow fields of view. This makes for less launch survivability. As a general rule, therfore, the CCD camera should not use a wide angle lens. A wide angle lens is defined here as a lens whose image diameter is larger than its focal length.

The spatial frequencies corresponding to the limiting diagonal resolution for each of the CCD photosensor arrays described in paragraph 3.2.3.1 are:

CCAID-100D............10 line pairs/mm
CCAID-244A............17.5 line pairs/mm
CCAID-244B............17.5 line pairs/mm
CCAID-488A............17.5 line pairs/mm
CCAID-488B............10 line pairs/mm

These spatial frequencies are rather low and should present no difficulties to the lens design effort. The spectral bandwidth from 0.4 to 1.0 micron is rather wide from a conventional photographic viewpoint but does not represent a difficult design problem. Fairchild, in another program, modified a convential f/1.0 lens design to achieve a modulation transfer of 0.83 at 20 line pairs per millimeter over the full 0.4-1.0 micron bandwidth.

3.2.3.3 Field-of-View (FOW) and Resolution

The resolution and field-of-view can be given in terms of matrices relating altitude and sensor type to the appropriate parameter for a particular lens focal length. This gives an immediate appreciation for camera performance not given by the equations relating the various parameters.

The lens focal lengths considered in Tables 2 through 5 are 50mm, 25mm, 12.5 mm and 6 mm (2", 1", 0.5" and 0.25", respectively). When the sensor diagonal exceeds the lens focal length, this corresponds to a wide angle lens and, as such, would not be suitable for the system. Such values will be marked with an asterisk in the matrices.

The resolutions given correspond to the sensor element diagonal. Somewhat smaller limiting resolutions pertain to the x and y sensor element spacings. For example, at an altitude of 2,000 feet, the CCAID-488A achieves a ground resolution of 2.8 feet (diagonal measure) with a 1-inch focal length lens. The corresponding vertical and horizontal limiting resolutions are 1.4 feet and 2.35 feet. Vertical and horizontal as used here refer to the rectangular TV picture format.

At an altitude of 2,000 feet, excellent ground coverage is achieved for:

1. the CCAID-244 used with a 1/4" lens
2. the CCAID-488A used with a 1/2" lens
3. the CCAID-488B used with a 1" lens

The ground resolutions achieved are respectively 11', 5.5' and 4' (diagonal measure).

A tank with dimensions 10' by 20' can be imaged at the 11' resolution by a 2 by 2 array of photosensors (4 sensor elements). This yields marginal detection. At the 5.5' resolution, the same tank can be imaged by a 4 by 4 array (16 sensor elements). This gives good detection. When the altitude is reduced to 1,000 feet, the 5.5' resolution goes to 2.8' and the tank would be imaged by an 8 by 8 array (64 sensor elements). Very good tank identification would then be achieved including perhaps some measure of damage assessment. This is consistent with the 1.4' vertical and 2.35' horizontal resolution that is actually achieved.

Examination of the matrices points up the fact that the best ground coverage and the best resolution cannot be achieved at the same time. Good coverage (1,380' by 1,840') for the CCAID-488A may require a 1/2" focal length lens but high resolution (2.8' diagonal measure) requires a 1" focal length lens. A multi-focal length system may be indicated.

TABLE 2

RESOLUTION AND GROUND COVERAGE
FOR
VARIOUS ARRAY AND LENS COMBINATIONS

	LENS FOCAL LENGTH			
	6.25mm(1/4")	12.5mm(1/2")	25mm (1")	50mm (2")
CCAID-100D	16.0' 960' x 1,280'	8.0' 480' x 640'	4.0' 240' x 320'	2.0' 120' x 160'
CCAID-244	11.0' 1,400' x 1,850'	5.5' 690' x 920'	2.8' 345' x 460'	1.4' 172' x 230'
CCAID-488A	*	5.5' 1,380' x 1,840'	2.8' 690' x 920'	1.4' 345' x 460'
CCAID-488B	*	*	4.0' 1,200' x 1,600'	2.0' 600' x 800'

Camera Altitude..... 2,000'

Resolution
....
Grd. Coverage

TABLE 3
RESOLUTION AND GROUND COVERAGE
FOR
VARIOUS ARRAY AND LENS COMBINATIONS

	LENS FOCAL LENGTH			
	6.25mm(1/4")	12.5mm(1/2")	25mm (1")	50MM (2")
CCAID-100D	8.0' 480' x 640'	4.0' 240' x 320'	2.0' 120' x 160'	1.0' 60' x 80'
CCAID-244	5.5' 700' x 920'	2.8' 345' x 460'	1.4' 172' x 230'	0.7' 86' x 115'
CCAID-488A	*	2.8' 690' x 920'	1.4' 345' x 460'	0.7' 172' x 230'
CCAID-488B	*	*	2.0' 600' x 800'	1.0' 300' x 400'

Camera Altitude..... 1,000'

Resolution
Grd. Coverage

TABLE 4
RESOLUTION AND GROUND COVERAGE
FOR
VARIOUS ARRAY AND LENS COMBINATIONS

	LENS FOCAL LENGTH			
	6.25mm(1/4")	12.5mm(1/2")	25mm (1")	50mm (2")
CCAID-100D	4.0' 240' x 320'	2.0' 120' x 160'	1.0' 60' x 80'	0.5' 30' x 40'
CCAID-244	2.8' 345' x 460	1.4' 172' x 230'	0.7' 86' x 115'	0.35' 43' x 58'
CCAID-488A	*	1.4' 345' x 460'	0.7' 172' x 230'	0.35' 86' x 115'
CCAID-488B	*	*	2.0' 600' x 800'	1.0' 300' x 400'

Camera Altitude..... 500'

Resolution
....
Grd. Coverage

TABLE 5
RESOLUTION AND CROUND COVERAGE
FOR
VARIOUS ARRAY AND LENS COMBINATIONS

	LENS FOCAL LENGTH			
	6.25mm(1/4")	12.5mm(1/2")	25mm (1")	50mm (2")
CCAID-100D	2.0' 120' x 160'	1.0' 60' x 80'	0.5' 30' x 40'	0.25' 15' x 20'
CCAID-244	1.4' 172' x 230'	0.7' 86' x 115'	0.35' 43' x 58'	0.18' 22' x 29'
CCAID-488A	*	0.7' 172' x 230'	0.35' 86' x 115'	0.18' 43' x 58'
CCAID-488B	*	*	0.5' 150' x 200'	0.25' 75' x 100'

Camera Altitude...... 250'

Resolution .... Grd. Coverage

There are two possible approaches, a lens turret or a zoom lens. A lens turret can contain lenses of 1/2", 1" and 2" focal lengths. By automatically indexing the turret to each of these lenses in turn, both good resolution and good coverage can be achieved before the altitude of the camera has changed appreciably. The same results can be achieved with a zoom lens. For example, Canon manufactures an f/1.8 zoom lens that zooms from a 12 mm (~1/2") focal length to a 50 mm (2") focal length. This lens design can be the starting point for a launch-survivable design. In any event, the advantages of a multi-focal length system must be weighed against the increase in system cost and complexity.

The lens turret and its driving mechanism can be a fairly simple, reliable device. The major disadvantage is that the longest focal length lens establishes the axial length of the mechanism. Consequently, a larger volume is required for the lens turret assembly.

Less volume is required for a zoom lens. However, the mechanical movements required are axial (in the direction of the launch set-back). This complicates the design of a driving mechanism that can survive launch.

It should be noted that ground coverage is not simply a function of lens angle of view but also depends on the winds and camera sway. A 30-knot wind corresponds to a 50-foot per second horizontal velocity for the camera. By the time the CCD TV camera descends 1,000 feet at the parachute's 15 feet-per-second rate, a 30-knot wind will have blown it sideways by more than 3,000 feet. Normally, better resolution of a target is achieved when the camera descends to a lower altitude. Under the influence of winds, however, the target may no longer be within the field-of-view when the lower altitude is achieved. A variable focal length system would provide both the synoptic (overall) view and the high resolution imagery before the target of interest drifts out of the field-of-view.

Figure 12 shows the ground coverage achieved by the CCAID-488A with a 0.5" focal length lens for three different wind conditions; a 30-knot wind, a 15-knot wind and dead calm. The 30-knot wind provides as much as four times the ground coverage achieved under no wind conditions. Again, a variable focal length system would provide considerably greater reconnaissance information.

Finally, ground coverage decreases very rapidly as the camera altitude drops below 1,000 feet. At 1,000 feet, the coverage is only one-quarter that at 2,000 feet, and at 500 feet the coverage is only one-sixteenth. Radio communication becomes increasingly more difficult at lower altitudes due to line of sight limitations and multi-path propagation. The paucity of reconnaissance information that is obtained at these lower altitudes mitigates against trying to communicate under these special handicaps. It further reinforces the case for a variable focal length system.

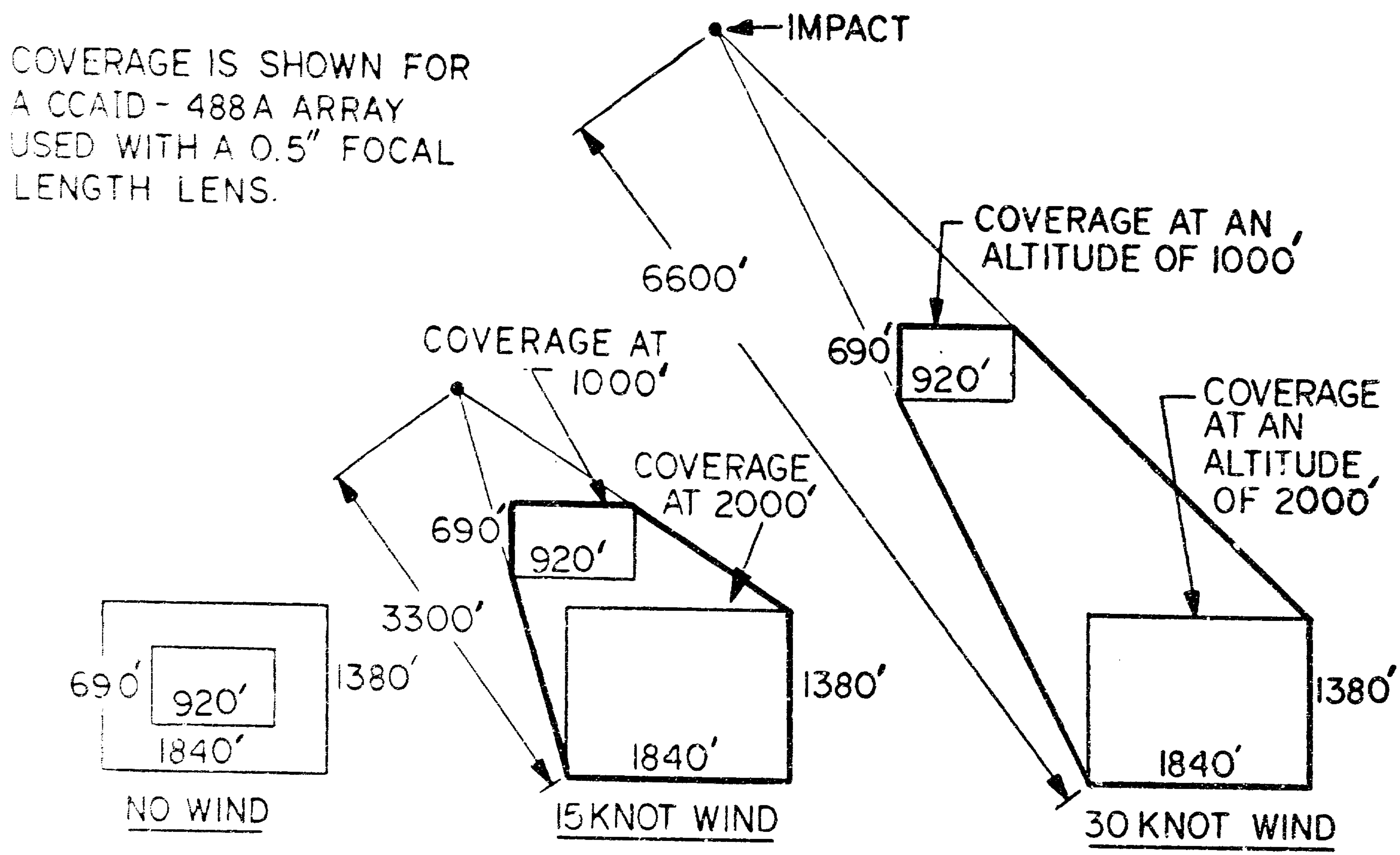


FIGURE 12. CCD CAMERA GROUND COVERAGE UNDER VARIOUS WIND CONDITIONS

3.2.3.4 Image Motion Considerations

Image motion arises from angular and translational velocities of the CCD TV camera during its parachute descent. Zooming a lens also produces image motion because of the scale changes achieved.

The image diagonal corresponding to a single photosensor element is about 1 mil (0.001") for the CCAID-488A. For the various lens options discussed previously, the angular resolutions achieved are:

1. 2" focal length ... 0.03°
2. 1" focal length ... 0.06°
3. 0.5" focal length... 0.12°
4. 0.25" focal length.. 0.24°

At the standard TV frame rate of 30 frames per second, the effective exposure time is 1/30th of a second. At 30 frames per second, the angular rates that would produce image smear equal to an element diagonal (the limit of detectability for image smear) are:

1. 2" focal length ... 0.9°/second
2. 1" focal length ... 1.8°/second
3. 0.5" focal length ... 3.6°/second
4. 0.25" focal length ... 7.2°/second

These are the limitations on the pitch and yaw angular velocities. Rotations about the optical axis of the camera produce image smear at the format extremes. The angle subtended by a corner photosensor element when viewed from the center of the CCAID-488A array is (.001"/0.25") radians or about 0.2°. The allowable angular velocity about the optical axis subject to the same element diagonal smear criterion is 6°/second. Higher rotational velocities are allowed if image smearing at the format corners is acceptable.

Translational velocities in the horizontal plane produce detectable image smear only when the camera movement from one frame time to the next exceeds the limiting ground resolution. For a 30-knot wind and 30 frames per second, the camera's horizontal translation would be 1.6 feet. At this wind level, the resolution achieved by the CCD TV camera would be limited by image smear to about one or two feet.

Rapid changes in scale produced by zooming a lens, or by a rapid descent of the camera, produce image smear at the format extremes. Detectable smear occurs for the CCAID-488A when a scale change of 1/488 occurs during the time between frames. Scale is directly related to camera altitude. At 1,000 feet, a scale change of 1/488 is produced by a 2-foot change in altitude. At the frame time of 1/30th of a second, this change could only be produced by a descent velocity of 60 feet per second. This is four times greater than the nominal descent velocity. Smear produced by lens zooming is best avoided by stopping the lens zoom at preselected focal lengths for a period equal to several frame times. If this is not done, the time required to zoom from one focal length extreme to the other becomes excessive if image smear is to be avoided.

The image smear criterion used in the above discussion assumed that the observer was looking at single TV frames. This is analogous to looking at single frames of a film reconnaissance camera. However, as is well known, multiple TV frames are integrated by the human eye to give an effective increase in resolution. Thus, the same image smear criterion cannot be applied to TV imagery at 30 frames per second as is applied to static frames. There is a difficulty, however. Static frames allow for leisurely examination of the imagery. In this case, a given magnitude of image smear might be objectionable. On the other hand, the same magnitude of image smear would be undetectable at the standard TV frame rate. The only difficulty is that the imagery does not sit still for detailed analysis. The level of image smear that could be tolerated can only be determined by actual use of the equipment in a variety of operational situations.

3.2.3.5 Camera Sensitivity

The charge coupled area imaging devices operate in the integration mode. The photoelectric current produced under the influence of light is integrated over a period equal to the frame time. The resultant photoelectric charge is stored in the potential wells associated with the individual photosensor elements. This charge is given by,

$$Q_s = K_s A I_a t$$

where,

Q_s = the photoelectric charge in coulombs

K_s = silicon sensitivity in amperes per unit area per unit of illumination

A = sensor element area

I_a = array illumination

t = array frame time in seconds

For black body radiation, the silicon sensitivity is a function of the black body color temperature. At the 5,500°K color temperature corresponding to sunlight, the CCD arrays have a silicon sensitivity of 10×10^{-12} amperes per square mil foot-candle. The silicon sensitivity increases for lower color temperatures. At 2,850°K, the silicon sensitivity for the CCD arrays is about 25×10^{-12} amperes per square mil per foot-candle.

The sensor area for the CCAID-488A is about 0.4 square mil per element. Assuming solar illumination and operation at 30 frames per second,

$$Q_s = 10^{-11} \times 0.4 \times L_a \times \frac{1}{30}$$

$$= (1.33 \times 10^{-13})\, L_a \text{ coulombs}$$

As the electronic charge is 1.6×10^{-19} coulombs, Q_s may also be expressed in electrons; i.e.,

$$Q_s = \left(\frac{1.33 \times 10^{-13}}{1.6 \times 10^{-19}}\right) L_a \text{ electrons}$$

$$\approx (0.8 \times 10^{6}) \quad L_a \text{ electrons}$$

The noise equivalent signal for the CCAID-488A is estimated to be 10-40 electrons when the floating gate amplifier structure is used. Using the conservative value of 40 electrons, the noise equivalent illumination on the array is 50×10^{-6} foot-candles.

The array illumination is related to the actual ground illumination by the following equation:

$$L_a = K_r\, T_{air} \left(\frac{T_{lens}}{4f^2}\right) M_a\, M_o\, L_g$$

where,

K_r = target reflection factor
T_{air} = atmospheric transmission
T_{lens} = lens transmission
f = lens f-number
M_a = array modulation transfer at the target's spatial frequency
M_o = lens modulation transfer at the target's spatial frequency
L_g = ground illumination

Choosing conservative values for all of the above parameters; i.e.,

K_r = 0.1
T_{air} = 0.8
T_{lens} = 0.8
f = 2.0
M_a = 0.6
M_o = 0.7

The array illumination is then given by,

$$L_a = \left(\frac{0.1 \times 0.8 \times 0.8 \times 0.6 \times 0.7}{4 \times 2 \times 2}\right) L_g$$

Or,

$$L_g = 600\ L_a$$

Using the noise equivalent array illumination of 50×10^{-6} foot candles that was determined previously, the minimum ground illumination needed for operation of the CCD TV camera is 0.03 foot-candles. This illumination level is somewhat greater than that produced by a full moon under clear sky conditions.

This analysis is somewhat conservative. A four-fold improvement could be gained by using the 10-electron noise equivalent signal value. Use of the CCAID-488B would yield another four-fold improvement to bring the minimum ground illumination down to about the 10^{-3} foot-candle level.

3.2.4 Communication System

3.2.4.1 Communication Path Considerations

Communication between the parachute-borne CCD TV camera and the ground station will be maintained over a maximum range of 14.6 Kilometers. For reasons that will be given later, it is assumed that the ground receiving station is located at the artillery battery that launched the camera round. The transmitting frequency used should be greater than 150 MHz (λ = 80 inches) to minimize the antenna sizes required. In any event, the radio transmission will be line-of-sight.

The radio line-of-sight communication range over a smooth earth from an airborne transmitter to a ground receiver is given by,

$$R_1 = \sqrt{2h_x}$$

where,

R_1 = line-of-sight communication range in miles
h_x = transmitter elevation in feet

If both the receiver and transmitter are elevated over the smooth earth, the communication range, R_2, is given by,

$$R_2 = \sqrt{2h_x} + \sqrt{2h_r}$$

where,

h_r = receiver elevation in feet

h_x	R_1
2,000'	63 miles
1,000'	45 miles
500'	32 miles
250'	22 miles

Even at the lowest altitude, the line-of-sight range is considerably greater than the maximum communication range needed.

A major problem in line-of-sight communications is the interference between the direct and reflected radio rays. Multi-path fading becomes significant when the elevation angle of the direct ray drops below 3°.

Natural obstacles such as mountain ridges also cause communication problems. If the obstacle is above the direct ray, severe transmission losses occur. If the obstacle is sufficiently sharp, knife-edge diffraction can reduce the magnitude of these losses. For example, a nomograph for the diffraction loss at an ideal knife-edge given in "Reference Data for Radio Engineers, Fifth Edition" yields the following data:

Range	14 Km	14 Km
Obstacle Height (above the direct ray)	100 feet	10 feet
Transmitting Frequency	3 GHz	3 GHz
Diffraction Loss	15 db	7.5 db

As natural obstacles depart considerably from an ideal knife-edge, actual losses may be 10 to 20 db greater. The magnitude of these diffraction losses make it mandatory that the CCD TV camera be deployed at a sufficiently high altitude to achieve an unobstructed direct line-of-sight between the transmitter and the receiver.

The optical line-of-sight from the ground receiver to the airborne camera has an elevation angle that depends on the range to the camera and the camera's deployment altitude (referred to the ground receiver). These elevation angles are given in Table 6 for various ranges and altitudes.

TABLE 6. LINE-OF-SIGHT ELEVATION ANGLES

	1,000' Altitude	2,000' Altitude
14.4 Km (47,000')	1.2°	2.4°
40,000'	1.4°	2.9°
30,000'	1.9°	3.8°
20,000'	2.9°	5.7°
10,000'	5.7°	11.3°

3.2.4.2 Antenna Considerations

3.2.4.2.1 Transmitting Antenna

The CCD TV camera package is a cylinder 4-1/4 inches in diameter by about 8 inches long; that is, the same size as the illuminant package in the M485 illuminating projectile. At one end of this cylinder is the point of attachment for the main parachute, whereas the camera lens is centered at the other end. Although the axis of the cylinder is normally deployed in the vertical direction, oscillations of 10° to 30° can occur. The orientation of the cylinder in azimuth is completely random.

To cope with the random orientation of the camera in azimuth, the transmitting antenna must have a full 360° azimuth coverage. Furthermore, its elevation coverage must be about 60° centered about the horizontal plane so as to deal with the maximum camera sway of 30°. Such a coverage is provided by a quarter-wave vertical stub. This stub must be placed on the axis of the cylinder to insure a symmetrical radiation pattern. Since the lens is centrally located at the lower end of the camera package, the only available location for the transmitting antenna is at the upper end of the cylinder, the end attached to the main parachute.

3.2.4.2.2 Receiving Antenna

The receiver signal strength is directly proportional to the area of the receiving antenna. The larger the antenna, the better the communication efficiency. Aside from cost considerations, large antennas are undesirable in combat situations, since they make excellent targets. Furthermore, large antennas have narrow beamwidths and require pointing accuracies that may present operational difficulties. Position location equipment such as radar may be needed to locate the camera package with sufficient accuracy. Normally, the camera position should be fairly well known. However, under the influence of winds, the planned position may be quite a bit different from the actual position. If the receiving antenna is not located at the artillery battery, both range-winds and cross-winds influence antenna pointing. If the receiving antenna is located at the battery, only cross-winds influence antenna pointing. A further advantage to placing the receiving antenna at the artillery battery is that, in a gross way, the antenna azimuth and the gun azimuth would be identical and the two units could be slaved in azimuth.

Not heretofore considered is the possibility that many gun-launched camera systems would be deployed at the same time. A serious interference problem could arise. This could be resolved by assigning different carrier frequencies to the camera rounds stocked by each battery. Narrow beamwidths for the receiving antenna could also discriminate between different camera systems and in addition, would provide some degree of protection against jamming.

3.2.4.2.3 Transmitting Frequency

As stated in paragraph 3.2.4.1, the transmitting frequency used should be greater than 150 MHz to minimize antenna size. Three frequency candidates were considered; 300 MHz, 2,000 MHz, and 20,000 MHz. For the purpose of making a choice, the receiving antenna was considered to be a four-foot diameter parabolic dish. This size was considered to be a suitable comprise between the needs of combat security and communication efficiency. The transmitting antenna was considered to be a quarter-wave stub. Table 7 shows appropriate performance parameters for each of the three frequency candidates.

TABLE 7. ANTENNA PARAMETERS FOR VARIOUS FREQUENCIES

Carrier Frequency	RF Wavelength	Transmitter Antenna Size	Receiving Antenna Beam Width
300 MHz	40"	10"	60°
2,000 MHz	6"	1.5"	9°
20,000 MHz	0.6"	0.15"	0.9°

At 300 MHz, a 10-inch long transmitting antenna presents some problems. The 10-inch length requires a collapsible antenna, and an erecting mechanism must be provided. Also, the 4-1/4 inch diameter end plate does not present a very good ground plane for a 10-inch long antenna. These problems are ameliorated when a 2,000-MHz carrier frequency is used. The antenna size of 1.5 inches can easily be stowed within the transmitter module and deployed when the main parachute is deployed. The 4-1/4 inch diameter end plate now represents an excellent ground plane. At 20,000 MHz, additional problems arise because of the extremely small dimensions involved. The radiated field patterns are easily disturbed by small changes in the conductive elements of the camera package.

The receiving antenna beam width of 60° at 300 MHz provides very little angular discrimination between multiple camera rounds. The 60° beamwidth does not help at all in suppressing multi-path transmission. A 9°

beamwidth, on the other hand provides good discrimination between multiple camera rounds and some discrimination against multi-path. Referring to Table 6, the line-of-sight elevation angles range from 1.2° to 11.3°. A two-position elevation setting for the receiving antenna would allow a 9° beamwidth to cover this entire range; a 4° setting for far ranges and an 8° setting for close-in ranges. Going to 20,000 MHz, the 0.9° beamwidth achieved presents severe pointing problems. At the extreme range of 47,000 feet (14.4 Km), a 1,000-foot change in altitude represents a change in elevation angle of 1.2°. The receiving antenna would have to track the camera in elevation as it fell....and the situation worsens as range is decreased.

All the factors point to 2,000 MHz as the carrier frequency of choice. The 2,000 - 2,400-MHz band is, furthermore, a standard telemetry band. There are, also, further options that can be made to improve system performance. The four-foot receiving antenna with a beamwidth of 9° may be faulted because of its size (increased vulnerability during combat) and the minimal antenna tracking required (a 30-knot cross-wind would change antenna azimuth by 9.5° as the camera descended from 2,000 feet to 1,000 feet at a distance of 20,000 feet). Changing the parabolic dish diameter to 2 feet would provide an 18° beamwidth and less combat vulnerability. There would be, however, a four-fold drop in antenna gain and increased vulnerability to multi-path fading. The precise antenna size used would really depend on the actual combat situation. A variable diameter dish might be the answer.... a basic two-foot diameter parabolic dish with extendable sections to provide four-foot diameter capability when needed.

3.2.4.3 System Path Loss Analysis

The system path loss analysis is summarized in the tabulation given below:

Operating Frequency..........	2,000 MHz		
Transmitter Power	1.5 Watts	+	31.0 dbm
Transmission Mode	FM		
Transmitter Antenna	1.5 inch stub		
Antenna Gain		+	3.0 db
Receiver Tracking Antenna	4 foot dish		
Antenna Gain		+	25.6 db
Total Effective Power		+	59.6 dbm
Path Length	10 Miles		
Free Space Loss		-	122.8 db
Misc. Losses (transmission line, coupling etc.)		-	2.0 db
Total Losses		-	124.8 db
Median Received Carrier Power		-	65.2 dbm

RF Bandwidth .... 4.5 MHz		
Noise Power (KTB)	-	107.5 dbm
Assumed Noise Figure	+	4.0 db
Equivalent Noise Input (Receiver Sensitivity)	-	103.5 dbm
Median Carrier-to-Noise Ratio	+	38.3 db
FM Improvement Ratio	+	10.0 db
Receiver Signal-to-Noise Ratio	+	48.3 db

3.2.4.4 Path Reliability Considerations

The methods of assessing propagation reliability for fixed line-of-sight links, involving consideration of Fresnel clearance and Rayleigh fading are not applicable to this type of air-to-ground link. The radio link, as proposed, will provide a fade margin of 38.3 db over the noise improvement threshold when subject to 122.8 db of free space loss. This margin is adequate to ensure that the received carrier remains above threshold under the following combination of circumstances:

1. Parachute range at 10 miles maximum.
2. Parachute attitude such that the effective transmitting gain falls to zero.
3. Receiver antenna pointing errors up to about 2°.

It should be noted that in terms of signal fade margins, the peak-to-peak signal to RMS thermal noise of 48.3 db is conservative for a video signal. Good useful picture transmission will be maintained down to a carrier-to-noise ratio of about 23 db. Stated in the more familiar notation, the system will possess a fade margin of approximately 26 db.

3.2.4.5 Video Quality

System path analysis indicates that a minimum usable signal-to-noise ratio of 48.3 db into the video monitor will provide an excellent picture quality performance.

Table 8 lists picture-quality definitions for different values of signal-to-noise ratio. These definitions are based on reports by Television Allocations Study Organization (TASO). The levels given have been adjusted to represent RF measurements as opposed to video measurements.

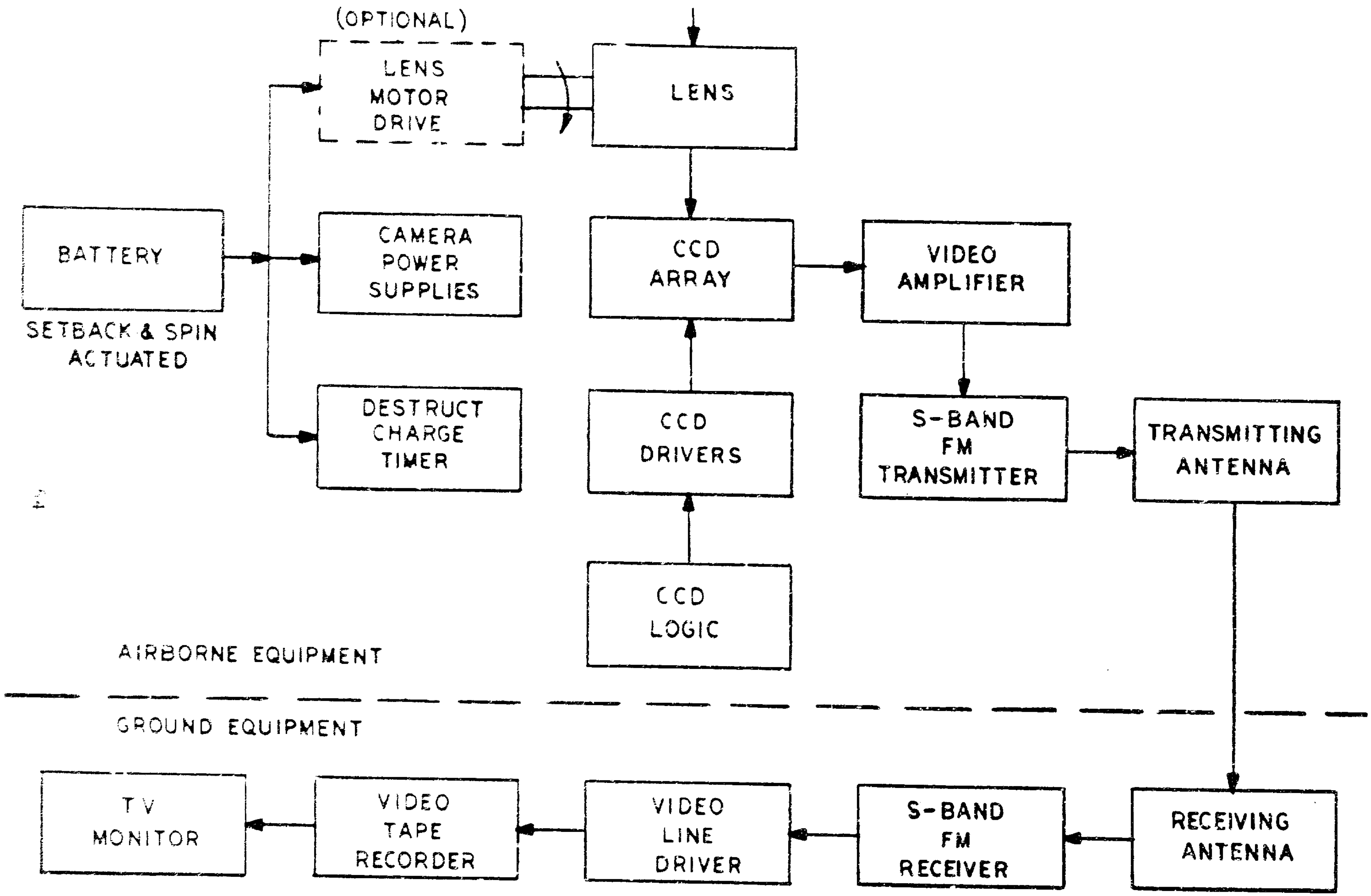


FIGURE 13. CCD TV RECONNAISSANCE SYSTEM BLOCK DIAGRAM

TABLE 8. PICTURE QUALITY VERSUS S/N RATIO

S/N Ratio (db)	Picture Quality	Picture Quality Definition
49	Excellent	Snow free pictures
39	Fine	Just perceptible background snow
33	Good	Snow in picutre but not objectionable
29	Marginal	Somewhat objectionable snow

3.3 CCD TV RECONNAISSANCE SYSTEM DESIGN

3.3.1 System Block Diagram

The CCD TV Reconnaissance System block diagram is shown in Figure 13. The battery of the airborne equipment is energized both by the setback and spin occurring at launch. Battery voltage comes on in less than 1 second and power is then provided to the following units:

1. Lens motor drive (if multi-lens system is used)
2. Camera power supplies
3. Destruct charge timer
4. RF transmitter

The output video signal from the CCD photosensor array is amplified by the 4-MHz video amplifier that provides the modulation input to the S-band FM transmitter. The transmitter frequency is in the 2,000-2,400-MHz telemetry band. The transmitter output is fed to a quarter-wave stub antenna that produces a toroidal radiation pattern.

The transmitted signal is picked up by the receiving antenna, a four-foot parabolic dish. The video output from the S-band FM receiver is conditioned by the video line driver before it is recorded on the video tape recorder. The read-after-write signal output of the video tape recorder is then displayed on a standard TV monitor.

3.3.2 Airborne Camera-Transmitter Assembly

The canister assembly for the M485 illuminating projectile will be used for the TV Reconnaissance System with the illuminant container being replaced by the CCD camera-transmitter assembly. Figure 14 shows a preliminary layout of this assembly.

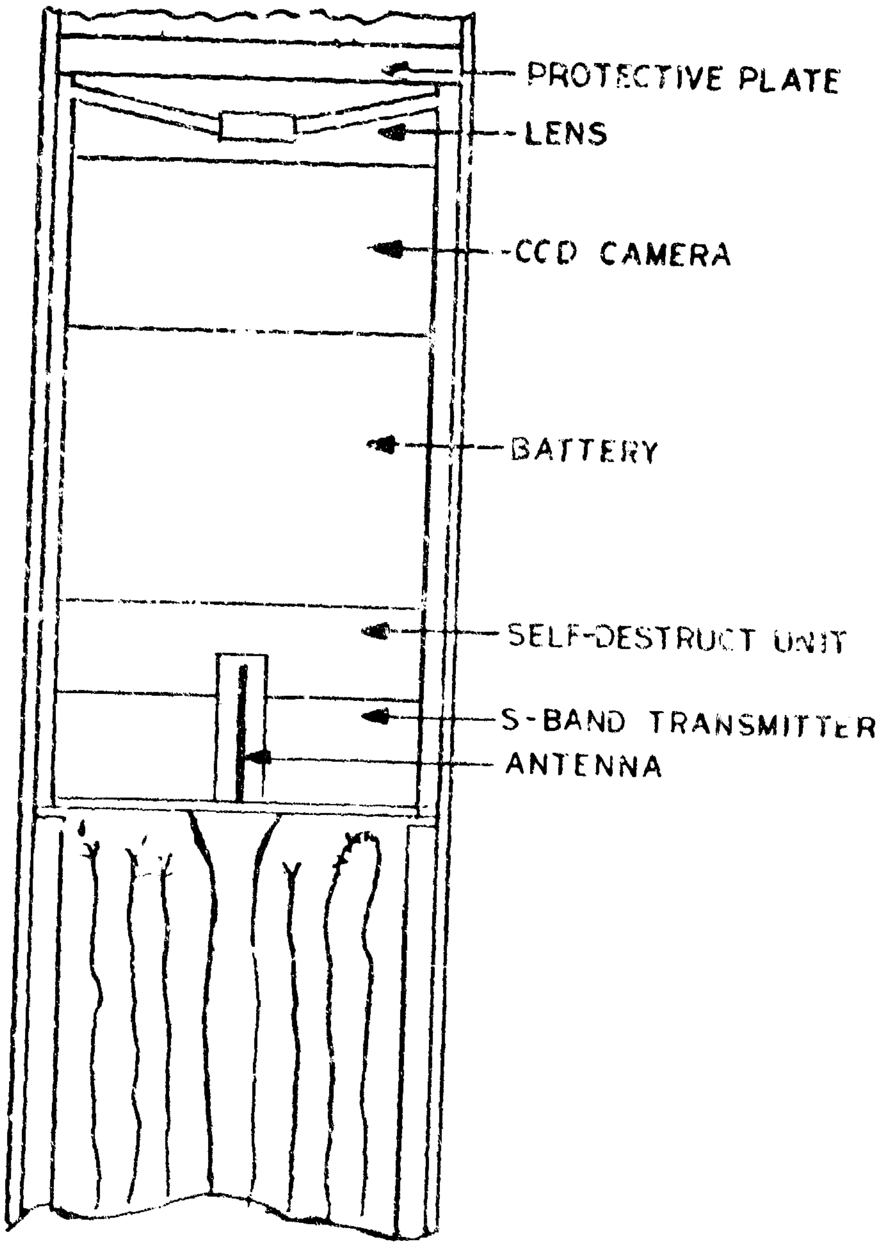


FIGURE 14. CCD CAMERA-TRANSMITTER ASSEMBLY

The lens is protected from the blast of the secondary expelling charge by a heavy metal disc. This disc transmits the explosive force to the housing of the camera-transmitter assembly and eventually to the canister base plate. The pins holding the base plate are sheared away and the main parachute and the camera-transmitter assembly are expelled from the canister.

The CCD camera subassembly is a disc about 2 inches deep by 4-1/4 inches in diameter. Similarly, the RF transmitter is a disc about 1.0 inch deep. In the center of this disc is the 1-1/2 inch long stub antenna. It is fully recessed normally but will be extended when the main parachute is deployed.

The remainder of the volume is taken up by the battery and the destruct charge and its timer.

3.3.2.1 CCD TV Camera

A block diagram of the CCD TV camera is shown in Figure 15. The total component count for the camera is about 32 DIP's (Dual In-line Packages). To meet the launch environment, all components will be used in chip form and connected as hybrids. All subassemblies will be potted.

3.3.2.2 S-Band Video Transmitter

A block diagram of the signal flow in the video transmitter is shown in Figure 16. The transmitter is composed of a series of thick/thin film substrates packaged in a 4" diameter disc about 1 inch thick. This technology is used to eliminate component leads that would have difficulty surviving the launch environment. The use of an epoxy potting compound to secure all the transmitter elements would not satisfy the dielectric constant requirements of microwave circuits. Therefore, the design uses all active devices in chip form. These include the large RF power transistors. These large power handling components are located at the surface of the transmitter package, to insure adequate heat dissipation.

3.3.2.2.1 Video Telemetry Transmitter Specifications

Outline dimension	4 inch Diameter, 1 inch thick
Shock (survival)	20,000 G's
Frequency	S Band, 2.2 to 2.3 GHz
Power Output	0.5 watt minimum
Frequency Stability	± 0.05% over temperature range
Operating Temperature	20° to +85°C

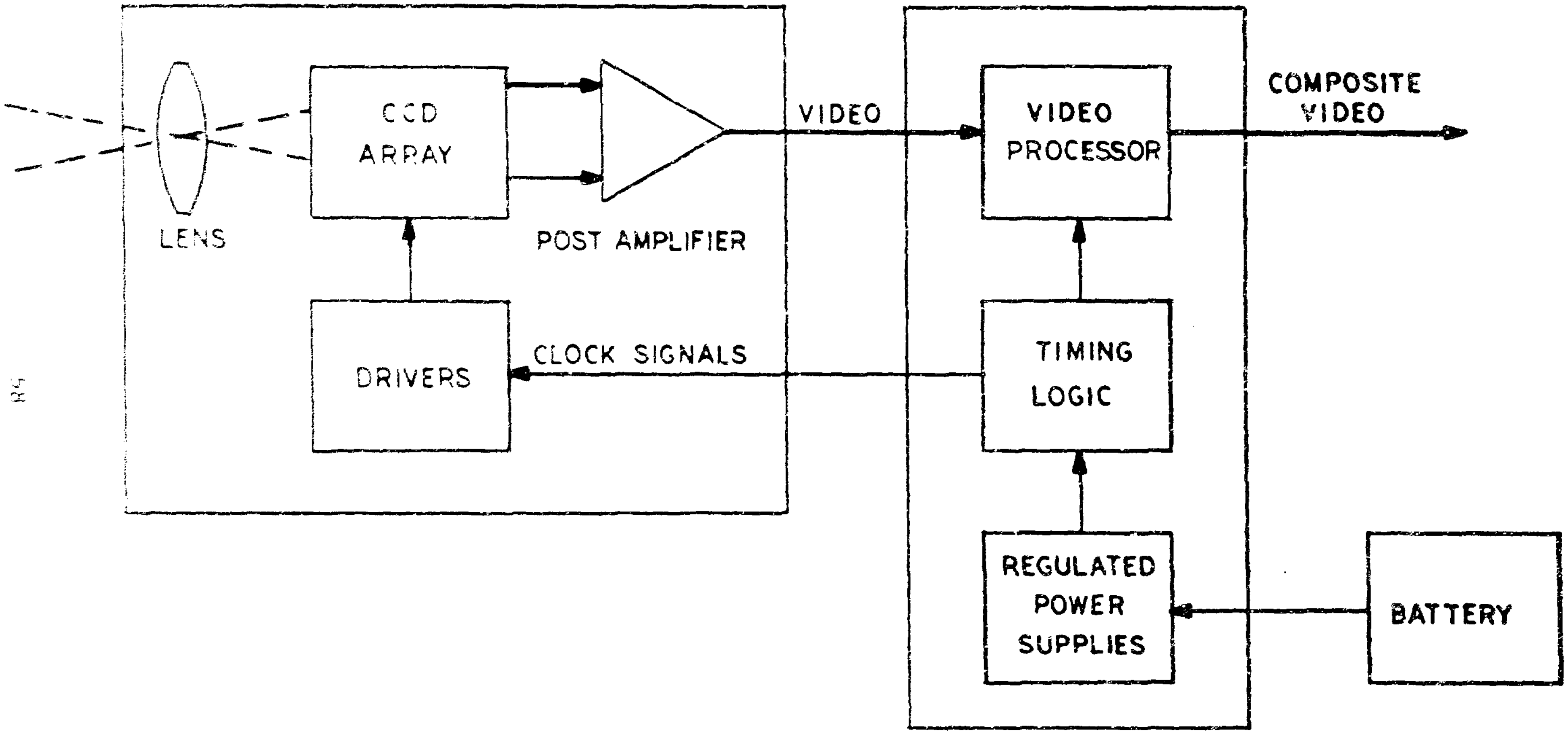


FIGURE 15. CCD TV CAMERA SYSTEM

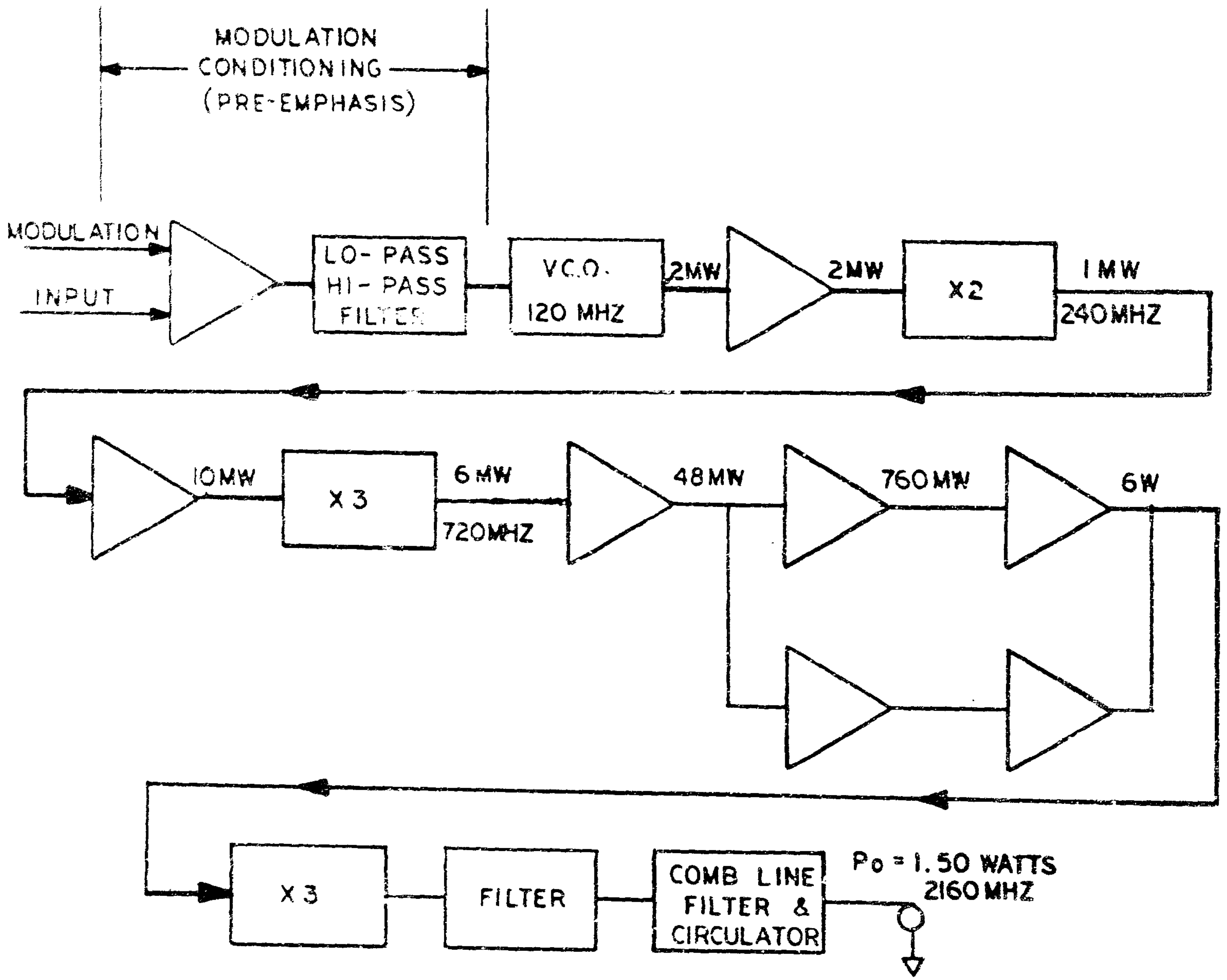


FIGURE 16. VIDEO TRANSMITTER SIGNAL FLOW BLOCK DIAGRAM

Modulation	
Type	True FM
Frequency Response	10 Hz to 4.5 MHz at 3 db
Deviation	±10 Mhz maximum (adjustable)
Input Impedance	50 ohms
Input Level	20 mw
VSWR	1.5:1 any phase angle
Output Impedance	50 ohms
Spurs	IRIG 106-71 (10 log power)
Operating Voltage	+24 VDC ± 20%
DC Efficiency	15% approximate
Weight	8 ounces

3.3.2.3 Destruct Charge

The ignition of the destruct charge cannot be accomplished reliably by impact, since the parachute will limit the magnitude of the impact forces, especially if it becomes fouled in a tree. A more reliable fuzing method is the use of a time delay element actuated by the battery voltage. At a descent rate of 15 feet per second from an altitude of 2,000 feet, the total elapsed time to impact is about 130 seconds. A delay time of 100 seconds would cause the camera unit to be destroyed before impact and, thereby, an enemy would be prevented from examining the unit.

3.3.3 Ground Equipment

The ground station can be made up of conventional commercial units or devices already in the military inventory. The S-band receiving antenna with a four-foot diameter parabolic dish probably already exists in the military or commercial inventory as does the S-band FM receiver. The video tape recorder and TV monitor could be standard commercial units such as the Sony Av-3400 Videocorder and the Sony CVM-920U 8" monitor. Video line drivers are available commercially. Military versions of these equipments could be provided.

3.4 SYSTEM COST ANALYSIS

3.4.1 Ground Station Costs

Ground station costs are not a major factor in the design of the TV Reconnaissance System, since the ground station is not an expendable item. The ground station comprises the following units:

1. S-band antenna (4-foot parabolic dish)
2. S-band FM receiver
3. Video line driver
4. Video tape recorder
5. TV monitor

Most of these equipments are commercially available or are already in the military inventory. Consequently, these costs were not evaluated in the present study.

3.4.2 Airborne Camera-Transmitter Costs

Development costs were not considered in this study. The only costs evaluated were the equipment costs for large quantity production.

3.4.2.1 CCD Camera Costs

The CCD camera, as stated previously, consists of the following major items:

1. Lens
2. CCD array
3. Electronics

3.4.2.1.1 Lens Costs

For a simple f/2 12.5 mm lens design, large quantity production costs could be under $20.00. A lens assembly for the Kodak Pocket Instamatic camera can be purchased for about $23.00. The lens is an excellent four-element f/2.8 25 mm focal length device. Ruggedizing the lens to survive the launch environment should not add significantly to its cost if production quantities are large enough.

Zoom lens with motorized controls are quite a bit more expensive. Canon makes a motorized f/1.8 zoom lens that zooms from 12 mm to 50 mm and lists for $175.00. Although this lens is a commercial item, the number of lenses produced is probably quite small. The two-thirds inch vidicon camera tube for which this lens was designed is not that popular an item. Even if large production quantities of this lens were made, it is unlikely that a ruggedized version of this lens would sell for under $100.00.

In summary, system lens costs should be:

1. f/2, 12.5 mm lens.......... $15.00
2. 3-lens turret 50.00
3. zoom lens.................... 100.00

3.4.2.1.2 CCD Array Costs

The present cost of the CCD-201 (a 100 by 100 element CCD array) is about $400.00 for single unit orders. This array is not now in large quantity production. It is anticipated, that when large quantity production is achieved, the price will drop to under $[illegible].00.

The CCAID-244 and the CCAID-488A arrays have not yet been produced and the price of these arrays can only be conjectured. The price is very dependent on the yield statistics that will be achieved for these devices. Yield is very much a function of the amount of money spent on perfecting the semiconductor processing and where the semiconductor manufacturer is on his learning curve. The CCAID-488A is a large chip with a diagonal measurement greater than 0.5 inch. This device is larger than any that has ever been made commercially. Fairchild cannot, at this time, make any estimate of the cost of this device for large production quantities, but a price of $50 to $200 can be assumed.

3.4.2.1.3 Electronics

The CCD camera electronics includes about 32 active devices. For MIL-standard components, the average price is about $3.00 per device for large volume procurements. The total cost of these active devices is, therefore, about $100.00. The cost of fabricating these devices into a piece of equipment depends on the amount of money spent in automating production. This cost could run anywhere from $50.00 to $300.00 depending on the degree of production automation achieved. Consequently, the cost of the electronics could range from $150.00 to $400.00 for large production quantities.

3.4.2.2 S-Band Transmitter Costs

Contact was made with a company that manufactures S-band FM transmitters that survive an 8,000 G environment. This manufacturer quoted a price of $475.00 in 20,000 piece lots, for a transmitter that would meet the requirements of the TV Reconnaissance System. The $60,000.00 non-recurring development cost that was also quoted does not represent a large capital investment in production facilities or in designing the unit for cost-effectiveness. A unit cost of less than $350.00 could be achieved by a larger non-recurring cost expenditure.

3.4.2.3 Cost Summary

The costs for the Airborne CCD Camera-Transmitter unit are summarized below:

Lens	$ 15.00	-	$100.00
CCD Array	50.00	-	200.00
Electronics	150.00	-	400.00
FM Transmitter	350.00	-	425.00
Total Costs	$565.00	-	$1125.00

No costs were allocated for the battery, destruct charge and canister assembly. These are considered to be Government-furnished materials. It is envisioned that the battery and destruct charge will be provided as Government-furnished material to be assembled into the CCD camera-transmitter unit. The CCD camera-transmitter would then be delivered to the Government for assembly into the CCD reconnaissance camera projectile.

3.5 RECOMMENDATIONS FOR FUTURE PROGRAMS

The feasibility of using a gun-launched parachute-carried CCD TV camera to collect reconnaissance data has been demonstrated in the present program. The value of CCD imagery was shown during actual flight tests of a CCD TV camera. System studies carried out during the program, as detailed in this report, indicated that the ground resolution and coverage that could be achieved in an eventual system would provide a valuable reconnaissance capability. The questions of how valuable and at what cost have been dealt with in a preliminary way in the system studies. Tasks that must be addressed to bridge the gap between the work accomplished under the present contract and the final operational system are as follows:

1. Demonstrate that the CCD camera-transmitter assembly can be packaged into the available space in the M485 illuminating projectile canister.

2. Demonstrate that the above assembly can survive the launch environment.

3. Demonstrate that the CCD camera and the RF transmitter can meet their operational specifications after launch.

4. Determine the parachute dynamics for the actual CCD camera-transmitter package configuration under various meteorological conditions. This task would also involve modifying the package configuration to achieve useful camera dynamics; sway, quasi-vertical operation, etc.

5. Determine, by actual operational tests of a prototype TV Reconnaissance System, the best compromise between system resolution and coverage. A sub-task of this effort would involve testing the system with lenses of various focal lengths. This sub-task could be implemented by changing lenses from one flight to another, by the use of a lens turret in the camera or by the use of a zoom lens.

6. Determine the operation of the RF transmission system under all sorts of operational conditions.

7. Configure the final operational system by evaluating the results of the preceding tasks and using value engineering principles to produce a cost effective design for the TV Reconnaissance System.

All of the technology now exists to demonstrate launch survivability of a CCD camera-transmitter assembly. Such an assembly could be built now with the CCD-201, the 100 by 100 element array. The operational capability of such a camera would, however, be somewhat limited. A better sensor choice is the CCAID-244A, the 244 by 190 element array, which is now in the early stages of fabrication. The CCAID-244A will have excellent sensitivity and coverage that approaches that of the CCAID-488A. Since the availability of the CCAID-488A is still quite a way off, configuring the demonstration equipment around this device would cause a considerable delay in the development program. Consequently, the recommended follow-on program proposes the use of the CCAID-244A.

3.5. Proposed Follow-On Program

The tasks to be accomplished in the proposed follow-on program are described below:

1. Design and fabricate ten to twelve CCD camera modules, employing the CCAID-244A, configured for the 155 mm M485 illuminating projectile.

2. Design and fabricate ten to twelve RF transmitter modules, configured for the M485 round.

3. Design and fabricate ten to twelve power supply modules, configured for the M485 round.

4. Carry out a packaging design effort involving the following activities:

    a. Overall packaging of the CCD camera, RF transmitter and power supply modules.

    b. Development of a module interconnect technique.

    c. Development of construction techniques that will enable the equipment to withstand the 12,000 to 20,000 G's of force occurring at launch.

5. Perform environmental test program including air gun tests.

6. Perform non-operating actual firings.

7. Perform operating firing tests.

8. Design and develop the ground station equipment.

9. Investigate parachute stability for desired in-flight motion.

10. Conduct design-to-cost investigation throughout program.

PARALLEL-TRANSFER-REGISTER CHARGE-COUPLED IMAGING DEVICES

A. L. Solomon
Fairchild Camera and Instrument Corporation
Research and Development Laboratory
4001 Miranda Avenue
Palo Alto, California - 94304

INTRODUCTION

One year ago a paper was presented to this conference that included a brief description of two charge-coupled imaging devices that had been developed at the Fairchild Semiconductor Research and Development Laboratory.[1] These charge-coupled imaging devices are being produced in sample quantities and are commercially available. This paper contains a more detailed description of these devices and of a more recently developed image sensor.

The first produced charge-coupled sensor was the 1 x 500 photoelement CCD 101, which may be employed in slow-scan TV or facsimile systems. The second product is the CCD 201, a 100 x 100 photoelement area-array, which may be used to detect moving images under low-light-level illumination. The third and most recent device is the CCD 110; it is a 1 x 256 photoelement linear array which should find application in high-speed optical character recognition systems. In comparison to other solid-state photosensing arrays, these devices possess a higher dynamic range by virtue of their low noise properties. They can, therefore, be used at relatively low illumination levels. This property is obtained with little loss in image quality because of the high efficiency obtained when photosignal charge is transferred from the photoelement array to an on-chip detector-preamplifier.

A significant portion of this paper is devoted to a design property these charge-coupled image sensors possess in common. This property contributes both to obtaining distortion-free image reproduction and in some applications to a more flexible mode of operation. The design property is the use of separate photosensors and signal-tranfer elements. The signal charge is transferred to the detector-preamplifier by a charge-coupled device (CCD) analog shift register which is located parallel to a given linear photoelement array.

BASIC FUNCTIONAL DESIGN CONSIDERATIONS

The basic functions of a CCD image sensor are (1) to sense and store photon-generated charge in an array of depletion regions or potential wells that are formed by an MOS-type capacitor, (2) to transfer the signal from each element in the photosensing array in the form of a packet of charge which is moved or clocked through a series of potential wells to a detector-preamplifier. The conceptually simplest method of accomplishing these functions is to transfer the charge packets serially through the same potential wells that perform the sense-and-store function. This method, however, introduces image smearing unless either the transfer is carried out at a speed considerably in excess of the light sensing or integration time, or the transfer is performed in the dark. Further, when the output data rate is different from the transfer rate, it is necessary to provide an additional buffer store. When this method is used for a rectangular-area photoelement array, it is called "frame transfer".

An alternative design that avoids these problems is the parallel-transfer-register which is shown conceptually in Fig. 1. The photoelement array is formed beneath an electrode which runs the length of the array and is called the photogate. Because the device is most conveniently illuminated at the top of the silicon substrate or front-side, the photogate electrode consists of a film of polycrystalline silicon that is thin enough to transmit visible radiation. The individual photoelements are defined or electrically isolated by a channel stop. This may be formed in the case of an n-channel device by a narrow p-type region in the silicon substrate. Charge packets generated by light under the photogate are transferred in parallel to the adjacent CCD shift register, which is opaque. The packets are then stepped or clocked to the detector-amplifier. In the case of an area sensor, which consists of columns of photoelements, this design has been called "interline transfer".

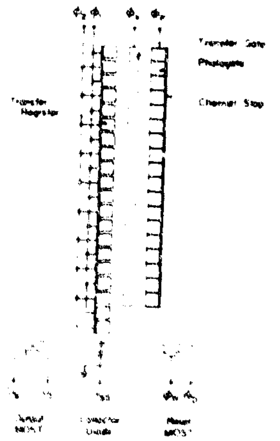


Fig. 1 Gate Electrode Schematic of a Parallel-Transfer-Register CCD Image Sensor

Although it is apparent that by separating the two basic CCD sensor functions the problems of the frame transfer design are obviated, it is also apparent that the interline transfer register requires approximately half the silicon area in the area photosensor array to be opaque, the photoelement charge capacity is therefore half that of the frame-transfer design for the same photosensor area. Because of the low noise properties of the device, this does not limit the dynamic range. In terms of silicon-area usage, the two designs are comparable since the interline-trans-

Preceding page blank

fer does not require a buffer store. It will be seen subsequently that the interline-transfer has other advantages.

Another silicon-area usage aspect of the interline-transfer design, which becomes apparent in Fig. 1, is that for a 2-phase CCD transfer register two electrodes are required for each photoelement in the adjacent column. This difficulty is solved by transferring packets from every other photoelement in a column in one field of information, which is stepped to the amplifier; the second field of information is then transferred and stepped. The two fields are interlaced at the display.

ADVANTAGES OF THE PARALLEL-TRANSFER-REGISTER DESIGN

A summary of those advantages of the parallel-transfer-register design over a serial-transfer through-the-photoelement-array design, which have been discussed, is as follows:

- Smearing of the sensed image is avoided.
- High speed transfer in excess of the line data rate is not required.
- There is no need for a separate buffer store to convert the output data rate.
- Overall silicon area is conserved.

In addition to these advantages are two that result in a less distorted image for high spatial frequency information. One of these has been described by D. F. Barbe and M. H. White.[2] An interline-transfer design is compared to a frame-transfer design, where the photoelement area, which includes the interelement opaque regions, is the same. Their analysis points out that the interline-transfer design possesses an optical sampling aperture which is approximately one-half that of the frame transfer. This property results in a modulation-transfer-function (MTF) that does not decrease as much at higher spatial frequency, as shown in Fig. 2.

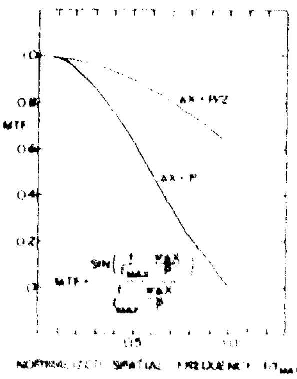


Fig. 2 MTF vs. Spatial Frequency for Frame and Interline Transfer From Barbe & White, CCD Applications Conference Proceedings

When all factors are taken into consideration, the relative signal for the interline transfer also remains higher at high spatial frequency as shown in Fig. 3.

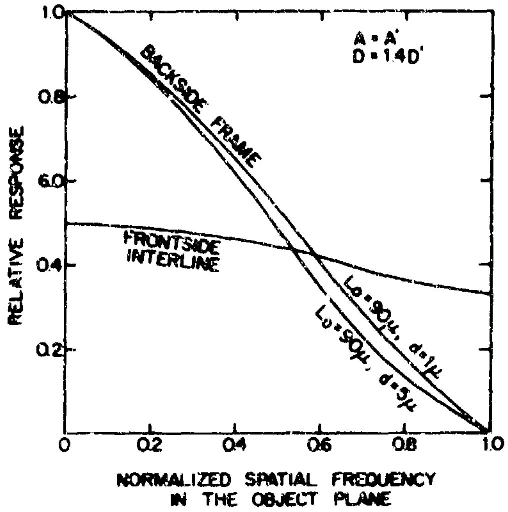


Fig. 3 Relative Response vs. Spatial Frequency for Frame and Interline Transfer From Barbe & White, CCD Applications Conference Proceedings

A more recent analysis in our laboratory indicates that the MTF is expected to be high at high spatial frequency for both linear and area arrays when the video information is read out in two or more fields.[3] This analysis relates to the influence of charge-transfer inefficiency on the degradation of MTF. MTF as a function of spatial frequency with transfer inefficiency as a parameter for a single-field readout of a linear array is shown in Fig. 4:

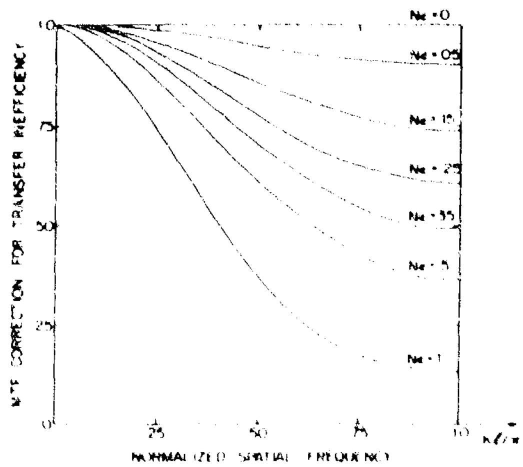


Fig. 4 MTF Correction for Transfer Inefficiency For a Single-Field Readout

N is the number of transfers and ε is the fraction of signal charge that is not transferred with the proper packet. It may be seen that the MTF decreases monotonically to the Nyquist limit. No MTF degradation other than that caused by transfer inefficiency is considered. This consideration also applies to Fig. 3.

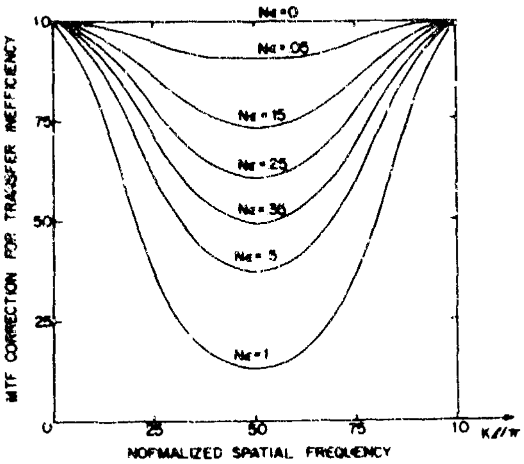


Fig. 5 MTF Correction for Transfer Inefficiency for a Two-Field Readout

Here, however, MTF is plotted for the case of a 2-phase parallel-transfer-register where the video information is readout in two fields, as it was shown in Fig. 1. It may be noted that a minimum MTF appears at half the Nyquist limit rather than the limit. The MTF is replotted in Fig. 6 to take into account MTF degradation, or decrease in response, for an aperture with square response at spacing 1.

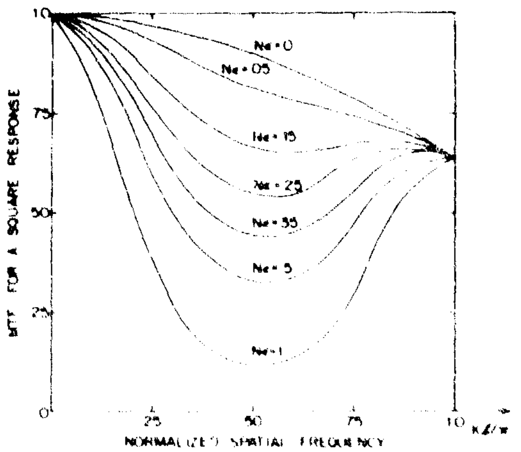


Fig. 6 MTF vs. Spatial Frequency for a Two-Field Readout

Considerable discussion has arisen regarding the appearance of aliasing in discrete photoelement arrays with a high response at high spatial frequency. Current opinion is that the MTF roll-off for lenses used in cameras can by design be used to suppress aliasing to a great extent. This may be seen in Fig. 7 where the effect of lens MTF on aliasing is estimated

2/3

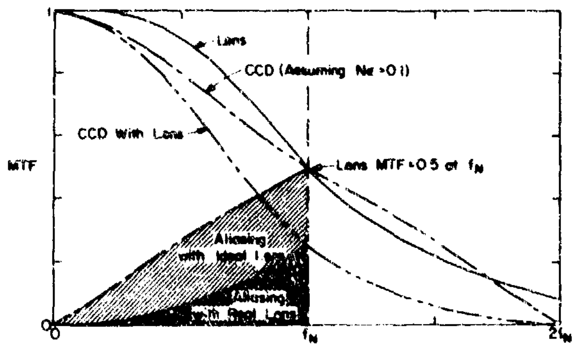


Fig. 7 Effect of Lens MTF on Aliasing

for an "ideal" lens, which has an MTF of unity to twice the Nyquist limit (f_N) of the CCD, and for a "real" lens, which has an MTF of 0.5 at the Nyquist limit.

CCD 101 LINEAR IMAGING DEVICE

The CCD 101 was the first commercially produced charge-coupled image device. It possesses a 500 photoelement linear array 0.6 inch long and 1.2 mils wide. The parallel-transfer-register design is shown schematically in Fig. 8. Two 3-phase, 250 bit,

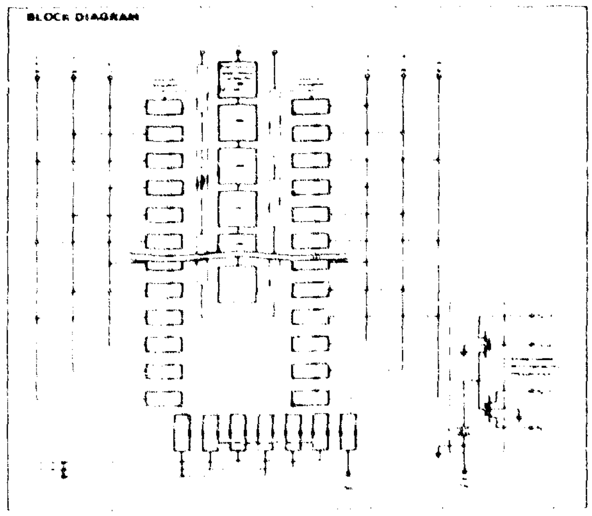


Fig. 8 Schematic Diagram of the CCD 101

analog CCD shift registers are located on either side of the photoelement array. For an output bit rate of 1 MHz photoelectrons are generated and stored for 0.5 millisec under the photogate. Within 20 microsec the photoelectrons are clocked by transfer gates to the two parallel shift registers. Charge packets from the odd-numbered photoelements are moved to the right register; packets from even-numbered to the left. The packets are then transferred at a 500 KHz clock rate to a 2-bit output register where they are interlaced and appear in photoelement order at the detector-preamplifier. This on-chip device consists of a collector diode, a reset MOS transistor and an output MOS transistor.

The chip is shown in Fig. 9 with a magnified section of the photoelement and the shift register.

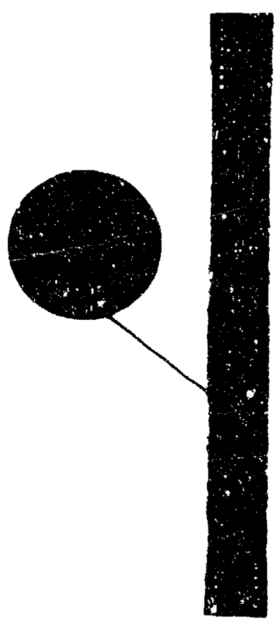


Fig. 9 CCD 101 Chip

The serpentine channel stop, which isolates the photoelements can be seen clearly. The chip is assembled in a 24-lead dual in-line package with a 610 mil x 6 mil glass window, as shown in Fig. 10.

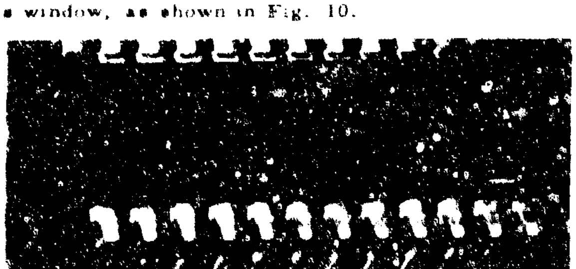


Fig. 10 Packaged CCD 101

Although these devices are classed to guarantee a dynamic range of 200:1, some have shown a dynamic range well in excess of 1000:1, as may be seen in Fig. 11.

Fig. 11 CCD 101 Image

From (a) through (d) are images at near-saturation illumination, 1/10th this illumination, 1/100th and 1/1000th. This result attests to the high charge-transfer efficiency and low noise properties that can be obtained.

CCD 201 AREA IMAGING DEVICE

The CCD 201 possesses a 100 x 100 array of 1.2 mil x 0.8 mil photoelements. As shown schematically in Fig. 12, parallel-transfer registers

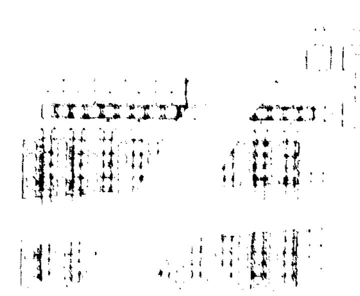


Fig. 12 Schematic Diagram of the CCD 201

are located between columns of photoelements. Several changes of the CCD 101 linear-array design have been made to conserve space. The registers are 2-phase with implanted barriers rather than 3-phase, and there is one register for each column of photoelements rather than two. The principle of using two interlaced fields of information is, however, retained. In one field every other element in a column of photosensors is transferred to a vertical register and is stepped line-by-line to a horizontal collector register. Information in the collector is then clocked to the gated-charge integrator on-chip preamplifier. The process is then repeated for the second field of alternate photoelements.

The silicon chip, as shown in Fig. 13, with

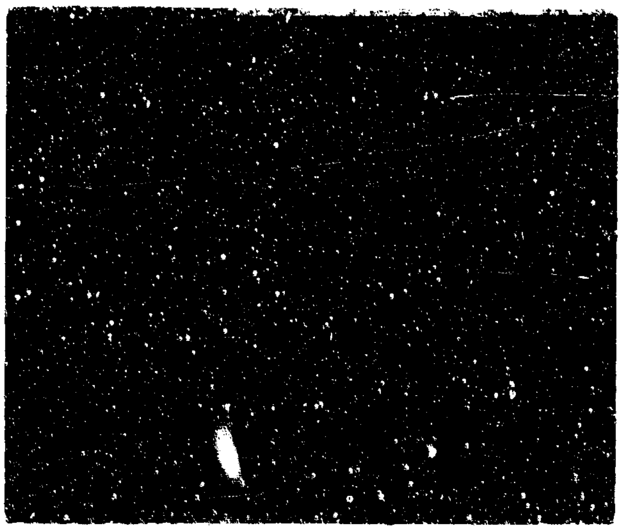


Fig. 13 CCD 201 Chip

bonding pads is approximately 160 mils x 190 mils. Two other significant differences in design from the CCD 101 should be mentioned. A comb-shaped channel stop is employed rather than the serpentine. A transfer-gateless structure, which has been described previously, is employed in place of the transfer gate to save space.[1]

"Live" images taken at 40 frames/sec are shown in Fig. 14

1/1

Fig. 14 CCD 201 Images

CCD 110 LINEAR IMAGING DEVICE

The CCD 110 is a 256 linear 0.5 mil x 0.9 mil photoelement-array imaging device that is designed to operate at an output bit rate of 10 MHz. The functional organization of the device is similar to the CCD 101, as it may be seen in Fig. 15. Again,

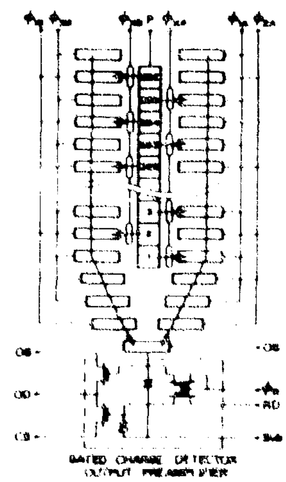


Fig. 15 Schematic Diagram of the CCD 110

two parallel-transfer registers are employed. Instead of a 2-bit output register, each transfer register has two additional bits which channel the signal charge to an output gate, where odd-even photoelement information is interlaced and is then fed to the gated charge integrator. It may also be readily noted that 2-phase registers are used.

The order of magnitude increase in bit-rate capability of the CCD 110 over the CCD 101 for comparable charge-transfer efficiency is derived mainly from the difference in the center-to-center spacing (W) of the transfer-register cells. For a comparison of the two devices, it is convenient to define a charge-transfer time constant (τ) as a function of W. The definition of τ is complicated because there are three parallel processes that govern charge transfer: drift, diffusion and gate-fringe-field or field-aided forces. At low charge densities diffusion and field-aided are the more significant. The time constants for these processes for a buried-channel charge-coupled device are plotted as a function of cell spacing in Fig. 16.[4]

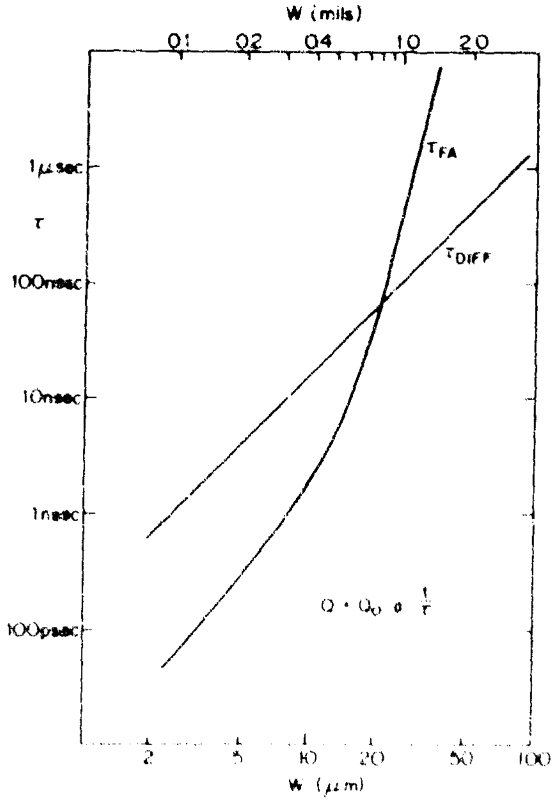


Fig. 16 Field Aided and Diffusion Time Constants as a Function of Cell Spacing

It may be seen that the field-aided force change more rapidly with cell spacing than diffusion and it predominates at low cell spacing. An approximation of relative bit-rate capability can be made by consideration of the field-aided constant (τ_{FA}) for the two devices. The spacing is 0.8 mils for the CCD 101 and 0.5 mils for the CCD 110. For this data τ_{FA} is found to be 70 nsec for the CCD 101 and 3 nsec for the CCD 110.

CONCLUSIONS

The advantages of a charge-coupled image-device design that employs charge-coupled analog shift registers, which are separate from the photoelement array, to transfer charge packets from the photoelements to an on-chip detector-preamplifier have been discussed. These advantages mainly result in relatively distortion-less image reproduction.

The separate transfer registers are located parallel to linear arrays or sub-arrays of photoelements in three charge-coupled imaging devices: the CCD 101, a 500 photoelement linear array, the CCD 201, a 100 x 100 photoelement area array, and the CCD 110, a 256 photoelement linear array, which possesses a 10 MHz output bit rate and high charge-transfer efficiency.

REFERENCES

1. Amelio, G. F., "Physics and Applications of Charge-Coupled Devices", IEEE Eastcon '73 Record.
2. Barbe, D. F. and White, M. H., "A Tradeoff Analysis for CCD Area Imagers: Front-side Illuminated Transfer vs. Backside Illuminated Frame Transfer", CCD Applications Proceedings, 18-20 September 1973.
3. Hosack, H. H., To be published.
4. Phillips, L. D., Private communication.