RECON 6 - A REAL-TIME, WIDE-ANGLE, SOLID-STATE RECONNAISSANCE CAMERA SYSTEM FOR HIGH-SPEED, LOW-ALTITUDE AIRCRAFT

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ABSTRACT

The maturity of self-scanned, solid-state, multielement photosensors makes the realization of "real time" reconnaissance photography viable and practical. This paper discusses a system built around these sensors which can be constructed to satisfy the requirements of the tactical reconnaissance scenario. The concept chosen by Perkin-Elmer is the "push broom" strip camera system -- RECON 6, which represents the least complex and most economical approach for an electronic camera capable of providing a high level of performance over a 140 degree wide, continuous swath at altitudes from 200 to 3000 feet and at minimum loss in resolution at higher altitudes.

I. INTRODUCTION

Low-altitude, visible imaging reconnaissance missions require wide field of view (FOV) cameras capable of producing imagery with resolution adequate for tactical scenarios. In the past, this requirement was met by using frame or panoramic film cameras. The maturity of self-scanned, solid-state, multielement photosensors now makes it practical to realize "real-time" photography for this application. This paper discusses Perkin-Elmer's RECON 6, a system built around these sensors which can be constructed to satisfy the requirements of the tactical reconnaissance scenario. Typical real-time camera specifications are:

Platforms:	RF-4, RF-14, RF-15, RF-16, and RF-111, remotely piloted vehicles (RPV's), etc
Altitude range:	200 to 2000 ft AGL (Above ground level)
v/h range:	0.25 to 4.0 rad/sec
Roll angle:	$\pm 30^{\circ}$
Roll rate:	$\pm 30^{\circ}$/sec
Cross-track FOV:	140° (5500 ft at 1000 ft + AGL)
Target illumination:	3000 to 100,000 lumen/meter^2
Target contrast:	1.4: 1 to 100:1
Required resolutions:	1.5 to 2.5 ft at 1000 ft AGL
Data link bandwidth:	15 MHz
Size Weight Power Cost Unreliability Maintenance	*Minimal!*
Output:	Hard copy on dry processed material in essentially real time.

II. MECHANIZATION OF THE RECON 6

The concept chosen by Perkin-Elmer to mechanize a system to meet the above requirements was the "push broom" strip camera system which we call RECON 6. Self-scanned, solid-state detector arrays provide electronic cross-track scanning, while the platform's forward motion provides in-track scanning (see Fig. 1). Thus, the camera can be realized with no moving parts. This had decided cost and reliability advantages over panoramic or flying spot-type implementations.

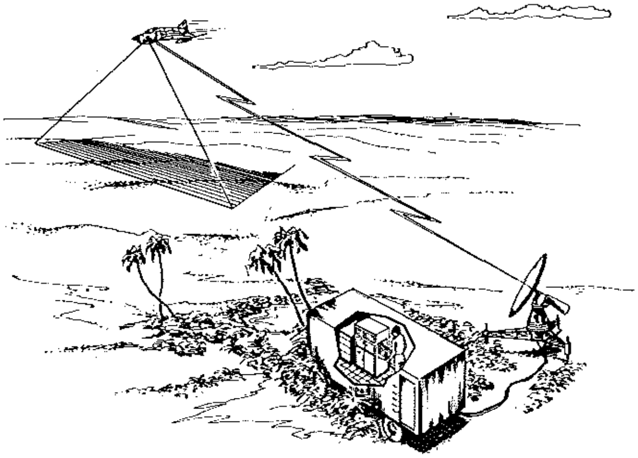
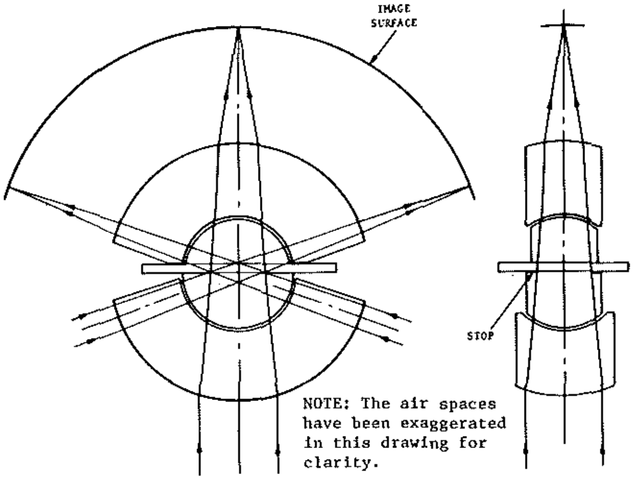


Fig. 1. RECON 6 - Electronic solid-state, wide-angle camera system

The resolution requirement of 1.5 feet resulted in a ground sampled distance (GSD) of 0.75 foot, assuming the generally accepted criterion of two samples per line pair for a sampled data system. Dividing this into the cross-track coverage that is required resulted in the need for a minimum of 7500 detector elements. Since linear charge coupled device (CCD) photodetectors and multielement photodiode arrays are available with 1728 and 1872 elements, respectively, it can be seen that multiple arrays will be required to cover the cross-track swath.

Next in order of consideration was the optical system. The most straightforward lens system for this application is the flat field mapping type. These have been built with field angles approaching 140 degrees (with difficulty). They also suffer from off axis illumination degradation in accordance with $\cos^4$ of the field angle. Additionally, they are expensive to manufacture. For these reasons, this type of lens was discarded.

Another interesting single lens which can cover the 140 degree field is the "Ball Lens" shown schematically in Fig. 2. Illumination through this lens falls off only as $\cos^1$; this made it more attractive than the mapping lens. However, its focal plane is curved. This would require curved detectors or fiber optic interfaces, both considered prohibitively expensive for this application.



NOTE: The air spaces have been exaggerated in this drawing for clarity.

Fig. 2. Spherical focal plane 73.1 mm f/3 ball lens with 140° FOV

Finally, then, the choice narrowed down to multiple lenses to cover the field. For today's visible-to-near infrared silicon sensors, double gaussian and telephoto refractive designs result in the best performance at minimum cost (see Figs. 3, 4 and 5).

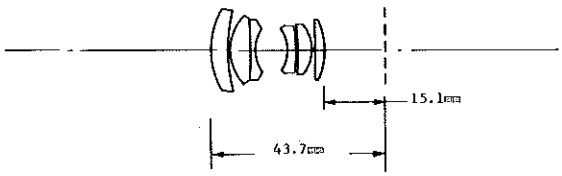


Fig. 3. 28.28 mm f/3 lens, 43.32° FOV

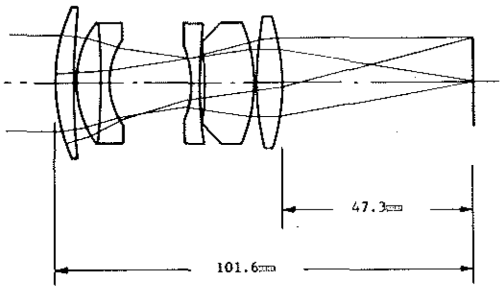


Fig. 4. 72 mm f/3 lens, 17.7° FOV

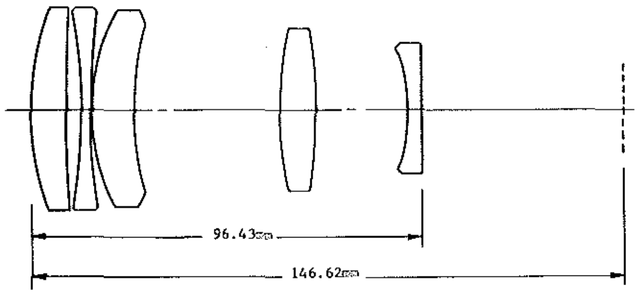


Fig. 5. 145 mm f/3 lens, 8.8° FOV

III. PERKIN-ELMER'S RECON 6

Fig. 6 is a block diagram of the RECON 6 wide-angle, electronic, solid-state, real-time camera system. It consists of an airborne sensor subsystem containing a six camera assembly, a video processing electronics assembly and data link transmitter. Alternatively, the transmitter could be replaced by an onboard recorder. The video data can be transmitted to a ground station containing a receiver, reconstruction electronics, laser beam recorder, and film processor.

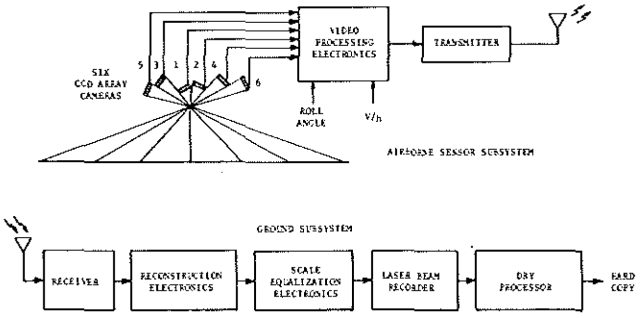


Fig. 6. RECON 6 system block diagram

A. AIRBORNE SENSOR SUBSYSTEM

The RECON 6 airborne sensor subsystem represents the least complex and most economical approach for an electronic camera capable of providing a high level of performance over a 140 degree wide, continuous swath at altitudes from 200 to 3000 feet and at minimum loss in resolution at higher altitudes.

1. Six Camera Assembly

This is a segmented six-lens strip camera where each lens provides an image to a single line array, 1728 elements wide. Fig. 7 shows the six camera assembly model of RECON 6. The total airborne sensor subsystem weight is 42.6 pounds. Each detector element is 0.013 mm wide and 0.017 mm long. The array length is 0.013 x 1728 = 22.46 mm. The focal lengths of the lenses were selected to provide equal worst-case, cross-track, ground resolved distance (GRD) of 1.5 feet at the edges of the field (see Fig. 8). The cross-track coverage of the six lenses is ±70 degrees, and the system is operated nominally at 0 degree pitch angle. The focal lengths and field angles of the three lenses covering 0 degree to 70 degrees are as follows:

Focal length (mm)	Field angle (degrees)	Nominal cross-track pointing angle (degrees)
28.3	±21.67	21.67
72.1	± 8.86	52.18
145.3	± 4.42	65.45

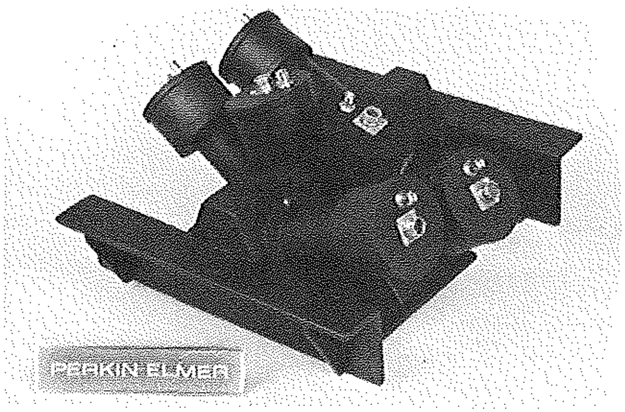


Fig. 7. Photograph of RECON 6 model

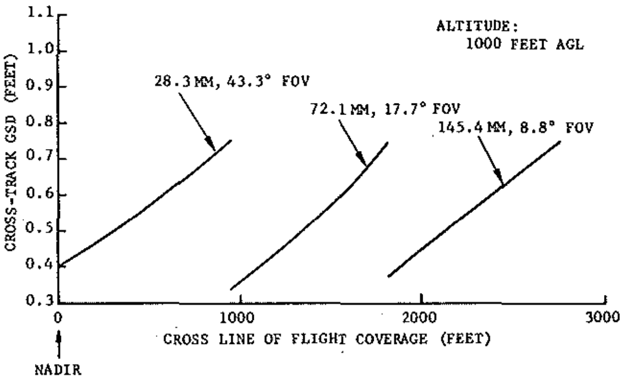


Fig. 8. Cross-track ground sampled distance versus cross line of flight coverage

A second set of three identical lenses provides coverage from -70 degrees to 0 degree. The relative f/3 aperture of the lenses was selected to provide a high level of image illuminance at minimum complexity in optical design. The individual camera assemblies consist of a lens cell assembly and a detector array assembly. The three different focal length lens cells are unique in their optical design, but a common interface between the three lens cells and the detector array is maintained, thus providing universal interchangeability between subsystems. Perkin-Elmer's designs for these lenses provide for a weighted polychromatic MTF (modulation transfer function) in the spectral region of the detectors of 0.6 at 40 line pairs/mm over the entire field.

The configuration of the camera is such that the strip image plane is tilted with respect to the ground across the track. Therefore, the projection of the detectors on the ground is variable, producing undesirable scale changes in the imagery. However, the RECON 6 system rectifies the image electronically in the ground subsystem and thus provides uniformity of scale.

Fig. 9 shows the design layout of the six camera assembly. Pointing and alignment of the individual cameras, to provide contiguous coverage of the broad FOV, are provided through alignment and locating keys at the interface between the camera assemblies and the main frame. The interface between the airborne sensor subsystem and the aircraft is through passive elastomeric vibration isolators. Power, control signals, and video signals are processed in the common electronics package to interface the airborne sensor subsystem to the aircraft power bus and data link.

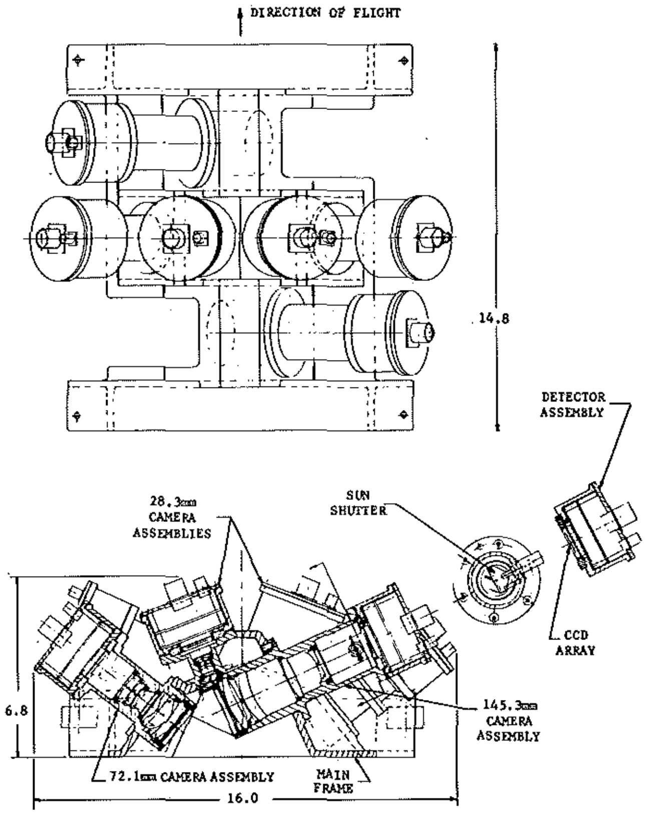


Fig. 9. Design layout of six camera assembly

2. Video Processing Electronics Assembly and Data Link Transmitter

The detector array and its first stage analog electronics are packaged in an enclosed aluminum housing. During assembly, the array is aligned and positioned with reference to the interface flange and locating pin. This technique assures alignment when the electronics housing is mounted to the lens assembly. Since the minimum amount of electronics are located adjacent to the detector array, noise generation related to thermal dissipation is minimized, and simple heat sink techniques are sufficient to maintain the detector assembly at its optimum temperature.

The airborne electronics system consists of six identical detector assemblies (one in each camera), a data processor which is common to all six cameras, and interfacing cabling. Each detector assembly contains a single 1728 element CCD array (Fairchild CCD 121H). A functional block diagram of the RECON 6 airborne sensor subsystem electronics is shown in Fig. 10. The camera video outputs are processed in contiguous pairs, requiring three subcarrier channels. The video data processing is simultaneous among the three pairs because the cameras operate in parallel. The serial channel data will modulate a selected subcarrier frequency, and the three channels will be summed at the input to the link transmitter. Video signals from cameras 1 and 2 will modulate the link transmitter directly, i.e., the subcarrier frequency is zero. Video signals from cameras 3 and 5 will modulate a 6.5 MHz subcarrier; the video signals from cameras 4 and 6 will modulate a 13 MHz subcarrier. During a blanking period, digital synchronizing and fiducial data will be generated and inserted by the composite video generator into the main data stream.

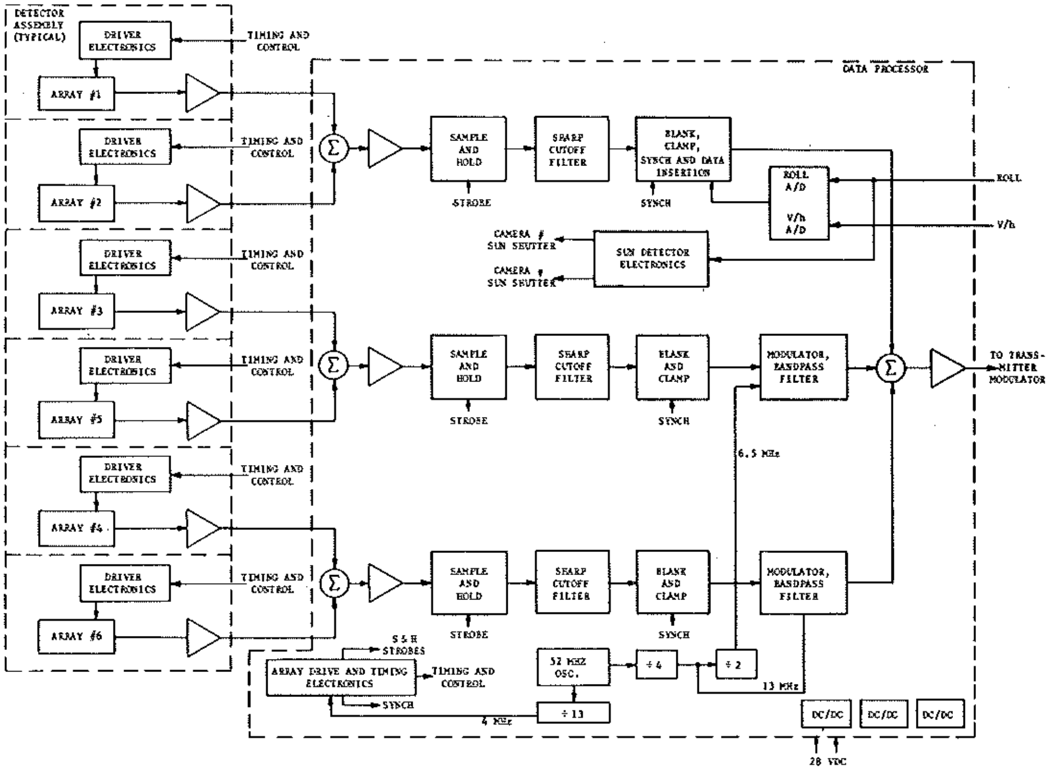


Fig. 10. RECON 6 airborne sensor subsystem electronics block diagram

B. GROUND SUBSYSTEM

Any part of the system that is not absolutely required to be in the airborne sensor subsystem is placed in the ground subsystem. The MTF of the ground subsystem is expected to be in the order of 0.6 at 38.5 line pairs/mm. Fig. 11 is a block diagram of the RECON 6 ground subsystem. The composite data from the data link receiver contains two channels of direct video data, four channels of video data superimposed on two subcarriers, and synchronization data. These data subsets are separated by appropriate filters. The subcarriers are routed to demodulators, the direct video data are routed to temporary storage, and the synchronization information is used to provide reference points for the timing electronics. Factory-generated calibration corrections of dark current for each pixel are added to the scene data after digitization as appropriate. The scene data is commutated from the three sources and fed to the laser recorder. Scale equalization and roll compensation take place within the temporary storage area of the laser recorder. All of the timing and control signals for this function are generated within the ground subsystem electronics.

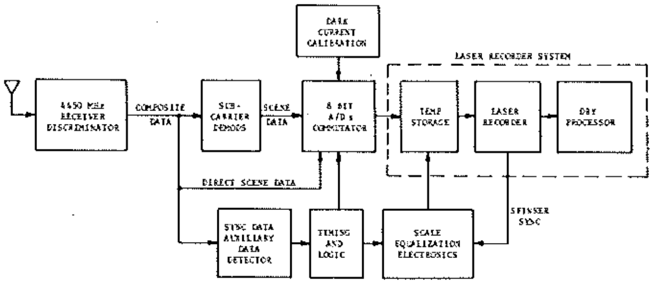


Fig. 11. Block diagram of RECON 6 ground subsystem

Stabilization of the image with roll angle requires that the data be shifted with respect to the scanning beam. Therefore, if the starting address for the data output is modified as a function of roll angle, the data is shifted with respect to the beam position. A simple PROM (programmable read only memory) is used to generate starting address values as a function of roll angle over the range of ±30 degrees.

Equalization of the imagery scale is accomplished by modulating the rate at which the data is written by the laser recorder. The scanner speed is not changed; only the clocking rate of the data which has been stored in the recorder memory is changed.

CCD and photodiode arrays exhibit variations in dark current from pixel to pixel. If this variation were not compensated, fixed pattern noise would be apparent in the imagery gathered during very low light-level operation. Perkin-Elmer calibrates each detector array and stores the pixel-by-pixel dark current values in PROM. These chips, one per array, are installed in the ground subsystem electronics in positions consistent with the array's position in the camera. The correction is then subtracted pixel-by-pixel from the video data after digitization.

IV. SYSTEM PERFORMANCE PREDICTION

To predict system performance, the effects of the basic RECON 6 elements (which are the airborne sensor subsystem, the data transmission link, and the ground-based image reconstitution system) had to be considered. The principal source of image degradation is noise at the detector preamplifier. Video signal amplification will greatly amplify both the detector signal as well as the detector preamplifier noise prior to the addition of other sources of noise developed in the transmission and image reconstitution link. These latter sources of noise will have a very small effect on the reconstituted imagery. Similarly, the signal reduction of the image recorder will be

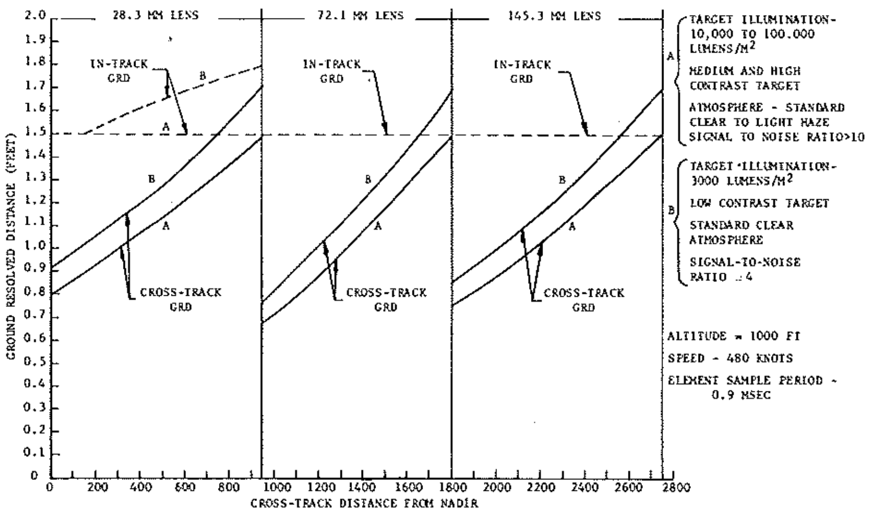


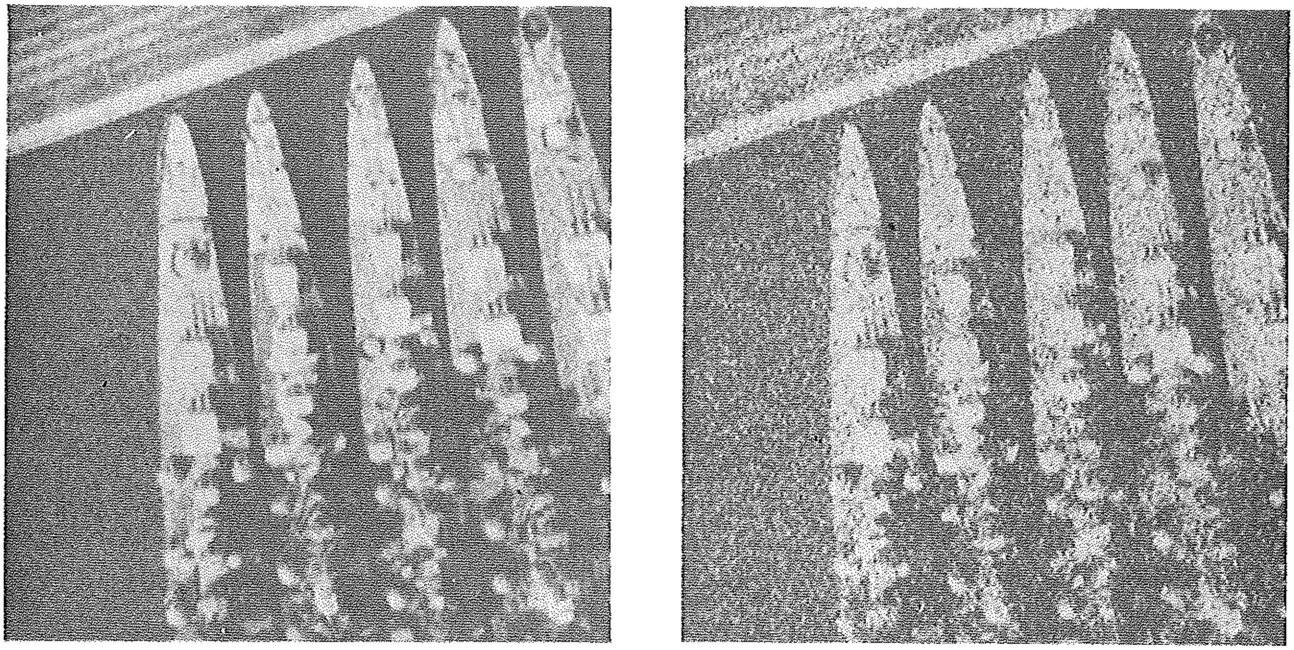
Fig. 12. RECON 6 system performances versus cross-track distances

neglected, primarily because both signal and noise are reduced by the recorder characteristics. Signal pre-emphasis may also be utilized to regain modulation loss at the higher spatial frequencies. Gain control is included in the ground subsystem to maximize the dynamic range of the video for the specified scene brightness levels.

Fig. 12 shows predicted system performance as a function of distance from nadir at 1000 feet AGL. Note that GRD varies between 0.8 feet to 1.8 feet in the cross-track direction and between 1.5 feet and 1.75 feet in the in-track direction, depending on the position in the field as well as illumination conditions. It should be noted that Fig. 12 shows equivalent object resolution at the output of the transmission link. The scale of the image is rectified electronically prior to reconstitution.

Performance criteria for electro-optical imaging systems have long been the subject of experimental and theoretical study at Perkin-Elmer. The principle evaluation criteria revolved around minimum signal-to-noise requirements. One of our studies had shown that, in the presence of white noise, 3-bar targets may be detected with signal-to-noise ratios between 0.5 and 0.8 provided that the targets are viewed at a magnification optimized for the MTF of the eye. However, at these low signal-to-noise ratios, the pictorial information is not "pleasing" to the eye. Simulated imagery provides a subjective criteria for acceptable levels of signal-to-noise.

Typical imagery produced on the Perkin-Elmer Line Scan Image Generator (LSIG), at simulated signal-to-noise ratios of 4:1 and 10:1, is shown in Fig. 13. Reasonably good imagery results for signal-to-noise ratios as low as 4:1.



PROJECTED SPOT SIZE = 1.5 FT

$$\frac{\text{SIGNAL}_{(\text{PEAK-PEAK})}}{\text{NOISE}_{\text{RMS}}} = 10:1$$

PROJECTED SPOT SIZE = 1.5 FT

$$\frac{\text{SIGNAL}_{(\text{PEAK-PEAK})}}{\text{NOISE}_{\text{RMS}}} = 4:1$$

Fig. 13. Typical simulation imagery produced by Perkin-Elmer's LSIG

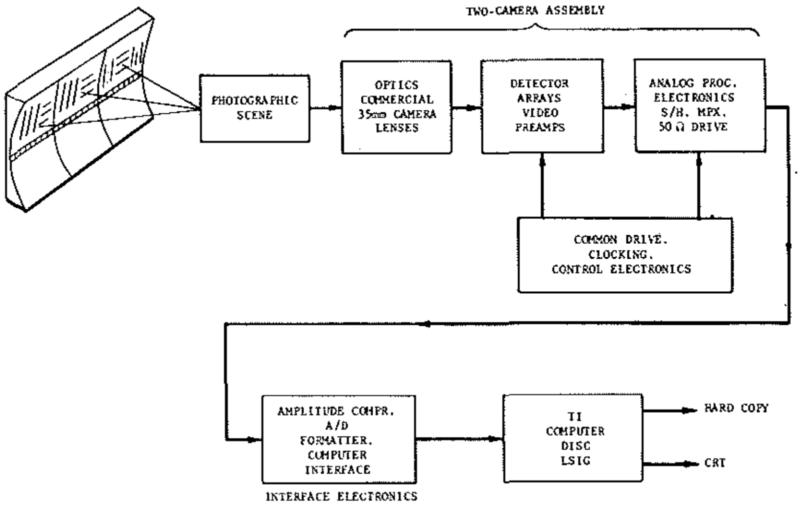


Fig. 14. RECON 6 breadboard

V. BREADBOARD TESTING

In order to demonstrate the salient features of the RECON 6 system, Perkin-Elmer constructed and tested a breadboard of a portion of the system. Two of the RECON 6 cameras, covering about 60 degrees, comprised the breadboard camera system.

Fig. 14 is a block diagram of the RECON 6 breadboard. Each of the two cameras consists of a lens purchased from a selection of off-the-shelf 35 mm camera lenses, a Fairchild 1728 element CCD imaging line array, a video preamplifier, and a sample-and-hold circuit. The two cameras were mounted in a common housing and contain the drive, clocking, control, multiplex, and drive electronics necessary to make the two cameras perform as an imaging system. In-track image motion is provided by a mechanism. The LSIG made the hard copy imagery. The LSIG, its TI computer, and disk memory offered the ability to perform a scale equalization demonstration.

A montage shown in Fig. 14 was constructed with linear dimensions of 6 ft x 9 ft and curved about a horizontal axis to a radius of 5 ft. Imagery and targets with a scale of 1 inch = 16.67 ft were provided.

Hard copy output photographs obtained from the breadboard are shown in Figs. 15 and 16. Fig. 15 shows the scale distortion inherent in the camera, requiring scale equalization. Scale equalized imagery is shown in Fig. 16.

VI. SUMMARY AND CONCLUSIONS

The maturity of self-scanned, solid-state, multielement photosensors makes the realization of "real time" reconnaissance photography viable and practical. This paper has shown that a system built around these sensors can be constructed to satisfy the requirements of the tactical reconnaissance scenario.

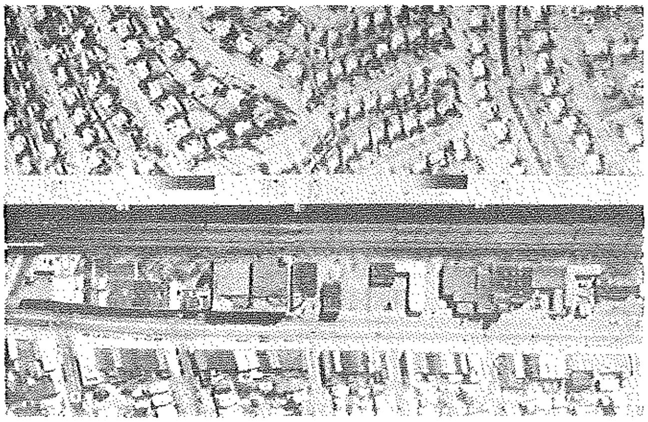


Fig. 15. RECON 6 breadboard (output as photographed)

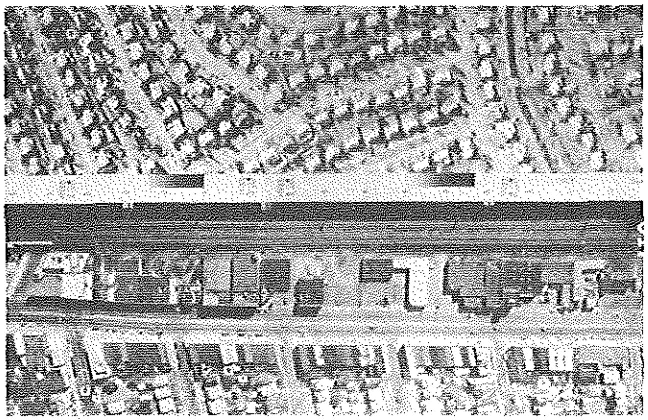


Fig. 16. RECON 6 breadboard (Output from breadboard - after electronic rectification)