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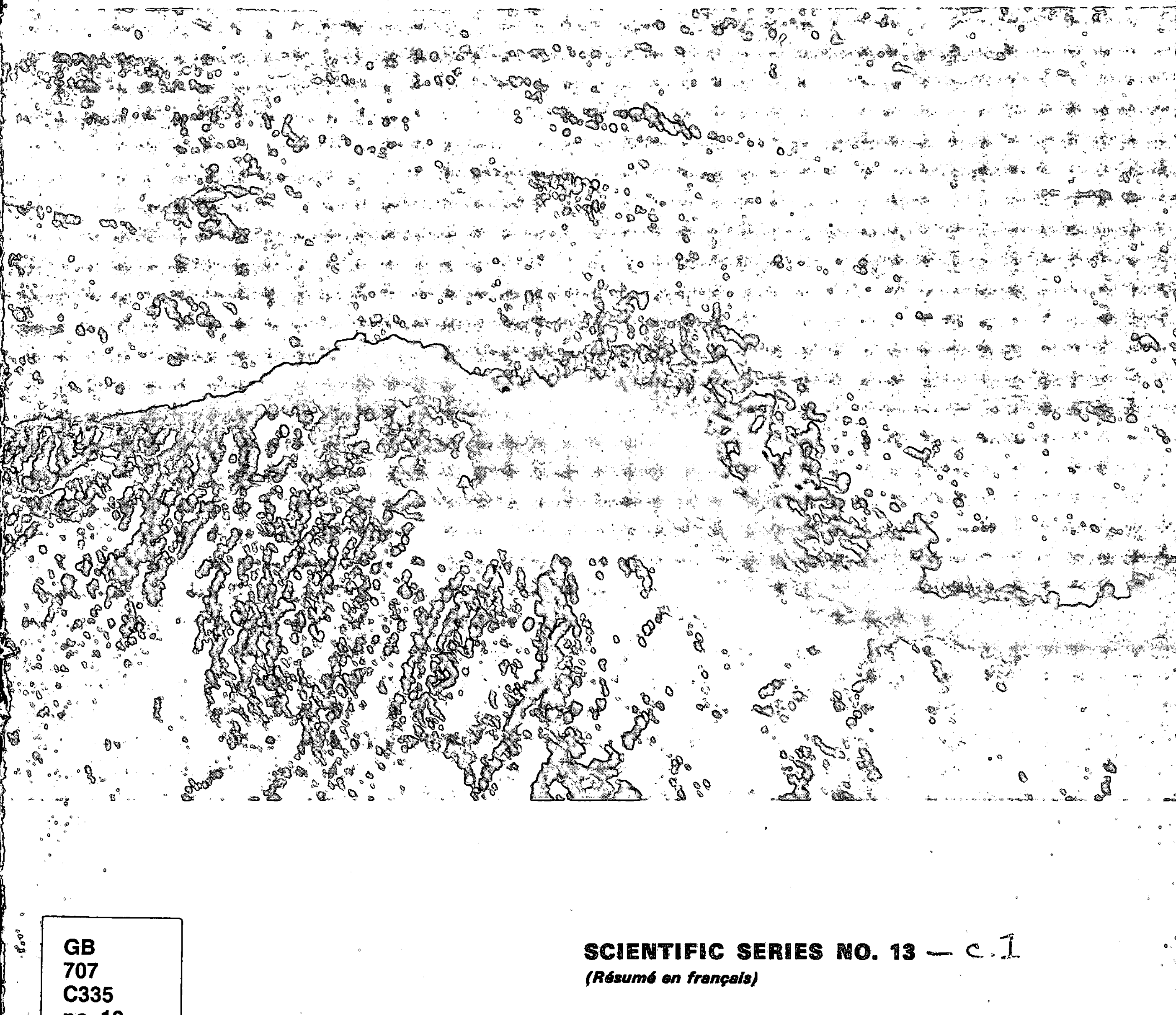
Remote Sensing at Canada Centre for Inland Waters

Progress Report

R. K. Lane, W. D. McColl and K. P. B. Thomson



SCIENTIFIC SERIES NO. 13 — c. 1

(Résumé en français)

CANADA CENTRE FOR INLAND WATERS,
BURLINGTON, ONTARIO, 1972.

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Contents

Illustrations

Illustrations (cont'd)

Tables

Abstract

This report summarizes the infrared remote sensing program conducted by the Lakes Division, Canada Centre for Inland Waters, from 1966 through 1970.

It describes the approach taken to develop a program of remote sensing on the Great Lakes and comments on the general results from this program. Most of the imagery acquired during this program is displayed and accompanied by a brief descriptive narrative. Present development of the equipment and future plans for the remote sensing program are described.

Résumé

Ce rapport récapitule les étapes importantes du programme de détection à distance par infrarouge entrepris par la Division des Lacs du Centre canadien des Eaux Intérieures, de 1966 à 1970.

Il décrit l'approche suivie pour mettre au point un programme de détection à distance par dessus les Grands Lacs, et examine les résultats qui en sont obtenus. La plupart des images obtenues durant ce programme sont présentées dans le rapport et y sont accompagnées de commentaires succints. En outre le rapport décrit le développement actuel de l'équipement ainsi que les plans d'avenir du programme de détection à distance.

CHAPTER 1

Discussion of the Program

INTRODUCTION

Modern remote sensing instruments for measuring various portions of the electromagnetic spectrum from the ultraviolet through the visible and infrared have potential application to hydrologic research (Lane, 1968).

The 8 - 13 micron band in the infrared is particularly interesting for lake studies because it is the wavelength region of peak emission from natural water surfaces. The radiation in this waveband is relatively unaffected by atmospheric absorption, and it can be measured with a variety of detectors. Infrared scanners incorporating these detectors may be used to produce two-dimensional "thermal" images of any target area. The recognition of the potential of this type of instrument was the impetus for a program of Great Lakes airborne surveys as part of the physical limnology research program of the Great Lakes Division*. The primary objectives of this feasibility program were as follows:

1. To determine if an infrared scanner could detect and delineate distributions of thermal plumes.

2. To determine if infrared imagery of the lake surface would delineate thermal features which are interpretable in terms of dynamic or thermodynamic processes.

3. To determine if infrared imagery would delineate distinct thermal features of the lake water such as the "thermal bar", nearshore upwelling, or groundwater discharge.

4. To determine if infrared imagery strips could be constructed to form a mosaic covering a large area of the lake surface. Such a mosaic would produce a nearly synoptic thermal map of the lake surface.

5. To investigate the possibility of making quantitative temperature assessments from the thermal imagery.

FEASIBILITY PROGRAM

In order to carry out the above objectives, HRB Singer Co. was contracted to carry out a series of flights using a modified HRB Singer Reconofax IV infrared scanner. The surveys consisted of a number of flights around the perimeter of Lake Ontario and Lake Erie, and two series of flights over western Lake Ontario for the purpose of producing mosaics.

In general, this imagery showed considerable potential for delineating thermal features of the lake surface. Specifically, the imagery proved capable of delineating a great variety of thermal features and the distributions of thermal plumes at the surface. In the mosaic of western Lake Ontario, thermal features extending over a large area, such as the effluents from the Niagara River, Port Weller and Port Dalhousie, were clearly presented (Figure 1). This imagery also demonstrated that thermal features apparently associated with large-scale lake phenomena were indeed observable.

As a result of these tests and others carried out by federal agencies, a Reconofax IV infrared scanner was purchased by the Inland Waters Branch, Defense Research Board, and the Geological Survey of Canada, for further infrared programs. The new infrared scanner was installed in a North Star aircraft belonging to the National Aeronautical Establishment of the National Research Council. NAE undertook the responsibility for operations and further developments of the scanner system.

SCANNER SPECIFICATIONS

A schematic of the infrared scanner system is contained in Figure 2. The instrument is a two-dimensional line-scanning device. One dimension on the imagery is produced by the forward motion of the aircraft, while the second dimension is produced by a revolving mirror which scans the terrain in the direction transverse to the line of flight (Figure 3). The incoming radiation, emitted from the terrain, strikes the plane-surfaced scanning mirror which is rotating at a high RPM. This mirror reflects the radiation onto a parabolic mirror which focuses the radiation on the detector via the folding mirror. The small detector, which is maintained at liquid nitrogen or liquid helium temperatures, emits a signal which is proportional to the incoming radiation. The signal is amplified and used to modulate a lamp in the recorder. The modulated light spot is reflected onto the 70 mm film (TRI-X PAN) by a folding mirror which rotates on the same shaft as the scanner mirror. This light exposes the film in a series of scans at the same rate at which the scanning mirror is viewing the terrain. At the same time, the film continuously advances across the scanning slit at a speed proportional to the forward velocity of the aircraft.

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*Now Lakes Division.

The total scan angle of the system is 120°, the scan rate is 11,000 rpm and the effective focal length of the system is 28.6 mm.

Two infrared detectors have been used with the scanner. One is a liquid nitrogen-cooled InSb detector sensitive to the 3 - 5 micron region of the infrared spectrum. The other is a liquid helium-cooled GeHg detector sensitive to the 8 - 14 micron region. These detectors have different thermal and spatial resolutions and are used for different purposes. The InSb detector has a three milliradian field of view which provides relatively high spatial resolution. For over-water flights, this detector is best used at night to avoid the effects of reflected solar radiation in the 3 - 5 micron spectral region. The GeHg detector has a 16 milliradian field of view and a relatively high thermal resolution, a desirable feature for imaging water areas. This detector may be used for daylight over-water flights because reflected solar radiation is extremely small in the 8 - 14 micron region, compared to the radiation emitted by the water surface.

The high responsivity of these detectors makes it difficult to record the full range of signals that are normally encountered in a land/lake environment within the grey scale range of the film. Because of this problem two types of amplifiers have been used. The standard amplifier in the system is A.C. coupled and uses automatic gain control. A modified system employs D.C. restoration with manual gain and level controls.

The A.C. coupled system with automatic gain control (AGC) produces a response so that the signal averaged over an entire scan is reduced to a fixed, average level. For any given scan that contains only small incoming signals, the AGC will increase the amplifier gain to utilize the full grey scale of the film. Similarly, for a given scan that contains a large contrast in signals, the AGC will reduce the gain in order that the larger signals will not saturate the film.

This AGC system produces imagery which is high in quality with fine thermal details, the background is uniform and the imagery lies within the grey scale of the film. However, this system does have a disadvantage when imaging nearshore areas. For a given scan that includes both land and water areas, the signals emitted from the land are usually much larger than the signals emitted from the water so that AGC reduces the system gain to a point where the land signal will not saturate the film. Consequently, the relatively small water signals are not imaged on the film. Because of this property, flights which follow the shoreline, imaging both land and water areas should be avoided. Also, on any flight line that crosses the shoreline at an angle other than ninety degrees, the water detail is usually lost on any scan that includes the land area.

The D.C. restored amplifier system uses manual gain and level controls in order that the scanner operator may choose the level and intensity of the signal to be imaged on the film. This system has several advantages. Nearshore areas can be imaged without loss of water detail from the over-riding land signal. The scanner operator may choose a level and gain setting to image the water detail and allow the unwanted land signal to saturate the film. Also, when imaging water areas that do not contain extreme temperature gradients, the operator may select an appropriate fixed gain and level to image a given area. In this situation comparisons of the surface water temperature can be made from comparing the tone density of the imagery.

The chief disadvantage of the D.C. restored system is that the proper manual adjustments for level and gain are difficult to achieve in order to produce the desired quality of imagery. Usually, it is necessary to change the level and gain frequently in order to maintain the imagery within the grey scale of the film if the operator is attempting to image small thermal features. Each time the level and gain are adjusted, the background grey tone is changed. This distortion is especially prominent when the imagery is joined to form a mosaic.

The common problem with both the A.C. and D.C. systems is that quantitative measurements over a large area of the imagery cannot be made from a comparison of tone density on the imagery. The absolute surface temperature of the water cannot be measured from the imagery, with the present equipment.

OTHER SENSORS AND CAMERAS

To complement the thermal imagery and assist in the problem of imagery interpretation, several additional sensors recording in the visible and infrared have been employed.

A Barnes PRT-5 infrared radiation thermometer is used in conjunction with the scanner to record the temperature of the terrain that is observed on the nadir line of the imagery. This device detects 8 - 14 micron radiation emitted from the terrain within a 2° angular field of view. It is designed to have a radiometric temperature accuracy of ± 0.5°C. The thermometer provides an aid to overcome the problem of nonquantitative thermal imagery. From the temperature data approximate isothermal contours can be placed on the infrared mosaics, providing care is taken to allow for atmospheric effects.

A super wide angle 35 mm tracking camera is used to record the entire flight tract. These photographs are useful in correlating visual features such as turbidity gradients and surface slicks with the thermal imagery.

Two 70 mm Vinten cameras have been employed largely for multispectral tests to determine the best spectral regions and film/filter combinations for recording such features as turbid plumes, surface pollutant slicks, and surface evidence of physical features such as upwelling, convergence zones and internal waves.

A nine-inch format Wild RC-8 aerial camera has been employed on several occasions for high resolution photography of selected near shore areas of the lake. This type of photography has proven useful using both colour and false colour film to resolve features such as algae and other biological material, near shore bottom features, and surface pollutant slicks.

Two Kipp solarimeters, sensitive to radiation within the 0.3 to 3 micron region were tried in an experiment to compare the total incoming solar radiation and the component reflected from the water. Difficulty was encountered in leveling these sensors in the air and they were subsequently removed from the aircraft.

REMOTE SENSING AIRCRAFT

Several aircraft have been employed in the remote sensing programs from 1968 through 1970.

The initial aircraft, which was modified for the equipment installation and the one used exclusively until the spring of 1970, was a North Star belonging to NAE. This is a long-range aircraft capable of operating at any location and carrying the required payload of instrumentation, personnel and maintenance systems for extended missions. All the instrumentation listed may be carried and operated simultaneously with the exception of the RC-8 camera which is an alternate package to the two Vinten cameras. The aircraft contains both 60 Hz single phase and 400 Hz three phase inverters required to power the infrared scanner. The one disadvantage of this aircraft is the large number of personnel required for operation of the complete system. This adds to logistics problems with the short lead times often required by remote sensing operations due to weather conditions, availability of ground truth measurements or the time scale of the features to be recorded.

Beginning in the spring of 1970, a twin Cessna 310 belonging to Spartan Air Services was employed. This aircraft has been fitted with the infrared scanner, a radiation thermometer, and one Vinten 70 mm camera. A nine-inch format aerial camera may be fitted but only as an alternate to the infrared scanner. This aircraft has proven to be an excellent platform for this limited instrumentation payload. It requires only a three-man crew, has a reasonable range, and an operating ceiling above 24,000 feet. This provides excellent flexibility and lessens the logistics problems especially on short range missions. This aircraft does require one man to operate all the equipment which necessitates a relatively automated system. Although the aircraft has extra-power generating capacity, the high power demands of the scanner load the system. Some power difficulties have been experienced when operating the scanner and the Vinten camera simultaneously. With the smaller aircraft a limited amount of maintenance equipment may be carried for extended field trips. This is a problem in that the scanner system and especially the cryogenic cooler requires periodic servicing.

The third aircraft outfitted in the fall of 1970 for the remote sensing program was a Canadian Armed Forces CF-100. The aircraft is capable of carrying several configurations of remote sensing equipment including the infrared scanner, radiation thermometer, a wide angle Wild RC-8 nine-inch format aerial camera, and a bank of four Vinten cameras. This aircraft has the advantage of high speed and a usable ceiling over 40,000 feet.

A common problem with all three aircraft is the lack of accurate Doppler navigation instruments. True ground speed is a necessary parameter in calculating the speed/altitude ratio for film speed setting on the infrared scanner. Accurate film speed is needed to produce imagery of correct longitudinal scale which is most important for forming infrared imagery mosaics.

PROGRAM – 1968

During 1968, seven surveys of western Lake Ontario, and one of Lake Okanagan were performed (Table 1). The latter is not included in this report.

Ground truth for the Lake Ontario surveys was acquired sporadically, the main difficulty being a lack of success in coordinating aircrafts and ships. Nevertheless, mosaics constructed from the surveys revealed a good deal about the quality of the imagery and the possibilities for interpretation of important lake features. Comments on each mosaic are included in Chapter 2 (see also Lane, 1970).

The high quality of the 1968 imagery and the obvious need for better ground truth led to a continuation of these surveys in 1969 in conjunction with surface programs.

PROGRAM – 1969

Table 1 contains also a summary of the 1969 surveys. The intention was to undertake three series of surveys of western Lake Ontario during periods of concentrated surface measurements. The latter program was termed Massive Effort in Lake Ontario (MELON), conducted during May, and August - September. Auxiliary programs were also conducted during July. Surface measurements included buoy measurements of currents and meteorological factors; shipboard collections of meteorological and radiation data; lake temperature profiles and surface temperatures from thermistors and a radiation thermometer; and programs of dye diffusion study. Involved were the M.V. MARTIN KARLSEN and CSS LIMNOS from CCIW and the CGS PORTE DAUPHINE under the direction of the Great Lakes Institute, University of Toronto.

A good deal of the MELON data has yet to be fully utilized, although some reports have been produced (Elder and Lane, 1970; Weiler and Murthy, 1970) which involve imagery interpretation.

Table 1. Infrared Scanner Surveys, 1967 – 1970

Date		Location	Altitude (feet)	PRT-5	Air Photos	Comments
1967						
Aug	24	W. Lake Ontario		no	no	
1968						
May	23	W. Lake Ontario	5000	no	Pentax colour only	
July	11	W. Lake Ontario	9000	yes	Pentax colour only	
	12	W. Lake Ontario	9000	yes		
Aug	13	W. Lake Ontario	9000	yes	Pentax colour only	
	15	W. Lake Ontario	9000	yes	Pentax colour only	
Sept	13	W. Lake Ontario	9000	yes	Pentax colour only	
Oct	8	W. Lake Ontario	9000	no	Pentax colour only	
Dec	5	Okanagan, B.C.	8000	no	2 Vintens colour & blk & wht	
	8					
1969						
Feb	21	E. Lake Erie	6000	no	yes	
May	21	W. Lake Ontario	7000	yes	35 mm blk & wht MK 7 camera	35 mm photos are poor quality.
	23	W. Lake Ontario	7000	yes	” ”	Hand held Pentax photos successful.
	26	W. Lake Ontario	7000	yes	” ”	
	27	W. Lake Ontario	7000	yes	” ”	
July	8	W. Lake Ontario	7000	no	35 mm colour MK 7 RC8 blk & wht	Scanner breakdown.
July	11	W. Lake Ontario	7000	yes	35 mm colour MK 7 RC8 blk & wht	Terminated-cloudiness
	14	W. Lake Ontario	7000	yes	F95 70 mm colour F95 70 mm false colour	
	15	W. Lake Ontario	7000	yes	” ”	
	24	Lake Winnipeg	6000	no	MK 7 35 mm colour	RT malfunction
Aug	22	W. Lake Ontario	7000	yes	35 mm colour MK 7	MK 7 malfunction
Sept	3	W. Lake Ontario	7000	yes	35 mm colour MK 7 RC8 colour	
	3	Lakeview Power Generating Station	1500	yes	35 mm colour MK 7 RC8 colour	
	8	W. Lake Ontario	7000	yes	35 mm colour	Terminated-cloudiness
Dec	5	E. Lake Ontario	500-1000	yes	nil	Special tests over
1970						
Feb	13	Chedabucto, N.S.	variable	yes	2 Vintens plus 35 mm super wide angle camera	
	14					
	15					
May	14	Oshawa	3000-12000	yes	Pentax only	
	20					
July	16	Oshawa	3500-12000	yes	no photos	
	17					

Other surveys during 1969 included southern Lake Winnipeg; a special low-level survey of the thermal plume from the Lakeview power station, west of Toronto on Lake Ontario; a low-level survey in eastern Lake Ontario; and a survey of ice and water conditions in eastern Lake Erie in conjunction with hovercraft trials (Cooper, 1970).

PROGRAM – 1970

The same general approach to surveys of western Lake Ontario as in 1969 was planned for 1970 (Table 1), except that surveys covered a smaller region near Oshawa. Again flights were done in series, in May, July and October, to coincide with surface programs. These include buoy networks to collect current meter and meteorological data, radiation measurements, dye diffusion studies, and lake temperature surveys conducted by CCIW, along with a complementary program of coastal studies by the University of Waterloo. Data from the May and July surveys, with comments, are included in Chapter 2.

In February, advantage was taken of the disastrous incident where the oil tanker ARROW broke up in Chedabucto Bay, Nova Scotia, to obtain infrared imagery of oil slicks on water (Thomson and McColl, in press). This imagery is also contained in Chapter 2.

CHAPTER 2

Description of the Imagery

INTRODUCTION

This section contains a brief description of the infrared imagery obtained in the program outlined in Chapter 1. Where the imagery has been used in publications the appropriate reference is made in the text. A summary of the 1967 - 1970 remote sensing program is given.

AUGUST 24, 1967

This imagery was obtained using manual level and gain controls. The changes in image grey scale resulting from manual adjustments are very distracting but good detail is apparent in the nearshore features, (see Figure 1). The Niagara River plume dominates and several points in it are worthy of note:

1. the clear delineation of the main body of the effluent

2. the relatively sharp boundary at the edge of the plume except at the northernmost portions, where large-scale entrainment seems associated with a well-defined counter-clockwise eddy

3. the wave-like pattern present over a large area at the northwestern portion of the plume (these may be associated with the generation of internal waves at the interface of the thin lens of Niagara River water at the extremities of the plume)

4. the direction of the plume is consistent with those from the Welland Canal and Twelve Mile Creek (west of Niagara River).

The warm water next to the shore in the lower portion of Figure 1 may be due at least in part to local effluent sources. The one cool region nearshore between the warm coastal water and the Twelve Mile Creek effluent may be due to divergence as a result of recent easterly winds.

MAY 23, 1968

This imagery was obtained using AGC. Consequently, most regions immediately near the shoreline contain no thermal detail (Fig. 4).

This is the first of several surveys made during the period when Lake Ontario is developing stratified conditions in a stable nearshore region ($T>4^{\circ}C$) which is separated from a more or less thermally homogeneous central region ($T<4^{\circ}C$) by a strong horizontal thermal front (the thermal bar - Rodgers, 1965). In this imagery, the thermal bar is evident along the north shore as a more or less continuous line exhibiting, however, considerable intricate detail. Off Toronto Island, for example, large wave-like characteristics are present, and extensions of warm water out into the deeper region give the impression of "breaches" in the thermal bar. The thermal bar is not so evident off the south shore, where the Niagara River plume seems to dominate. Nevertheless, long streams of warm water seem to be extended out into the deep region (note the eddy-like features associated with these).

The Niagara River water on this occasion appears to be cooler than the ambient lake temperature near the mouth which, however, is warmer than the central lake water.

The May 23rd imagery was the first indication of the amount of thermal detail which could be revealed in the scanner data.

JULY 11-12, 1968

These two surveys (Figs. 5 and 6), from consecutive days, when the lake was thermally well stratified, exhibit the following main features:

1. a general lack of detail over the central portion of the lake

2. a "thermally clastic" region off eastern Toronto and Oshawa

3. a cyclonically-shaped swirl in the central region, which persisted in the second survey

4. no sharp contrast between the major effluents along the south shore and the main body of the lake.

AUGUST 13-15, 1968

These two surveys (Figs. 7 and 8), were taken following a 6-day period of westerly winds. On the 15th, winds were light and south-easterly.

Along the north shore, there is no strong evidence of upwelling in the 13 August data although (in light of the second set of data) a band may have been developing off eastern Toronto. In the northeast portion of the mosaic for

August 13, parallel bands separated by a few hundred metres distance suggest the surface manifestation of internal waves. The Niagara River plume is directed eastward, along the New York coast, but is not strongly contrasted, away from the immediate source.

The 15 August data clearly reveals several major features:

1. one generally continuous band of cool water, interpreted as a zone of upwelling more or less parallel to the north shore, centered off Toronto Island, and two other bands of relatively cold water in the northwestern corner of the lake (also interpreted as upwelling).

2. the major effluents along the south shore are generally dispersed straight out into the lake, with the large Niagara River plume distinctly separated from the remnants of its previous disposition along the New York shore.

The August 15 data presents a picture of the lake which suggests that the large-scale divergence induced by the previous westerly winds is still present, while the surface effluents on the south side have responded quickly to the wind change and reflect the present conditions.

SEPTEMBER 13, 1968

This mosaic (Fig. 9), contains a marked lack of thermal detail in the main body of the lake. The major plumes along the southern shore are oriented along the New York coast. There is some slight evidence of possible upwelling developments along the north shore (note the scalloped edge of the feature east and offshore from Toronto Island).

OCTOBER 8, 1968

This is one of the most interesting pieces of thermal imagery obtained in the program. Ground truth data revealed that almost one third of the surface of Lake Ontario consisted of upwelled water (northwestern portion of the lake, Figure 10). In the lower portion of the mosaic, large areas of indifferent detail, representing epilimnion water having a surface temperature of approximately 16°C, are separated in intricate fashion from meso- and hypolimnion water with temperatures from 8°C at the boundary down to 4°C along the Toronto coastline. Large-scale thermal features, including cyclonic swirls, dominate the northern portion. Unfortunately, no PRT-5 data were obtained on this survey. A continuous sharp thermal boundary, parallel to the coast east and south of Toronto Island, cannot be explained.

MAY 21-27, 1969

A considerable amount of ground truth was obtained with these 4 surveys (Figs. 11-18), and more work has been done in the interpretive analysis than for other imagery (Elder and Lane, 1970).

The period of the survey was similar to that of May 23, 1968, although the thermal bar was further advanced. The major features are:

1. the detailed delineation of the Niagara River plume

2. the two contrasting types of imagery:

   (i) May 21 and May 26 imagery, when surface wind mixing was present, lacks fine detail, surface temperatures reflect the thermal bar condition;

   (ii) May 23 and May 27 imagery, when surface winds were virtually absent, contains extensive detail, higher surface temperatures, no evidence of thermal bar condition

3. the fine structure in the central portion of the lake, especially adjacent to the northern boundary of the Niagara River plume, is of great interest (these have not been adequately explained but seem to be associated with convective mixing)

4. the May 21 imagery in particular contains examples of apparent extensions of warm coastal water out "through" the thermal bar into the central part of the lake

5. the 4°C isotherm moved offshore at a rate of 3 to 6 km per 5 days, between May 21 and 26

6. a few of the west-east ship tracks, covered by white tape in the May 23 imagery, had a remarkable zig-zag pattern, with each segment almost at right angles to its neighbours (segment lengths were approximately 200 - 300 metres)

7. one of the west-east ship tracks, running east from off the Niagara River mouth was broken at a shear line (in cases where a ship can be located in the imagery and its speed determined, shear speeds could be calculated).

JULY 14-15, 1969

On the first of these two days, the thermal contrast in the lake features was low (Fig. 19), similar to the imagery of July and August, 1968. Except for the coastal region on the north side, where they were as low as 17.5°C, PRT-5 values (uncorrected) were between about 18.5°C and 20°C. Values a few tenths of a degree higher were recorded east of the Niagara River mouth. Although a relatively warm-appearing plume was evident from the Niagara River, the core of the river effluent was colder (a few tenths of C°, from PRT-5 data) than the ambient waters.

In the coastal region west of the Welland Canal, a banded structure exists which is reminiscent of the July and August, 1968, imagery near Toronto.

The July 15th imagery (Fig. 20), is also characterized by a lack of major thermal features. However, the PRT-5 data contains values of 2-4°C higher than those of 14 July. The entire Great Lakes region during this period was covered by an atmospheric high pressure area. Air temperature values at stations around western Lake Ontario also increased by a few degrees Celsius.

AUGUST 22, 1969

The PRT-5 data associated with this imagery (Fig. 21), points out the cooler surface temperatures along the north coast which is consistent with a predominance of westerly-component winds prior to this survey. During the survey, surface winds were generally south-westerly at Toronto Island airport so that the streakiness noted in the imagery in the western portion would roughly parallel the wind.

SEPTEMBER 3, 1969

A striking feature of this imagery is the occurrence of apparent eddy-like structures along the edges of thermal boundaries (Fig. 22). Several of these boundaries, some apparently associated with the major effluents along the south shore extend well out into the lake. Another is oriented parallel to the north shore eastward from just west of Toronto Island.

The narrow cool band situation eastward and northward from the Niagara River mouth is confirmed in the PRT-5 data. These data from along the entire south shore suggest that a rather broad region of cool surface temperatures exist, interrupted by the warm effluents from the 3 major rivers. This is consistent with the predominance of south and east winds during the period of the survey.

MAY 14, 1970

Two surveys (Figs. 23 and 24) of the coastal region adjacent to Oshawa were separated by about 3.5 hours. Some of the features, such as the track of the survey launch or the curved plume on the eastward end of the imagery, persisted throughout the 3.5 hour period. Other features such as the cellular structure and the near shore thermal structure changed over the same time period (Elder and Thomson, 1971). The former has dissipated by the time of the second flight, and the latter has changed to a more turbulent structure.

The dissipation of the cellular structure is consistent with the interpretation that the cells are the result of daytime heating in the absence of strong surface mixing. It is interesting to note that launch observations indicated calm or glassy surface conditions in areas where the cellular structure occurred. In areas where ripples or small waves were reported, no cellular structure occurs.

MAY 20, 1970

These three mosaics (Figs. 25, 26 and 27) show, in general, a uniform surface structure without any well-defined major thermal features (Elder and Thomson, 1971). The apparent movement of colder water towards shore and the near disappearance of the cell structure may be related to the change in surface wind. The wind was light, 2-3 mps, during the first two periods but increased to 6-7 mps during the last period.

JULY 16 and 17, 1970

The infrared imagery of July 16 shows a good example of upwelling along the Oshawa shore (Fig. 28). The time required to produce the upwelling can be estimated from meteorological data (Elder and Thomson, 1971). In this case, only about seven hours had elapsed since the change from an onshore to an offshore wind. The apparent warm "plumes" along the shore line also give an indication of an eastward along-shore transport.

The mosaics for July 17 show (Figs. 29 and 30) that warmer water is moving inshore again in rapid response to a wind change, though a narrow band of cold water remains near the shore. The large offshore eddy of cold water is evident but unexplained. It should be noted that the image of July 17, differs in scale from that of July 16.

LAKE ERIE ICE SURVEY

This infrared imagery was obtained in February 1969, during an ice and water survey of Lake Erie. The example shown in Figure 31 is a section of the Lake Erie shoreline. The dark area adjacent to the shore is due to the AGC of the scanner. Ground truth of the area covered by this image indicated that the ice conditions on the lake were rough and consisted of ridges and fractures. In this particular area there was no open water present.

CHEDABUCTO OIL SPILL SURVEY

In February, 1970, the oil tanker ARROW went aground in Chedabucto Bay, Nova Scotia. Through the efforts of the Physical Limnology Section at CCIW a number of flights were made over the wreck. During the flights both photographic and infrared imagery were obtained. It was hoped that this imagery would assist in the monitoring and control of this, and future oil spills of this nature. (Lane, McColl, and Thomson, in preparation).

Figure 32 (Plus-X film with a blue filter) shows the twin plumes of oil leaking from the two halves of the ship which were separated by about 300 m. An example of the infrared imagery is shown in Figures 33 and 34. The very dark patches on infrared imagery are due to emission from the more concentrated and central parts of the slick. As the distance from the center of the slick increases the contrast on the infrared imagery decreases. However, the main body of the slick is reasonably well outlined. There is time lapse of about 2 hours between the aerial photograph and the infrared imagery.

SUMMARY

In terms of the initial objectives of this program, infrared imagery has proven that it delineates clearly major surface thermal features in large lakes (represented by Lake Ontario). These include effluent plumes, upwelling boundaries, and the thermal bar. Ground truth has confirmed the interpretations concerning these features.

Further, the imagery appears to reveal information on the dynamics of these and other large-scale features, such as the large gyre-like feature noted in Figure 1. Thus far, lake current data have not been available, or if available, data were not fully exploited for confirming these qualitative yet dynamic interpretations. However, thermal patterns along the boundaries of the thermal bar, as shown in the imagery, have presented a picture of the dynamic complexity of this important feature, revealing the occurrence of long tongues of coastal water extending far into the central part of the lake, and providing insight into the nature and extent of shear in the vicinity of the thermal bar. Also, the apparent complexity of an upwelling boundary on one occasion (Fig. 4) and the apparent simplicity on another (Fig. 5) may in the future be of value in studies of the dynamics of this common event in the Great Lakes. The use of repeated survey data in cases like this, where the features are identifiable from survey to survey, is also of use in water movement analyses, especially where the response of the lake to changing external factors can be determined (Weiler and Murthy, 1970, for example).

In addition to the delineation of large-scale features the imagery is capable of revealing intricate thermal structure of smaller scale. For many of these cases, it is doubtful whether boat survey techniques will ever be able to collect ground truth sufficiently detailed to compare with the imagery. Much of the detailed structure at the borders of the larger scale features, such as the leading edge of thermal plumes, small eddies, and the banded structure often noted in coastal regions are examples. However, the most interesting example of small-scale structure has been the cell-like phenomenon located in May 1969 (Fig. 13), and May 1970 (Fig. 25), offshore from the thermal bar. Surface conditions have been favorable in each case for strong thermal convection in the lake in these regions and the interpreter of the imagery is led to consider the mechanism of Benard convection cells. A more detailed future examination of this feature may reveal much about the mixing processes due to surface heating prior to complete spring circulation.

An infrared scanner can be expensive, in terms of both capital outlay and operational/maintenance costs. The experience of using a scanner in an experimental program has led to the following recommendations:

Surveys of relatively large-scale thermal features can be conducted satisfactorily without ground truth but should include airborne infrared thermometer measurements. These surveys can be most useful for making assessments of the surface characteristics of phenomena of importance to movements of heated waters and the pollutants they may contain and of other features of significance to water quality in large lakes, such as upwelling and the Lake Ontario thermal bar. However, while these surveys will add to the knowledge of the behavior of these features, additional work must be done *in situ* coincident with the aerial surveys, in order to enable future interpretations of surface data in terms of sub-surface conditions. In order to properly conduct such air/surface studies, aerial data must be processed more quickly than at present, to enable rapid redeployment of surface facilities when necessary.

Infrared scanning can be very useful in studies of smaller-scale features and processes, such as thermal convection, internal waves and the detailed structure of other important thermal features. It is recognized that studies of these phenomena are necessary if limnologists are to improve their understanding of basic physical processes in lakes. It is clear, however, that experiments of this type must rely on well planned and executed ground truth programs. Airborne surveys alone can provide much food for speculation and may ultimately lead to appropriate surface surveys but it is felt that enough of this type of survey has been done, at least for the Great Lakes (specifically Lake Ontario) and that future programs must be a part of specialized *in situ* studies.

In Lake Ontario, many large-scale thermal features revealed in the infrared imagery are also observed in "standard" photography, because river plumes are turbid and thermal stratification is usually qualitatively correlated with turbidity stratification. Consequently, one can visually "see" thermal plumes, the thermal bar, and upwelling boundaries. The extent to which this is generally true should be examined, not only for Lake Ontario but for representative lakes of other types, so that less expensive camera systems can be substituted for scanners for appropriate surveys. For studies of the nature of subsurface sediment transport, however, photography may be useful in combination with scanner imagery for separating the purely surface aspects from deeper turbidity plumes.

The value of infrared thermometry surveys is well known, as shown by the success of the periodic Meteorological Service of Canada surveys of the Great Lakes (Irbe, 1969). However, in addition to the well recognized problems associated with correcting for atmospheric effects, two other general points are proposed:

(i) On days when solar heating is at a high level and lake surface mixing processes are minimal, the "skin" temperature of the lake may be several degrees Celsius higher than the temperature which may be observed even with a bucket technique. For certain uses, such as computations of air/lake heat exchange and evaporation, this skin temperature value is useful. However, for synoptic limnological studies, including studies of the thermal bar (where specific temperature values under normal mixing conditions are important), these relatively transient values may be very misleading.

(ii) Infrared thermometry surveys along widely spaced tracks may also be misleading during periods of complex lake activity (spring and autumn), where items of major significance may be between the tracks. Ship surveys suffer from the same limitations but often must make the sacrifice for reasons of time economy. Airborne programs during these periods should attempt to trade off some of their "synopticity" advantage for more detailed coverage.

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APPENDIX

FIGURES 1 – 34

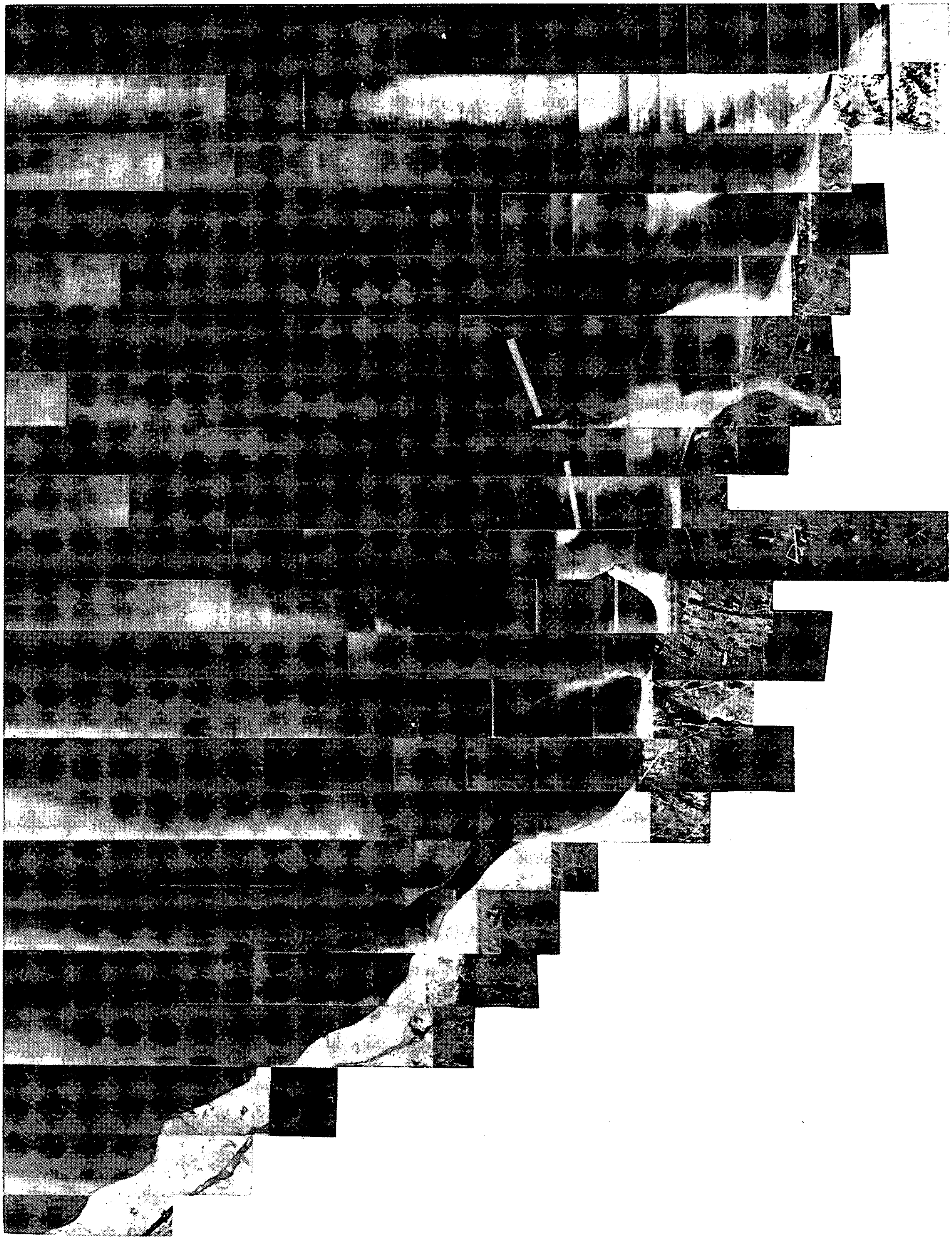


Figure 1. Infrared imagery, August 24, 1967.

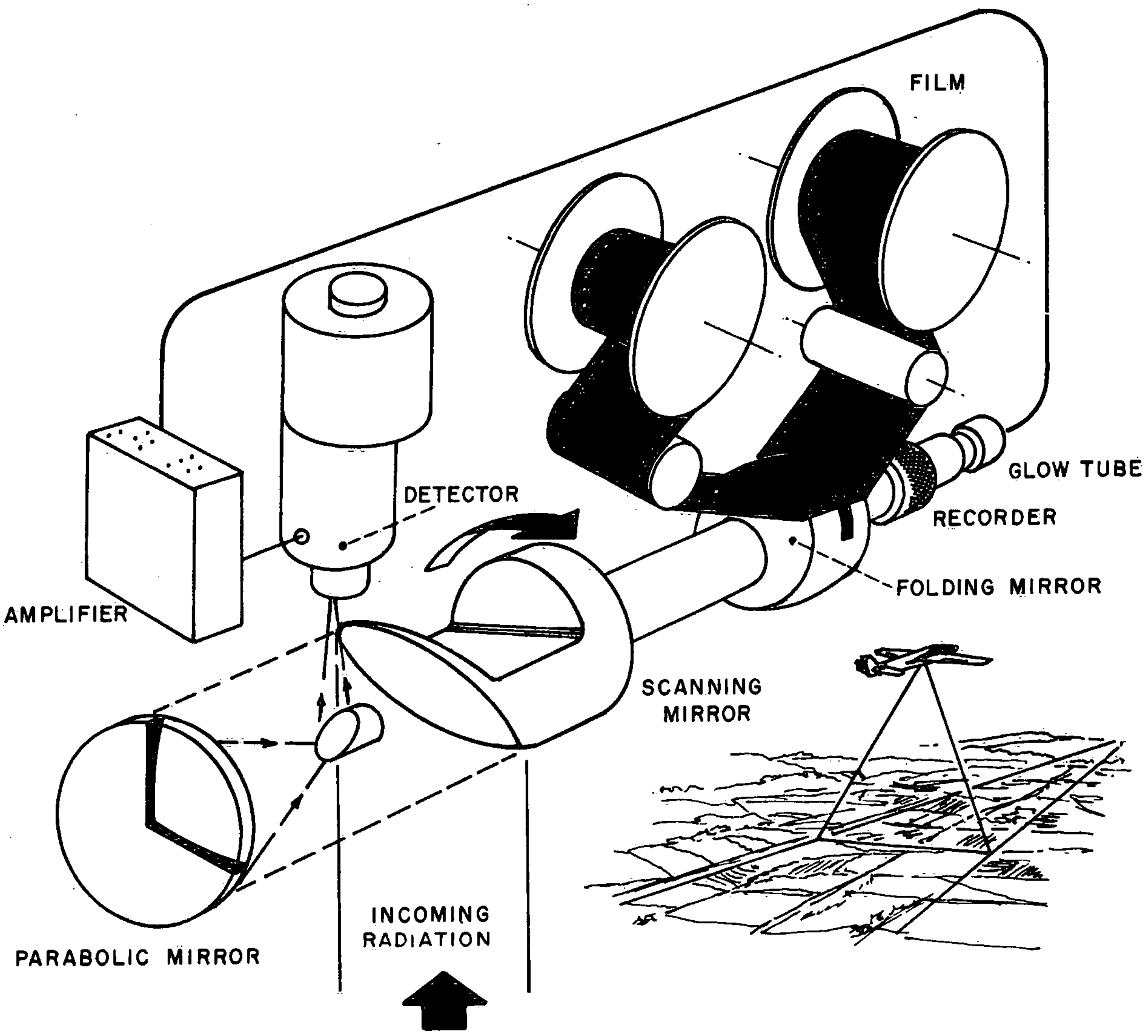


Figure 2. Infrared scanner system.

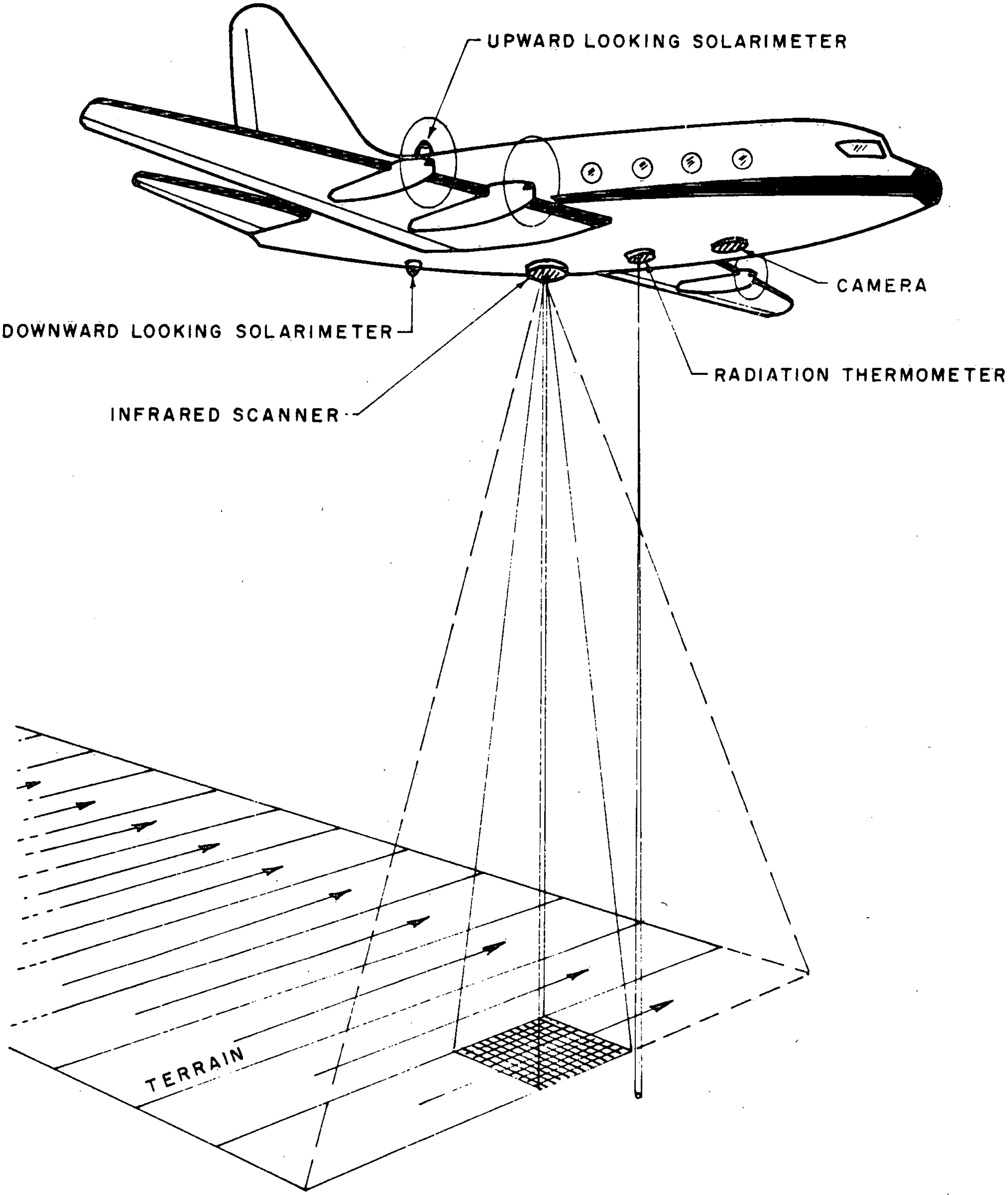


Figure 3. Airborne line scanner.

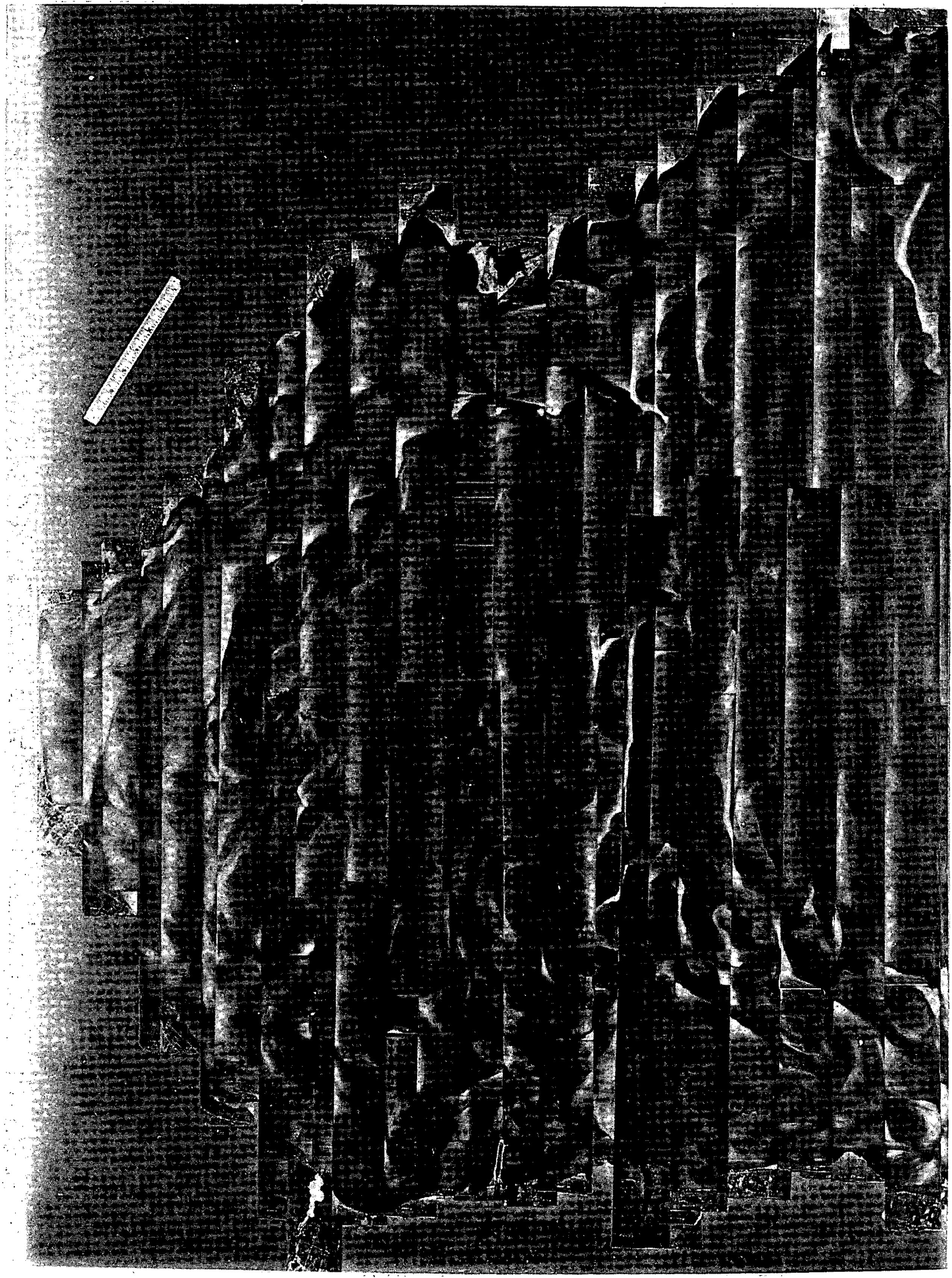


Figure 4. Infrared mosaic, May 23, 1968.

Figure 5. Infrared mosaic, July 11, 1968.

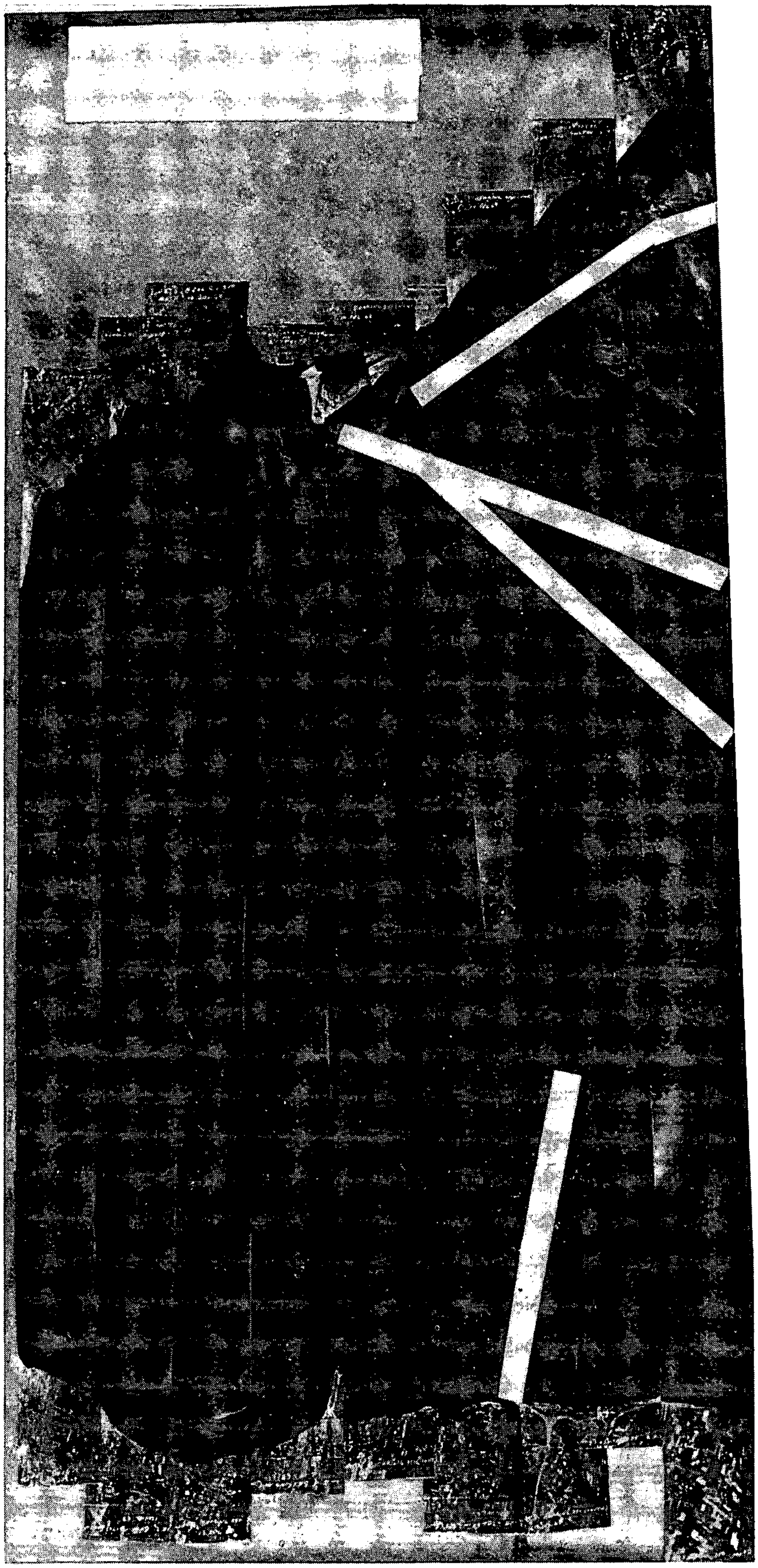


Figure 6. Infrared mosaic, July 12, 1968.

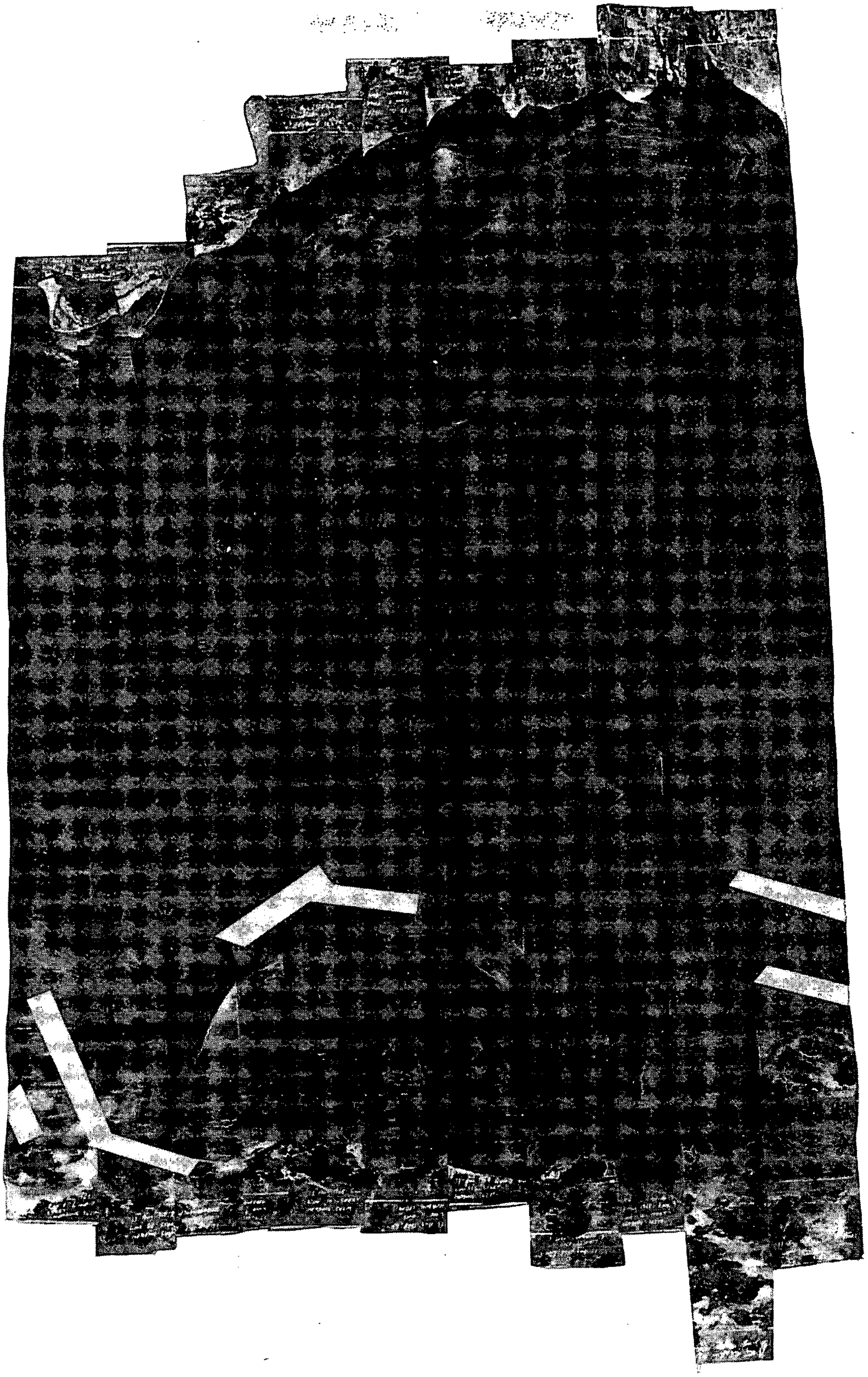


Figure 7. Infrared mosaic, August 13, 1968.

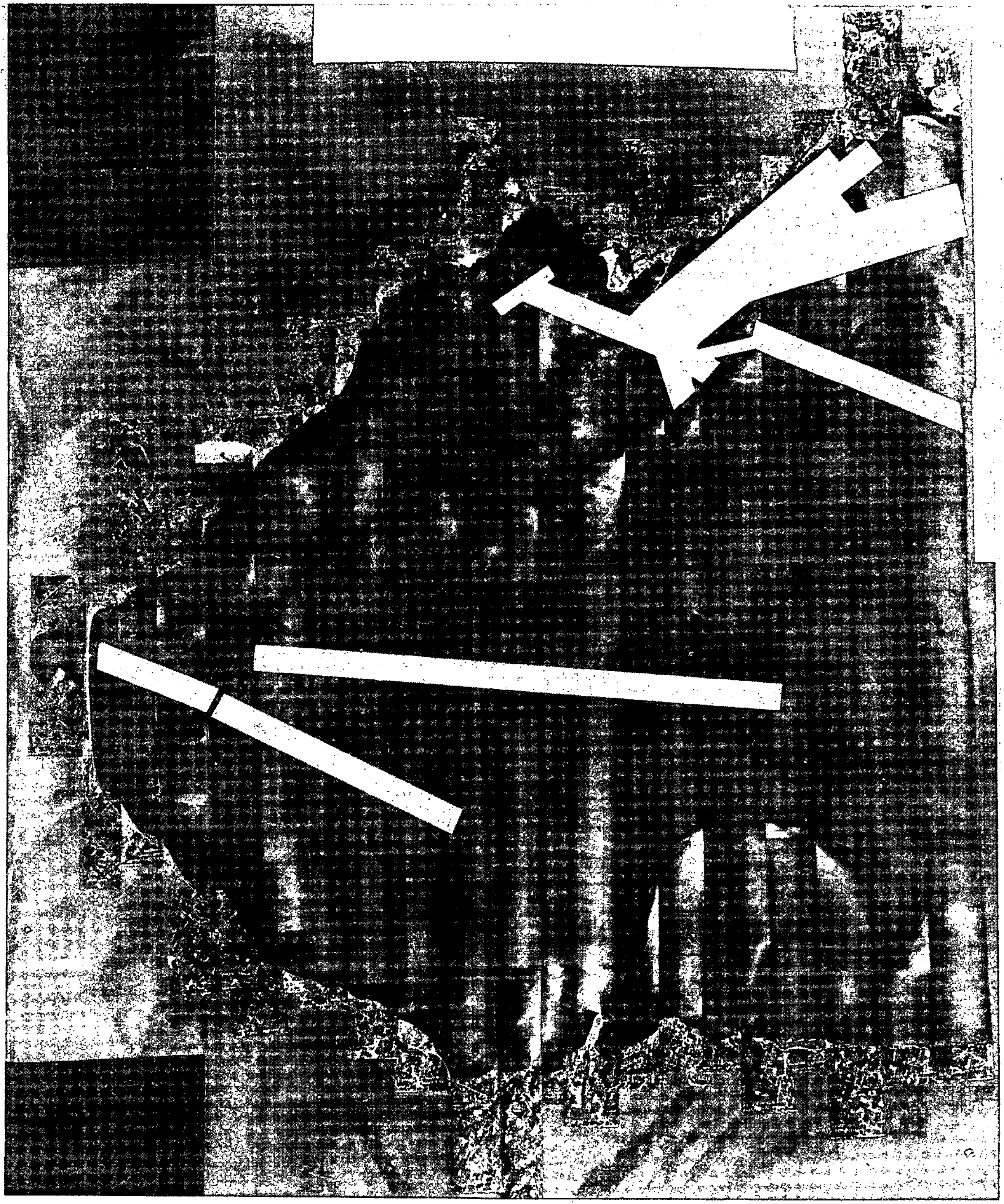


Figure 8. Infrared mosaic, August 15, 1968.

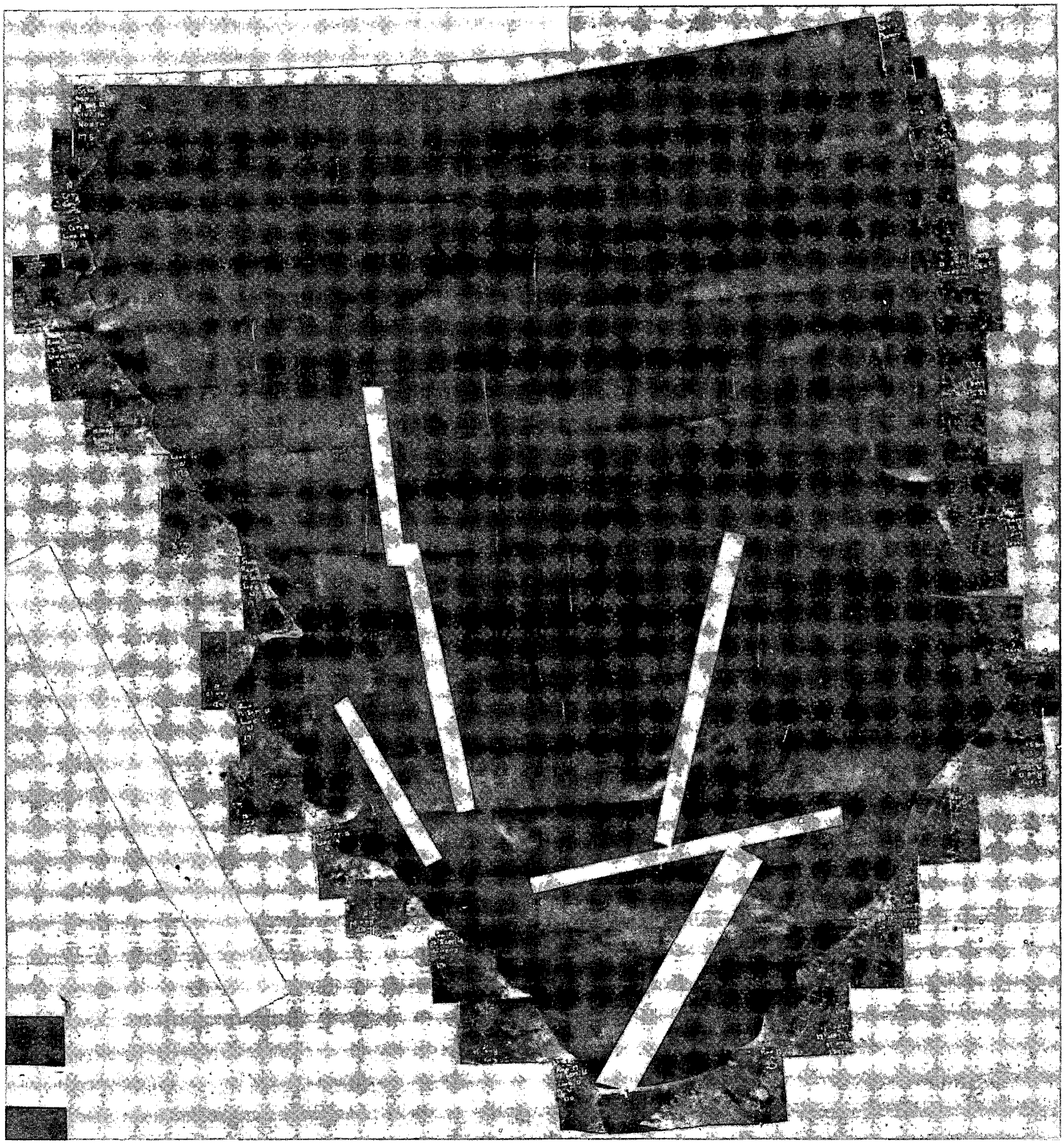


Figure 9. Infrared mosaic, September 13, 1968.

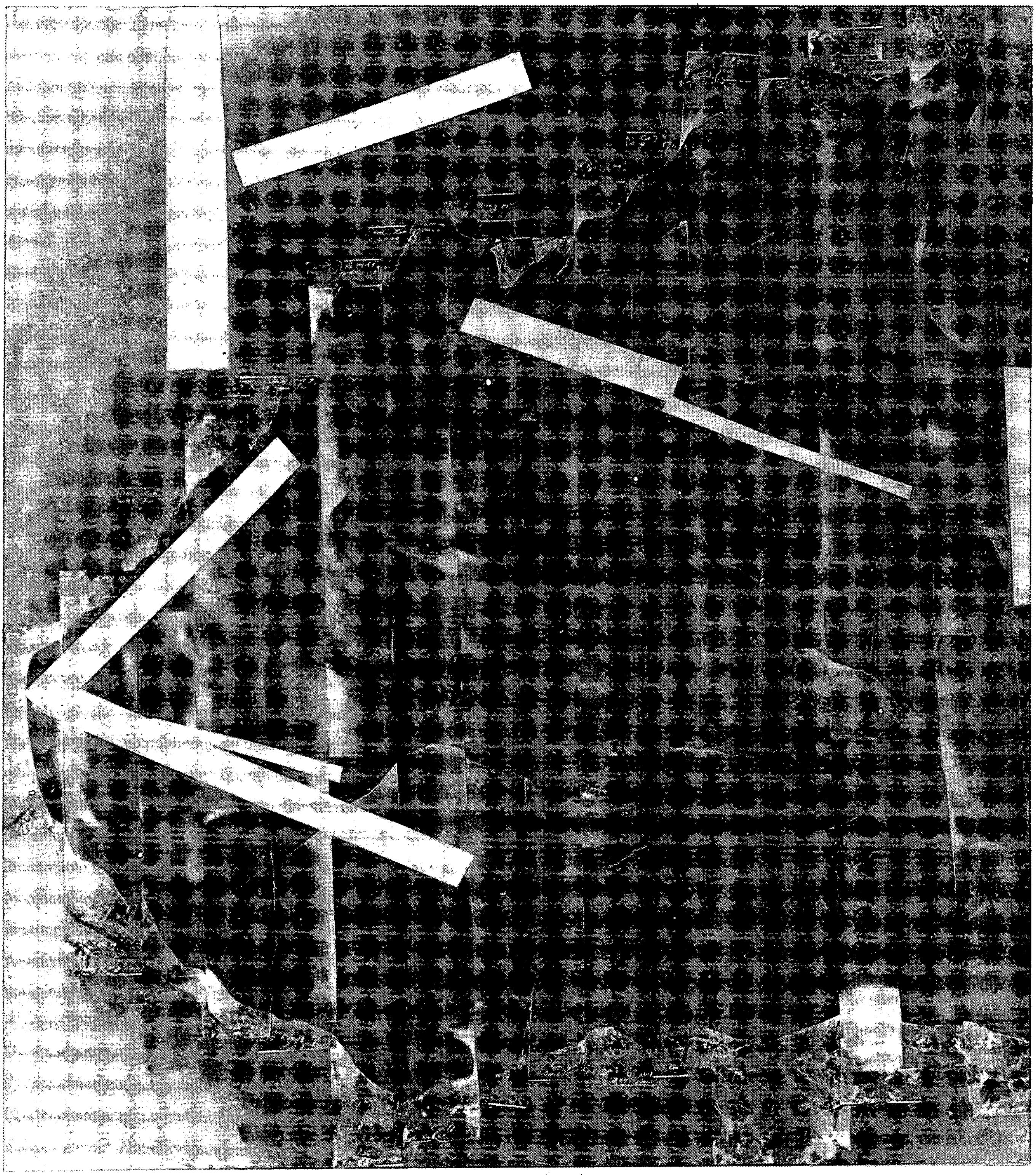


Figure 10. Infrared mosaic, October 8, 1968.

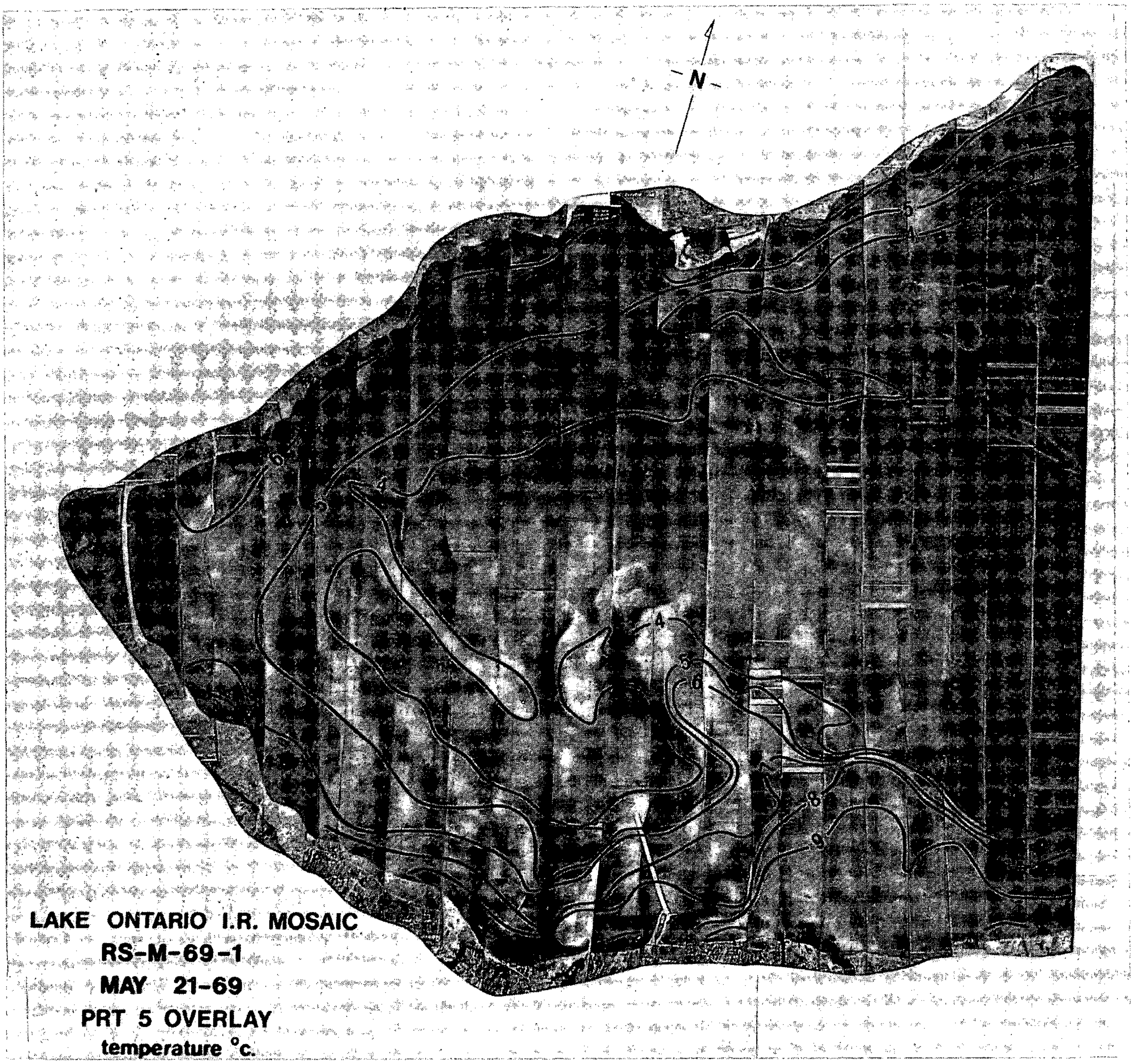


Figure 11. Infrared mosaic, May 21, 1969.

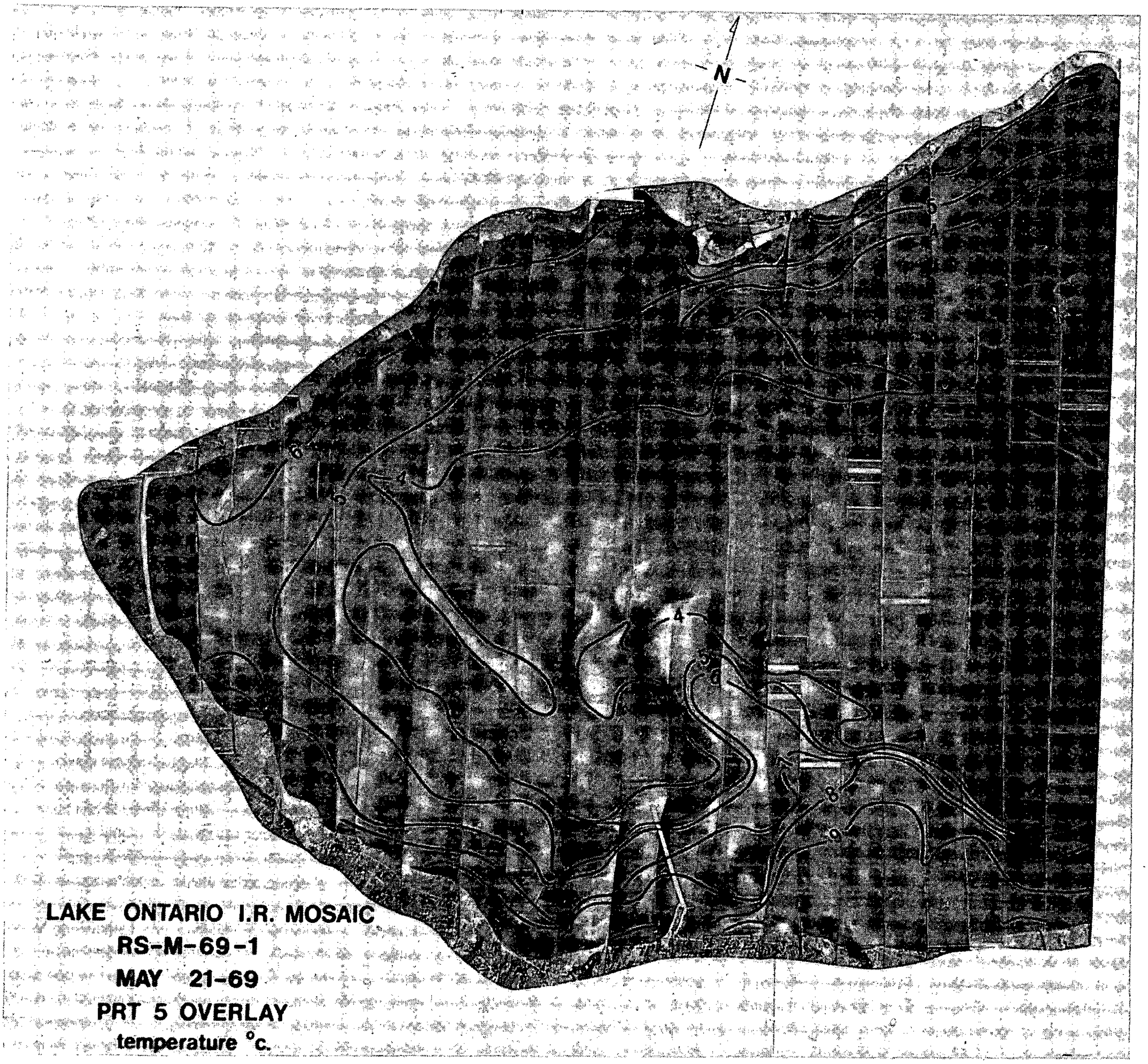


Figure 12. Infrared mosaic, with PRT-5 overlay, May 21, 1969.

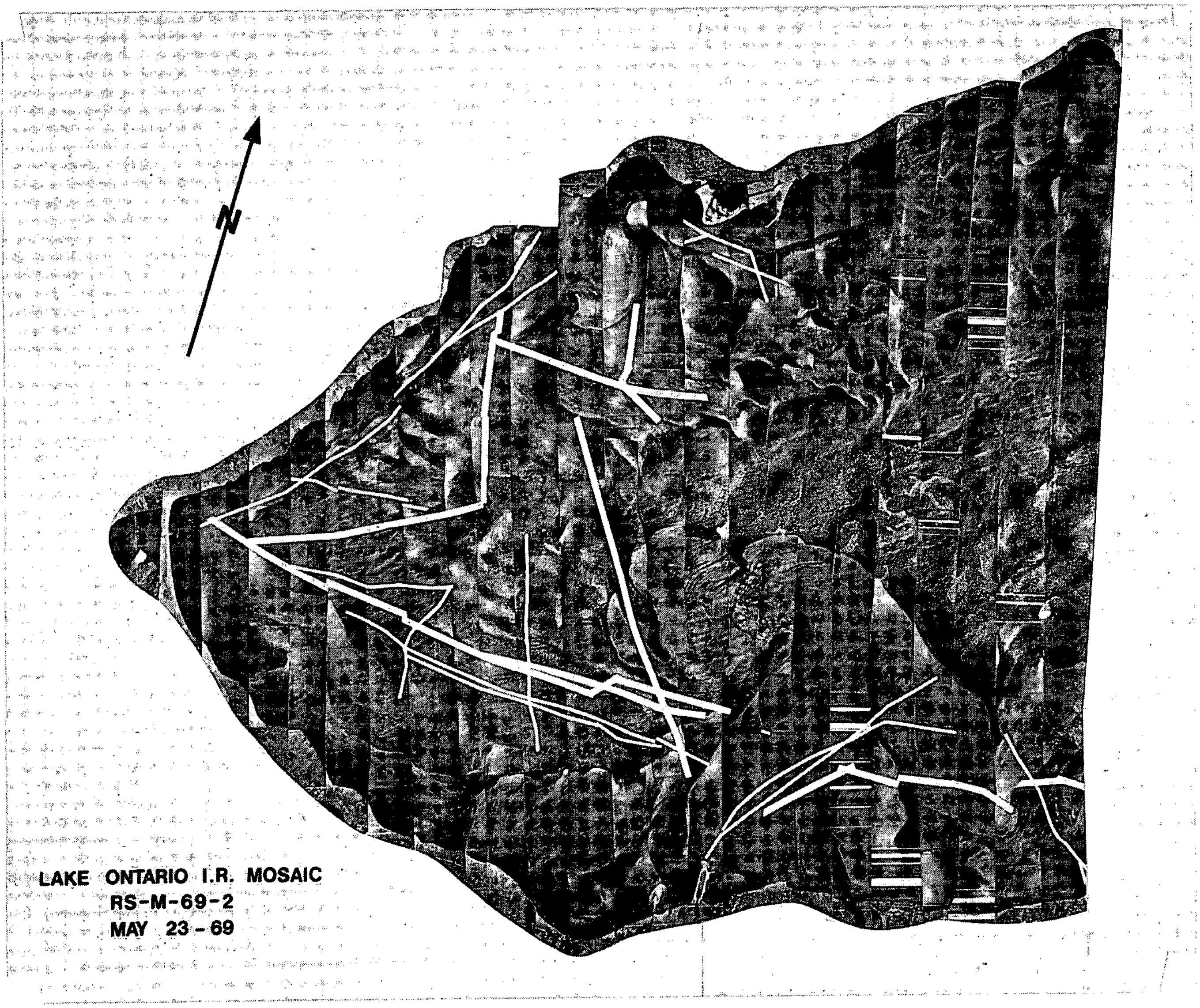


Figure 13. Infrared mosaic, May 23, 1969.

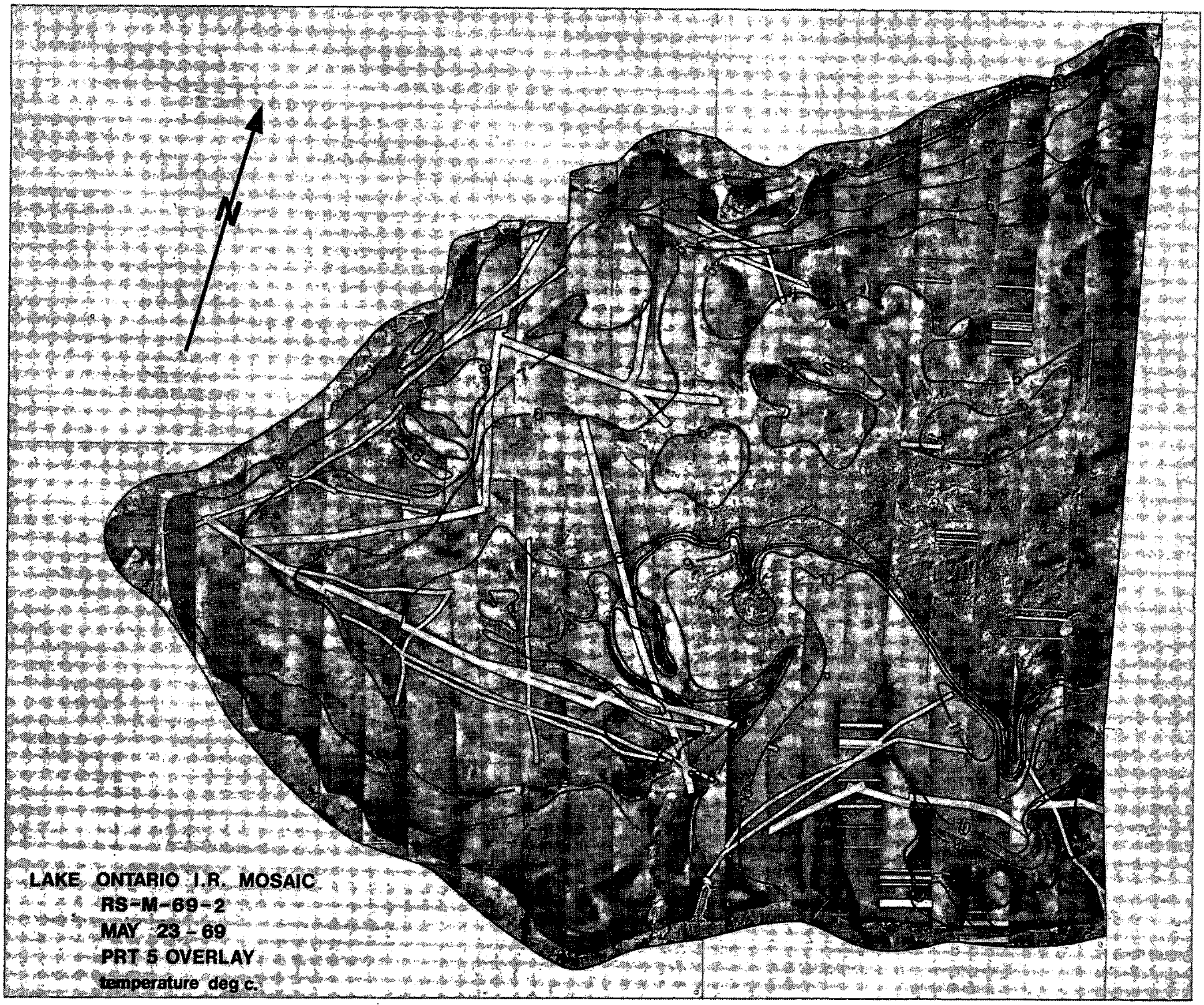


Figure 14. Infrared mosaic, with PRT-5 overlay, May 23, 1969.

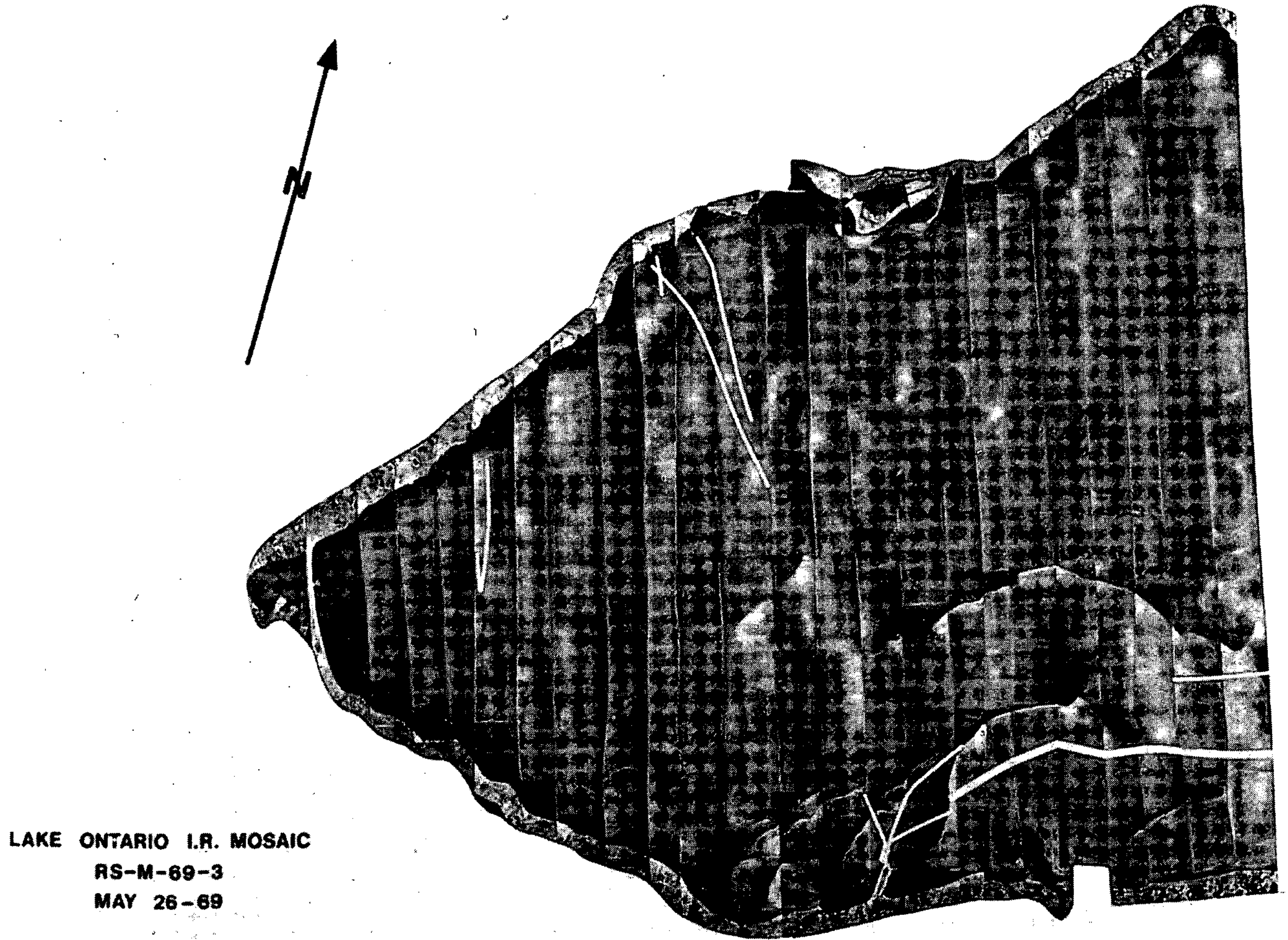


Figure 15. Infrared mosaic, May 26, 1969.

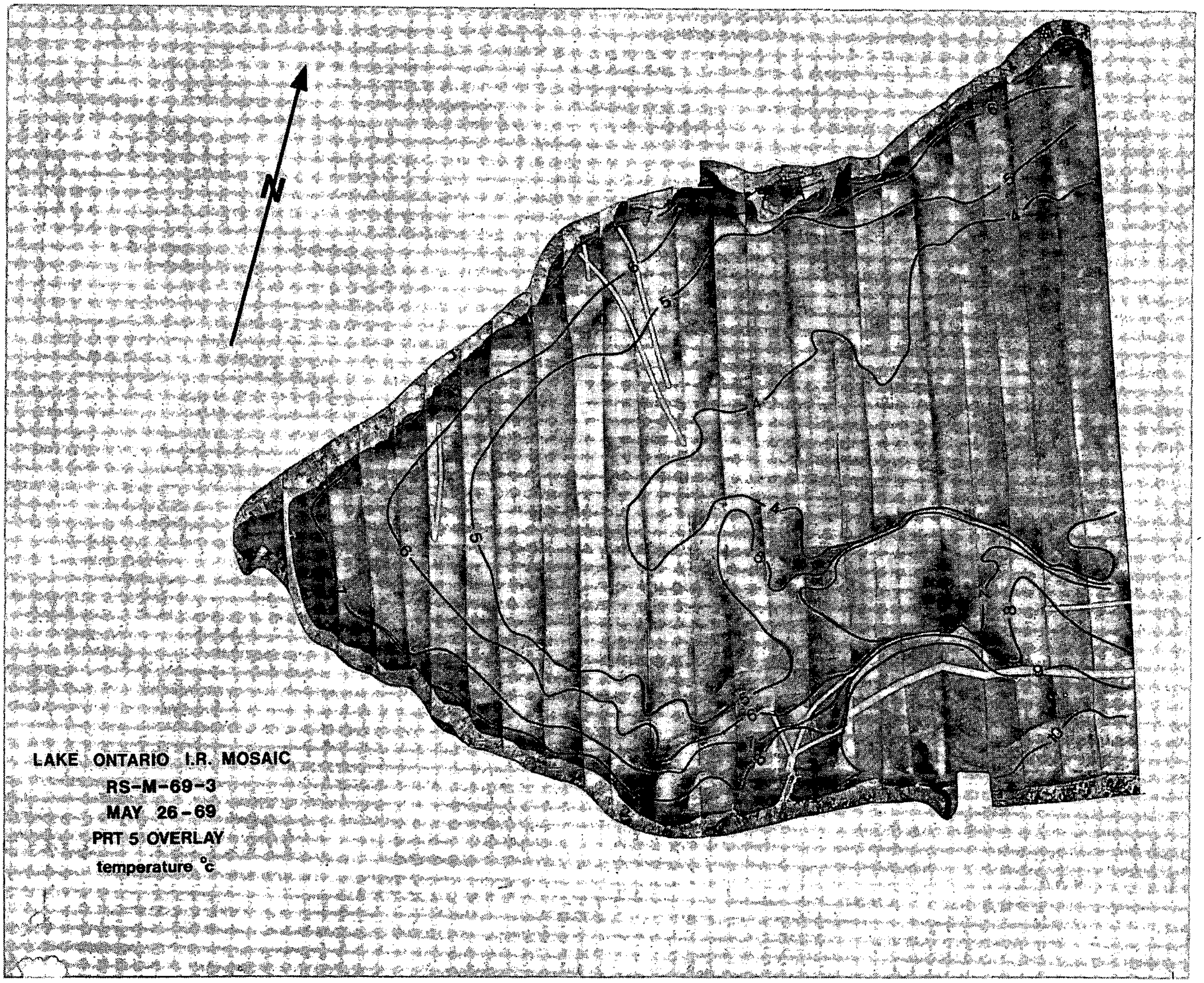


Figure 16. Infrared mosaic, with PRT-5 overlay, May 26, 1969.

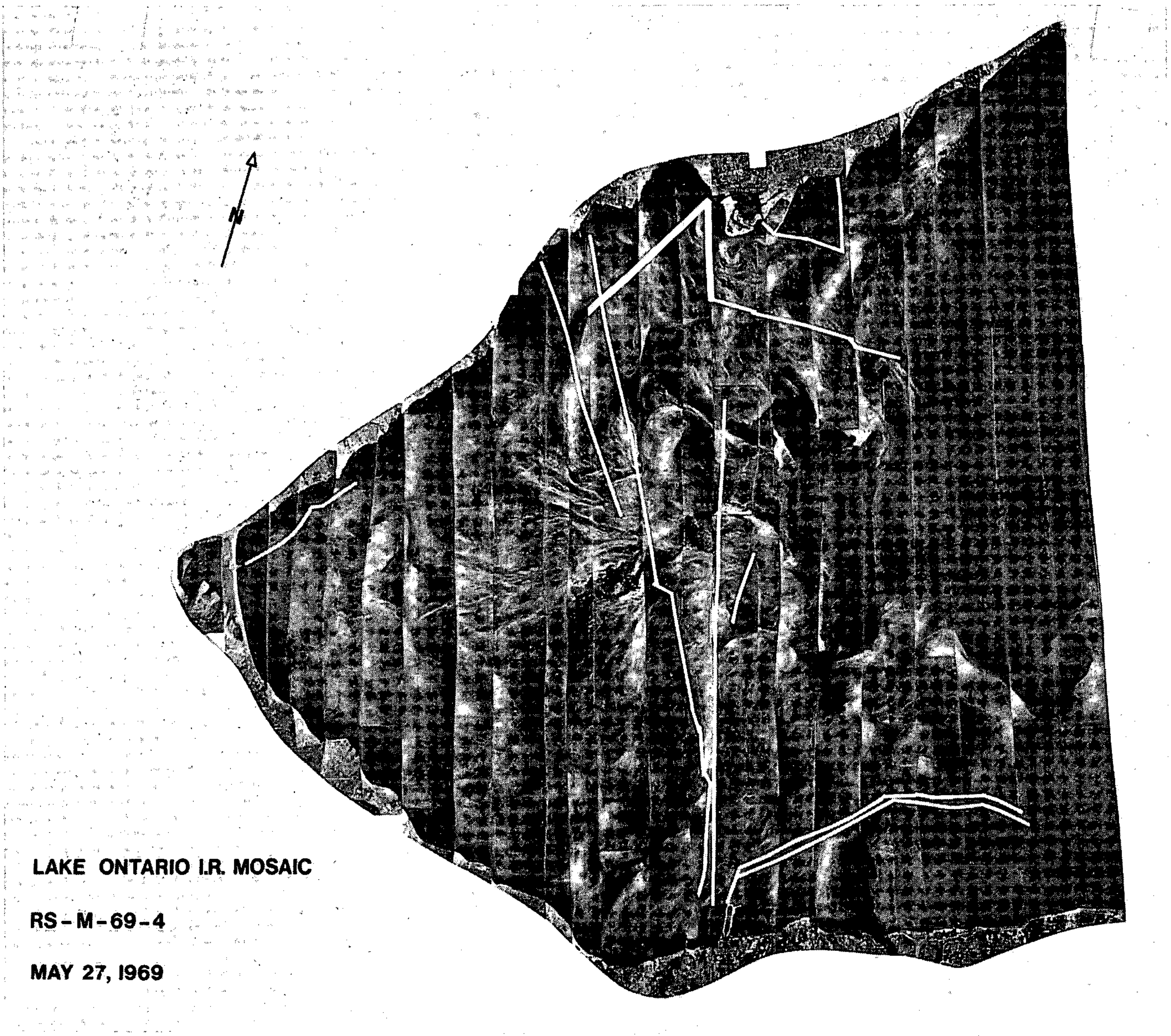


Figure 17. Infrared mosaic, May 27, 1969.

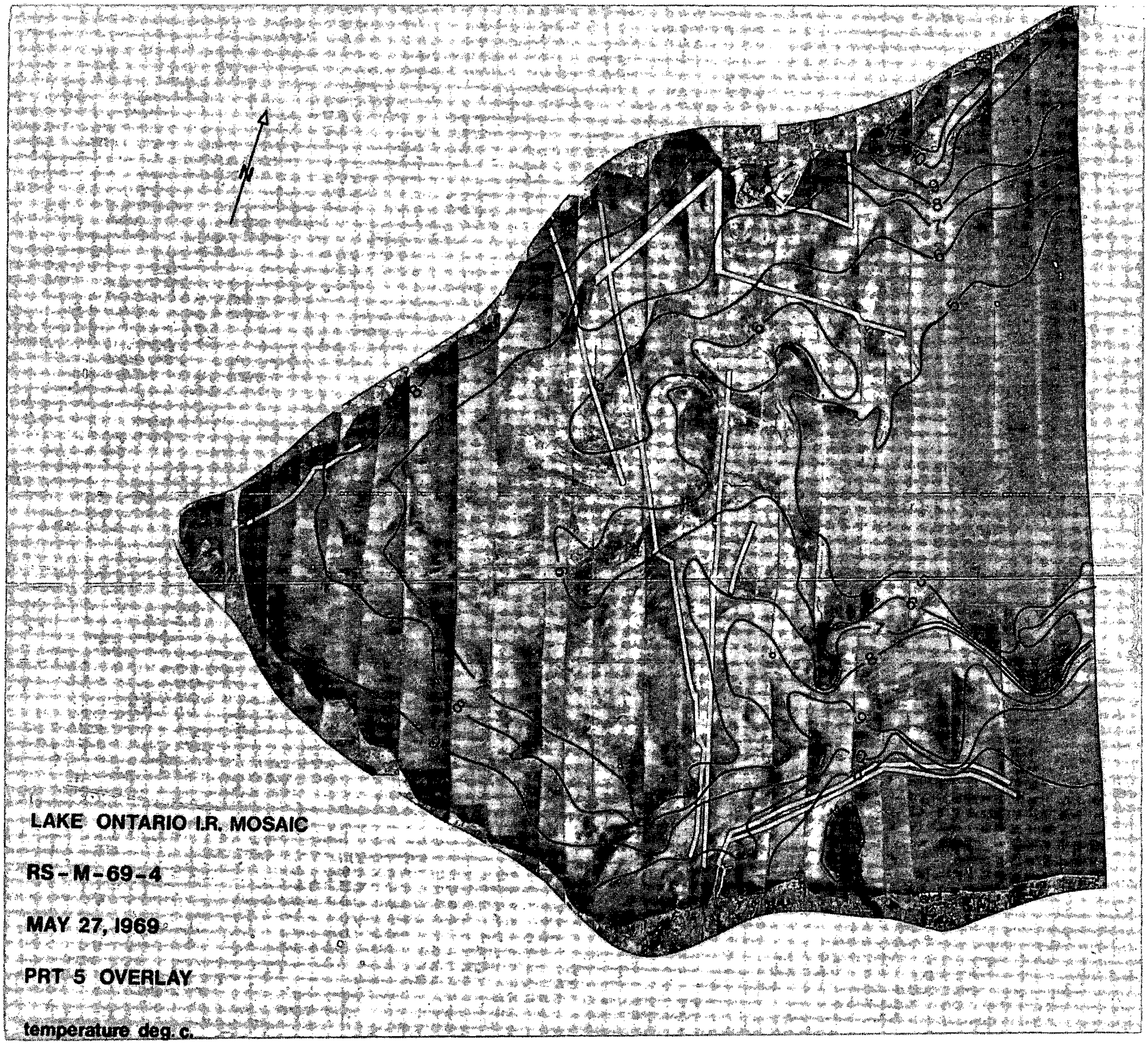


Figure 18. Infrared mosaic, with PRT-5 overlay, May 27, 1969.

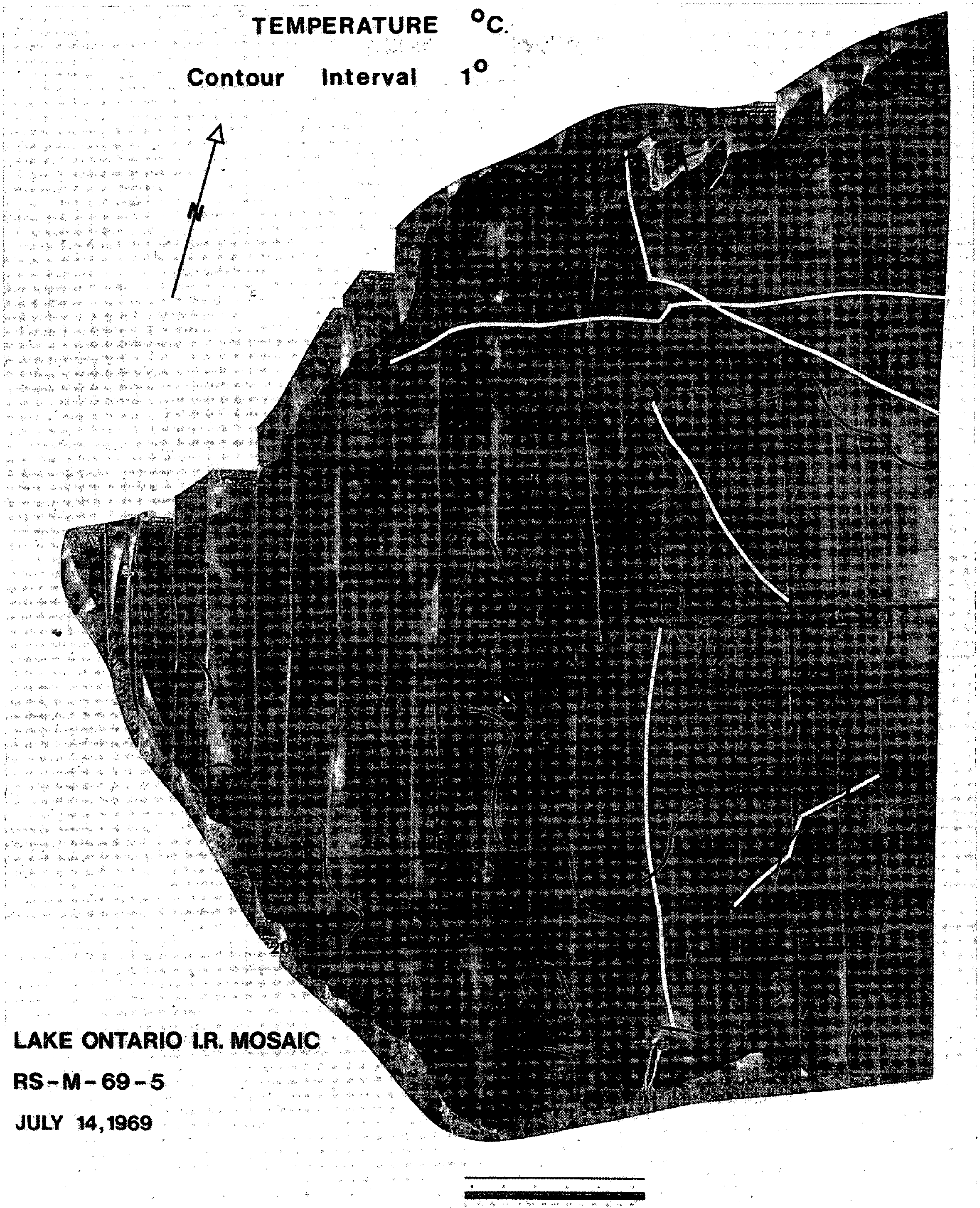


Figure 19. Infrared mosaic, with PRT-5 overlay, July 14, 1969.

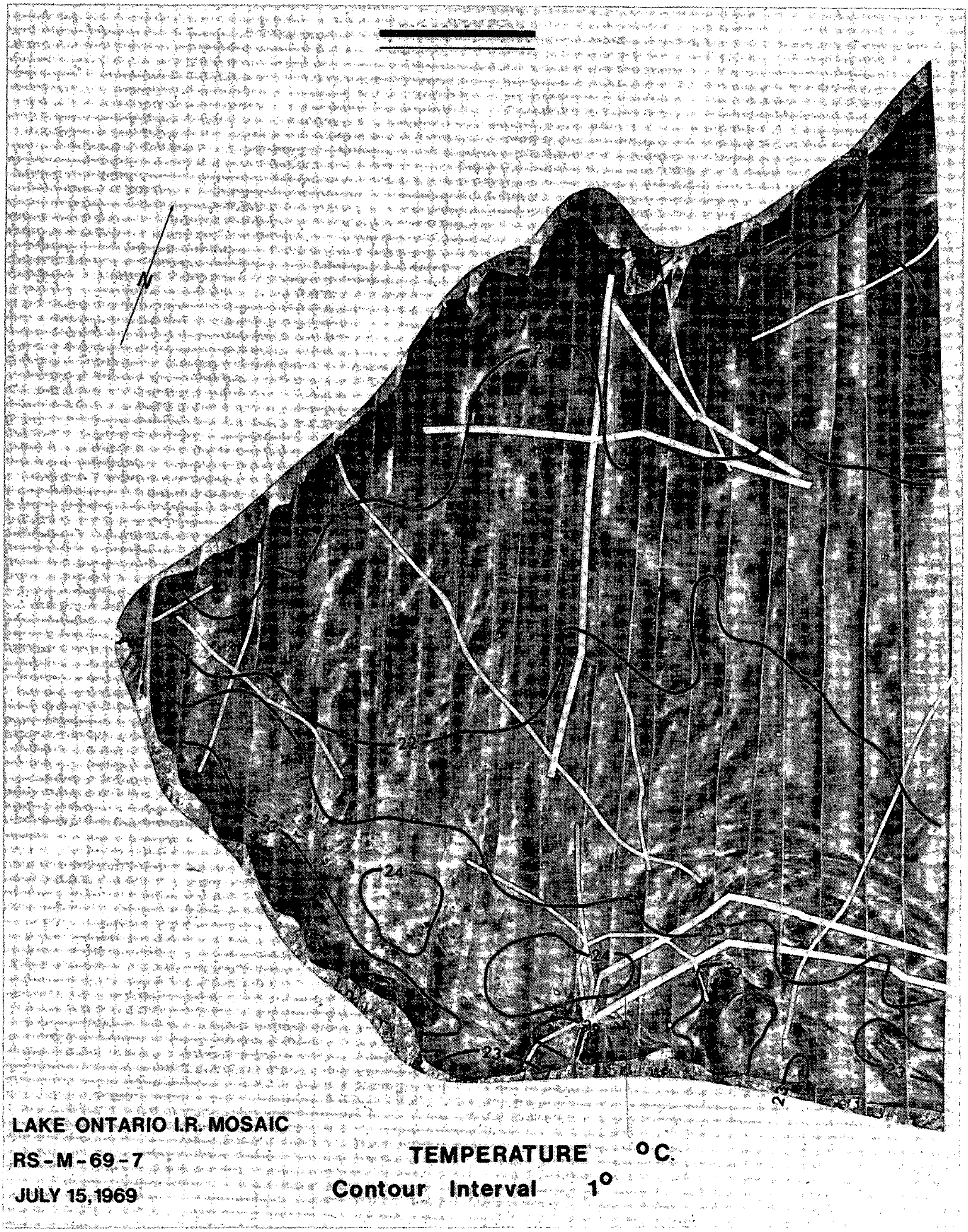


Figure 20. Infrared mosaic, with PRT-5 overlay, July 15, 1969.

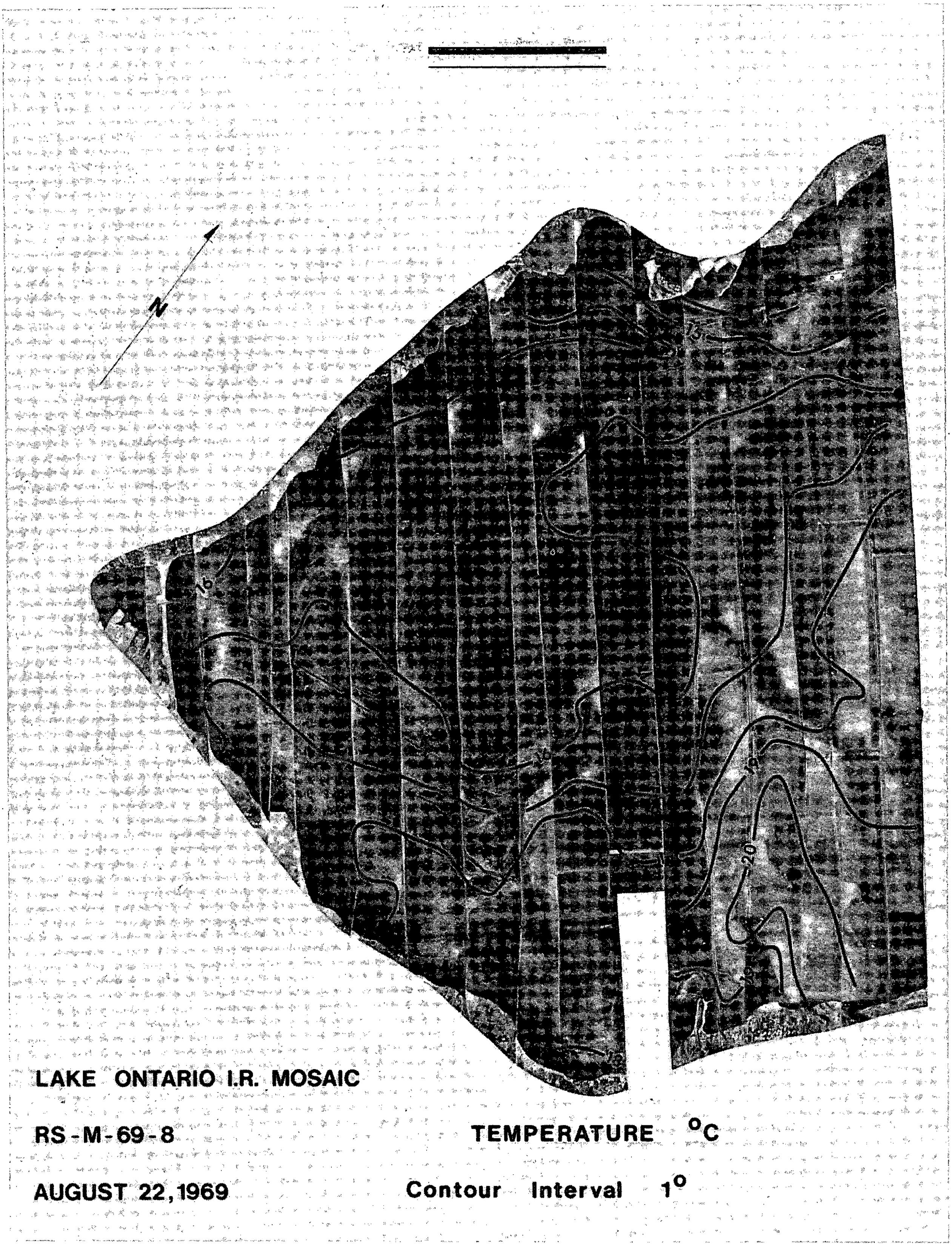
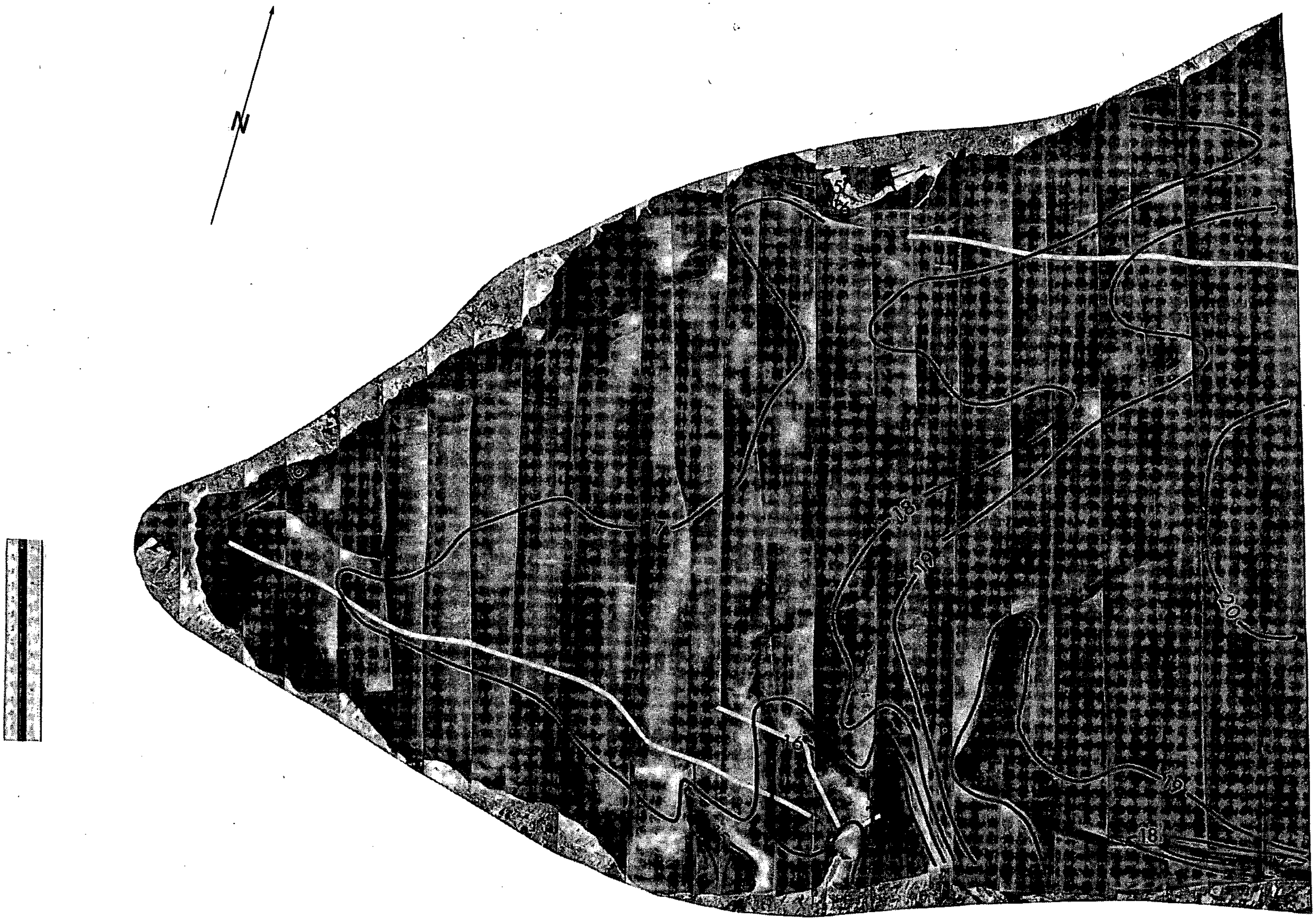


Figure 21. Infrared mosaic, with PRT-5 overlay, Aug. 22, 1969.



LAKE ONTARIO I.R. MOSAIC

RS-M-69-9

SEPTEMBER 3, 1969

TEMPERATURE °C.

Contour Interval 1°

Figure 22. Infrared mosaic, with PRT-5 overlay, Sept. 3, 1969.

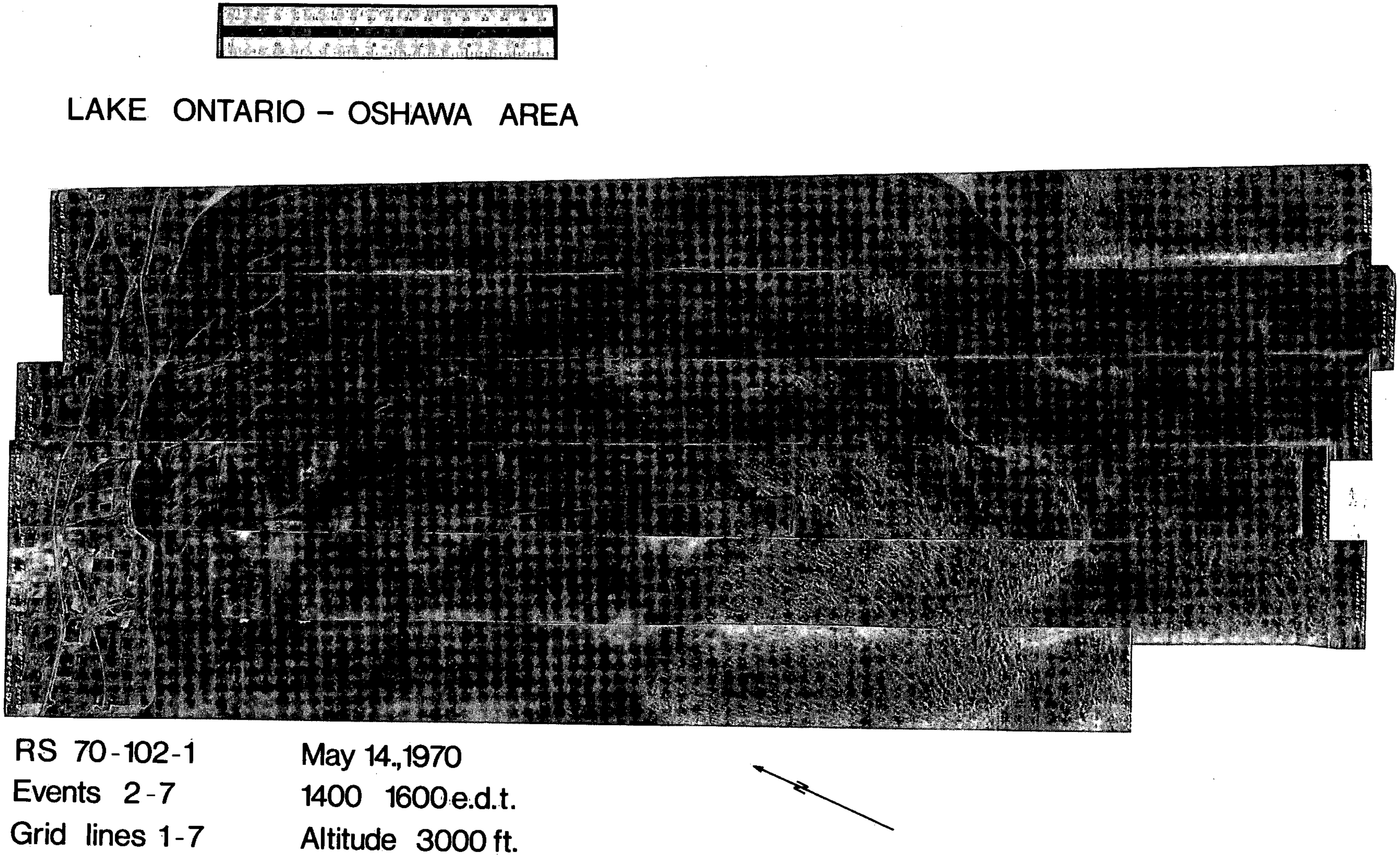


Figure 23. Infrared mosaic, 1400-1600 e.d.t., May 14, 1970.

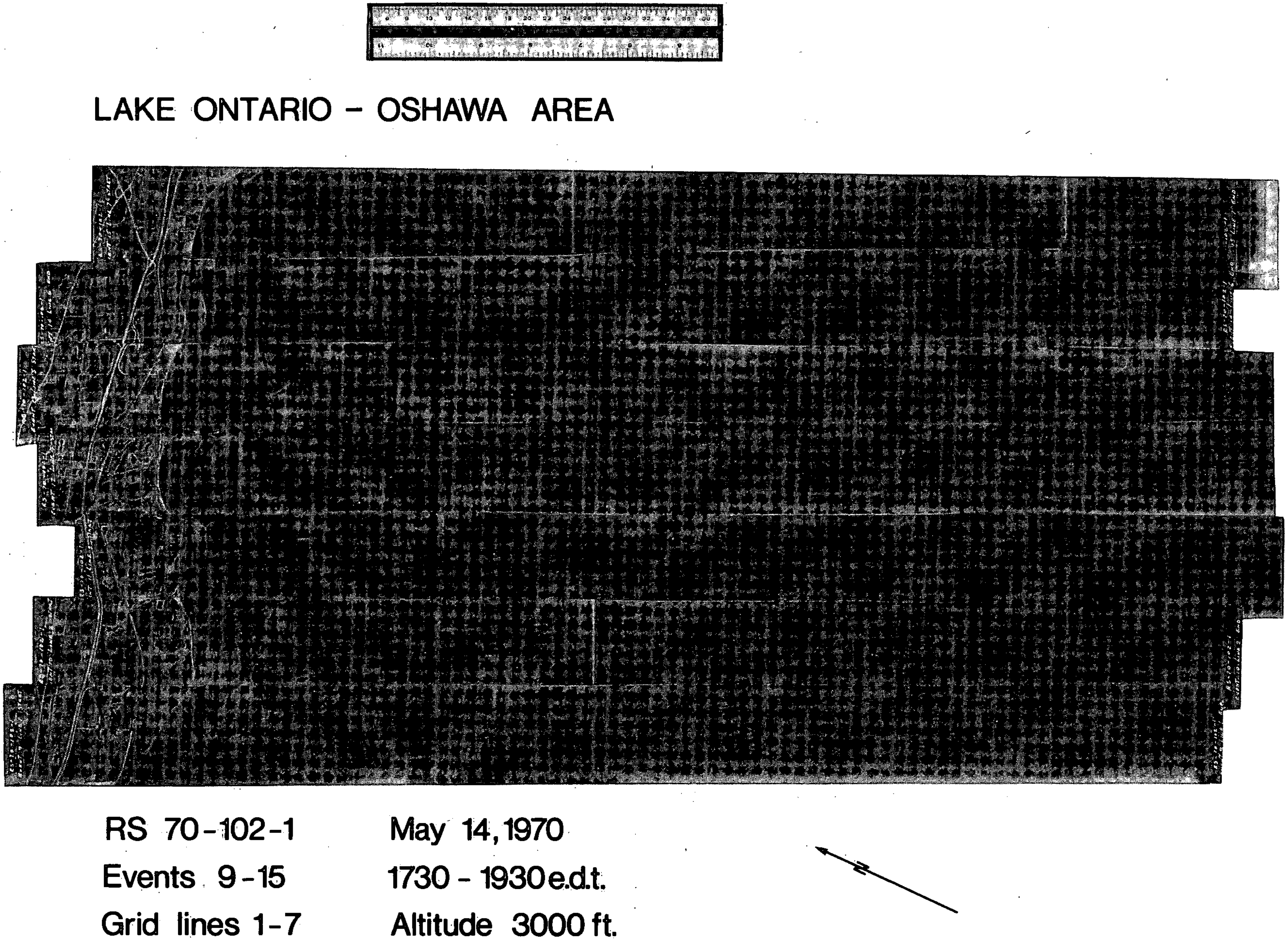


Figure 24. Infrared mosaic, 1730-1930 e.d.t., May 14, 1970.

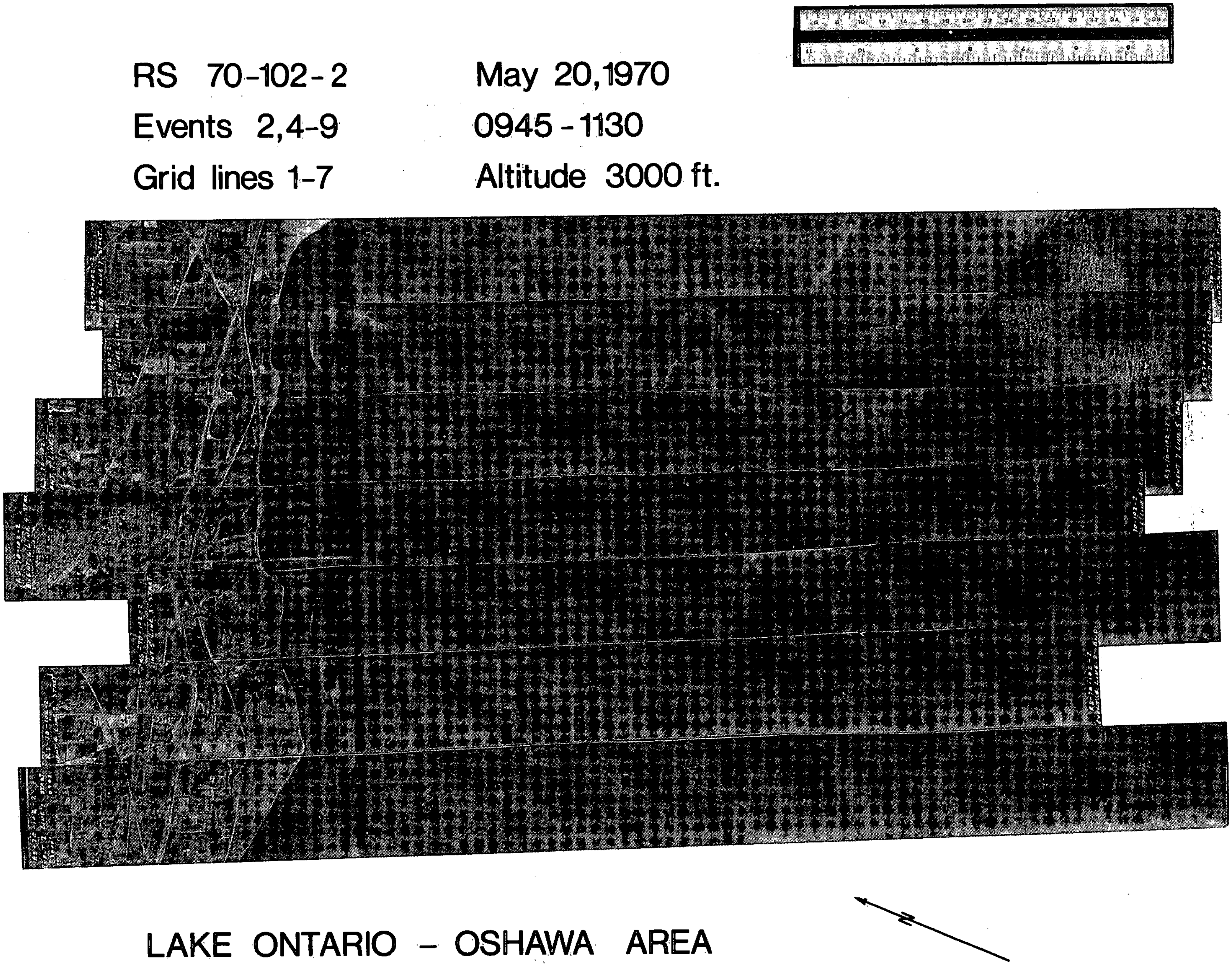


Figure 25. Infrared mosaic, 0945-1130 e.d.t., May 20, 1970.

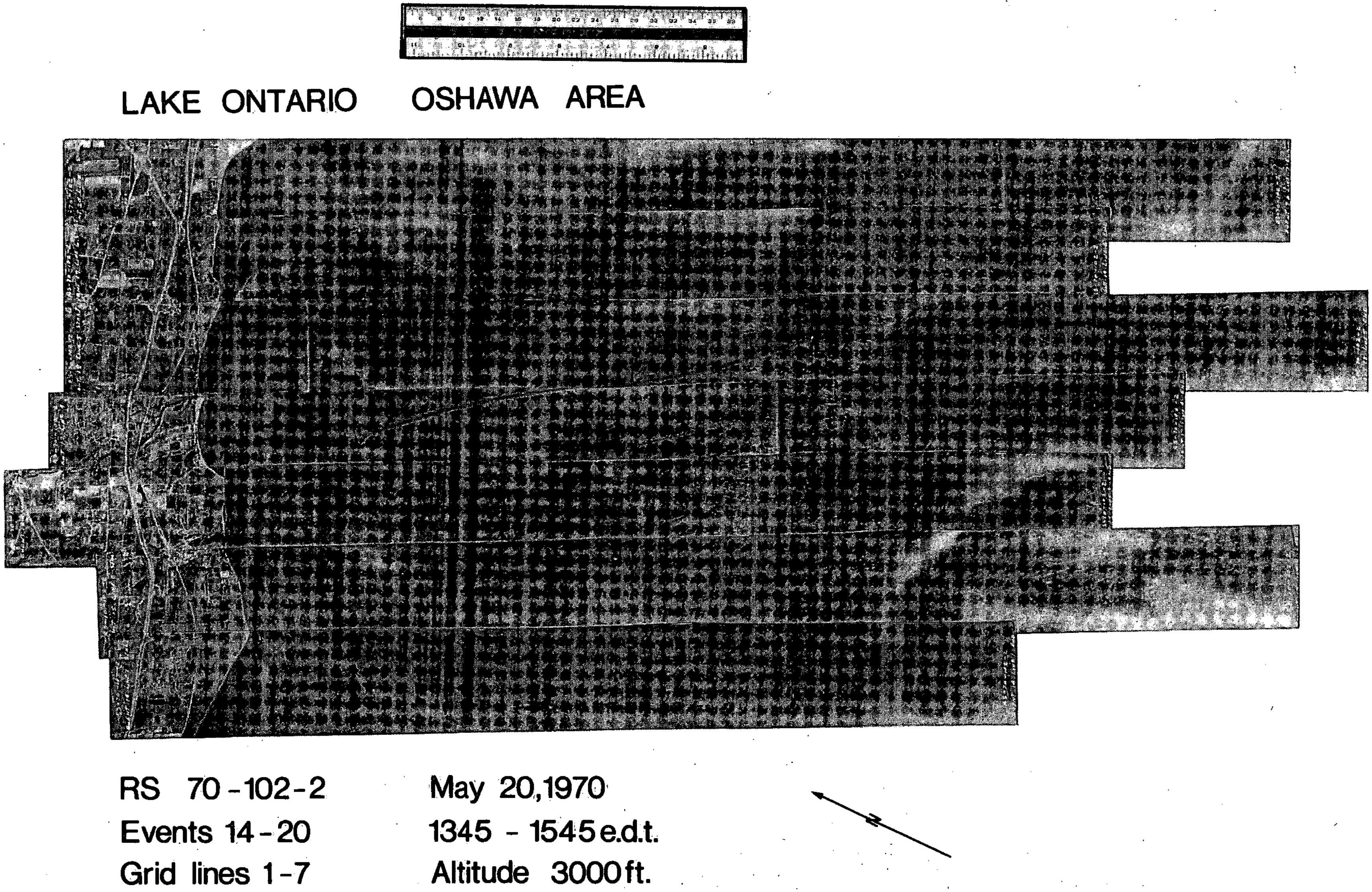


Figure 26. Infrared mosaic, 1345-1545 e.d.t., May 20, 1970.

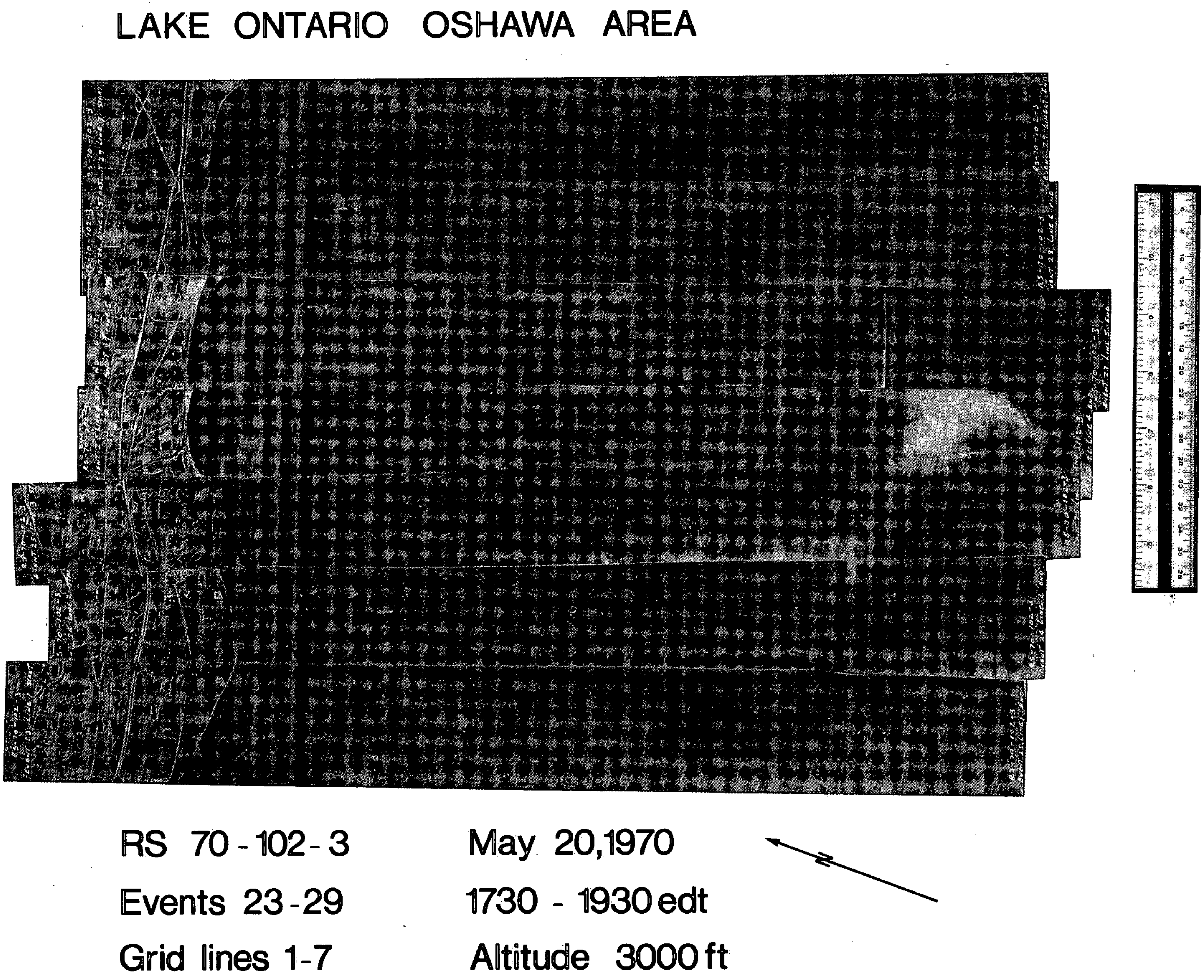


Figure 27. Infrared mosaic, 1730-1930 e.d.t., May 20, 1970.

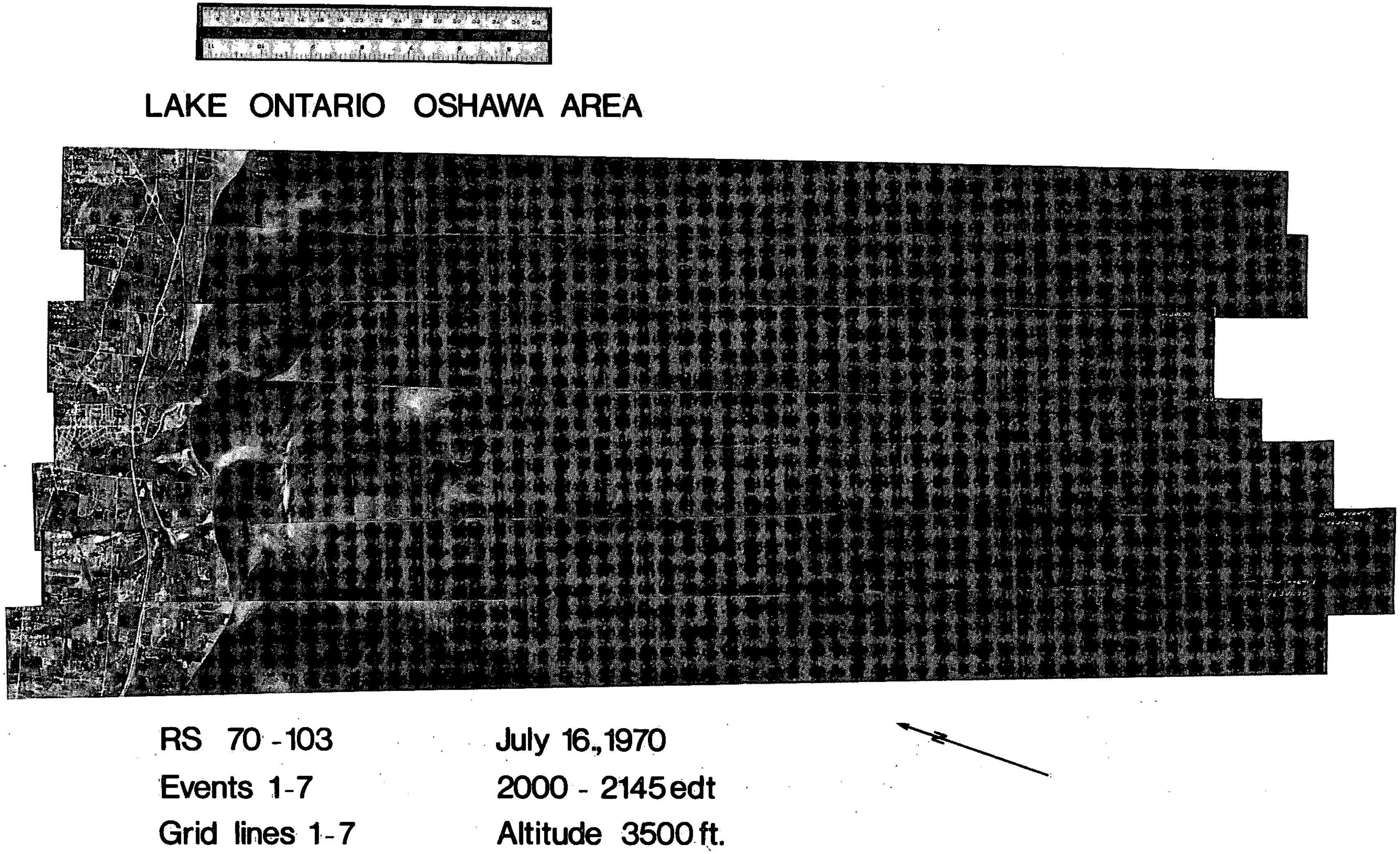


Figure 28. Infrared mosaic, July 16, 1970.

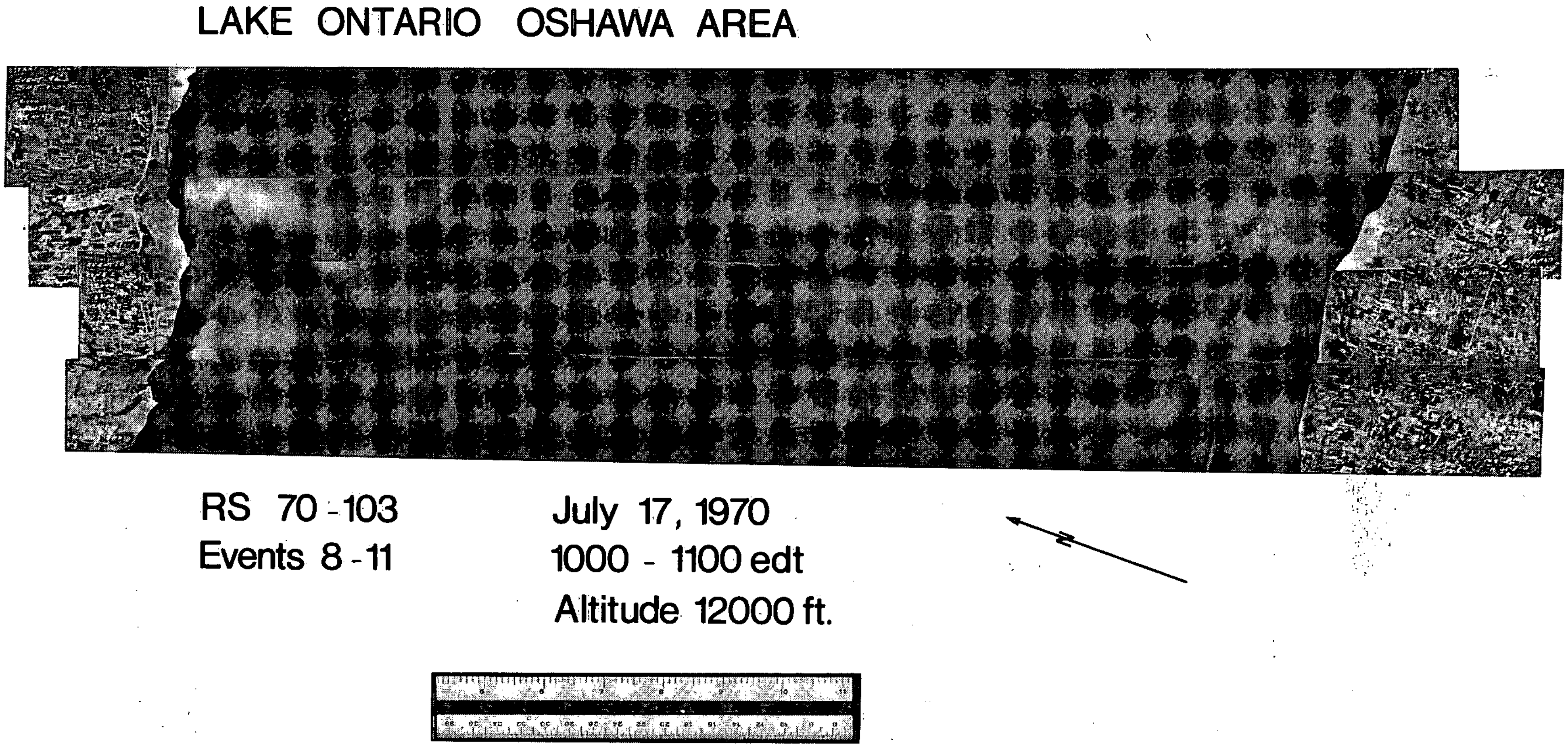
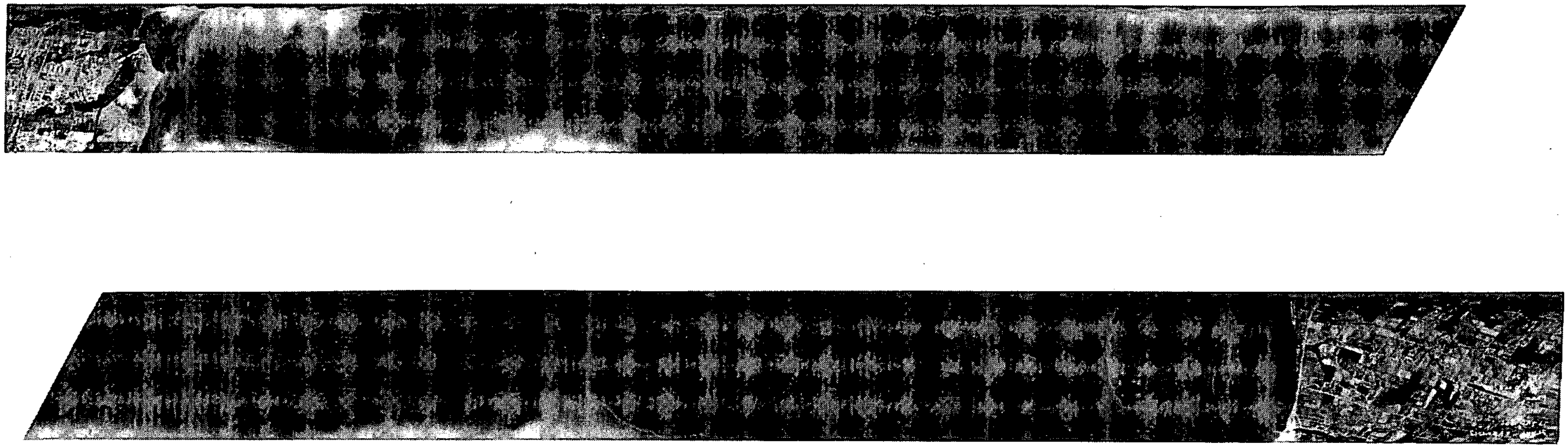


Figure 29. Infrared mosaic, 1000-1100 e.d.t., July 17, 1970.

LAKE ONTARIO OSHAWA, Ont. to OLCOTT, N.Y.



RS 70 - 103 July 17., 1970 1140 edt

Event 13 Altitude 6000 ft.

Figure 30. Infrared mosaic, 1140 e.d.t., July 17, 1970.

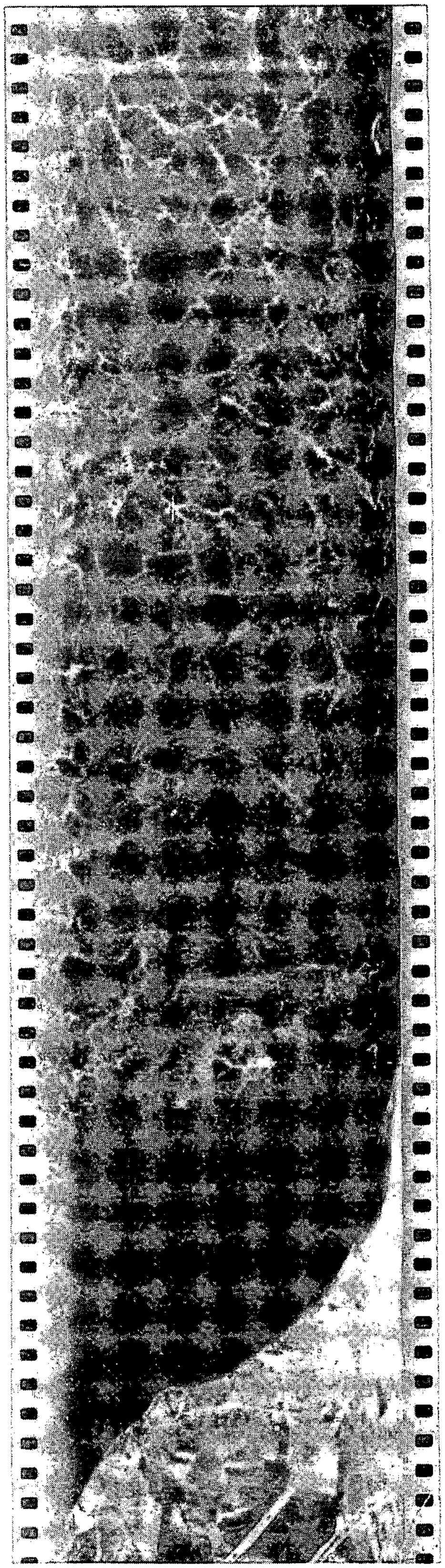


Figure 31. Infrared imagery of ice on Lake Erie, February 21, 1969.

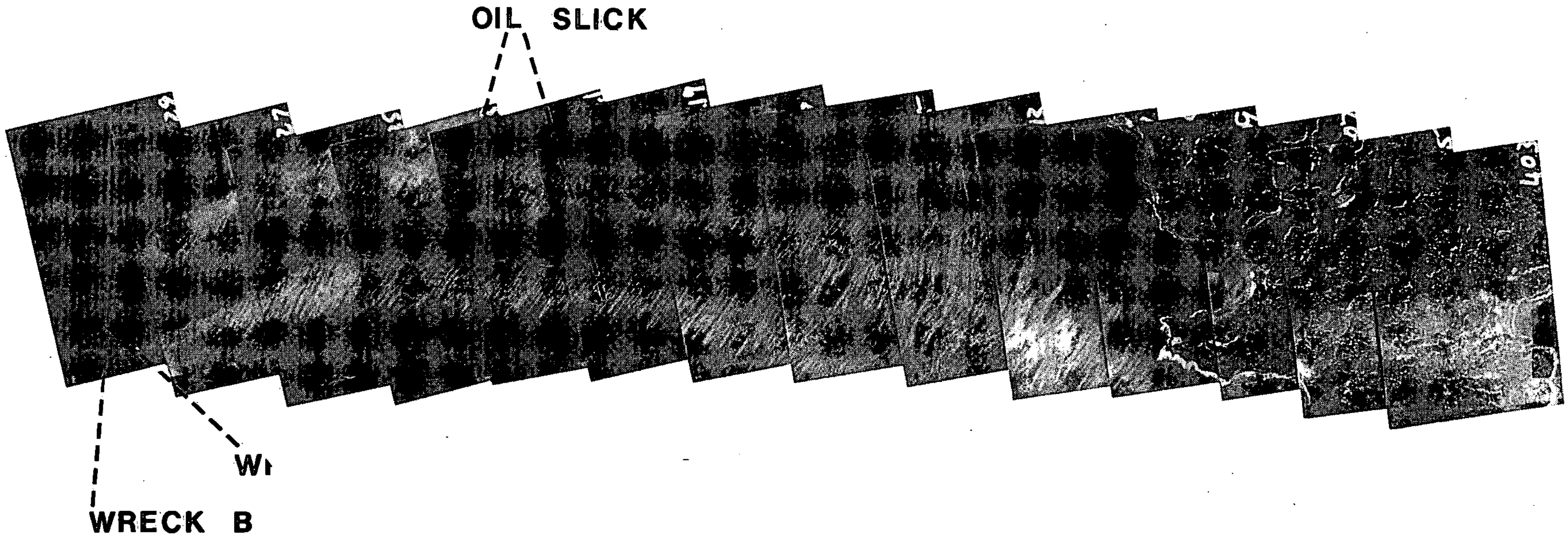


Figure 32. Aerial photographic mosaic of Chedabucto oil slick, taken with Plus-X film and a W 39 filter, February 13, 1970, 1230 m.s.t. Distance between the two parts of the wreck is about 300 metres.

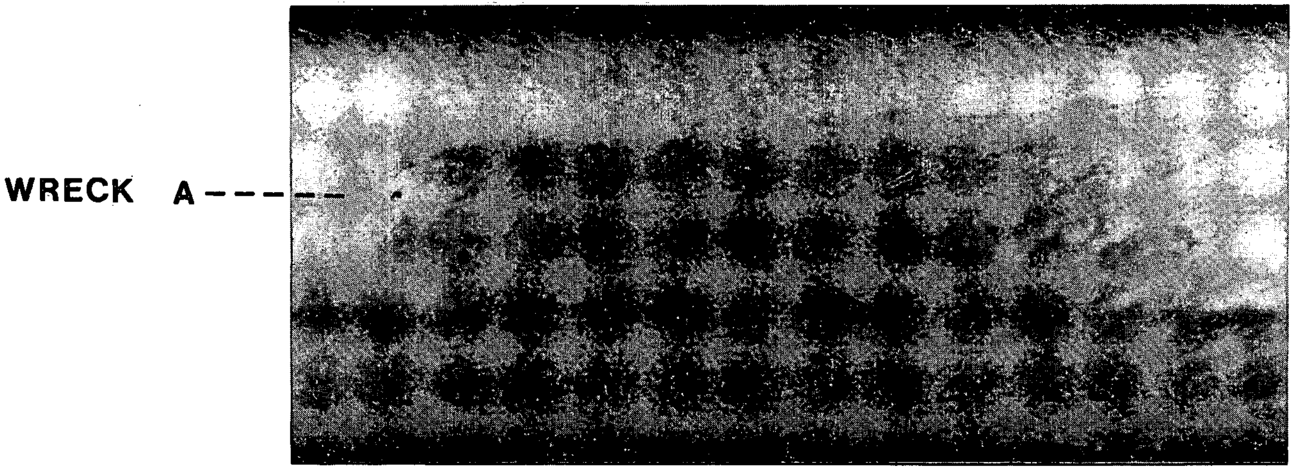


Figure 33. Infrared imagery of Chedabucto oil slick taken on February 13, 1970, 1100 m.s.t. See figure 32 for location of the slick.

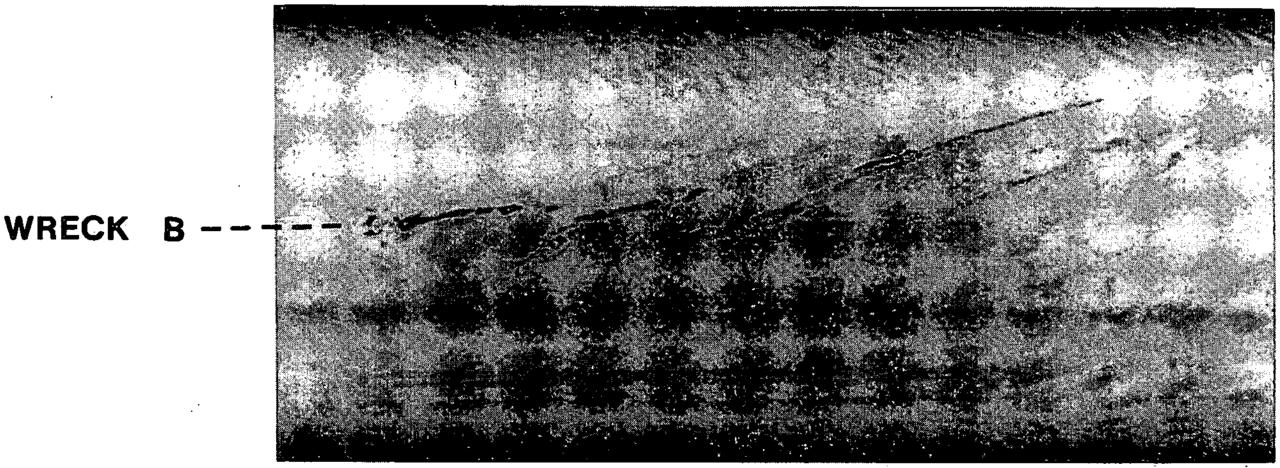


Figure 34. Infrared imagery of Chedabucto oil slick taken on February 13, 1970, 1050 m.s.t. See figure 32 for location of the slick.