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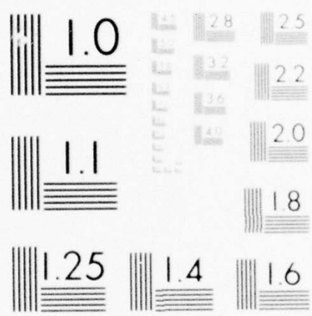
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AFAL-TR-77-185

TEST FACILITY FOR TELEVISION SENSORS APPLIED TO THE DETECTION OF SATELLITES

Reconnaissance and Weapon Delivery Division

September 1977
TECHNICAL REPORT AFAL-TR-77-185
Final Report for Period May 1972 - May 1975

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FOR THE COMMANDER

Kenneth E. Kissell

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFAL-TR-77-185	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Test Facility for Television Sensors Applied to the Detection of Satellites		5. TYPE OF REPORT & PERIOD COVERED May 1972-May 1975 Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Peter L. Manly, Capt USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Reconnaissance/Weapon Delivery Division Air Force Avionics Laboratory Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Reconnaissance/Weapon Delivery Division Air Force Avionics Laboratory Wright-Patterson AFB, Ohio 45433		12. REPORT DATE September 1977
		13. NUMBER OF PAGES 34
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)

Television Sensors
Satellite Detection
Point-Source Response
Moving Target Indicator
MTI
Ebsicon Camera
SIT Camera
Photometry

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

See Reverse Side.

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

A facility was established to demonstrate the adequacy of 1973-1974 state-of-the art television sensors to detect faint spacecraft so as to confirm that technology would be available for a new generation of optical surveillance cameras. This facility is described in detail and the results discussed of testing an Ebsicon (Silicon Intensified Target) camera system, along with associated MTI devices, for detection of stellar and satellite sources.

FOREWORD

This report describes the development and use of an electro-optical sensor test facility for evaluation of low-light-level television sensors to be used in satellite search, acquisition, tracking, and identification. This effort was performed under Air Force Avionics Laboratory Work Unit 7660-03-18. The effort was begun specifically to support the Spacetrack Augmentation Program of SAMSO/DY and ESD/XRT (responsibility for this program at ESD was recently transferred to ESD/OCT).

AFAL personnel responsible for the direction of the program were Lt Col John E. Rudzki, Dr. Kenneth E. Kissell, and Mr. James H. Huckaby. Other AFAL personnel making significant contributions included Capt David D. Ratcliff, Mr. Melvin R. St. John, Dr. Eugene W. Rork, and Mr. Ronald E. Wiensch. Personnel of two contractors made major contributions in elaboration and in the daily operation of the facility. J. Ebert of Grumman Aerospace Corp and D. Pedrick and J. Sellers of Systems Research Laboratories, Inc., participated in the engineering and operations of the camera testing portion of the observatory.

This effort was also supported by aspects of two parallel AFAL efforts, Work Unit 7660-03-20, a contractor evaluation of the RCA IVK-531-I^2V doubly-intensified vidicon camera under Contract F33615-73-C-1169 and Work Unit 7660-03-31, engineering modifications to the system by Systems Research Laboratories under Contract F33615-74-C-1080.

This document is the Final Report for Work Unit 7660-03-18.

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INTRODUCTION

GENERAL BACKGROUND

In 1958 the Air Force assumed operational responsibility for detection, tracking, and identification of space objects, such as earth satellites, which are potentially a military threat to the United States. Various techniques and systems, radar and optical, now exist to perform these missions and are in either operational or experimental use. There is an established and continuing need for improved capabilities as new space systems present more formidable surveillance problems. Earth synchronous satellites, now being deployed for strategic missions, for example, involve greater slant ranges and lower effective optical and radar detectabilities. Since 1958 the Air Force Avionics Laboratory has been engaged in the development of television sensors for use in detecting faint point-source objects against the night sky and recognizing the motion of satellites against the star field. This early AFAL work led to the establishment of test facilities at Cloudcroft, New Mexico, and at two Ohio sites where image orthicon cameras were evaluated.

In the 1960's an attempt was made by the 496L System (SPACETRACK) to deploy an operational sensor using multiple image orthicon cameras in conjunction with a unique, large-aperture optical system. This system, the FSR-2 Passive Optical Surveillance System (POSS), was constructed by RCA and Perkin-Elmer Corporation to use the best image orthicon camera tubes then available; however, the combined optics, fiber optics coupling system, and I/O camera tubes proved to be significantly lower in performance than the existing KG-13A (Baker-Nunn) satellite tracking cameras.

The FSR-2 approach was abandoned in 1968 to wait for the perfection of new types of camera tubes then in the research phase. The new sensors were expected to perform at markedly higher sensitivities against point sources. In 1972, these tubes became available in quantity and with sufficient quality to consider another attempt at augmenting the existing radar and optical surveillance network (SPACETRACK System) with a passive optical sensor. Reference 1 discusses the camera tube deficiencies in 1965.

Initial design studies of the Spacetrack Augmentation System indicated a lack of reliable data on the point-source response of modern television sensors, since the majority of low-light-level sensors were developed and used against extended-area sources. It has been shown that the television response to point sources does not follow the theory of extended-area response.*

BRIEF HISTORY OF THE PROJECT

In the Spring of 1972 the Air Force Avionics Laboratory contracted with the RCA Corp. for the fabrication of the IVK-531-I^2V doubly intensified vidicon slow-scan camera. The camera was used initially at the Air Force Avionics Laboratory OPOS Observatory, located at Sulphur Grove, Ohio, with a 2.8-inch aperture f/2.5 lens for initial familiarization with the equipment. The Grumman Aircraft Corp. was at that time under contract to SAMSO to develop software capable of separating satellite motion from the stars. Grumman personnel made video tapes at slow-scan rates of wide field-of-view stellar scenes including calibrated star fields and orbiting satellites for reduction at their facility.

*The Army Night Vision Laboratory has performed extensive studies for SAMSO and ESD on the point-source response of low-light-level television sensors and has been of great help in efforts at AFAL. A point-source response model is being developed by NVL, and can be found in Reference 1.

The IVK-531-I^2V was then shipped to RCA for detailed laboratory evaluation by RCA under AFAL work unit 7660-03-20. After the laboratory tests the camera was taken to the Air Force Avionics Laboratory Electro-Optics Facility located at Cloudcroft, New Mexico, for field tests under the same contract. The camera was subsequently modified by removing the doubly intensified vidicon and installing an RCA C-21145 Ebsicon. More tapes were made for the Grumman Corp. using the modified camera on the Cloudcroft 48-inch aperture telescope at f/3 and with a 2.5-inch aperture f/3 lens.

The modified IVK-531 camera was then installed at the AFAL OPOS Observatory, relocated in 1973 to John Bryan State Park, Ohio, on a 16-inch aperture, f/11 Celestron telescope. The C-21145 tube was evaluated there by AFAL personnel (Reference 3). RCA had contracted with SAMSO to develop the IVK-531-SD, an auxiliary analog MTI device matched in scan rates to the AFAL-owned IVK-531 camera. This device was brought to the JBSP Observatory and evaluated with the IVK-531 camera in the Fall of 1973. The RCA MTI device was subsequently returned to RCA for improvements and modifications based on the evaluation at JBSP (Reference 4).

A second MTI device was also evaluated during the Fall of 1973. Goodyear Aerospace Corp. produced a device called the Correlatron under subcontract to Northrop under a SAMSO contract to study sensor and MTI devices (Reference 5).

In the Spring of 1973 the parameters of the conceptual ground-based surveillance system (now called GEODSS) became sufficiently clear to enable definition of a sensor test set and optical system dedicated to the Spacetrack Augmentation System developments. Previous tests had been conducted on available telescopes which did not conform to either the ground-based or space-based Spacetrack Augmentation System operational concepts. The sensor test facility and optical system described in this report were designed for use at the AFAL OPOS Observatory at John Bryan State Park, Ohio, where they could be collocated with an existing 24-inch telescope used for SOI(space object identification). Using this test facility, an evaluation of the Westinghouse WX32432 deep-etched metal-capped target Ebsicon tube was conducted (Reference 3), and operational experience was gained in the use of a ground-based electro-optical satellite detection system (Reference 6). This tube was also used for the generation of video data for tests of a MITRE Corp. digital preprocessor. The camera itself was used in the evaluation of an MIT/LL-owned WX32432 Ebsicon similar to the AFAL-owned WX32432. This particular combination was also used to generate video tapes for use by the Aerospace Medical Research Laboratory in studies of the human factors of satellite detection and by RCA for laboratory evaluation of the modified IVK-531-SD MTI device.

TEST-BED SYSTEM REQUIREMENTS AND CONFIGURATION

In the Spring of 1973 the results of several contractor studies indicated that the ground-based satellite detection system would probably use a telescope of 24-inch to 36-inch aperture with a field of view of 3° to 5°. The tube type, video chain and MTI methodology had not yet been determined. There existed a requirement to test a variety of candidate tubes under typical operating conditions, including different scan rates and integration times, and with several candidate methods of MTI. The configuration of a tube test facility to meet these requirements were proposed to SAMSO in May 1973 and work was begun immediately to procure components.

OPTICAL SYSTEM

The main requirements in satellite search are to examine the greatest possible area of the sky in a short time with the greatest possible system sensitivity. In general, the sensitivity will increase with the telescope effective collecting area. The signal-to-noise of the system, however, will decrease with decreasing f/number (i.e., faster optical system) due to increasing background brightness with the decreasing f/number.* For greatest sensitivity, one would want a large aperture with a large f/number, but this implies a long focal length with an unacceptably small field of view since the active area of the sensors under consideration ranges only from 25 mm to 80 mm diameter. A tradeoff must then be made to obtain the largest practical aperture with a short focal length (widest field-of-view) without going to the low f/numbers which would limit sensor

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*In actuality the background decreases with the square of the f/number.

performance due to high background levels at the image plane. Experience with the IVK-531-I^2V and the IVK-531-ST (the same camera with the C-21145 tube installed) indicated that f/numbers below approximately f/3 limited the performance by producing background levels high enough to saturate the sensor under typical night-sky operating conditions.

The practical limit for aperture and plate scale, using an 80-mm active format at f/3, is about 36 inches. In the interests of economy and because 80-mm format tubes were not available at that time, a 25-inch aperture telescope was selected. The wide field required that some form of optical field correction be used on the telescope, either of a Schmidt design or a Wynne-type focal plane corrector (Reference 7). The Wynne corrector at prime focus was chosen even though it meant that the camera would then be located within the optical system, blocking the central part of the incoming beam and generating heat in the incoming path thus causing some distortions in the incoming wave-fronts. It was found that the camera diameter could be made as small as 8 inches (10% obscuration), which is no more than the obscuration required for a Cassegrain secondary mirror. Most of the heat-generating elements of the camera were then removed from the optical path and placed in an auxiliary electronics package on the side of the telescope.

TELESCOPE MECHANICAL SYSTEM

An equatorial mount was chosen since the majority of the tests would be conducted in siderial drive. This eliminated the problems associated with image rotation of the star fields that another type of mount would produce. Two drives were incorporated on each of the axes, a 2°/sec fastpositioning slew drive and a variable-velocity stepping drive capable of motion from 0 to 75 arcseconds/sec used for fine setting and satellite tracking. Both axes had 15-bit absolute encoders with remote displays.

CAMERA SYSTEM

The camera system was designed to test vidicon camera tubes of nearly all types, against point-source objects specifically, in the presence of an overall background illumination. The camera system is unusual, in that it was designed to scan at a wide variety of vertical and horizontal rates and is capable of supplying voltages and currents to match virtually any camera tube."

The camera head, shown in Figure 1, is basically a tube and yoke holder, mountable at the prime focus of the telescope as shown in Figure 2. The camera head can accommodate image sections up to 80 mm in diameter and is long enough to accommodate return-beam camera tubes. For longer tubes, extension bars have been provided for the camera head. A second camera head, tailored to the requirements of return-beam camera tubes, is also available and is essentially identical in mechanical design to the vidicon camera head although it is substantially different electrically. Both camera heads have an auxiliary electronics package that is normally mounted outside the forward end of the telescope. This box contains the deflection amplifiers and high-voltage power supplies. It is separated from the camera head to remove the heat-generating circuitry from the optical path and to minimize center-blocking of the optical system by the camera head.

*A complete description of the camera system is available in the final report on Contract F33615-73-C-0381 (Reference 8).

The tube testing requirements for Spacetrack Augmentation called for operation at a variety of scan-line densities ranging 200 to 2000 lines per frame and a variety of readout rates ranging from 1 frame per second to 30 frames per second. The camera timing system is capable of variable scan rates over the entire range. Vertical drive, horizontal drive, composite sync, and composite blanking are also generated at all scan rates. In addition, the camera is capable of blanking the reading beam for an integral number of frames to increase the target integration time up to 2000 frames. Operation can be at either 1:1 or 2:1 interlace, although there is little use for 2:1 interlace in this problem, especially if digital MTI is used. The ramp generators are capable of driving almost all types of yokes and can be adjusted over a wide range of both sizes and centering to vary the aspect ratio of the scanned area.

The video chain is composed of a wide-bandwidth (50 MHz) preamplifier and three selectable postamplifiers with bandwidths of 500 KHz, 5 MHz, and 50 MHz. Sync and blanking can be added to produce EIA standard video. Finally, the video is filtered with a matched set of low-pass filters with a 40 db/octave roll-off. The camera and filter set is virtually identical to a camera operated by the Army Night Vision Laboratory at Ft. Belvoir, VA, for laboratory tube tests. This NVL system has been used in laboratory tests on tubes for comparison with tests performed at AFAL.

TEST CONSOLE AND DATA ACQUISITION SUBSYSTEMS

The test console, shown in Figure 3, was used both to control the experiment and to collect data. The majority of the data are taken as direct oscilloscope readings of video waveforms and as photographs of the monitors. The test console includes line-selecting oscilloscopes, the camera control units, and variable rate monitors, some of which have a P-7 phosphor to minimize flicker when operating at slower than standard scan rates. Difficulty was experienced in taking data at slow-scan rates with the conventional line-selecting oscilloscope due to the low repetition rate of the trace when frame rates were as low as one per second. The problem was only partially solved by using a variable-persistence oscilloscope. In addition, the line-selecting oscilloscope is difficult to use when examining point-source video, since the line selected for measurement must be the line with greatest amplitude. An underscanned display was therefore employed.

For an underscanned display, while the camera scans the entire target, vertical and horizontal gates are developed within the raster using variable-duration delay generators. Horizontal underscan ramps are generated within the horizontal gates only during the vertical gate. A vertical underscan ramp is also generated during the vertical gate. These ramps are then fed into a separate monitor to present a "blow-up" of the video as shown in Figures 4a, 4b, and 4c. This is often helpful when the resolution of the video chain is limited by the monitor. When the horizontal underscan and video are fed into the X and Y inputs of an oscilloscope, the display is the superposition of only that video contained within the vertical and horizontal gates. Although the repetition rate of the display is not improved over the use of a line selector, the larger number of lines displayed is easier on the operator's eye. This does allow all of the lines encompassing a point source to be superimposed rather than strung out as with the conventional line-selecting oscilloscope. If there are many stars on each line, this becomes invaluable in identifying the correct star on adjacent lines. Finally, the video can be summed with a portion of the vertical underscanned ramp, displacing each line of displayed video slightly and producing a pseudo three-dimensional plot of video amplitude as shown in Figures 5a and 5b. This has been most helpful in understanding blooming effects and other area-related phenomena at the target.

Data recording of video for use by other agencies and/or contractors is made with a Sangamo Sabre III, a seven-track IRIG Wideband Group II instrumentation recorder. Due to the large range of scan rates, it was not possible to use a conventional video tape recorder where the recording head is synchronized to the scan rate. Any one of the conventional machines would have been incompatible with recorders belonging to some agencies and contractors receiving the tapes. The IRIG Group II recorder is more universal but limited to slow scan for FM recording (500 MHz bandwidth). Most tapes produced so far have been FM. Two of the agencies receiving tape data, AMRL and MIT/LL, brought their own standard-rate video recorders for data collection.

In addition to the telescope, camera, and associated controls, two other subsystems are provided. First, a Navy TRIM camera, using an intensified SEC vidicon tube and a 2.8 inch aperture f/2.5 lens, provides a wide-field finder system for coarse guiding. The limiting magnitude for this system, operating with 875 lines per frame and 30 frames per second is about $m_v 7$. Second, a sky-brightness meter is utilized to measure the background sky brightness and extinction during tests. This system was developed at the Aerospace Research Laboratories. A complete description of the system and its use is in Reference 9.

A simulated star field incorporating a representative field of stars like point-sources variable background, and target satellites within the field-of-view was used for bench tests of the camera and set-up of the tubes. This allowed the time-consuming operations of set-up, calibration, and camera optimization to be done during the daylight hours or on cloudy nights. This simulator was also used to set up tactical MTI problems not commonly obtainable and not repeatable in real sky scenes (Reference 10).

TESTS CONDUCTED

IVK-531-I^2V TAPES PRODUCED FOR GRUMMAN

Slow-scan video tapes were made using Grumman recording equipment. The data were initially recorded in analog form and digitized at Grumman. The first tapes were made at the Sulphur Grove Observatory with a 2.8 inch aperture f/2.5 lens on the doubly intensified vidicon camera. The object of the test was to obtain wide field-of-view data applicable to a spaceborne conceptual system using a representative state-of-the-art television sensor. Recordings were made of the calibrated star fields provided by Prof. Arlo Landolt (Reference 11) and of synchronous satellites. More tapes were obtained with the same 2.8 inch f/2.5 lens at the Cloudcroft Observatory using lower-altitude satellites, and tapes were also recorded with the Cloudcroft 48-inch aperture telescope operating at f/3.0. Similar recordings were also made after replacing the I^2V tube assembly with the RCA C-21145 Ebsicon tube.

After digitizing at the Grumman plant, the data were processed on a digital MTI simulation effected on a general purpose computer. This served to evaluate the MTI algorithm devised as part of a study by Grumman and IBM under contract to SAMSO (Reference 12). Portions of these tapes were subsequently loaned to RCA and Northrop for laboratory evaluation of MTI concepts.

IVK-531-I^2V LABORATORY AND FIELD TESTS

The objective of this evaluation, performed by RCA at the Burlington RCA facilities and at the Cloudcroft Observatory, was to calibrate the point-source response of the camera system, both in the laboratory, under carefully controlled conditions, and in the field under real-world conditions. The results of the lab and field evaluation are reported in Reference 13.

IVK-531-ST/IVK-531-SD TESTS

The IVK-531-I^2V doubly intensified vidicon camera was modified by removing the vidicon and intensifiers and replacing them with an RCA C-21145 Ebsicon (also called a SIT) and thereafter the camera was called the IVK-531-ST. RCA also contracted with SAMSO to fabricate the IVK-531-SD analog MTI (moving target indicator) device. It used an analog storage tube to detect frame-to-frame differences in the video, resulting in a video signal that showed only the objects moving in the field of view. The IVK-531-SD was designed to match the scan rates and integration times of the IVK-531-ST camera. After the IVK-531-ST camera was installed on the 16-inch aperture, f/11 Celestron telescope at John Bryan State Park, the IVK-531-SD was brought to the observatory for field tests. The test objective was quantification of the ability of an analog MTI device to separate satellites from background stars when the telescope was driven siderially. The analog MTI device proved to be camera-performance limited and could detect a moving satellite automatically about 0.5 m_v brighter than the limiting magnitude for the camera, whatever the ambient operating conditions were.* The MTI device could be used effectively as an enhancement device if the threshold of the output of the device were set low enough. This

*The limit of camera performance was defined as the stellar magnitude that produced a SNR of 6 at the camera output. The IVK-531-SD required a SNR of about 10 at the camera output for detection.

would allow the brightest stars in the field to "leak" through, but the enhancement in contrast of the satellite relative to the stars made it very effective for man-in-the-loop operation. For complete results on the evaluation of the device when used as a fully-automatic MTI, see Reference 14.

Based on this evaluation and operating experience in the field, the device was returned to RCA for modifications. Tapes were later made with the SRL camera and the 25-inch aperture, f/3 telescope and with the AFAL star-scene simulator for use by RCA in evaluating the device in the laboratory after these modifications were completed.

GOODYEAR CORRELATRON TESTS

During the Fall of 1973, an alternate method of detection and MTI was evaluated. The Correlatron is a combined sensor/MTI device constructed in one tube envelope. The device has a conventional photocathode but the photoelectrons are used to write both positive and negative charge patterns on a special storage target using conventional soft landing of electrons to produce negative charge patterns and secondary-electron effects to produce positive charge patterns. The two types of charge storage are employed in sequence, the charge pattern of the stars cancelling and the charge pattern of the moving object remaining. The target is then read out non-destructively to obtain a conventional TV signal (although at slow-scan rates). The device testbed had a smaller than desirable field of view when used with the 16-inch aperture f/11 telescope and lacked sensitivity. Although a growth version of the device was projected and the basic principle of charge storage and cancellation worked, the effort was dropped for more promising sensors and techniques. A complete description of the sensor and test results can be found in Reference 13.

IN-HOUSE TESTING OF CAMERA TUBES

Three tubes were evaluated during in-house tests; the I^2V tube assembly, the RCA C-21145 Ebsicon, and the Westinghouse WX32432 Ebsicon. For complete results of these evaluations a separate report is being prepared (References 13 and 15).

In general, the I^2V tubes are as sensitive, if not more sensitive to point sources than the SIT or Ebsicon types, but the I^2V presently lacks the capability to handle large signals (bright stars) without excessive blooming. This blooming masks small signals in the vicinity of bright stars. In the operational sense, this implies that there are several hundred isolated areas of the sky near the brighter stars that could never be seen by the I^2V. Using the 16-inch Celestron telescope with the I^2V at the Sulphur Grove Observatory, a m_V=3 star would bloom to envelop the entire picture. Assuming that a 2° x 2° field-of-view with the same aperture would be used in an operational system (in actuality a larger aperture will be used, causing even more blooming), there would be 560 square degrees of the sky that could never be seen, based on 140 stars at least of m_V=3 scattered over the celestial sphere. It has been suggested that a large part of the blooming resulted from the light scattered in the fiber-optic faceplates of the intensifiers. Intensifiers have now become available with dark-clad fiber-optic faceplates. In view of the excellent sensitivity of this type of tube, further testing is warranted for the I^2V using the improved fiber-optic faceplates. In addition, the fabrication of larger area vidicon-type storage surfaces within the camera tube (up to 80 mm diameter) is much less complicated than fabrication of similar-sized SIT targets. This becomes important as growth versions of the present sensors are developed to enable larger image formats to be used and therefore increase the field-of-view of the system.

The SIT or Ebsicon type tubes exhibit much less blooming, allowing operation at full sensitivity even with the brightest stars within the field of view. These sensors have proven to be very expensive to fabricate with targets larger than 25 mm diameter.

OPTIMIZATION OF THE CAMERA SYSTEM

The operation of low-light-level television sensors, originally developed for looking at extended-area scenes, for point-source detection calls for non-standard operating procedures in this application, since the camera must handle an extremely wide variation in intensities and must respond to signals whose area is on the order of a single resolution element. When operating a television sensor against extended-area targets, the generally accepted rule of thumb for specifying the required video bandwidth is to take the number of resolution elements in the scene, divide by two, and multiply by the number of frames scanned per second. For instance, when operating at 4 frames per second, 650 lines per frame, the conventional bandwidth rule would indicate using a bandwidth of 845 KHz. This would produce optimum results for extended area sources and would work well if the camera were viewing a standard TV test chart.

In tests in the field, however, it has been observed that the point-source response of a system changes only slightly with a reduction in bandwidth factor of 2. This improves the SNR since the noise decreases by a factor of the square root of 2. Figure 6 shows the effect of this bandwidth reduction. It should be noted that this implies a decrease in the effective resolution of the system since the point-source video pulse has widened appreciably. It is, however, effective in increasing somewhat the sensitivity of the system. The technique does not work for greater decreases in bandwidth. Precise optimization of the bandwidth of the system is a subject for future study.

It is suggested that success of the above technique is due to the images of stars and satellites not falling on a single resolution element as defined by the scanning beam. The point-source image is generally larger than the resolution element defined by the scan-line spacing (assuming equal vertical and horizontal resolution). Generally, point-source images cover two to four elements even if they are not blooming. It is not clear if this is an effect of the optics, the atmosphere at the test site, or the storage target. The video pulse covers two or more resolution elements with a corresponding decrease in the higher-frequency video components, allowing lower bandwidths to be used without degrading the video amplitude. The use of narrower bandwidths does decrease the noise, which is predominantly made up of white-noise phenomena that are a function of the bandwidth. Thus, the signal-to-noise ratio is increased. The general rule of thumb, determined empirically, for the optimum bandwidth at a given scan rate is:

$$\text{Bandwidth} = \frac{1}{4} \; \frac{\text{resolution elements}}{\text{frame}} \times \frac{\text{frames}}{\text{second}} \qquad (1)$$

If the resolution of the sensor system were increased, for instance by using a wider-field system, so that atmospheric dancing is not a factor, it is not clear that higher bandwidths would be helpful in order to utilize the full response of the system. The size of the charge image of a star as seen by the read beam may instead be limited by the resolution of the reading process itself, indicating that either more scan lines are needed or larger storage targets are needed.

Using a 32mm to 40mm-format sensor on the present telescope, the resolution of the system is ultimately related to the atmospheric dancing (blurring); in practice other elements of the system may limit it. Atmospheric image blur of 5 arc-sec will produce star images of about 1/650 of the field-of-view with the present 25-inch f/3 telescope. For this reason the sensor is usually operated at 650 lines per frame.

The integration time of the sensor is usually limited by background saturation. Some very dark nights produced such low backgrounds that the preamplifier or thermally induced "dark current" in the target was the limiting noise element. In general, it is desirable that system operation be limited by the background noise. This noise is generated by the overall background level set by the night-sky illumination rather than at the preamp limit, which would indicate that the system is limited internally. The background limit was reached with an integration time as short as 1/8 sec on bright nights (mv=16 per arcsec^2) and as long as 8 seconds of integration on the darkest nights, depending on the optical system used. Operations generally were not conducted with integration times greater than 1 second, since the slowest satellites of interest would move out of a resolution element in that time; further integration would not increase the satellite energy imaged into the resolution element, but would bring up the background noise and stars, cluttering the field. Generally, integration times of 1/4 sec, 1/8 sec, 1/16 sec, and 1/30 second were employed.

The slower frame rates, of course, produce a flickering display which can be compensated, to some extent, by the use of a P-7 or similar long-persistence phosphor. The ultimate operational goal of the system is to employ an automatic MTI device without a man-in-the-loop. Therefore, display flicker was not considered in the design of an optimum system. There is a requirement, however, to employ a man-in-the-loop interim system using manual or semi-automatic MTI until a sufficiently "smart" MTI can be developed. The evaluation of several MTI systems using man-in-the-loop is discussed elsewhere in this report, although it should be noted that almost all systems employ a scan converter or storage tube such that the operator seldom observes the raw video with its slow-scan flicker.

When operating with a background-limited system, using 650 lines per frame and a bandwidth given by Eq. 1, there is a wide choice of readout rates available. Optimum operation of the system will range between 1 and 1/30 sec per frame. Even the slowest satellites will move out of a pixel before the end of a frame with scan rates lower than 1 sec. Scan rates faster than 1/30 sec imply extremely large bandwidths and excessively short exposure times. As the readout rate is varied between 1 sec and 1/30 sec (keeping a constant line density per frame and proper bandwidth in relation to the frame rate), an optimum is reached that is a function of the background illumination. For fainter backgrounds, slower scan rates are better and will yield more sensitivity due to the longer integration times, up to the point that the background saturation and background noise predominate.

In the operational system one scan rate will probably be used, so a single, optimum scan rate must be chosen, usable in all background conditions. This would avoid the necessity of having multiple-bandwidth video chains. This scan rate would be able to handle the highest operational backgrounds (16 mv/arcsec^2). For fainter backgrounds, multiple-frame integration will probably be used to obtain longer integration times, up to the limit of the ambient background.

Two methods of increasing the integration time were examined to increase the system response for fainter backgrounds. Both performed the integration within the camera tube by varying the exposure time. The first maintained a constant readout rate by blanking the read beam for an integral number of frames, thereby increasing the storage-target integration time. The scan rate, bandwidth, and all system timing remained constant. Theoretically, the signal should increase linearly with the increase in integration time, providing (1) the signal does not become saturated and (2) no significant leakage of the stored-image charge occurs in the target during storage. The background will also increase linearly with integration time; the noise associated with background will then increase with the square root of the integrated background. The result is that the SNR should increase with the square root of the integration time. Our results show that saturation levels are reached quickly within a very few standard-rate frames of integration (typically four). This implies that a video chain is required that can handle the relatively large signals near saturation levels and yet be capable of passing small signals above the video chain noise when operating in the single-frame integration mode.

The second method of increasing the SNR is to decrease the readout rate, thereby increasing the integration time. This allows the bandwidth of the video chain to be decreased without limiting the signal information. The bandwidth is decreased in proportion to the readout rate, so that the relative bandwidth remains constant. In this case, the charge on the target will theoretically increase linearly with time but, since the read beam scans more slowly, the new result is that the signal current remains unchanged. The noise, however, decreases with the three-halves power of the bandwidth. The new result is that, as in the method of increasing the SNR by beam blanking, the SNR should increase with the square root of the increase in integration time. In practice, the low-level signals produced at low scan speeds demand careful attention to preamp noise, since the read beam is travelling very slowly and the tube response is a linear function of the read-beam velocity. Low-noise, low-bandwidth preamplifiers are available for use in such a system.

In practice, the SNR increase due to increasing the scanning time is greater than the SNR increase due to simple beam blanking. This is attributed to the fact that lower background noise levels are encountered at slower scanning rates due to the higher reading efficiency of the beam (Reference 14). This results in a lower residual charge from the previous frame with consequently reduced background and lower background noise. This is important in the GEODSS application since, in order to obtain the largest possible dynamic range, higher capacitance targets will be employed. We would then expect much greater lag in these targets, requiring high-beam reading efficiency. It has been observed that at faster scan rates the signal is beam-starved on the brighter stars, leaving a residual image for the next frame. At the slower scan rates the beam is seldom starved, allowing more complete discharge of the target. A pseudo three-dimensional display of a small section of the image obtained at slow scan rates is shown in Figure 7, illustrating the "top hat" produced by a bright star. The central high-level signal is indicative of the true optical spot size of the star image, and the level of the signal is well above the usual extended-area saturation level observed at high backgrounds. It is theorized that this represents a "dead short" in the target diodes due to excessive photo-electrons. This is substantiated by the fact that the central peak disappears immediately upon removal of the optical input and shows no lag, as does the wider plateau. The plateau signal level is about the same as the maximum extended area background signal level encountered. Its size is indicative of the charge migration commonly called blooming. It was noted that there seem to be no permanent effects on the target after several minutes' exposure to this optical input level.

In both the beam-blanking and slow-scan techniques, there is a "dark current" that predominates in the signal after about 1-sec integration. This is not the conventional thermionic emission from the photocathode, although that form of dark current contributes a small amount of noise. This is a background level generated by the thermal-induced conductivity in the target (Reference 14). As with any background signal, the random noise associated with it increases with the square root of the signal. More important, however, is the fact that this background charge can become high enough to seriously reduce the available dynamic range of the system if the target is warm. This is equivalent to the problem encountered in high optical-background environments.

This thermally-induced conductivity should be halved for every $10^{\circ}C$ that the target is cooled (Reference 15). It was noted that better performance from the system was obtained on cold nights. Camera cooling should be employed in any future systems and quantitative measurements made of its improvements in operation.

The optimization of any system is a series of tradeoffs. In this system, the best performance based on operations under all typical conditions appeared to be at 1/8-sec frame rate, 650 lines per frame. The bandwidth used was 1 MHz. All tube voltages were set as per manufacturer's specifications except the target voltage and G_1. The target voltage was set at 7.5v, rather than 5v, in order to reduce target saturation. This enhanced non-uniformities produced by target defects, but non-uniformities are less important here since we are interested in frame-to-frame differences rather than single-frame uniformity. The beam current, controlled by G_1, is operated with less than the manufacturer specified value since specifications are for standard-rate operations. With reduced beam current a sharper beam can be developed with a gain in spatial resolution. Since we are operating at lower scan rates, we can use reduced beam currents without becoming beam starved on the highlights. As an illustration of the attained resolution, Figure 8 shows the individual diodes on the target, as seen in one of the highlights. Although the beam is larger than one diode, what is observed is the modulation produced when the beam covers first an odd, then an even number of diodes as it sweeps across the target.

MTI DEVICES DEVELOPED IN-HOUSE

In order to evaluate the camera tubes against real spacecraft targets, the telescope system was pointed in the predicted locations of numerous artificial satellites. Initially several methods of MTI were tried simply as an acquisition aid for the main purpose of tube testing. Later several methods were tried with the express purpose of evaluating the MTI device itself.

One class of MTI devices depends on driving the telescope at siderial rates, fixing the stars motionless with respect to the sensor field-of-view, but allowing the satellite to move. This will produce either a trailed satellite image or, if the target is moving slowly, a series of video frames in which only one object has changed position. Normally, in order to detect the slowly-moving object, a comparison of two or more frames is required to verify the stars and recognize the satellite's motion as shown in Figure 9a through 9c. This class of motion detection suffers from the limited integration obtainable in the translating satellite image and is limited to the brighter targets in each velocity range.

Another class of MTI devices depends upon slewing the telescope along the predicted path of a target and offsetting about the predicted point to execute a search. Obviously, this type of search is useful only when a priori data are available, e.g., in the tip-off mode. The display will show the satellite as nearly a point but the stars will trail. This has the advantage, if the satellite has a low brightness and the predicted velocity nearly correct, of concentrating all of the energy from the satellite at one point of the storage target, maximizing the response of the system to the satellite. The trailing of the star images is a mixed blessing. If the star field is relatively faint, the integration time of the stars is insufficient for them to register, and the star clutter is markedly reduced. If the star field is dense with brighter stars, however, the trailing stars can obscure a great portion of the field. Since the satellite ideally appears as a stationary image point, it can easily be confused with blemishes on the target, causing false alarms. Usually the operator is familiar with the location of target blemishes and can ignore them. In practice at JBSP this method has been used only in the synchronous case; the satellites were often faint and the required motion to track the satellite was simple (no motion).

A special class of operation is a method useful only for synchronous objects with fully manual or semi-automatic MTI. In this scheme, the telescope is not driven siderially; rather, it is driven at a few arcseconds per second Northward or Southward in declination. All stars will then appear to move either upward or downward on a diagonal as the result of the combined siderial and telescope motion. Synchronous satellites will, in contrast, move vertically. It is very easy for the operator to detect this difference in movement, much easier than recognizing a stationary object in a group of moving objects. This method had been used with a storage tube to produce streaking (see Figure 12).

Analog MTI devices using siderial drive can use one of several methods of detecting satellite motion. The first of these is simply to add a number of frames in a storage tube. The stars will remain as points and the satellite will generate a streak or, if the satellite has a high velocity, a series of points in a line as shown in Figure 1. The method suffers from the fact that any noise (e.g., the points generated by scintillations) and the background level also add, cluttering up the picture. Buildup in background level may be controlled somewhat by thresholding or level slicing, often at the expense of sensitivity to the faintest satellites. The summation of many frames on a vidicon-type storage target also suffers from blooming of the brightest stars. Eventually, the storage tube becomes so cluttered with bloomed and false points as to become unusable. In the case of slowly-moving targets, if only one of every three or four video frames is added, the blooming and high storage levels will be lessened, and the satellite will be displayed as a series of dots in a straight line. Unfortunately, a surprisingly large number of star groupings form nearly straight lines, complicating the recognition problem. Further, most satellites vary in brightness and may be detected only part of the time. If the frames selected for addition in the scan converter are not those in which the satellite flashed brightly, the satellite may be overlooked. It is thus recommended that all frames over a suitable period of time, say 20 seconds, be added. In order to avoid the problem of blooming and high storage levels, thresholding and/or clipping should be employed. Low-level regenerated video signals are then fed to the storage tube. The levels are set so that no storage takes place in the blacks and that little storage takes place in the whites. This allows many frames to be stored without blooming or excessively high storage levels. All intensity information is lost in this process, however, allowing a satellite to be hidden behind a star. This is not considered serious since the area of the sensor occupied by stars will usually be low in comparison with the total area of the field if low-blooming tubes are used. Further, if the intensity information were retained, the low signal level inherent in faint satellites would be difficult to detect above most star signal levels, and impossible to detect above the saturated signals which usually occupy the area of the sensor occupied by stars.

Generally, the addition of frames is usable only with semi-automatic MTI. For fully-automatic MTI by frame addition, an analog or digital streak detector and dots-in-a-line device must be developed. The human eye is at this time the best device known for detecting a straight streak or line of dots in the midst of clutter, even though there is a probability of false alarms from natural star formations. The method of semi-automatic MTI has the advantage over a simple real-time monitor display of allowing the operator to remove his attention from the display for 20 or 30 seconds at a time, thereby increasing the hours he can work effectively. Another advantage to storage tube use, in the case of slow or blanked scans, is that the data may be read out at standard video rates, eliminating the flicker of slow-scan video. If a streak is detected, however, the operator should observe the streak develop in order to know the direction of satellite motion moving in the field-of-view. This also argues for short-term data storage for instant replay when a target has been discovered.

A second method of analog MTI with siderial drive is the subtraction of two or more frames to cancel or suppress the stars. One reference frame must be delayed or stored for later comparison with subsequent video. Several methods of storing video have been attempted, the most successful of which, in the tests reported here, was the analog storage tube (Reference 4).

Unsuccessful methods included storage of the video on a video tape loop. This method required timing to one part in 500,000 in the tape drive system in order to have the delayed video come off the loop at the same time that the subsequent data frames were read out of the camera in order that an analog subtraction could be made. Tape stretch and variances in tape capstan speed introduce errors in the playback which appear as displacements of the stars in the video frame similar to jitter on the scan ramps. These displacements are generally larger than the resolution element.

A second method tried was a small-scale shift register transferring threshold video (2 black levels). The length of the shift register needed in a full-scale system would be equal to the number of resolution elements, or about 500,000. The system works well enough for small shift registers but if applied to a full-frame MTI system, would require a shift register beyond the present state-of-the-art. It should be noted that this extremely-long shift register must shift 500,000 successive times without error to work properly.

In an attempt to eliminate the long shift register, most of which would contain zeroes representing the absence of a star or satellite, a method was tried where the video is thresholded and at the detection of a target or star, the one-shot timer is started with a duration equal to the frame time. During the readout of the next frame, the one-shot duration would be completed at the instant that the read beam was at the same point in the frame as it was during the first frame when the timer was started. If there were also a video detection at that point, then the target had not moved and would be ignored as a star. This method suffers from timing jitter in the one-shot. In an effort to eliminate the timing jitter, a 10^6 count-down chip, run from the camera clock, was used instead of the one-shot. This method works well. This circuit will handle one star in the field-of-view, delaying the video until the next frame. One equivalent circuit is required for each star expected, which can reach a thousand or more. The costs for this type of MTI could be several tens of thousands of dollars for components alone. The author believes it would be useful to explore this method further on a limited scale, say for ten lines of video out of a whole field.

An untried method of delaying threshold video, for an integral number of frames, is a sonic delay line. It appears that the frame-to-frame timing jitter on the line is acceptable but the long term (hourly) drift in the total delay is large. This can be compensated by varying the scan rate slightly to match the slowly varying delay of the line. The technique might be explored as an alternative to the above methods.

The most common method of storing video for an integral number of frames is the storage tube or a storage disk. The reference frame video is read into the tube during one frame and read out during the same time as the next frame is read out of the sensor. The two signals are then subtracted in an operational amplifier. The output of the subtraction should be zero for stars and background, and a positive or negative-going pulse for the positions of where the target was in the first and the second frames. This method offers the advantage that the same ramp-generating circuitry may be used in both the camera and the storage tube. Nonlinearities on the ramp are then cancelled. Frame-to-frame jitter on the ramps, hoever, will still affect the superpositioning of resolution elements in the reference and data frames. Jitter in this method is likely to be far less than the timing jitter encountered in the one-shot delay line.

The storage tube may be used as an analog storage with the video fed directly into the tube or as a "two shades of gray" device storing threshold video. This method is similar to the one used on the fast MTI channel of the FSR-2 system, which worked well at the relatively low star-background density of that system. If the storage tube is used as a fully analog storage device, the problem of losing the faintest satellites by thresholding does not occur, but the noise mechanisms in the system are additive. This is unimportant if the output is to be displayed to an operator. But, if the output were to be thresholded and detected automatically, it would be better to threshold first and then store, since the storage tube generally adds its own noise during the writing and reading of stored information.

RESULTS AND CONCLUSIONS

The test bed for television sensors used in satellite detection was employed for a wide variety of missions, in addition to actual testing of television sensors. These included (1) the generation of both real-time and video-taped data for the evaluation of candidate MTI devices, (2) the generation of data used in studies of the human factors involved in the man-in-the-loop MTI, (3) the evaluation of search pattern generations techniques, (4) the development of video sampling techniques for the capability to collect space-object photometric signatures for identification, (5) the validation of the accuracy of the star-scene simulator, (6) the acquisition of satellites for positional hand-off to other sensors (such as the collocated OPOS 24-inch SOI telescope and the AFAL Cloudcroft Observatory), and finally (7) the use of the entire system as a prototype operational sensor working as part of the present Spacetrack System with the Aerospace Defense Command. Since the test bed was utilized to support a large number of Government agencies and contractors, the detailed results of most of these tests and evaluations are contained within reports issued by AFAL and by those agencies and contractors. A list of the major contracts supporting this effort is given in Appendix I.

This document is one of three reporting directly on the facility. The other two are:

AFAL-TR-75-152, "Operational Experience with a Ground-Based Satellite Detection Facility", P. Manly, describing the operations conducted with the NORAD Space Defense Center in which the facility was operated as a part of the Spacetrack System, observing satellite positions and optical signatures and searching for unknown or "lost" satellites.

AFAL-TR-77-151, "Star-Scene Simulator for Use with Television Sensors", P. Manly and R. Wiensch, describing the development fabrication, calibration and use of the star scene simulator employed at the facility.

In conclusion, it has been demonstrated through the regular use of the test bed facility that the technology required in the systematic detection of satellites to synchronous attitudes is within the state-of-the-art. Although the facility as described in this report was designed to fill primarily a research role, and therefore was provided with flexibility required in the R&D exploration of the pertinent variables, it lacked some of the adjuncts required in the operational mission. These include a large data-handling capacity to process on-site the satellite orbital and look-angle calculations and space-object-identification information. Such adjuncts will not require an advance of the state-of-the-art, however, but rather will be comprised of engineering applications of technology that is well understood. In order to continue the effort initiated at AFAL, the test bed facility has been transferred to ESD/OCT, Project 4966, for incorporation into the Lincoln Laboratory-managed Experimental Test Site of GEODSS located at the Rimfire Site, White Sands Missile Range, near Socorro, New Mexico.

APPENDIX I

LISTING OF MAJOR SUPPORTING AND RELATED CONTRACTS

Contract Number	Contractor	Purpose
F33615-72-C-0568	AFAL/RCA	Fabrication of IVK-531-I^2V Camera
F33615-72-C-0569	AFAL/RCA	I^2V Tube Assembly
F33651-73-C-1169	AFAL/RCA	Laboratory and Field Calibration of IVK-531-I^2V Camera
F33615-73-C-0336	AFAL/RCA	C-21145 SIT Tube and Installation
F04701-73-C-0224	SAMSO/RCA	Fabrication of IVK-531-SD Analog MTI Device
F04701-73-C-0269	SAMSO/Northrop	Sensor Study Resulting in Fabrication of Camera with WX32432 Tube and Subcontract to Goodyear
Northrop Subcontract #194	Northrop/Goodyear	Fabrication of Correlator
F33615-73-C-0381	AFAL/SRL	SRL Camera and Return Beam Head
F33651-74-C-1080	AFAL/SRL	SRL Manpower
F29651-74-C-0076	AFAL/Group 128	25" Telescope and Dec Axis
F33651-74-C-0104	AFAL/Group 128	Telescope Polar Axis and Mount

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4. M. J. Cantella and H. Logemann, "Analogue Moving Target Indicator (MTI)", SAMSO-TR-74-78 (January 1974).

5. "Satellite Detection Experiment", Goodyear Aerospace Corporation Final Report Number GER-15973-S/4 (21 November 1973).

6. P. L. Manly, "Space Object Search and Detection Studies with a Ground-Based Television Sensor", AFAL-TR-75-152, (July 1975).

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12. "Report on IBM Processing of 4 July 1973 Cloudcroft Data", IBM Corporation/Federal System Division. (10 January 1974).

13. M. J. Cantella and H. Logemann, Jr., "Analogue Moving Target Indicator (MTI)", AFAL-TR-23 (January 1974).

14. Melvin R. St. John. Private Communication.

15. L. Arlan, et al., Ibid p. 11.

Figure 1
Vidicon Camera Head Assembly

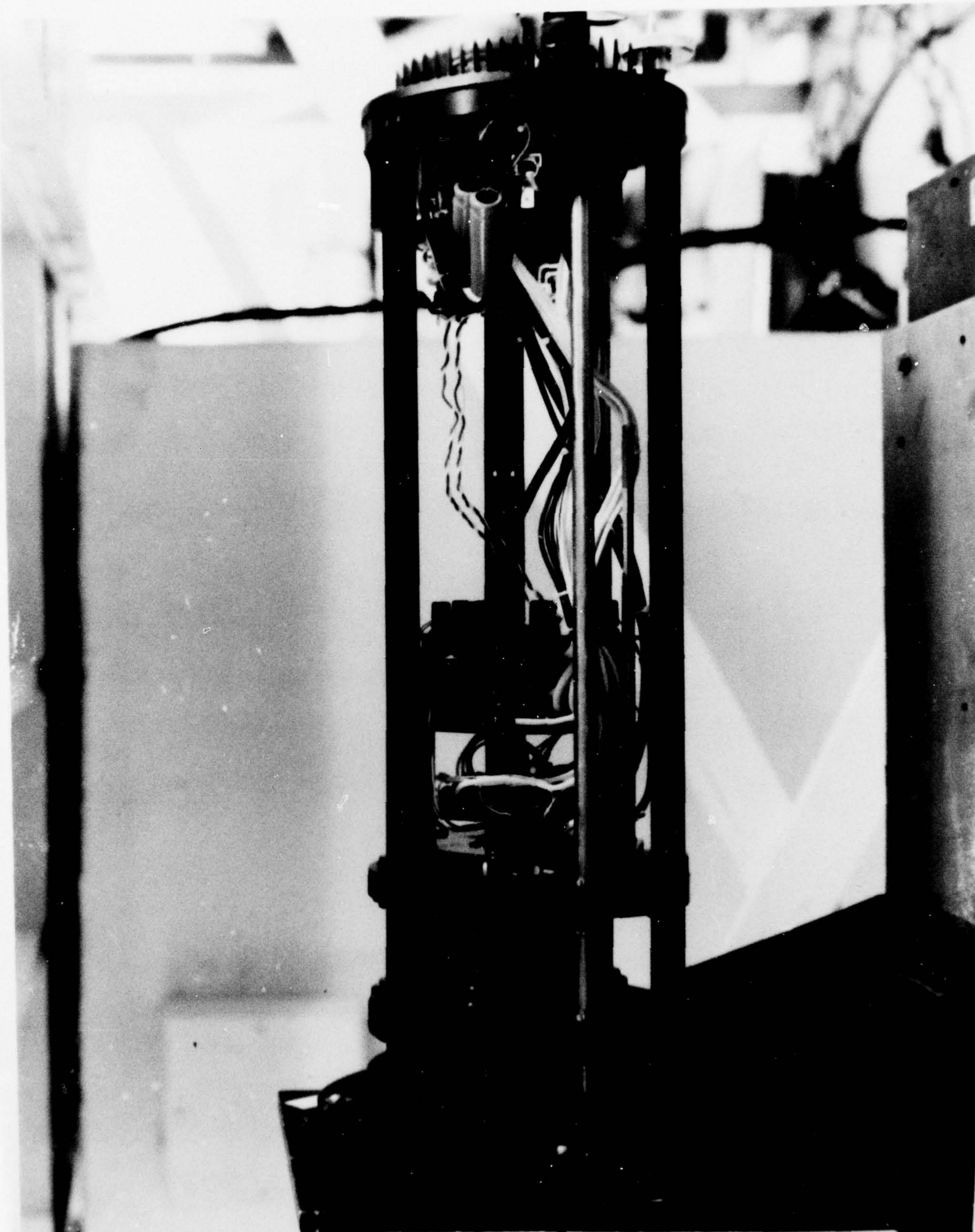


Figure 2. SRL Camera Head on 25-inch Telescope

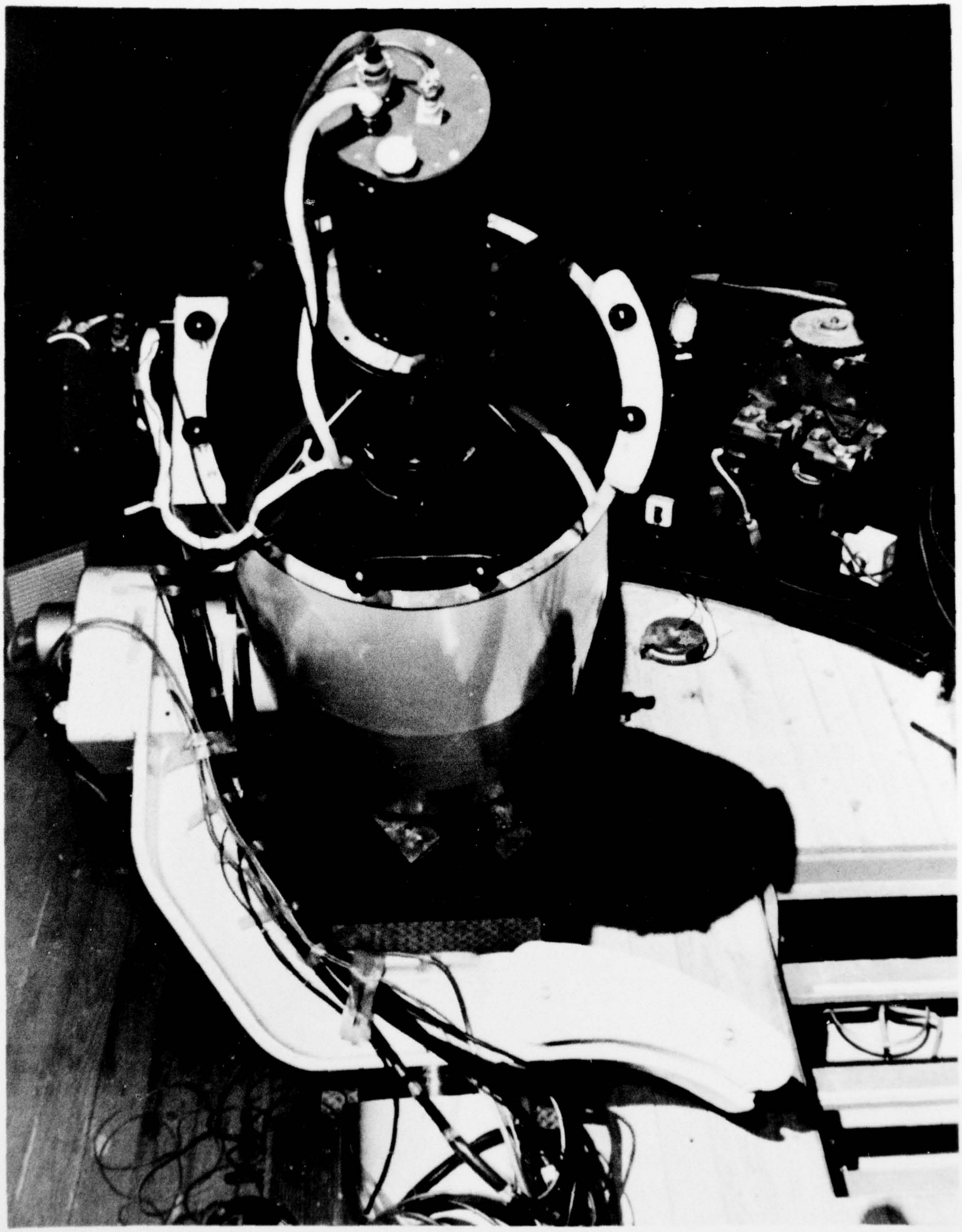
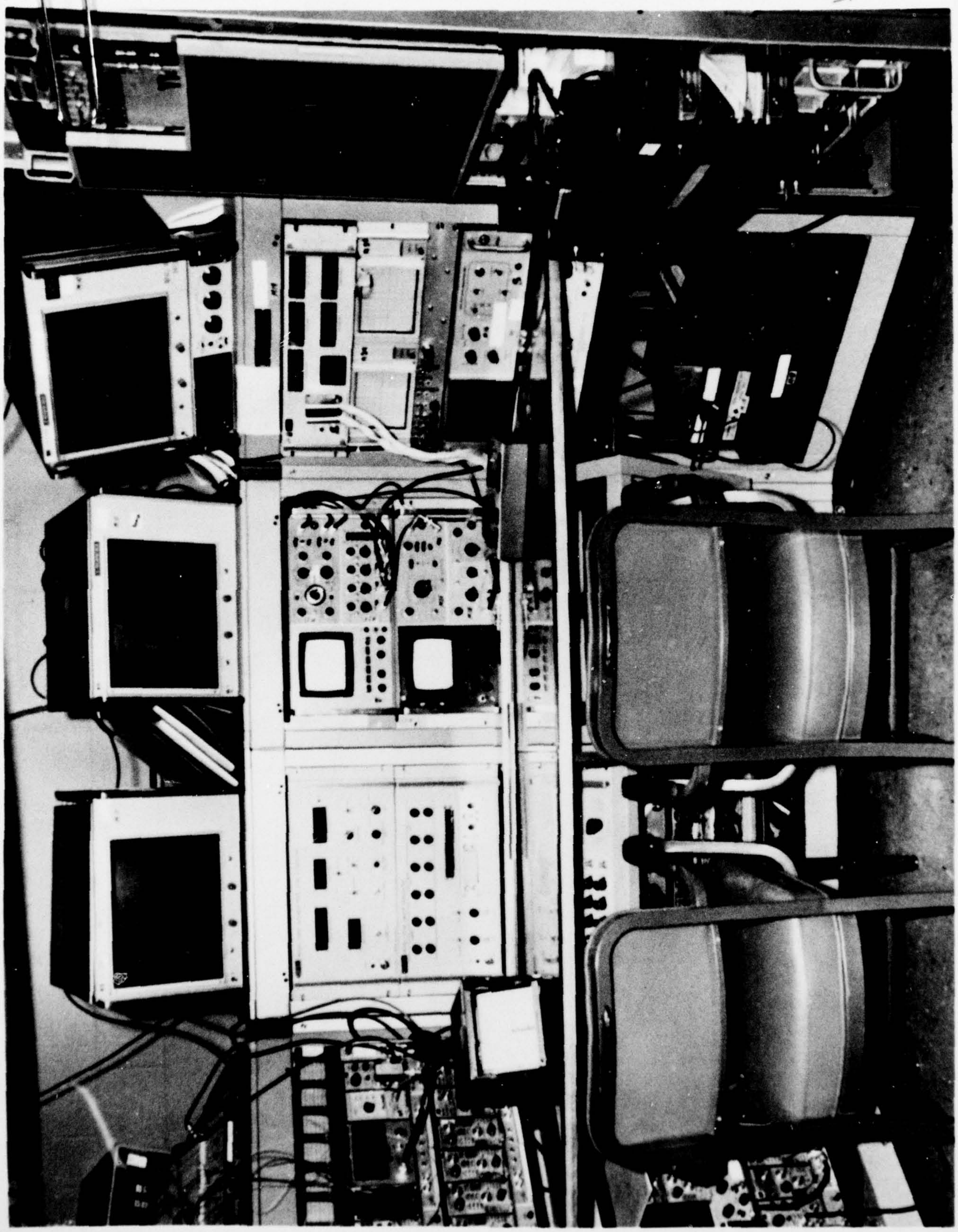


Figure 3. Test-Bed Control Console



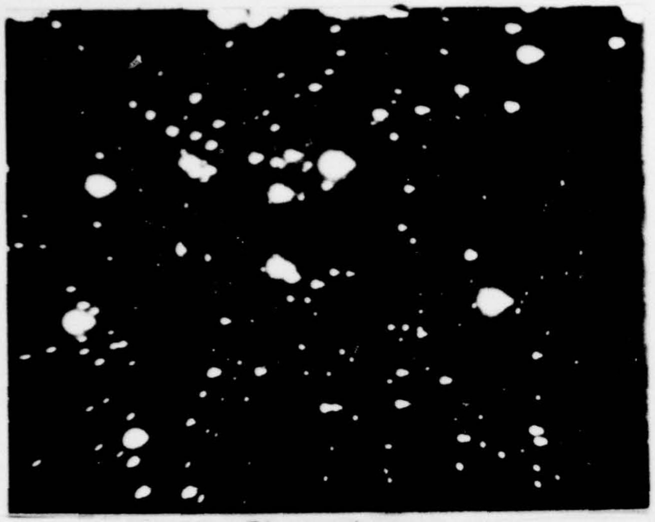


Figure 4a

Normal Monitor Presentation of Star Field

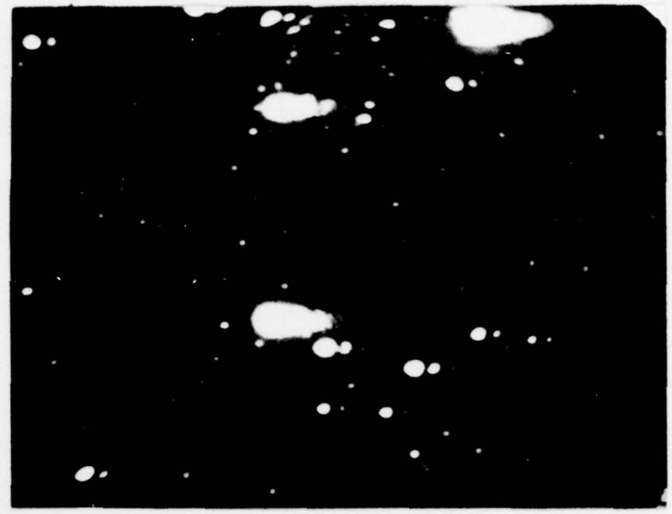


Figure 4b

Underscanned Presentation of Central Portion of Figure 4a

Figure 4c

Further Expansion of Display Showing Individual Scan Lines

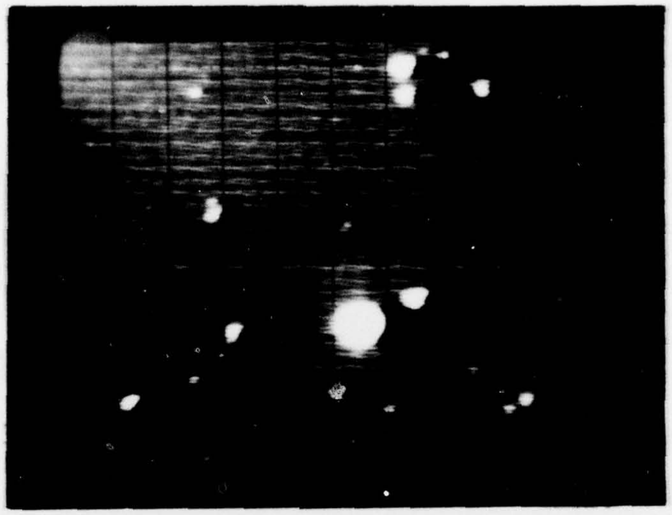


Figure 5a
Underscanned Monitor Presentation of Selected Area #110. 26% X 26% Underscan.

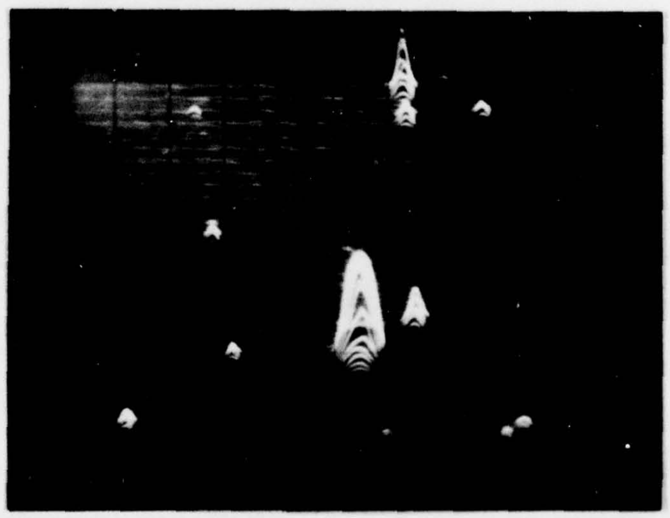


Figure 5b

Pseudo Three-Dimensional Display of Figure 5a by Addition of Video to the Underscanned Vertical Ramp

BW

2 MHz

1 MHz

0.5 MHz

0.25 MHz

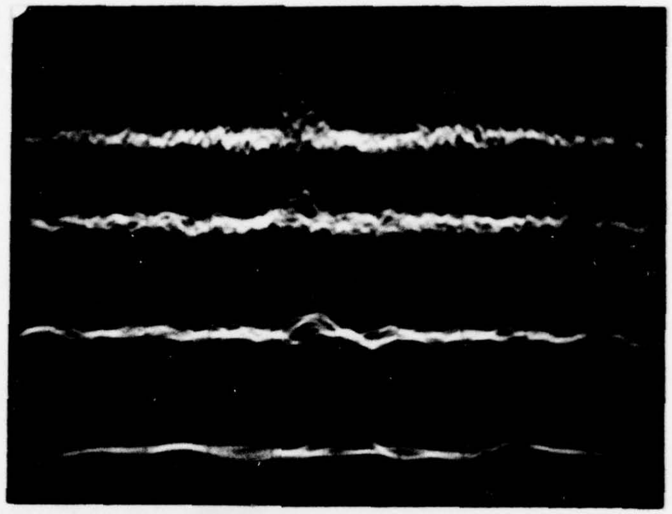


Figure 6

Variation of Signal with Variation in Bandwidth. Display of 10 Lines Adjacent to a Test Star when Operating at 4 Frames/Sec, 650 lines/frame.

Figure 7

Top Hat and Sombrero Effects, 3-Dimensional Display of SIT Response to a Bright Star. Central Peak (Sombrero Crown) Represents Optical SpotSize. Plateau Represents Bloomed Image Normally seen on Saturated Signals. 4 frames/sec, 650 lmes/frame 0.5 MHz Bandwidth

Figure 8.

Operation same as in Figure 7. Bandwidth 2 MHz. Diodes can be seen in the regular structure in the plateau of the bloomed area of the bright star. Defocusing the electron optics, a grid can be found just in front of the target exhibiting similar patterns although with a different grid orientation.

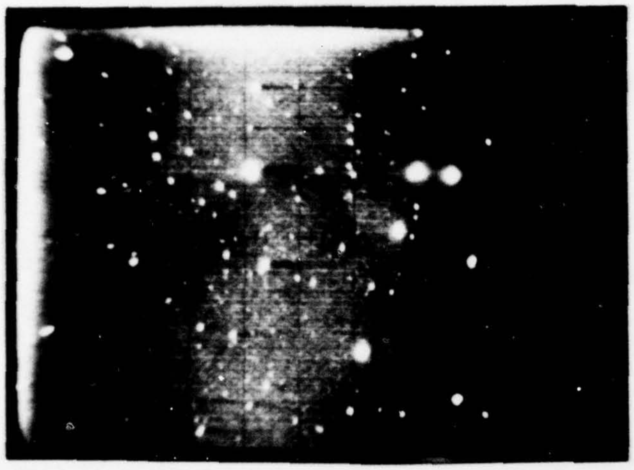


Figure 9a

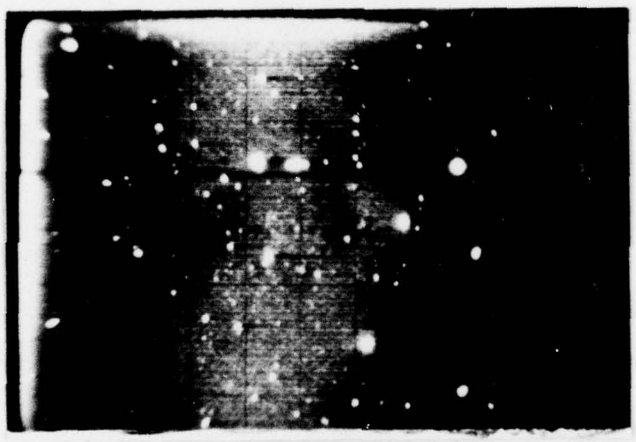


Figure 9b

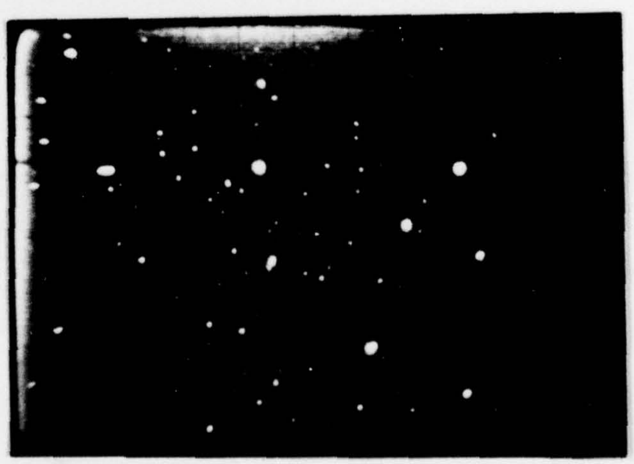


Figure 9c

Figure 9.

Typical display presentations (full scan) of a satellite passing through star field, taken several seconds apart to enable satellite detection by comparison of images. 30 June 1973.

Figure 10

Scan converter display showing summation of several seconds of data. Telescope is stepped slowly Southward with no siderial drive. The two synchronous satellites appear as vertical streaks.

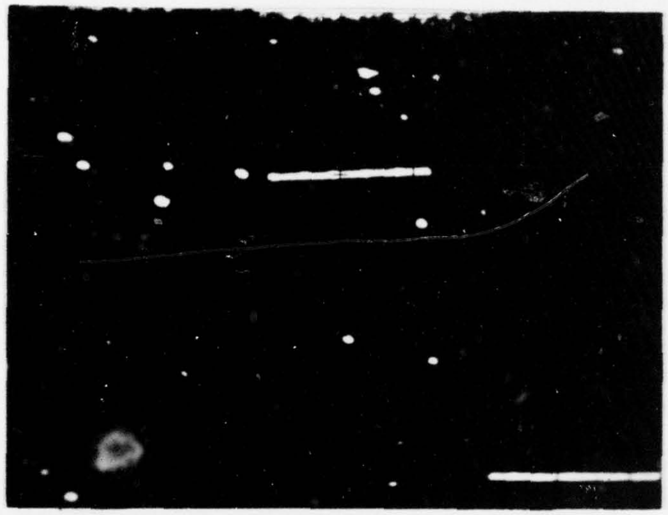


Figure 11

Two synchronous satellites generate streaks. (5 Mar 1975). Scan converter presentation showing several seconds of summed video.

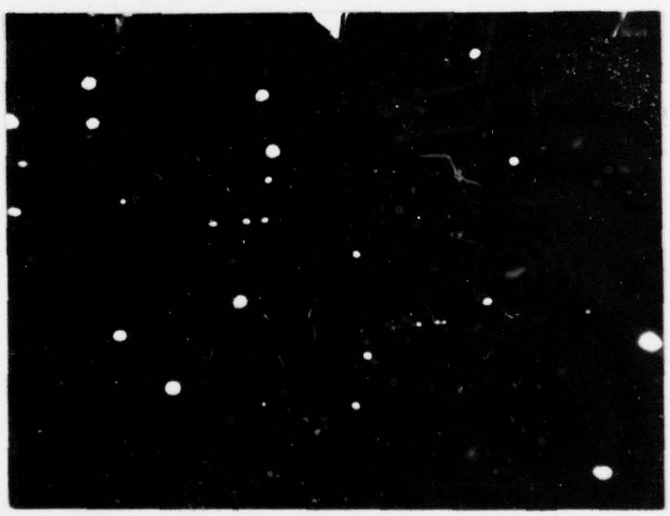


Figure 12

Two synchronous satellites which are varying in brightness above and below threshold generate lines of dots as they flash at different rates. (5 Mar 1975). Scan Converter Presentation showing several seconds of summed video.