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TECHNICAL REPORT NO. 17

INVAR - A FINAL REPORT

Scientific Engineering Institute

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June 30, 1965

SUMMARY

INVAR is a program to produce a high-resolution ground mapping radar to be used as an auxiliary sensor in the A-12 aircraft. The airborne equipment is the APQ-93 side-looking radar including a synthetic antenna. The hologram record is optically correlated on the ground by the 9015 optical ground processor. The final map is on two parallel strips of 9-inch roll film and represents a swath 20 miles wide over a range interval from 20 to 40 slant miles from the aircraft. The present equipment has a resolution of 25 feet and weighs 950 pounds.

Two complete flyable radar systems with spares, a third experimental system for flight tests in an F-101, ground support equipment, one continuous optical processor, and two static processors for detailed work have been produced under the program.

The radar includes a CFA transmitter which provides a 30 nanosec pulse with a peak power of 1 megawatt at a prf of 4 kc; a receiver with a parametric amplifier front end and a noise figure of 6. 5 db; a recorder with a 1 mil spot size; and a motion compensation system that steers the antenna and controls the LO frequency in the receiver. The optical correlator uses a carbon arc source, a wedge interference filter for range compensation and has a resolution capability of 20 1/mm on axis.

The radar has been test flown in an F-101 aircraft for a period of three years. Minor changes were made in the recorder and the correlator to accommodate a reduced altitude of 45, 000 feet and a speed of 850 knots. Under these conditions the map is 10 miles wide instead of 20, and under most conditions is about 90 miles long which is the limit of full speed flight for the F-101. These maps include all types of

targets and are believed to be the best radar maps in existence. Resolution in the range direction is limited by the transmitted pulse length and the bandwidth of the receiver to approximately 20 feet. Resolution in the azimuth direction is approximately 10 feet. However, corner reflectors separated 5 feet on the ground have been resolved in a radar image.

With the exception of resolution, the present INVAR system has been able to fulfill most of the specifications which were contained in the original proposal of 1960. It is now felt that the original resolution of 10 feet in both directions from full altitude can be obtained by a combination of available modifications. In addition to a resolution improvement, there is an urgent need to discover why the present maps do not reveal the detail that is implicit in the resolution already demonstrated. Recent theoretical analysis has shown that linear signal processing is necessary for high quality images. The original specifications compromised linear processing in order to accommodate the wide dynamic range of radar targets. It now appears that additional effort is necessary to extend the dynamic range of the recording system and to reduce the background light in the optical correlator. In particular, additional testing and experimenting on the optical correlation process is necessary to evaluate the practical limits of the dynamic range of the recording system and the minimum detectable signal in a practical correlator. This problem is further complicated by the fact that both the radar and the correlator use coherent sources for illumination. However, information gained from such an investigation is almost essential for an optimum design of a second generation system and promises the best chance for improved radar mapping, whether the radar is flown in airplanes or satellites.

It is recommended that the radar be given a final test in the A-12, that the quality of the radar image be improved and that a shorter transmitter pulse be incorporated in the present system.

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I. INTRODUCTION

INVAR is a program to produce a high-resolution ground mapping radar to be used as an auxiliary sensor in the A-12 aircraft. The airborne equipment is the APQ-93 side-looking radar including a synthetic antenna. The hologram record is optically correlated on the ground by the 9015 optical ground processor. The final map is on two parallel strips of 9-inch roll film and represents a swath 20 miles wide over a range interval from 20 to 40 miles from the aircraft. The present equipment has a resolution of 25 feet and weighs 950 pounds.

The APQ-93 operates in all kinds of weather including cloud cover and darkness and on those occasions when it is not possible to wait for good weather conditions it can get radar pictures which can be used for a "crises evaluation". Another advantage of the radar is that targets of interest present a different return at X-band than they do at visible light. Most metal objects and many man-made structures have an almost specular character at radar wave lengths. In this regard, radar provides the photo interpreter with additional information that can be used to increase his knowledge of the mapped areas or to decrease his time in locating and identifying certain specific targets.

In the original proposal in 1960 the resolution was set at 10 feet. It was felt at that time that 10 foot resolution would allow photo interpreters to discern and identify small installations; to recognize changes in these installations; determine a buildup or withdrawal of military concentrations; to spot new installations; new scars on the landscape; find new fenced areas. However, in 1960 there were no high quality radar maps made from holograms and it has since been learned that radar images made from holograms produced by synthetic arrays are not as clean as the images produced by conventional radars of the same resolution. This effect is associated with the coherent nature of both the illuminating radar and the optical correlator. Nevertheless, the resolution of synthetic antenna systems at these proposed ranges is so much better than conventional radars that the maps made with synthetic antennas are far superior. S.E.I. believes that the maps made from the F-101 in the INVAR program are the best radar maps in existence.

The original 6B proposal was made by S.E.I. and was prepared in cooperation with Westinghouse Aerospace and Itek Corporations. S.E.I. has acted as technical supervisor for the government. Westinghouse has designed and built the radar and conducted the tests in an F-101-B. Itek has designed and built the optical ground processor, correlated the flight test films, and under a separate sub-contract to Westinghouse has designed and built the recorder. Minneapolis-Honeywell under subcontract to Westinghouse has designed and built the single axis platform for motion compensation.

In the course of the design of the equipment it became apparent that the desired 10 foot resolution could not be achieved within the limitations of weight and space imposed by the vehicle, and the requirement upon resolution was formally reduced in January 1963 to 25 feet. Also at that time other changes to the transmitter and the motion compensation system were planned which increased the total weight of the equipment by about 50%.

Delivery of the first radar set was accepted by the government in January 1962. The ground processor had been accepted the previous December. The first flight test that produced satisfactory data occurred in May, 1962. During 1962 and much of 1963 various modifications to the radar and the processor were invented and implemented so that by December 1963 very good radar maps were made in flights S-86, S-87 and S-90. The complete radar and processor were shipped to the Western site in March of 1964 for flight testing in the A-12. That opportunity did not occur and the equipment was therefore sent to Baltimore in November 1964 to await a later opportunity for final testing and to serve meanwhile in the F-101 flight test program.

The radar and ground processor are now located at Westinghouse, Baltimore, where flight tests are continuing in the F-101. Itek has just completed a noise study on the optical processor utilizing the spare glassware from the main instrument. S.E.I. has been engaged in experiments and analysis to improve the image quality of the radar pictures.

The flight test program at Westinghouse is expected to continue until the end of the year. Various minor modifications of the system may still be made, but apart from final tests the original program has been essentially completed. S.E.I. is therefore concluding its active participation in the program.

This is a final report on the phases of the program supervised by S.E.I. and is intended to give a general account of the INVAR system and an appraisal of its capabilities and future prospects. It describes the major components within the system stating specific parameters and the measured performance for each component and indicates those limitations which are most serious. A few examples of flight test results in the F-101 show explicitly the present performance and serve as a guide for the predicted performance in the A-12. Finally, there is a section on recommended future developments which could improve the resolution and the map quality. An appendix includes photographs of the delivered equipment which indicate its general size and shape.

II. A GENERAL DESCRIPTION OF THE INVAR SYSTEM:

1. Original Design:

The original design of the INVAR system, as described in Technical Proposal 6B of April 1960[1], specifies a high resolution ground mapping radar with an overall resolution of 10 feet over 18.5 N.M. on 9" film and an expected weight of 600 pounds. The optical processor is a separate unit on the ground. In an effort to accomplish these design goals, the following developments were undertaken:

a. A transmitter to provide a 10 nanosec pulse with a peak power of 1 megawatt and a prf of 4 kc.

b. A compatible receiver with a noise figure of 7 db.

c. A recorder with a ½ mil spot size, i.e. 80 1/mm. capability.

d. A motion compensation system such that the overall phase stability of the radar and the vehicle would allow utilization of the synthetic antenna for 3/4 of a second.

e. A ground processor capable of producing useful information over 9 inches of film at a resolution of 40 1/mm.

These developments fell short of the goals for resolution by a factor of 2½ but were otherwise largely successful.

2. Present Design:

The present design as described in a status report[2] dated January 1963, has an overall resolution of 25 feet and a total weight of 950 pounds including the frame and truss. The delivered equipment has the following features:

a. A transmitter that provides a 30 nanosec pulse with a peak power of 1 megawatt at a prf of 4 kc.

b. A receiver with a noise figure of 6.5 db.

c. A recorder with a 1 mil spot size

d. A motion compensation system that has not been flight tested.

e. An optical correlator with a resolution capability of 20 1/mm. on axis.

Although the resolution that is claimed has not been demonstrated from design altitude, a resolution of 5 feet in azimuth and 20 feet in range has been demonstrated in an F-101 from one-half design altitude. In order to reach the original goals the resolution should be improved by a factor of 2½, and in order to improve image quality, the S/N ratio and the dynamic range of the system should probably be increased. Such an improvement requires that each component and sub-system performance be examined and that some or all of the following be accomplished:

(1) better signal to noise ratio, (2) increased dynamic range, (3) improved stability, (4) wider bandwidths, (5) smaller recorder spot size, (6) smaller final map area, (7) less grainy films, (8) less stray light in the correlator. Therefore, as the description of the system and its components is read it is also helpful to bear in mind what the requirement for improved resolution might mean for each particular part of the whole.

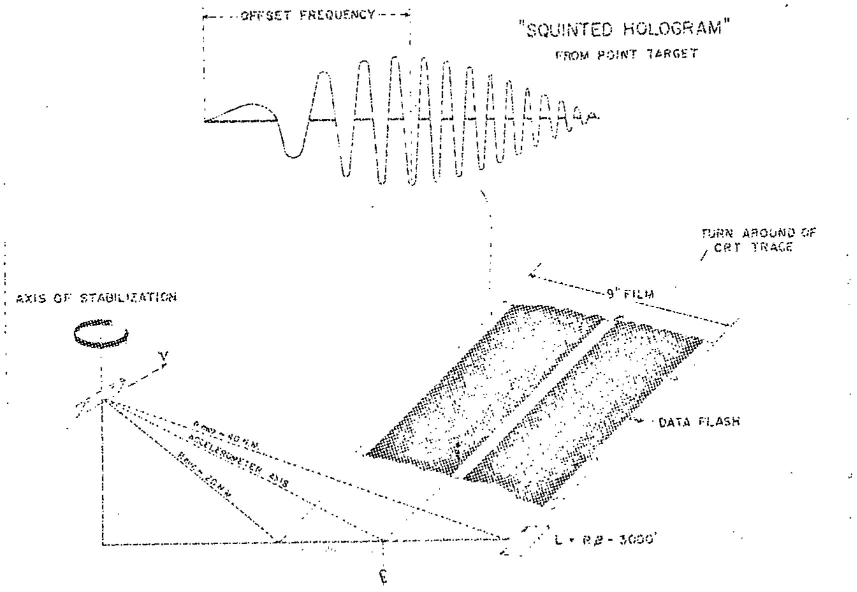


Fig. 1 - Schematic of APQ-93 System Operation

3. System Operation:

As shown in Figure 1, the radar, represented by an antenna, is designed to fly at an altitude of 90,000 feet and map a swath on the ground of 18.5 N.M. with a maximum slant range of approximately 40 N.M. The beam sweeps over the ground at 3000 ft/sec. with the center of the beam directly broadside to the flight path. Under these circumstances a target at maximum range would remain in the beam for approximately one second and half that time for a minimum range target. Returns from a single target are stored on film by an intensity modulated CR beam and have the appearance shown as a "squinted hologram" except that the drawing is exaggerated as there should be about 200 cycles in the pattern instead of the 13 shown.

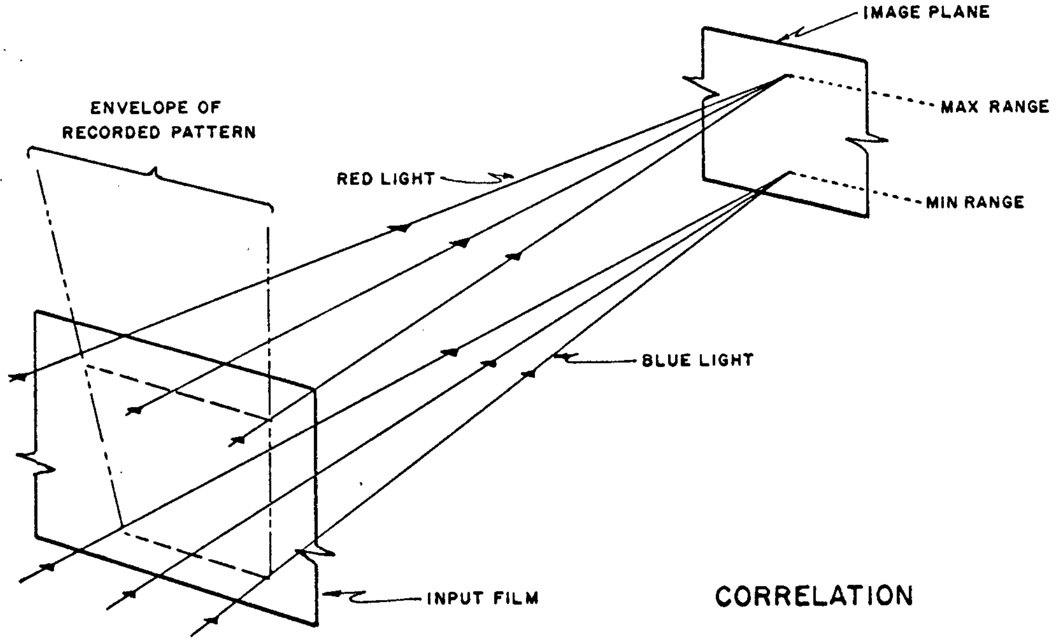


Figure 2. Schematic of Reconstruction Process

The recorder uses a single CR tube with a folded trace that is unfolded optically to produce a two strip map, as shown, on 9 inch film. In this way 1 inch of range data represents 2 miles on the ground while every single point target on the ground is spread out as a hologram pattern over nearly 2 inches of film in the "azimuth" direction.

The optical correlator accepts either the near or far range strip of raw data in its input platten and, as diagrammed schematically in Figure 2, collapses the recorded hologram into a reconstruction of the original point target that produced it. A different color is used for each range interval to compensate for the different focal lengths of the hologram.

In order for the radar system to provide holograms that focus properly it is necessary either that the antenna travel in a perfectly straight line or that the phase of the recorded signal be varied to compensate for any irregularities in the flight path. Uncompensated lateral motion of the aircraft will cause image defects such as lateral shift, improper focus, side lobes, and ghosts. Therefore, the specifications for system stability are dictated by the requirements for image quality[3].

The stability of the system is maintained in accordance with the diagram shown in Figure 3. The INS by Honeywell steers the antenna broadside to the flight path with an absolute accuracy of less than a beamwidth and a relative accuracy of a small fraction of a beamwidth.

When the antenna is nearly broadside the frequency of the returning signals will lie close enough to the frequency of the transmitted "stalo" frequency so that the beat signal between the two will fall in the bandpass of the DFT. Under this circumstance the DFT monitors the average doppler return and senses any deviation from zero doppler. The sensed error is used as a fine control on absolute steering.

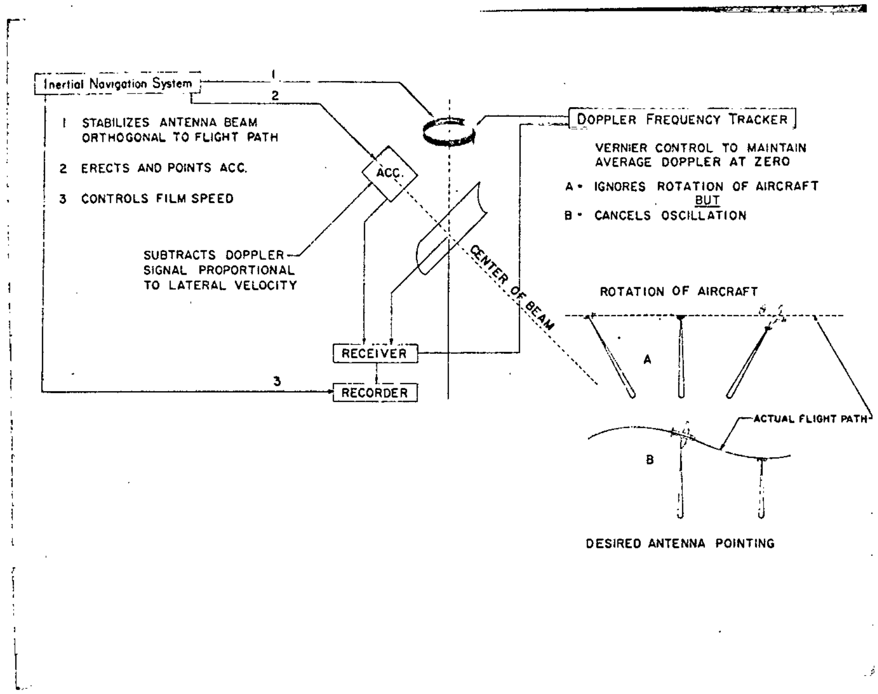


Figure 3. - Schematic of Motion Compensation System for APQ-93 Radar

The time constants of the INS and DFT are different so that rapid rotations about the yaw axis as in Drawing A will be removed by the INS and ignored by the DFT. But slow oscillations, magnified in Drawing B, will be compensated for by the DFT and are presumed to be beyond the limit of detection by the INS.

In addition to steering the antenna, the INS supplies a signal to erect the accelerometer which detects the lateral motion of the aircraft. The output from the accelerometer controls the phase of the recorded hologram by adjusting the frequency of the variable frequency oscillator (VFO) in the receiver. In this way, the Motion Compensation System maintains the radar antenna in almost straight and level flight and cancels the residual perturbations electronically before the radar hologram is recorded.

The space available for the antenna permits stabilization about only one axis, namely the yaw axis. Partial corrections for pitch or changes in angle of attack can be made, however, by using the single axis control to stabilize the direction of the central axis of the fan beam. This maneuver maintains the correct position for the center of the beam pattern but causes some degradation at the edge of the map. If the aircraft's ground speed changes, the INS will modify the film speed in the recorder accordingly.

From analyses on the present equipment[4] and from flight test data in the F-101 that is similar in performance, it is concluded that the motion compensation is more than adequate for a final map with the present 25 foot resolution.

4. Description of the Major Components:

The equipment produced under this program comprises two complete flyable radar systems with spares, a third experimental ("brassboard") system for flight tests in the F-101, ground support equipment, one continuous optical processor, and two static processors for detailed work. The equipment is located at Westinghouse Aerospace, Baltimore, and is currently producing radar maps for an F-101 aircraft. Photographs of the major components are included in Appendix A.

4.1 The Transmitter:

Three models of the present transmitter[5] (Figure A-1) have been delivered. It is enclosed under pressure in a semi-spherical tank 40 inches in diameter. It weighs 264 pounds. It delivers a 30 nanosec. pulse with a peak power of 1 megawatt at a PRF of 4 kc. from a crossed-field amplifier (CFA) and a TWT driver.

The original transmitter employed a resonant ring[6] developed at S.E.I. which produced a 10 nanosec pulse of 250 kw peak power. This transmitter represented an advance in the state of the art and achieved the pulse width that was originally specified, but the power output could not be increased and the ring had to be replaced.

The present CFA does have adequate power for the present operation but the 30 nanosec. pulse is three times as wide as originally planned. However, when used with a 1 mil recorder to map a 20 mile swath, the 30 nanosec. pulse will not degrade range resolution appreciably. It represents a state-of-the-art development for short pulse, high power, airborne transmitters. If the pulse width is reduced, or if linear signal processing can be successfully maintaned more power will be required. More is said on this topic later.

4.2 The Recorder

Four models of the present recorder[7] (Figure A-2) have been delivered. The package is 47 inches long, 14½ inches wide, and 19½ inches high. It weighs 185 pounds and holds 500 feet of thin base (3- mil) or 250 feet of thick base (5.5 mil) Eastman Kodak Plus-X film. It has a single Westinghouse WX4903 CRT with a p-11 phosphor which displays a rectangular pattern 4¼ inches long by ¼ wide. The pattern is produced by the combined action of a triangular sweep and step deflection circuits so that when it is unfolded by two parallel optical channels the two ends of the sweep trace are joined end to end on the nine inch data film.

The video signal is applied to the CRT grid to produce a corresponding variation in density on the recording film. The film is transported past the imaging slit at a speed that is precisely synchronized with the aircraft's ground speed.

In the original design the unfolding of the CRT sweep was to be done by means of a fiber array. The required array of optical fibers was built and achieved a resolution of 700 lines/inch, but it produced severe streaking. A second fiber-optic CRT[8] with only a single trace was built and tested in excess of 1000 lines/inch with no streaking but it was never incorporated into a recorder. It is presently being flown by Conductron Corp. in their experimental system. Also, in the original design the CRT was intended to have a $\frac{1}{2}$ mil spot everywhere along the $4\frac{1}{4}$ inch trace. In practice the best tubes currently available produce a spot approximately 0.65 mil at the center of the trace. Such measurements are made using about 11 cubic feet of laboratory power supplies with adequate shielding of either space or mumetal or both. The present recorder in the F-101 environment performs at 40 1/mm or 1000 lines/inch.

Other recorder problems that required considerable attention were the development of the high-voltage power supply for the CRT, the design of a variable speed film drive, the elimination of stray magnetic fields which perturb the CRT beam, the design of adequate vibration isolators, and the design of a flat optical image field.

4.3 The Receiver

The present receiver[5] uses a parametric preamplifier, a TWT rf amplifier, two IF amplifiers with a band-width of 60 Mc, centered at 120 Mc, a synchronous detector and a bi-polar video amplifier with a bandpass of 45 Mc. The response to a 30 nanosec. half-sine wave pulse stretches the pulse approximately 10%. The receiver uses a stable oscillator (STALO) as a reference signal to determine the phase of the received signal; a variable frequency oscillator (VFO) to maintain the desired"offset" and to adjust the phase of the recorded hologram in response to signals from the accelerometer; a separate channel for the DFT; and other specialized circuits. It has the required bandwidth and shaping for the present transmitted pulse; and the stalo is stable to a few parts in 10^{11}. If a new transmitter were to be built with a shorter effective transmitted pulse, then a new receiver with commensurate increase in bandwidth would have to be built also.

4.4 The Antenna

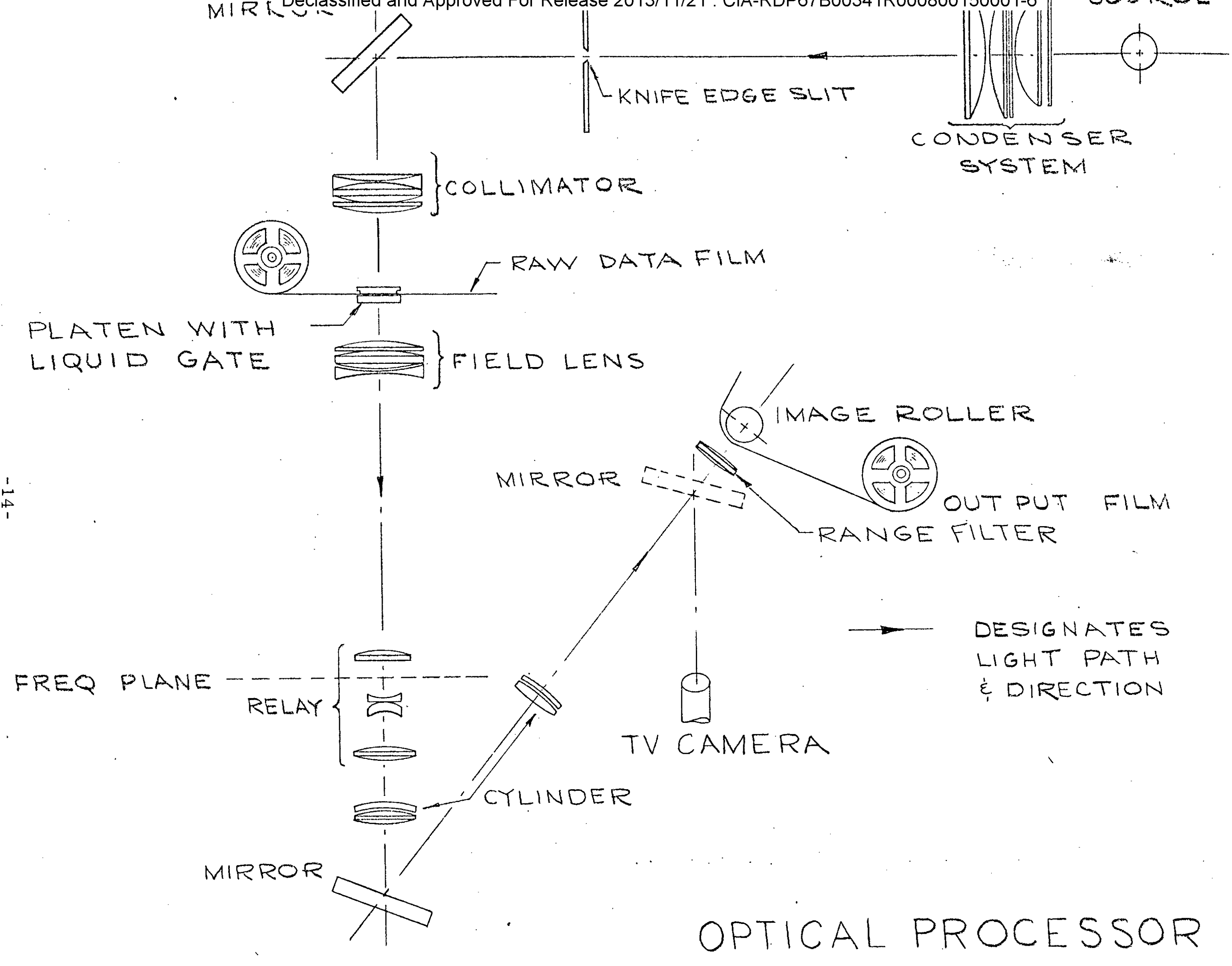
The present antenna[5] (Figure A-3) has a rectangular aperture 100 inches by 13 inches. It is composed of slotted waveguide rigidly supported by a honeycomb structure and fed from the center so that the radiation is broadside to within 15 minutes of arc. The beam width is 0.75 degrees between half-power points in azimuth while the vertical beam has a $\csc^2\theta \cos\frac{\theta}{2}$ pattern of approximately 20 degrees in width. The maximum gain is 31.5 db. This antenna is some 3 feet shorter than the original proposed design because of space limitations in the aircraft. The reduction in length has broadened the beam somewhat and reduced the gain by 2 db.

The length of the synthetic antenna is equal to the width of the antenna beam which is 3100 feet at 40 miles and is half that at 20 miles. The doppler spread at Mach 3 and X-band radar for this beam amounts to 760 cycles and is independent of range.

4.5 The Ground Processor

The present ground processor[10] or correlator shown in Figure A-4 is an optical system 12 feet long mounted on a steel frame approximately 4 feet wide, 6 feet long and 6 feet high. A schematic of the processor is shown on the next page. Light from the carbon arc is condensed on the knife slit, which is variable in width from 10-120 microns. Light from this line source is rendered parallel in the azimuth plane by the collimator. The data film, contained in a liquid gate, modulates the light beam. The field lens images the knife slit onto the stop at the frequency plane, inside the relay lens. The field lens also converges the real image produced by the hologram in the azimuth direction to a line somewhere ahead of the frequency plane. This real image is relayed to the image film by the cylindrical lenses which are, in effect, one lens made in two parts because of the redesign forced upon the correlator when the film speed of the recorder was increased. The range dependence of the hologram is compensated for by a variation in the color of the light. The range filter at the output then accepts the appropriate color for that range interval. The relay lens images the data film in the range direction onto the output film. The image roller tracks the input film through a close tolerance gear and rim drive mechanism. A TV monitor is available to view the output image with the aid of a mirror as shown.

The input film to the processor is 9½ inches wide and up to 500 feet long with two parallel data strips, the near range and the far range (see Figure 1). The chemical development of the data film is done on the ground under carefully controlled conditions. The output is on two 9½ inch films, one for each strip. Normal processing speed is 2 inches/minute of input data or .45 inches/minute of output film due to the



OPTICAL PROCESSOR

"stretch-out factor", which scales to approximately 30 miles/hr of final output map.

The processor has a resolution of 20 1/mm. in both range and azimuth which means that it can resolve targets separated by 15 feet on the ground when the data film is taken from full altitude or by 7½ feet on the ground when the data is taken at half-altitude as in the F-101.

There is also a Detail Correlator which uses the spare optics from the big machine and a neon gas laser. It can examine any selected area of raw data amounting to 3 inches in azimuth and 4 inches in range. The detail machine allows variation of the individual parameters of focus, squint, tilt, and exposure in order to optimize the correlation for selected data. In addition there is a second detail correlator available in Baltimore primarily as a research tool to investigate and optimize system parameters.

5. The F-101 Flight Test Installations:

Flight tests have been conducted at Baltimore in an F-101 bailed to Westinghouse and flown by Westinghouse personnel. The first recognizable map was made over Annapolis, Md. in May 1962. As of June 1965 there have been 169 flights and it is expected that the flight test program will continue into fiscal 1966. The equipment installed in the F-101 is the same equipment that was delivered for the final vehicle with the following exceptions: (1) the accelerometer is of different design and manufacture, (2) the INS is replaced by an APN-102, (3) the antenna is mounted in an external pod and stabilized only in pitch instead of yaw. Also, for the F-101, the recorder is temporarily modified to take account of the lower altitude and lower speed. (1) the sweep speed of the CRT is doubled, because the range interval covered by the antenna beam is only 10 miles instead of 20. (2) The film speed is reduced to 1.25 inches per second to maintain the proper focal lengths for the holograms. With these changes the holograms recorded at 45,000 feet and at 850 knots can be processed in the same system that will process the final data. An incidental consequence of this change in recorder parameters is that the recorder spot size and the processor resolution limit are less degrading on the present maps than they will be in the final version. Figures A-5 and A-6 show respectively the complete F-101 assembly mounted on the bomb bay door and the antenna pod suspended beneath the airplane.

III. RESULTS OF F-101 FLIGHT TESTS

All of the experimental results for the INVAR system to date have been obtained in an F-101-B aircraft at either half-altitude or quarter-altitude. By January 1965 the maps being obtained at half-altitude had achieved substantially the quality that they now have and are believed to be representative of the results to be expected at full altitude in the A-12. However, when the system is flown at full altitude there will be some reduction in resolution. Specifically, it is expected that the resolvable interval in range will increase from the present value of 20 feet to 25 feet. This increase will occur because neither the recorder nor the processor is quite able to handle twice the present amount of range information. The degradation in azimuth resolution is expected to increase from 10 feet to 15 feet because of increased speed and altitude. With regard to the signal-to-noise ratio, flights at quarter altitude have demonstrated that there is 15 db to spare in S/N ratio and the quality of the map is expected to remain about the same as it is now.

The pictures that are included here were chosen to show typical renditions of good areas, to allow a subjective evaluation of the resolution and image quality obtainable, to show how signal-to-noise ratios affect the maps, and to document the resolution obtained against a corner reflector test range. It should be pointed out that photo interpreters prefer to work with the original negatives and that different contrasts in the printing will affect the appearance of any map.

Flight S-137, flown 6 January 1965 over southeastern Pennsylvania, as shown in the accompanying overlay, Figure 4, has been selected as a typical 45,000 foot flight. The area mapped lies to the right of the aircraft and covers a strip approximately 10 miles wide and 80 miles long.

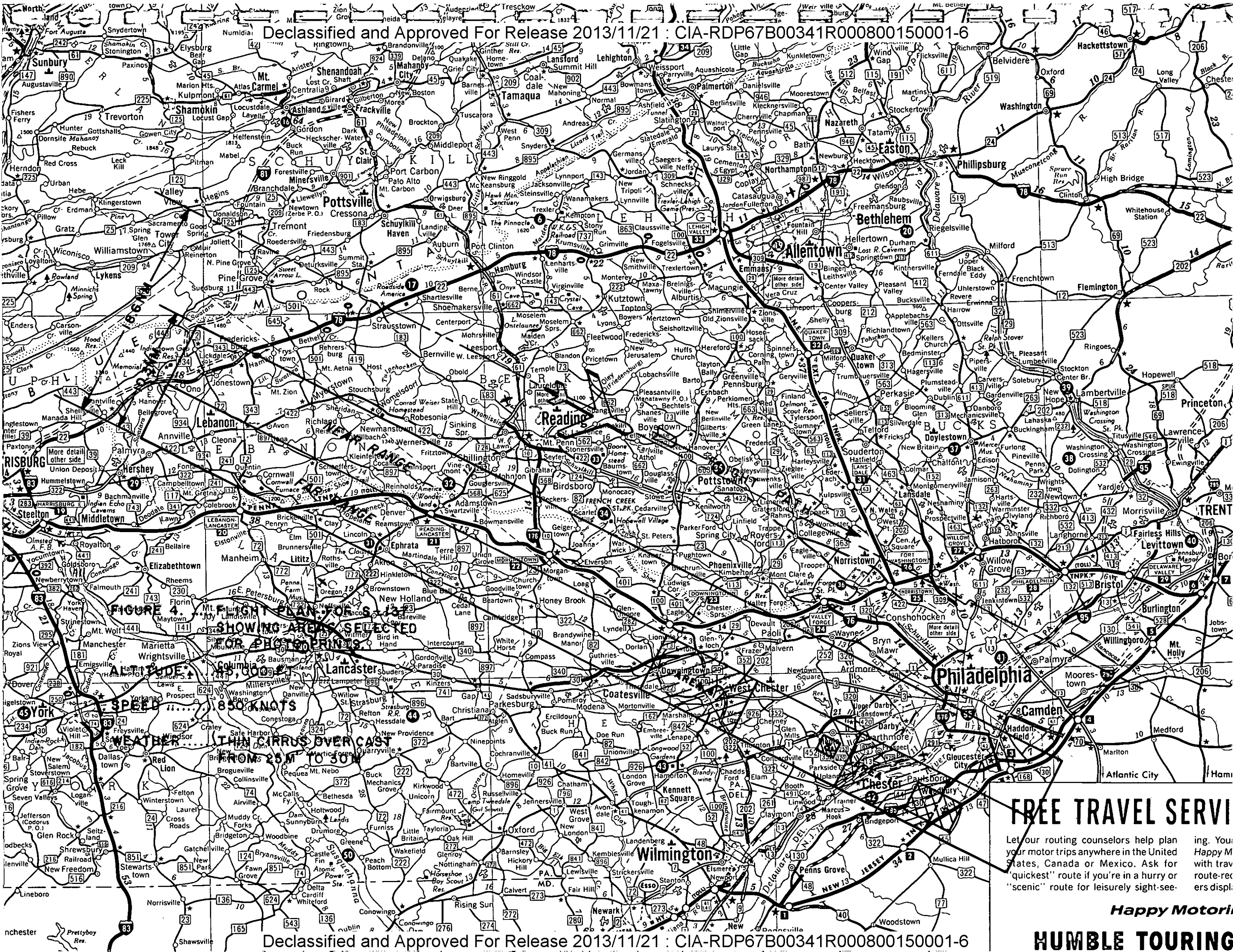


FIGURE 4. FLIGHT PLAN FOR S-137 SHOWING AREAS SELECTED FOR PHOTO PRINTS.

ALTITUDE . . . 45,000 FT.

SPEED . . . . . . 850 KNOTS

WEATHER . . . . . THIN CIRRUS OVER CAST FROM 25M TO 30M

The maximum slant range from the aircraft is 20 nautical miles which corresponds to 18.6 n.m. (112,000 feet) measured on the ground from directly beneath the aircraft. The flight lasted 6 minutes. Mapping was at 1400 feet/second. Five photographs and an Esso road map with a flight plan overlay have been selected. The last four photographs are oriented on the road map.

Figure 5 is a composite of a 25 mile stretch of both the near and the far range covering both rural and industrial complexes and showing on 3X reduced scale the kind of coverage expected. Comparing this picture with the road map of Figure 4 one can pick out metropolitan areas of southern Philadelphia, Chester and West Chester. Industrial facilities along the Delaware river, the city airport, and major highways are prominent features. The separation between the near and far range is due to the 5 microseconds lost in the turn-around of the CR trace and amounts to less than one-half mile.

Figure 6, Area #1 is of Chester, Pa. and the Delaware river, with the swamp lands of New Jersey just above the river. Points of interest that have been labeled on the overlay are the college and part of the town of Swarthmore, Spring Haven golf course, Rural cemetery, the Pennsylvania and the B & O railroads, the Billingsport Marine Terminal at the upper left and finally U. S. Highway 295.

Figure 7, area #2 is about half contained in area #1 but is shown magnified 2 times. It shows sections of both U.S. 295 and the New Jersey turnpike, a couple of branch railroads the Pennsylvania, Reading and Sea Shore, a high tension power line, the corner of a petroleum tank farm, and a mixture of industrial and rural topography.

Figure 8, area #3 is directly west of area #1 and magnified 4 times. This print was chosen to show detail obtained on an apple orchard in January and was printed to fairly high contrast. The regular spacing between the trees is estimated at 30 feet.

Finally, Figure 9, area #4 is a more rural area including towns of Downington and West Chester. The scale for areas #1 and #4 is the same, amounting to 3500 ft/inch in range and 4800 ft/inch in azimuth, and is a contact print from the correlated output. In addition to the map-like quality of the picture the elevation contours of the South Valley hills and the East Branch Brandywine Creek give an added effect which almost amounts to relief.

Flight S-123 was flown October 21, 1964 over Washington, D.C. at 22,500 feet to test resolution capability on an array of corner reflectors arranged on Bolling Field. Figure 10 shows the actual layout of the reflectors and their calculated cross section. In the insert there is a 20X enlargement of the radar correlation. The upper left targets which are separated 5 feet on the ground are resolved in the radar image.

Flight S-154 flown on April 4, 1965 mapped N.A.S. Oceana from 23,000 feet as shown in Figure 11. Four days later when the clouds had cleared a K-45 aerial camera took the photograph shown in Figure 12. The scale of the radar picture is 1400 ft/inch in both directions and for all parts of the picture. The photograph which has been printed to about the same scale and has about 5 foot resolution, has the usual optical distortion which makes parallel lines meet at infinity. It is interesting to compare the two renditions of the same target. The radar picture uses its own illuminating source and hence mirror-like objects tend to return very small amounts of energy. Flat surfaces like runways, aprons,

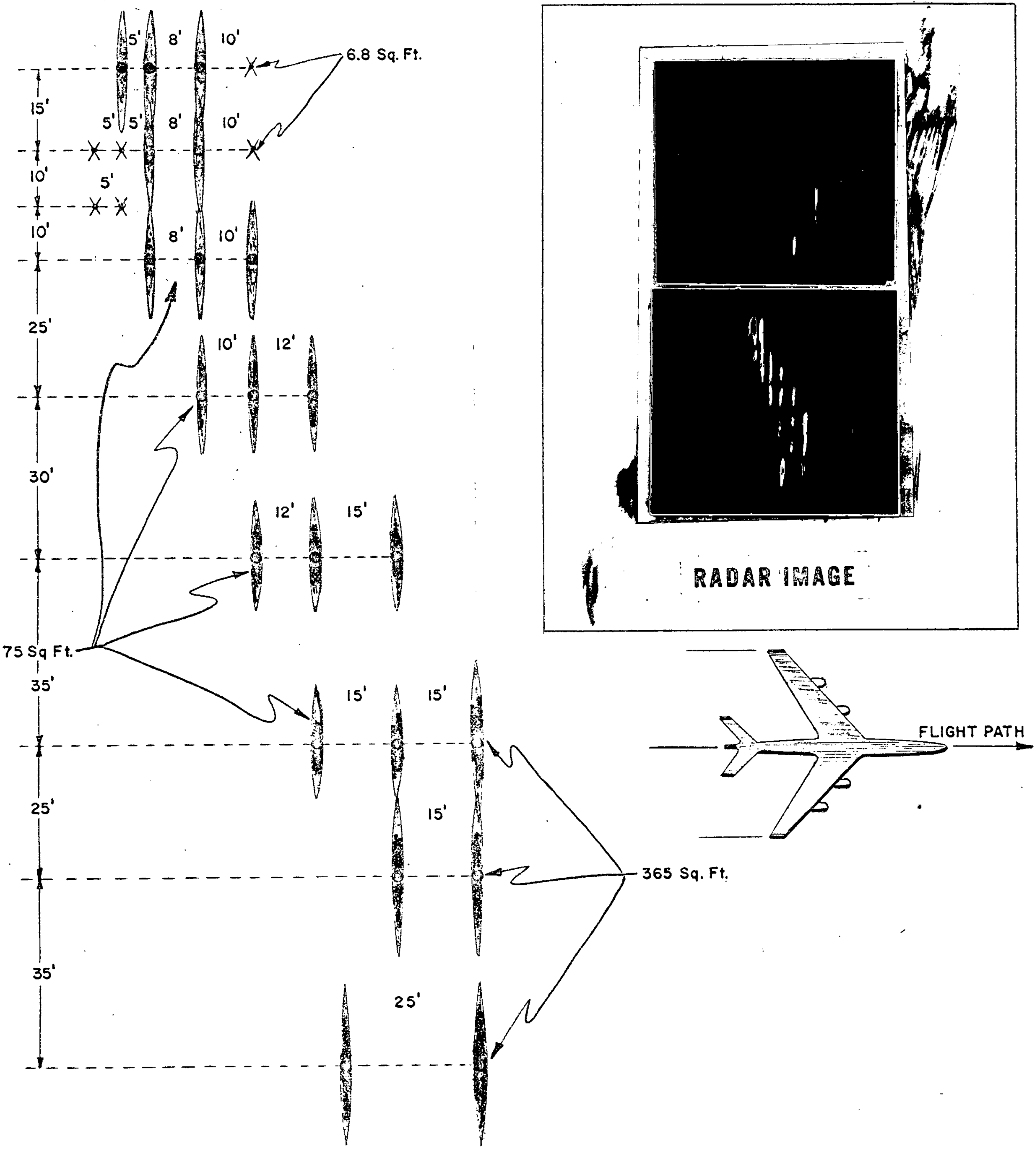


Figure 10. Layout of corner reflectors at Bolling Field and the radar image from a correlation of S-123 enlarged 20X. Elongation of the reflectors in the range direction is drawn to correspond to the pulse length. Strong targets are stretched more than small ones. Azimuth resolution of 5 feet is indicated but the 6.8 sq ft reflectors were not detected.

and roofs appear black, whereas vertical surfaces and strong scatterers appear bright. There is a sharp difference between the two pictures in the manner in which they portray the different vegetation. By looking carefully at the same area in both pictures a better appreciation of the actual condition at the Air Station can be obtained than from either picture alone. For instance, both pictures show the differences between the macadam, new concrete, and old concrete runways, but the differences are different in the two pictures. The same kind of differences are noted for the parking aprons and the planes parked on them.

Figure 13 is a radar picture and a K-45 picture of the U. S. S. America underway at 23 knots taken on April 5, 1965 as part of a Navy exercise. In this picture the radial velocity of the ship away from the F-101 shifted the doppler spectrum of the return signal by approximately 700 cycles/sec and caused the wake of the ship, which is largely stationary, to be displaced laterally from the image of the ship. Again the radar highlights the island and certain features of the ship while it misses some others which are detailed by the camera. Some radar difficulty occurs over water because of the absence of sufficient signal return to operate the DFT. Therefore, the antenna steering must be maintained by the vertical gyro and the APN-102 by themselves.

Finally, Figure 14 is from flight S-169 over Washington on June 2, 1965, and is included to show that there is sufficient power to map from full altitude. The F-101 flew at 23,000 feet and the sensitivity of the receiver was decreased by 15 db.

IV. POSSIBLE IMPROVEMENTS

1. Limitations of the Present Design:

Before making specific recommendations for future developments it is helpful to review briefly some of the major factors responsible for the present design. As in every design certain compromises were reached as a result of requirements imposed by other components or events not under the control of the radar designer. In a future development some of these compromises would be either different or unnecessary.

After acceptance of the 6B proposal by the customer in August 1960, a detailed engineering analysis of the system was undertaken concurrently with the design and construction of the major components. By the summer of 1961 it was apparent that a system design predicated upon the availability of a recorder with a $\frac{1}{2}$ mil spot size would have to be revised for a 1 mil spot. A $\frac{1}{2}$ mil spot could not be maintained under flight conditions which required light weight chassis and power supplies. This change required the recorder film speed to be doubled which had the effect of increasing the focal length of the holograms by four. Consequently, the optics of the correlator had to be partly re-designed. Also the increased spot meant more attenuation of high frequency signals which required tighter tolerances on the antenna steering because of the connection between antenna beamwidth, doppler spectrum, and pointing error. In the summer of 1962 the space available for the antenna was firmly established and it was less than expected. The antenna, therefore, had to be shortened by 3 feet, causing the beam width to increase by 30% and the gain to decrease by 2. 5 db. one way. The space available for the movement of the stabilized antenna amounted to ±3° in yaw and none in pitch. A third factor responsible for the present design was the requirement for additional transmitter power to overcome an accumulation of small losses in the system and to provide more power than could be expected from the resonant ring. The extra power is supplied by the CFA but this also increased the pulse width to 30 nanosec.

In spite of these difficulties, a system has been produced which has about one-half the proposed degree of resolution but otherwise has been able to fulfill the original specifications. On the other hand, many of the features of the design are now far from being optimum. The recorder has inadequate resolution, the modified processor has some optical imperfections, the antenna is shorter than it should be, the stabilization system has one axis instead of two and the transmitter has too long a pulse.

2. Need for Linearity.

Apart from the unfavorable features that are the results of compromise, there are two features that are now considered questionable even though they conform to the original specifications. One is that signal limiting occurs at a relatively low signal to noise ratio, the other is that the S/N ratio for desirable weak background signals will be small at full altitude.

A technical report[9] dated December 7, 1964, shows the effect on radar maps produced by coherent background and also shows that coherent background is always produced when clipping or limiting occurs in the receiver or recorder. From the conclusions in this report and from experimental evidence in some of the radar maps produced in the F-101 flight test it appears conclusive that linear signal processing is necessary for high quality radar maps. In practice this means that the dynamic range must be made as large as possible, so that most of the targets may be faithfully rendered most of the time.

Also, with regard to image quality, it is probable that the resolution already obtained is not being fully exploited because of the present shortcomings in signal processing. The coherent interference in the optical correlator between image signals and background signals of all kinds is a major cause of reduced image quality. These background signals include: (1) spurious signals produced by clipping, (2) stray light from the lens surfaces and the interior of the glass itself in the correlator, (3) light diffracted by the film grains, and (4) clutter from unfocused virtual images.

Present signal processing is faced with a serious problem. The dynamic range of the present system is limited to approximately 20 db.. The dynamic range of radar targets in an average scene is at least 35 db. and it may extend to as much as 60 db. between large bridges and open water. In present practice this wide dynamic range of targets is accommodated by severe clipping in the IF amplifier. If limiting must be used the best place to use it is in the IF stages[11], but any limiting or other non-linear signal processing will produce spurious images that focus in the output map and thus reduce image quality.

The linear dynamic range of the system is determined by the ratio of the largest amplitude signal that can be recorded without saturation to the smallest signal that can be recorded and detected in the final map.

To utilize fully the existing dynamic range it is necessary to adjust the receiver-recorder combination so that for the desired range interval the strongest targets just reach the maximum allowable density variation of the recording film without limiting. Under these circumstances the smallest targets that will be rendered on the final map will be those with signals that just exceed the noise of the stray light and film in the correlator.

3. Need for Reduced Background in Correlator

At present there is too much stray light in the correlator. Holograms recorded at modulation levels that exceed the radar noise and the noise of the recording film are obscured by this stray light at the output film plane. In the ground processor tracking of the output image by the output film over an appreciable range (0. 1 inch) tends to smear the stray light by destroying the coherence between it and the images. However, the large number of glass surfaces, the thickness of the glass, and the interference filter all contribute excessive stray light which reduces the dynamic range of the system. In the detail correlator there is no tracking and hence much of the advantage to be gained by the laser source is lost because stray light adds coherently to the images. A study recently completed at Itek[12] identifies many of the sources of this unwanted stray light.

4. Need for a Laser

The present ground processor was designed for a wide spectrum of colors from a carbon arc source in order to accommodate the range dependence of the hologram focal lengths. Since the original design was completed the laser has emerged as a new scientific tool. Today a new optical design for the single color of the laser and utilizing its great intensity could be expected to reduce the stray light and hence improve the dynamic range by a factor of 3 or more.

5. Need for Improved Sensitometry

As explained above the dynamic range must be made as large as possible. One requirement for a wide dynamic range is a long linear region on the data film response curve. The present film has a response curve which is linear to within 5% from 95% to 28% transmission when developed under the proper conditions. A second requirement is to have a film whose "noise figure" is very small. The smallest signal that can be recovered is limited by the noise fluctuations in the grains of the recording film. It is known that there are many films whose noise is less than the film presently in use but few of them have enough "speed" to qualify.

6. Need for System Optimization

In the first three years of the INVAR development, major problems such as stray fields and vibration in the recorder, variable frequency control in the receiver, and antenna steering difficulties all obscured the degradation caused by spurious clutter. Now that a reliable system exists and these major problems have been dealt with satisfactorily it is time to linearize the system, reduce the background noise, and optimize the sensitometry in order to produce the image quality we desire.

As an example of one step in such a program the most recent improvement in system performance came about when the bias level and the CRT drive was adjusted to yield the largest linear portion on the overall response curve of the CRT and recording film combination.

More work needs to be done in this same general area. The first attempts at linear signal processing conducted in flights S-168, and S-169 failed to show any substantial improvement in map quality.

this failure is attributed to other difficulties. In particular, the stray light in the correlator, which adds coherently to both images and clutter, is large enough to obscure the small targets and the fine detail of the map. However, there was improvement in linear signal processing. In the neighborhood of strong targets there was no evidence of spurious targets which indicates there are no cross modulation products produced in the modified receiver which was used for these tests. The modified receiver includes an amplifier whose gain is adjusted so that for some parts of the flights very few targets saturate the recording film. Under these circumstances the recording is nearly linear over a limited dynamic range. It is hoped that future tests will be able to correlate such linear recordings and render the desired fine detail.

7. Need for a Better Signal-to-Noise Ratio

Although the present S/N ratio is more than adequate for the F-101 flight tests and although it fulfills its promise of performing adequately according to present standards at full altitude, it now seems likely that additional transmitter power will be desired. This apparent paradox can be explained as follows: the present system has a limited dynamic range and hard limiting in the IF amplifier. The gain is adjusted so that the smallest discernible signal has a reasonable modulation level on the recording film and all signals 10 db. greater are limited in the IF amplifier. The future system should have a wide dynamic range and linear signal processing. The gain should be adjusted so that very few targets are limited. Under this circumstance the small targets receive very low modulation on the recording film and demand a more sensitive correlator to recover them. Such a correlator would not mask the noise of the radar and therefore a less noisy, or rather higher power, transmitter will be desired. In addition, when the fine detail does become available in the radar maps, improved range resolution will be very desirable, and this will also increase the demand for more transmitted power.

The effective transmitted power illuminating a specific target area can be increased in several ways. Two of these ways are (1) chirping the transmitted signal while maintaining the same peak power and (2) increasing the antenna gain by increasing either its length and/or width.

Chirping not only allows an increase in effective peak power by frequency dispersion but it also increases the efficiency of the CFA transmitter. In addition, a chirped transmitter allows the effective width of the transmitted pulse to be reduced and thus allows the original range resolution goal of 10 feet to be achieved. A chirped transmitter could improve both the resolution and the image quality of the radar map.

If a longer antenna could be installed, either in the present aircraft or in some future aircraft, an improved antenna design might produce the necessary increase in S/N. A narrower antenna beam would both increase the gain and reduce the clutter from unwanted signals existing at the edge of the present beam.

As a typical example, the present antenna is 8 feet long and has a beam width of 0.0132 radians and a measured gain of 31.5 db.. This antenna has a resolution limit in a focused synthetic system of 3.3 feet. A new antenna 14 feet long could have a beam angle of .008 radians and a gain of 34 db.. Such an antenna would have a resolution limit of 5.8 feet. The two-way gain in S/N amounts to 5 db. in this hypothetical example. If, in addition to a reduction in the horizontal beam pattern, a reduction in the vertical beam were also made, a narrower strip on the ground, say 10 miles wide instead of 20, would be illuminated with twice as much transmitted energy. Therefore, an antenna both longer and wider could conceivably increase the S/N ratio by 8 db.

V. RECOMMENDATIONS

S. E. I. recommends that the INVAR program be continued with emphasis placed on certain specific aspects of the program. First, the equipment should be given a complete test in the final vehicle; the radar has been given a thorough engineering evaluation, numerous tests and analyses have been made which predict satisfactory performance in the A-12, and everything is ready for a final test. Second, during the remaining tests in the F-101, there should be continued emphasis on linear signal processing in conjunction with efforts to reduce background noise in the correlator and to improve the sensitometry. There is good reason to believe that better maps can be made with the present equipment, that continued analysis and experiment can determine the particular limitations of the present equipment, and that the additional knowledge on this point to be gained would be useful in the design of a better system. Third and last, the design and construction of a prototype chirp transmitter would improve the range resolution and provide increased power for high quality mapping.

	REFERENCES	SOURCE
1.	Technical Proposal 6B dated April 1960	S. E. I.
2.	Status Report on INVAR, dated January 1963	S. E. I.
3.	STM-104; System Stability Requirements dated January 15, 1963	W
4.	STM-101; Motion Compensation for Side-Looking Radar 12/17/63	W
	STM-102; Motion Compensation for SOARD Flight Test 1/16/63	W
5.	Final Design Report of AN/APQ-93 (XA-1) Radar 5/12/65	W
6.	STM-128; Resonant Ring Transmitter 7/17/63	W
7.	High Resolution Radar Data Recorder, Final Report 3/10/64	Itek
8.	Recorder Follow-on Proposal 12/17/63	Itek
9.	Technical Report - Effects of Coherent Background in Radar Maps produced with synthetic antennas 12/7/64	S. E. I.
10.	Final Report Model 9015 Processor 5/1/64	Itek
11.	STM-122; Performance of IF limiting as a form of automatic gain control 5/28/63	W
12.	9015 Report for Period 1 January to 30 June 1965	Itek
13.	Project 9015 Final Report 1960-1964 (2 vol.)	Itek

APPENDIX

Photographs of Major Components

Figure A-1. CFA Transmitter
Figure A-2. Recorder
Figure A-3. Antenna
Figure A-4. Ground Processor (interior view)
Figure A-5. F-101 Door Installation
Figure A-6. F-101 Antenna Pod

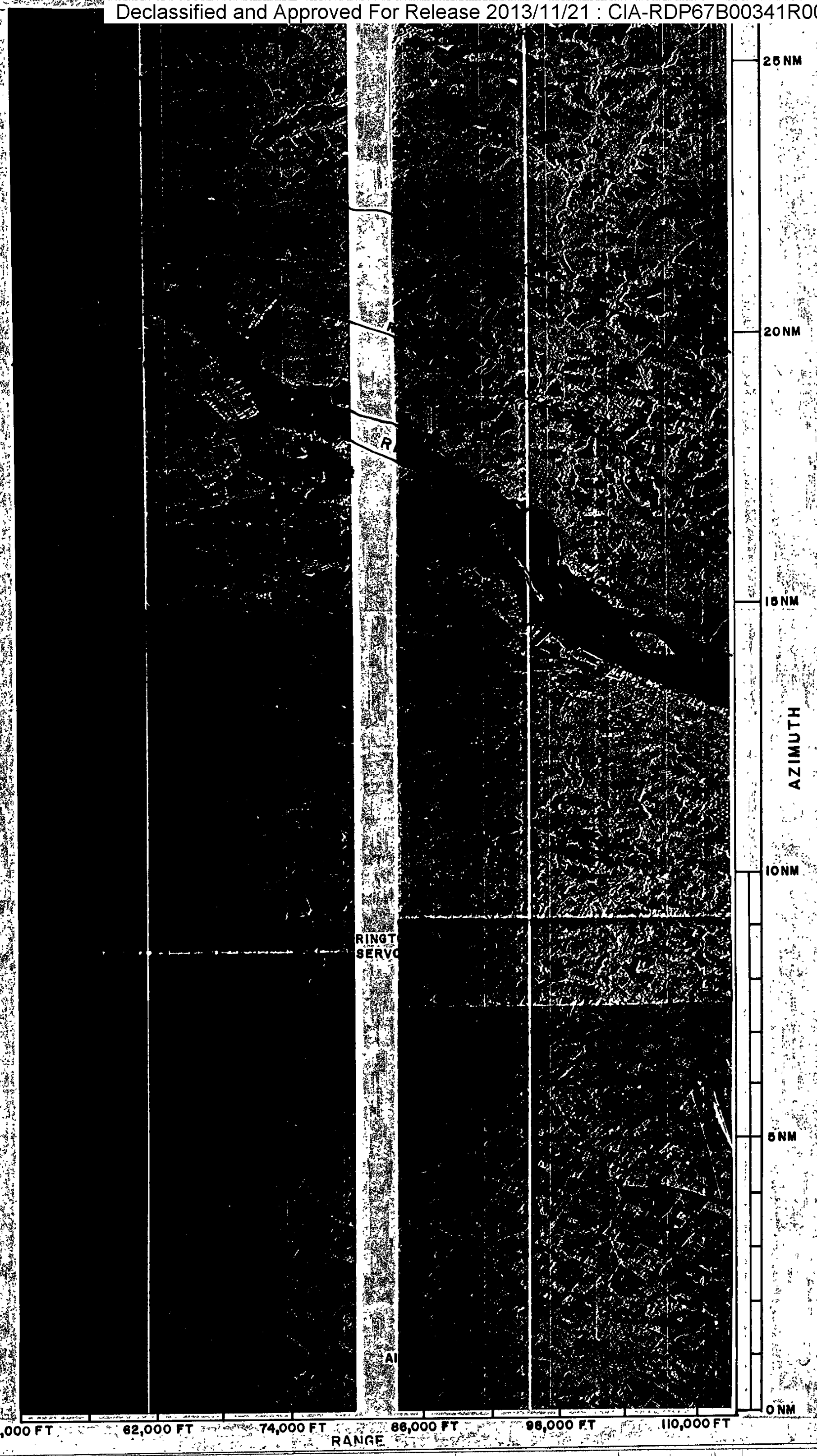


FIGURE 5.

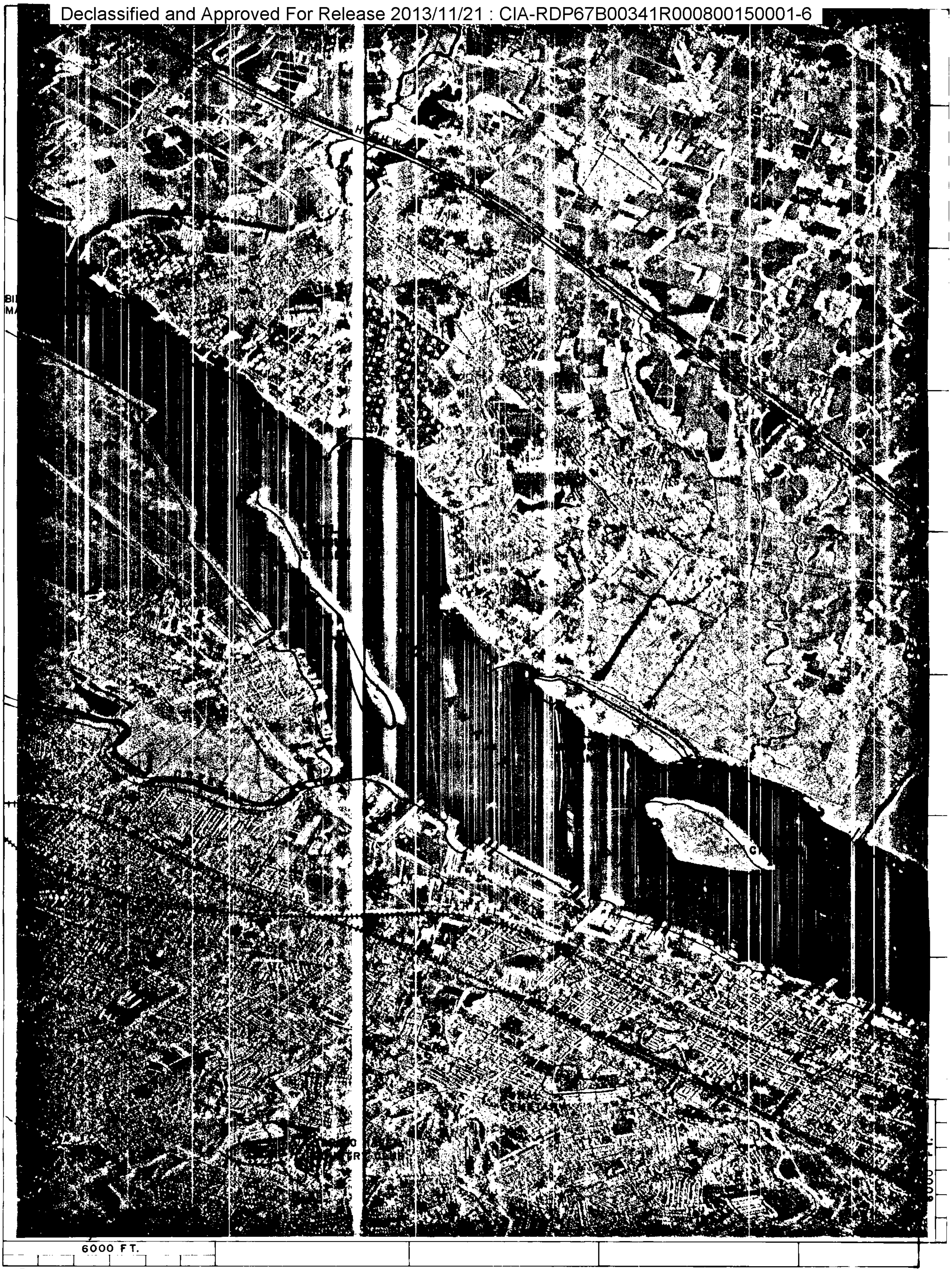
A COMPOSITE MAP REDUCED 3X SHOWING THE ENTIRE COVERAGE FOR THE LAST 25 MILES OF S-137.

APPROX. 1/2 MILE IS LOST IN THE CENTER OF THE STRIP DUE TO THE TURN AROUND OF THE CRT TRACE.

GROUP - 3
DOWNGRADED AT 12 YEAR INTERVALS;
NOT AUTOMATICALLY DECLASSIFIED

SECRET

SECRET


6000 FT.
85,000 FT.
6000

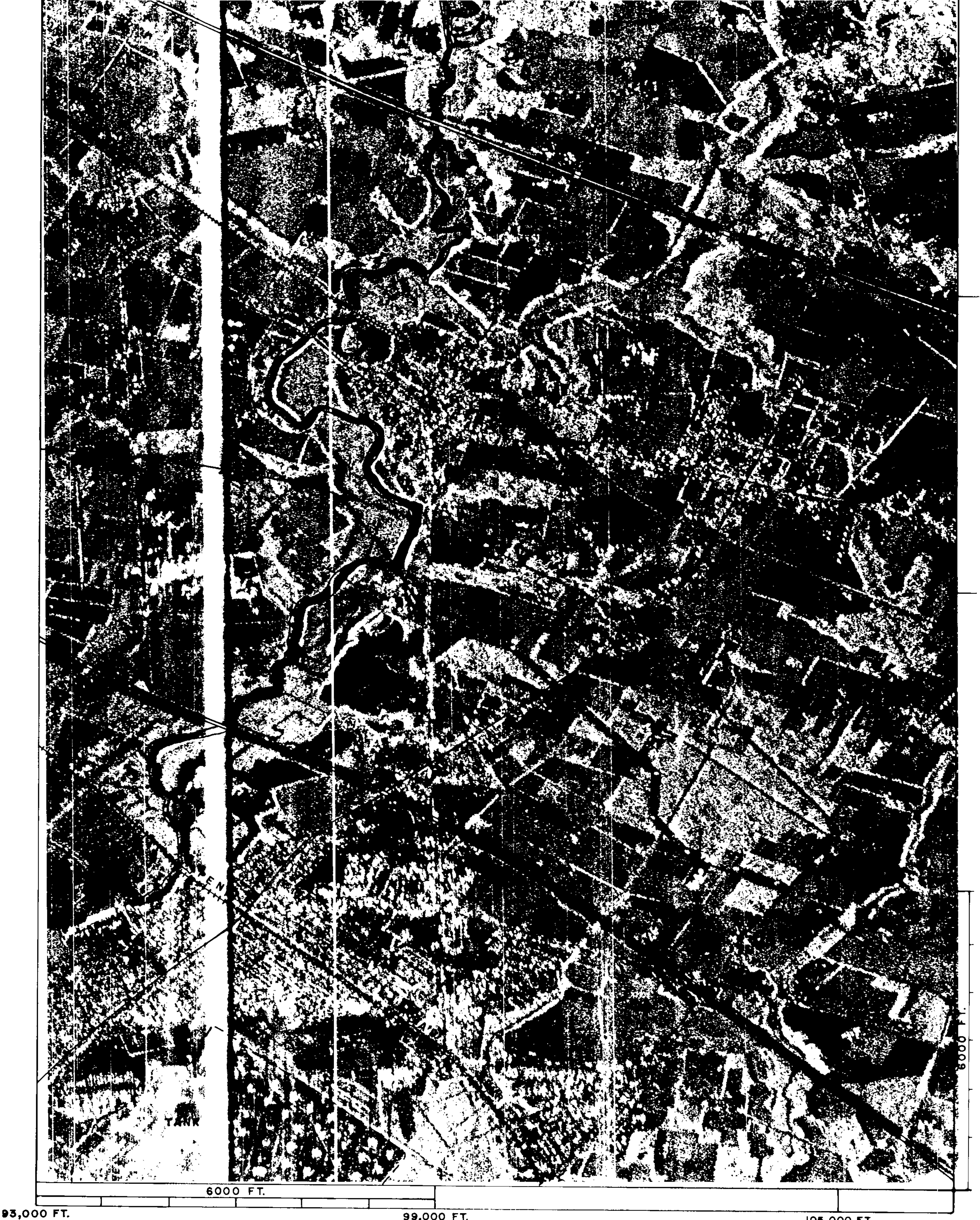
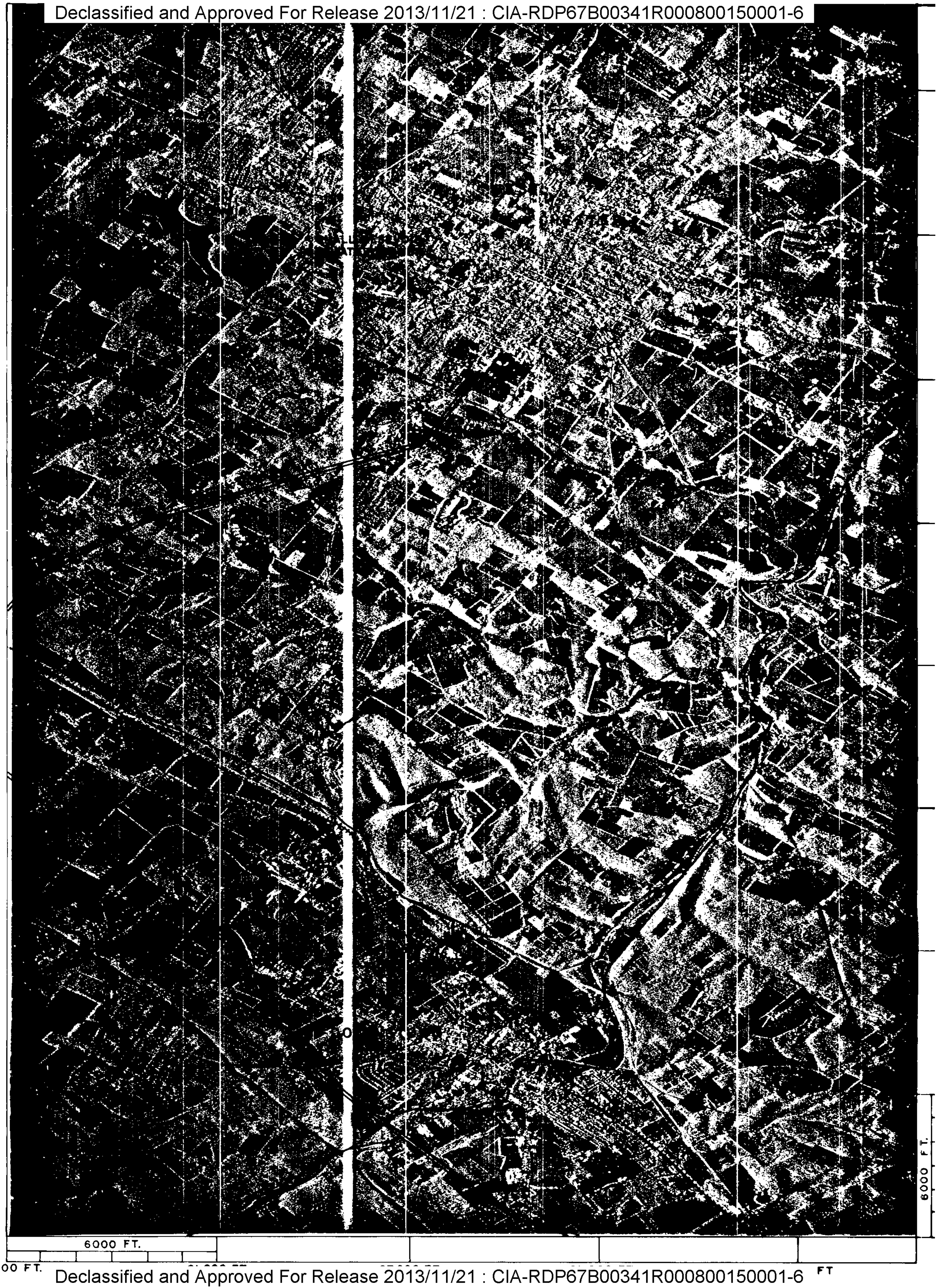


FIGURE-7. AREA NO. 2


G LTON
ORCHARDS
1000 FT.
6000 FT.


6000 FT.
85,000 FT.
6000 FT.
FT

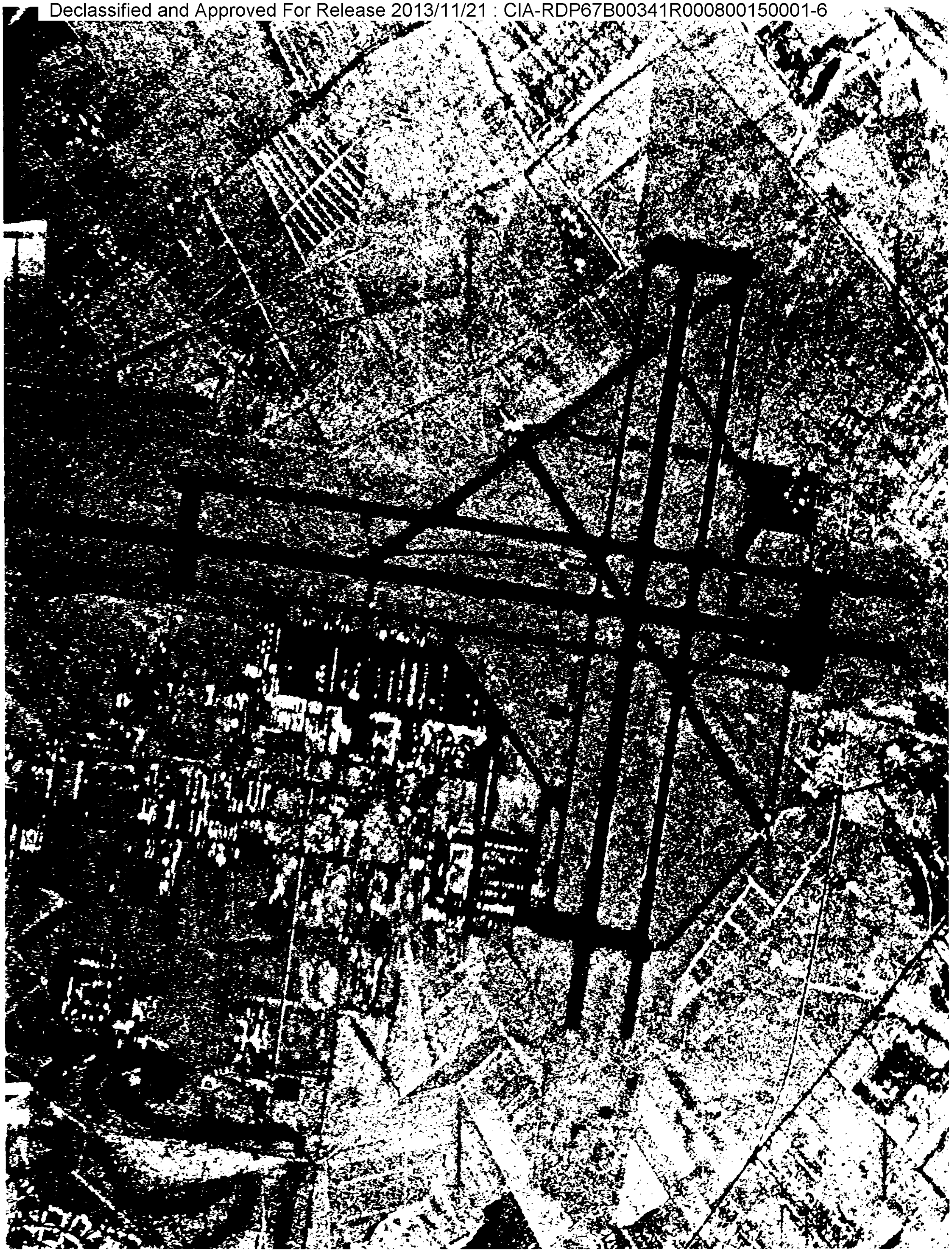


Figure 11. N.A?S. Oceana. S-154, 23,000 ft., 585 knots, Scale 1400 ft/inch

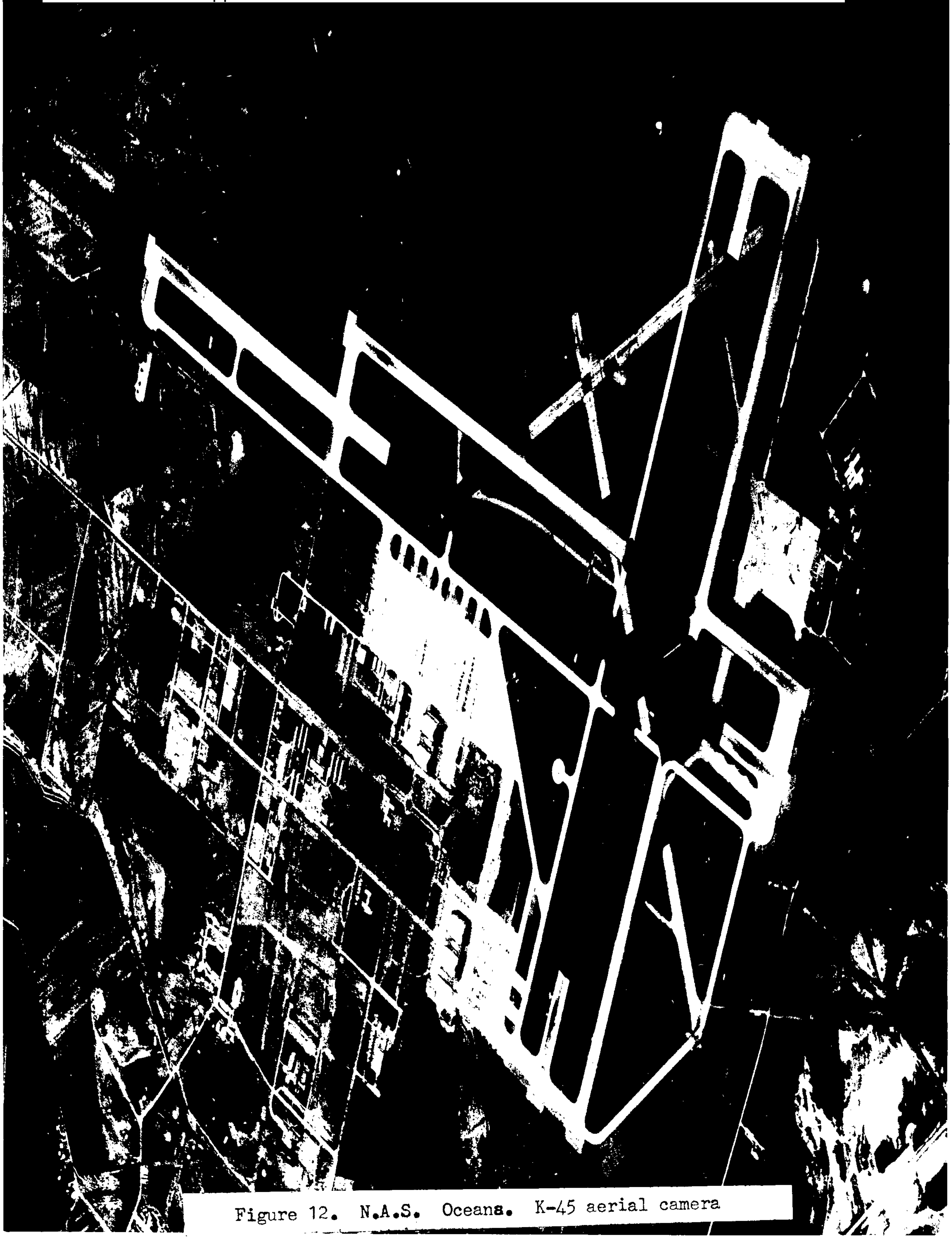


Figure 12. N.A.S. Oceana. K-45 aerial camera

Figure 13. U.S.S. America Radar Image and Camera Image.

A/C Flight S-155 date 4/5/65
A/C ground speed 570 knots
A/C standoff from target 7.9 n.mi.
Target speed 23 knots
Radar Scale: Az. 350 Ft/inch, Range 405 ft/inch
Weather: Clear, visibility to 15 miles; sea state = 1

Figure 14. Washington, D.C. Alt. 23,000 ft.,
Speed 580 knots, 15 db. attenuation

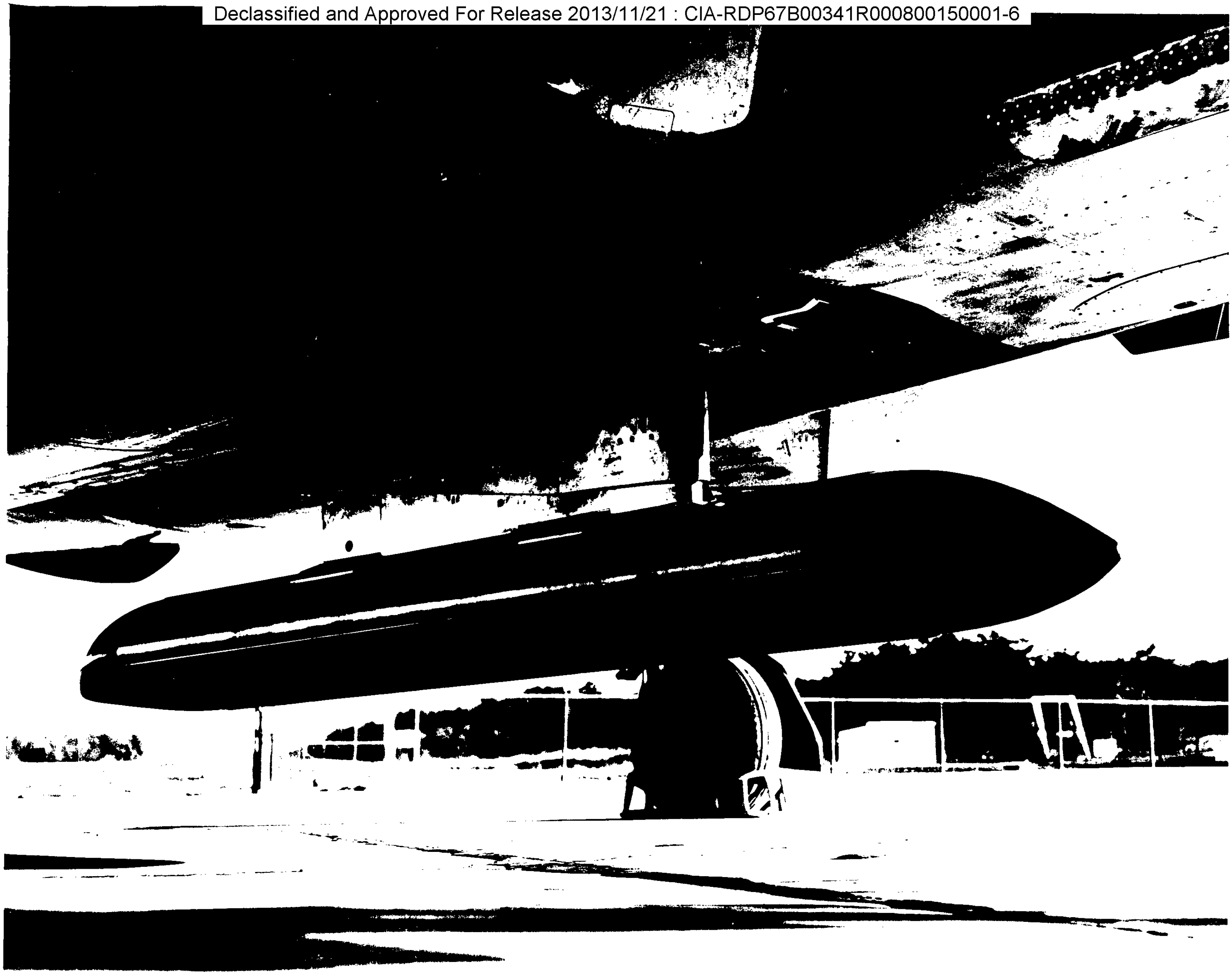
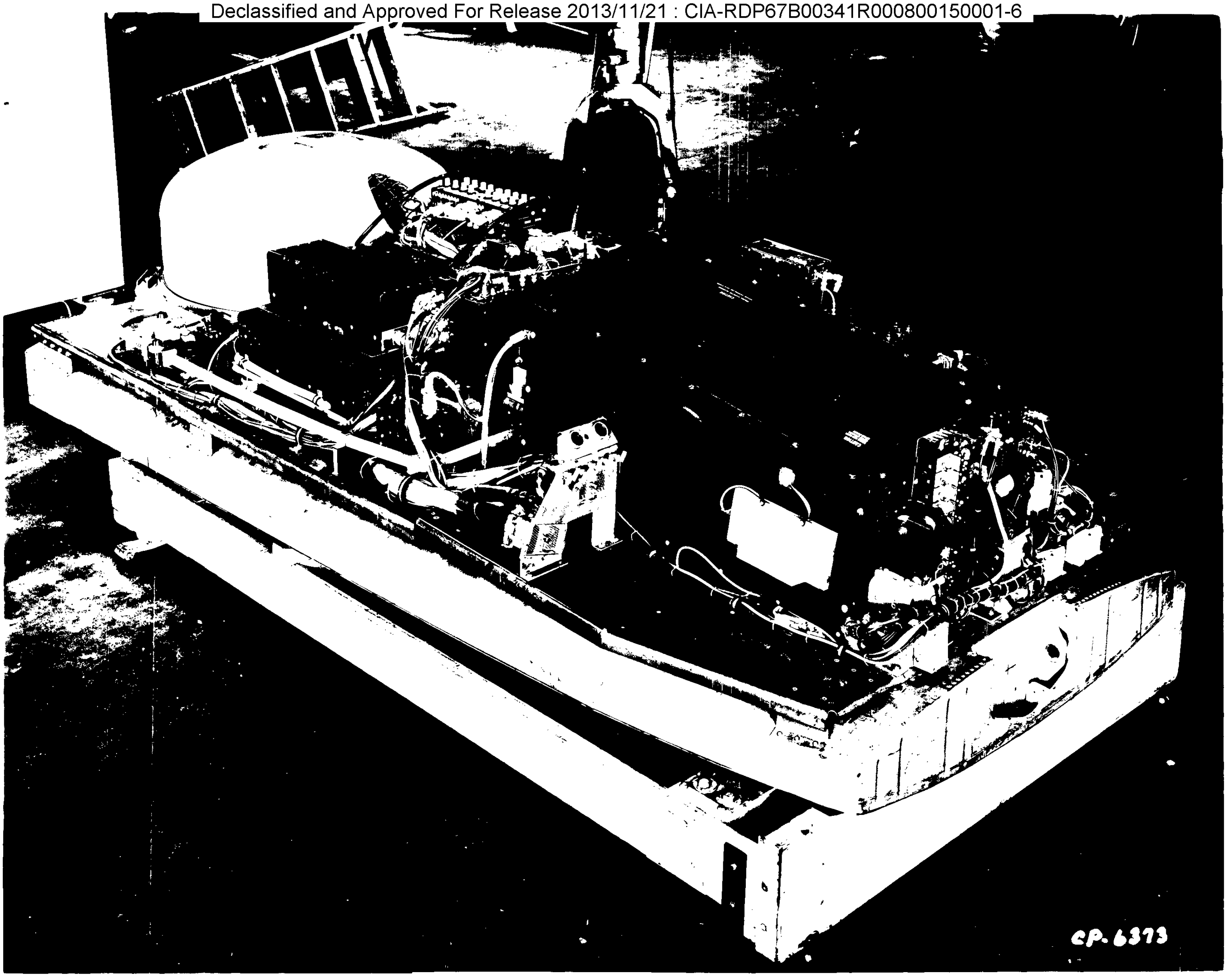
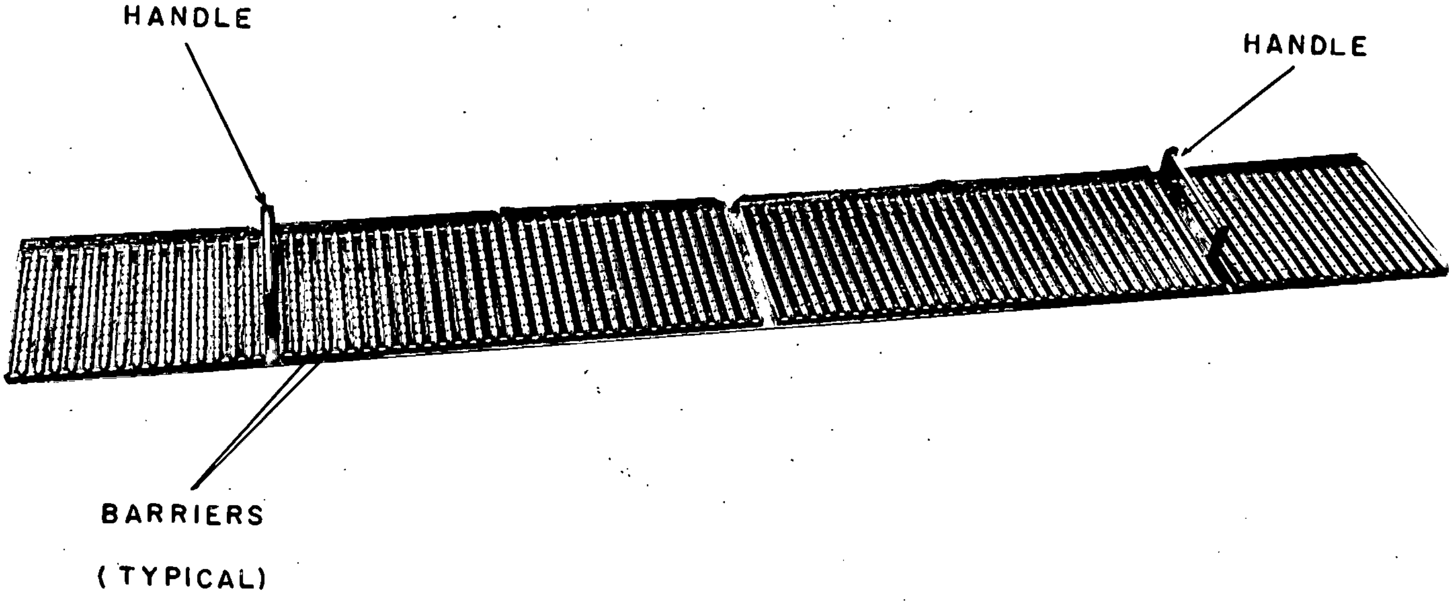


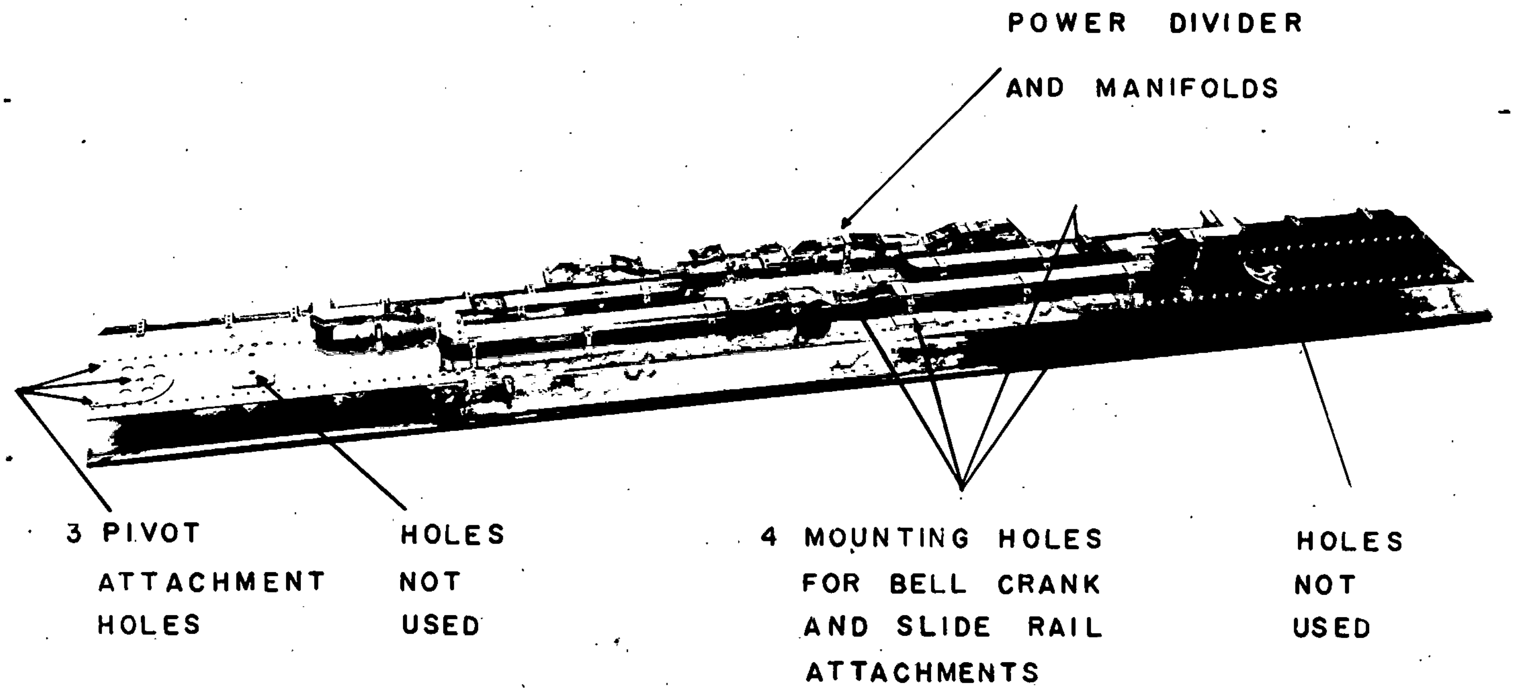
Fig. A-4 Ground Processor Interior view



CP-6373

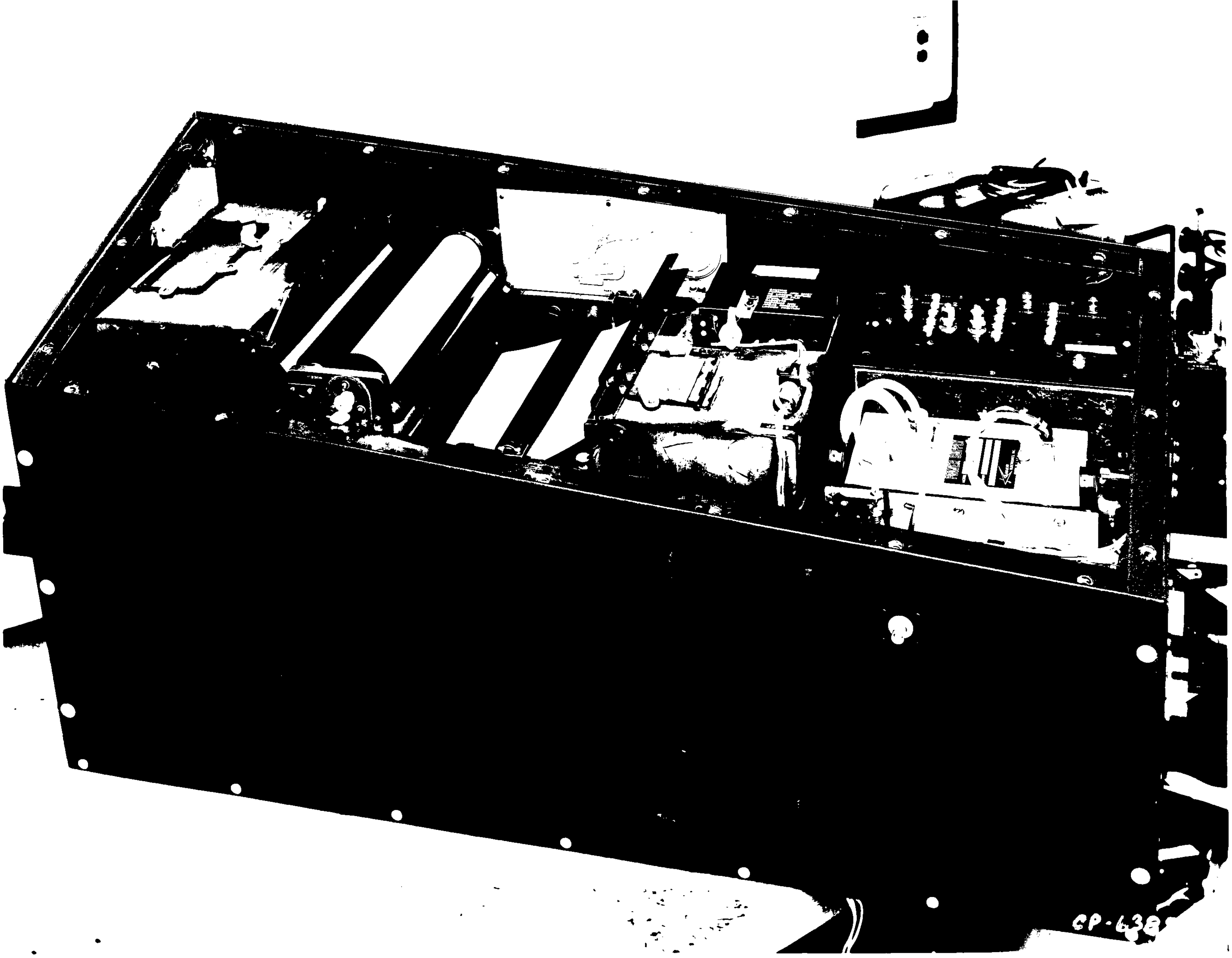


ANTENNA RADIATING FACE



BACK OF ANTENNA

Figure A-3. Antenna


CP-638