Environment Canada Imaging Cover Page

Report N.: 

SKP Box Number: 672572427

CANADA

DEPARTMENT OF TRANSPORT
METEOROLOGICAL BRANCH

AN EVALUATION OF THE INFRA-RED THERMOMETER AS AN AIRBORNE INDICATOR OF SURFACE WATER TEMPERATURES

BY

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CIR. 4354
TEC. 592
JAN. 4/66

15/4/66

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ABSTRACT

An infra-red thermometer (IRT) was installed on an aircraft as an airborne radiation thermometer (ART) and subjected to a program of test and evaluation as an instrument for measurement of surface water temperatures in the Great Lakes area. The first phase of the program dealt with the mounting and exposure of the sensor. The second phase, in conjunction with the research vessel "Porte Dauphine", dealt mainly with operational and theoretical aspects of the technique.

With some limitations, as outlined in the report, it was found that the ART provides a good method of making fast and reliable water temperature surveys. The present instrument and installation produced an absolute accuracy of the order of 1.0°C and a relative accuracy within 0.5°C. As a result of the evaluation program, it is planned to operate monthly surveys next year.

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ÉVALUATION DU THERMOMÈTRE INFRAROUGE UTILISÉ COMME INDICATEUR AÉROPORTÉ DE LA TEMPÉRATURE DES EAUX DE SURFACE

par

T. L. Richards
et
D. G. Massey

RÉSUMÉ

On a installé à bord d'un avion un thermomètre infrarouge devant servir de thermomètre de rayonnement aéroporté et on l'a soumis à un programme d'essais et d'évaluation pour la mesure de la température des eaux de surface dans la région des Grands lacs. La première phase de ce programme avait trait au montage et à l'exposition de l'organe sensible. La deuxième phase, effectuée avec le concours du navire de recherches PORTE DAUPHINE, portait surtout sur les aspects opérationnels et théoriques de cette technique.

Comme il est exposé dans le rapport, on a constaté que l'emploi du thermomètre de rayonnement aéroporté permet, dans certaines limites, d'effectuer des relevés rapides et sûrs de la température de l'eau. L'instrument et l'installation actuels ont permis d'obtenir une précision absolue de l'ordre du degré centésimal. A la suite de ce programme d'évaluation, on se propose d'effectuer des relevés mensuels au cours de l'année prochaine.

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(Manuscript Received October 29, 1965)

1. Introduction

The Meteorological Branch has had a long standing requirement for regular observations of surface water temperatures from the Great Lakes. These data are most useful for forecasting meteorological conditions over the lakes and their adjacent land areas and the data are also becoming increasingly important for assessing water losses through evaporation and in studies of the formation and dissipation of ice. For optimum results temperatures should be obtained over large areas and in a minimum length of time. In order to meet this requirement an infra-red radiation thermometer (IRT) was acquired for test and evaluation purposes as an airborne indicator of surface water temperatures (Airborne Radiation Thermometer, - ART).

Basic Principles

In brief, the IRT senses the radiant energy from the surface over which it is transported. The detector, - a thermistor bolometer, looks through an optical system alternately at the water surface whose temperature is desired and at an accurately calibrated reference black body. The difference between the two radiations is converted to an electrical signal that varies with temperature. The radiant energy is passed through an optical filter which limits transmission to between 8.0 and 14.0 microns. Hence, the detector is exposed to the radiant energy only in the region where the attenuation due to carbon dioxide and water vapour is fairly small, and, therefore, the measurements should be relatively independent of altitude.

The accuracy of such instruments depends very much on the particular design. The larger and more sensitive units are reported as being effective over a range of -2 to +35°C with an accuracy of $\pm$ 0.2°C. Smaller, portable units are available with essentially the same range but with an accuracy more of the order of $\pm$ 1.0°C.

Previous Applications

The first use of the ART technique was by Stommel (1) to trace the edge of the Gulf Stream. In a more sophisticated model developed by Richardson and Wilkins (2) the original Golay detector was replaced by the thermistor bolometer. During the past four years several commercial models of the IRT have become available and have been subjected to a variety of programs of test and evaluation, Pirart (3), Snowden (4), McFadden and Ragotzkie (5), Techniques for Infra-red Survey of Sea Temperature (6), Trites (7). As a result of these and other programs substantial improvements have been made in the instruments and in airborne techniques.

It was in order to exploit these recent advances that the Lake Investigations Unit (Hydrometeorology Section, Climatology Division) of the Meteorological Branch acquired a portable IRT for research and eventual operational purposes, and in co-operation with the Instrument Division, Basic Weather Division and the Radiation Section of the Research and Training Division undertook a flight test and evaluation program in the Great Lakes area during the winter, spring and summer of 1965.

The Instrument and Installation

An instrument manufactured by the Barnes Engineering Company (Model IT-2S) was selected on the basis that it was readily available, conveniently portable and reasonably priced. This particular model has an advertised mid-scale sensitivity of 3/4°F, and an absolute accuracy of 1 1/2°F. Its range is 10 to 110°F. The field of view is a 3° Cone with temperature read-out directly on a meter and attached recorder. The power requirement is 105 - 125 volts, 60 cycles per second and 25 watts.

The instrument was installed on a Lockheed 14 aerial survey aircraft chartered from Kenting Aviation Limited, Toronto International Airport. (Fig. 1). The complete unit consisted of a sensor or sensing head, an electronics console with temperature meter, a recorder and two Cornell-Dupilier Powercon 12ESW 25 power inverters. Two recorders were used during the test periods, - an Easterline-Angus (0-1 millampere) and a Honeywell Electronik 19. With the exception of the sensor all the equipment was shock-mounted on an instrument rack in the aircraft cabin (Fig. 2). The sensor was mounted on a bracket on the floor of the aircraft so that it was aimed through an opening in the camera hatch.

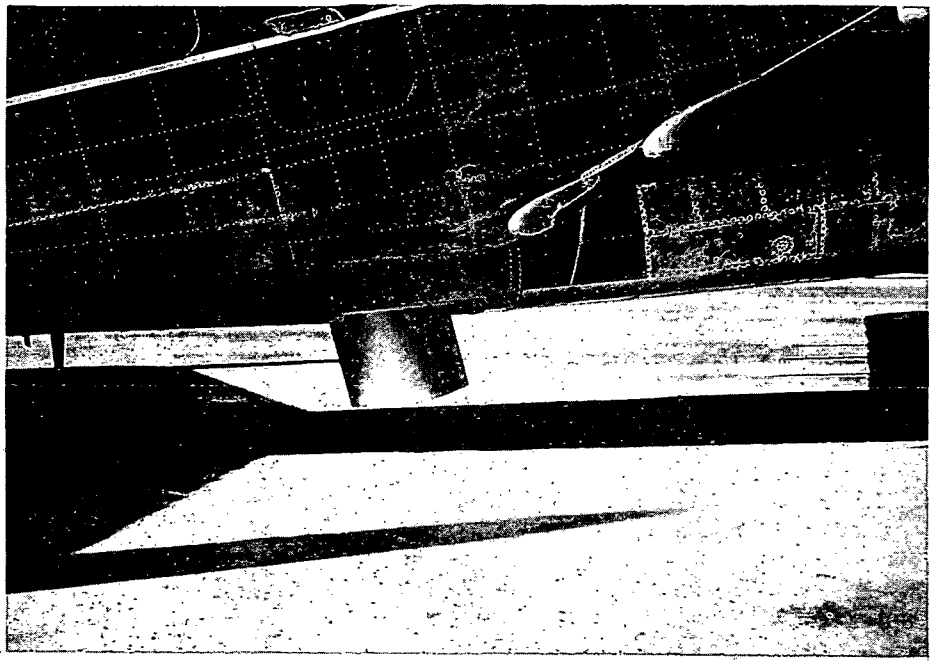


Figure 1
Aircraft Showing Outside Fitting

Figure 2
Interior of Aircraft Showing Instrument Rack
and Sensor Mounting (Right Foreground)

The Test and Evaluation Program

The 1965 test and evaluation program was planned in two phases. Phase I was in conjunction with regular Meteorological Branch ice reconnaissance flights over the Great Lakes and was designed to test the installation and mounting of the instrument. Phase II consisted of six special flights over Lake Ontario and Lake Erie in co-operation with the research vessel CCGS "Porte Dauphine". This latter phase was designed to test the effectiveness of the ART at different altitudes, to prove the instrument on actual full-lake surveys and to assess the environmental errors inherent in the technique.

2. Phase One - Installation Tests

During January and February, 1965, the unit was test-flown on four ice reconnaissance flights over the Great Lakes. The routes and altitudes were entirely dependent on the requirements of the ice survey and no deviations for the sake of the ART test were possible. These restrictions did not, however, reduce the value of the flights for preliminary test purposes. It had been intended to check temperature readings against those obtained by the research vessel "Porte Dauphine", but because of a scheduled refit the ship was not available.

Flight 1.1 (January 25, 1965)

On the first flight the indicated temperature remained off-scale (below -12°C) as long as the sensor was in its bracket mounting. A strong turbulent flow of cold air (-7°C) was detected entering through the opening in the camera hatch and the heater light on the sensing head at no time went off indicating that the reference cavity never reached operating temperature.

During the flight the sensor was removed from its mounting and pointed manually through the opening from a few inches above floor level. The readings returned to on-scale but showed very wide fluctuations, -5° to +5°C over water, -10°to +2°C over ice (Fig. 3).

Although no useable data were obtained, results did show that it was necessary to induce the air to flow out of, rather than into the aircraft. To solve this problem a 6-inch diameter pipe about 18 inches long constructed of sheet aluminum was mounted on the

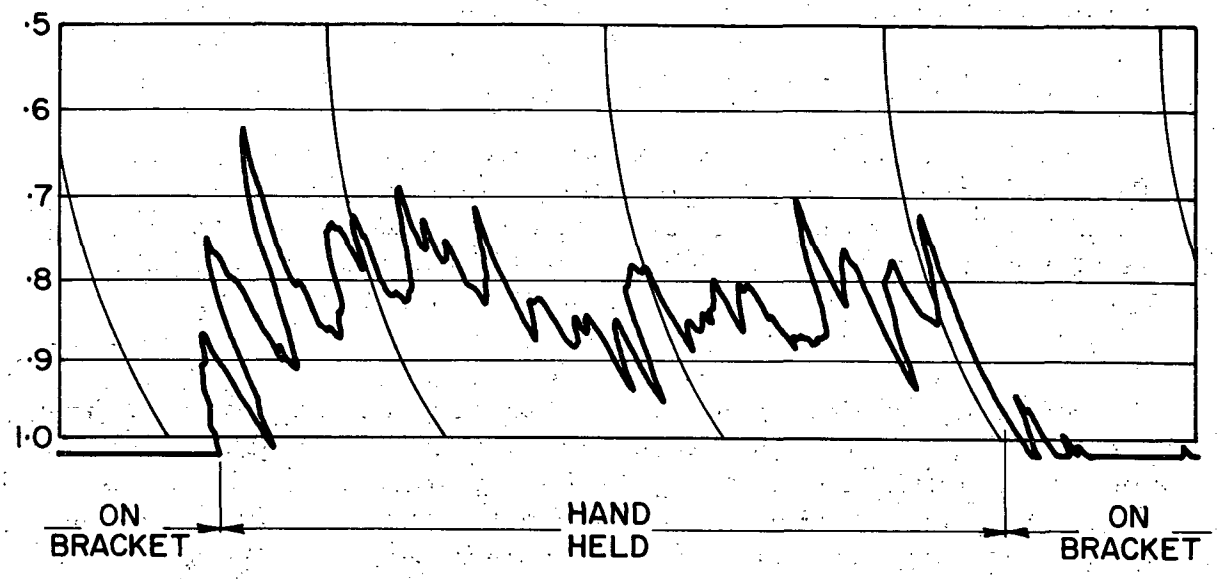


Figure 3
ART Trace Flight 1.1
Off-scale with Sensor on Original Mounting,
On-scale but with Large Fluctuations When held inside Cabin

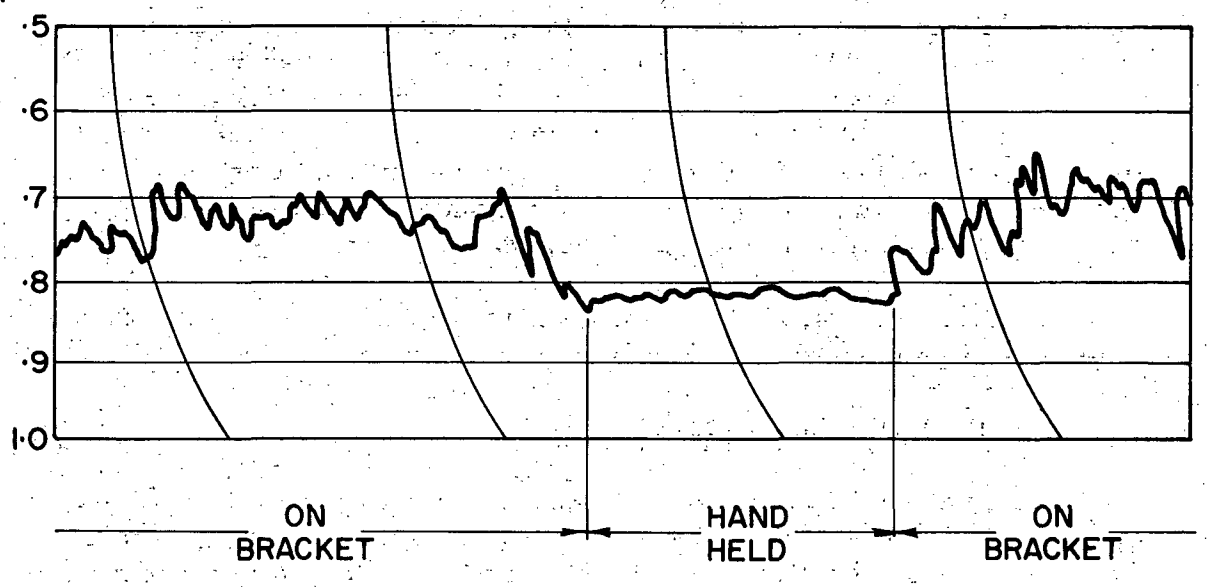


Figure 4
ART Trace Flight 1.2
Improved Trace Due to Outside Pipe Fitting and Further
Improvement when Sensor Held Inside Cabin

underside of the aircraft directly below the opening in the camera bay (Fig. 1). In order to reduce turbulence and drag the pipe was fitted with a stream-lined fairing. No change was made at this time to the sensor mounting inside the aircraft.

Flight 1.2 (February 8-9)

The new installation proved partially successful on the second flight in that it produced a noticeable outflow through the camera bay opening. Temperatures remained on-scale and showed a direct relationship to the nature of the surface flown over, i.e. - land, ice and open water. The fluctuations were reduced although they were still of the order of 4 to 6°C (Fig. 4).

While flying over open water the sensor was again removed from its mounting and held about three inches above the floor. An immediate and pronounced change in the character of the trace was noted (Fig. 4). The fluctuations were reduced to about 2 degrees and the average temperature read 1°C, - consistent with open water with ice floes present.

Flight 1.3 (February 15)

The third flight was made with the same installation as on Flight 2. Two tests were carried out. In the first one, the sensor was again removed from the bracket held by hand about three inches above the floor. The fluctuations were again greatly reduced (Fig. 5) and the indicated water temperature immediately fell from 6°C to a more realistic 0°C. As a second test the sensing head was remounted and a sheet of polyethylene film was placed over it. This reduced the fluctuations (Fig. 5) but produced an average water temperature reading about 2 or 3 degrees too high.

The tests indicated that best results would be obtained with the sensing head mounted three to four inches above the floor.

Flight 1.4 (February 22-23)

The final flight of Phase I was made with the sensor mounted on an adjustable shock-resistant bracket three to four inches above the floor. Although the flight was hampered by low cloud and snow flurries brief periods of fair weather produced meaningful results, i.e., Fig. 6 shows the recorder trace at 2000 feet MSL (approximately 1400 feet above lake level) travelling from the open water of Lake Huron to ice and then to land near Southampton.

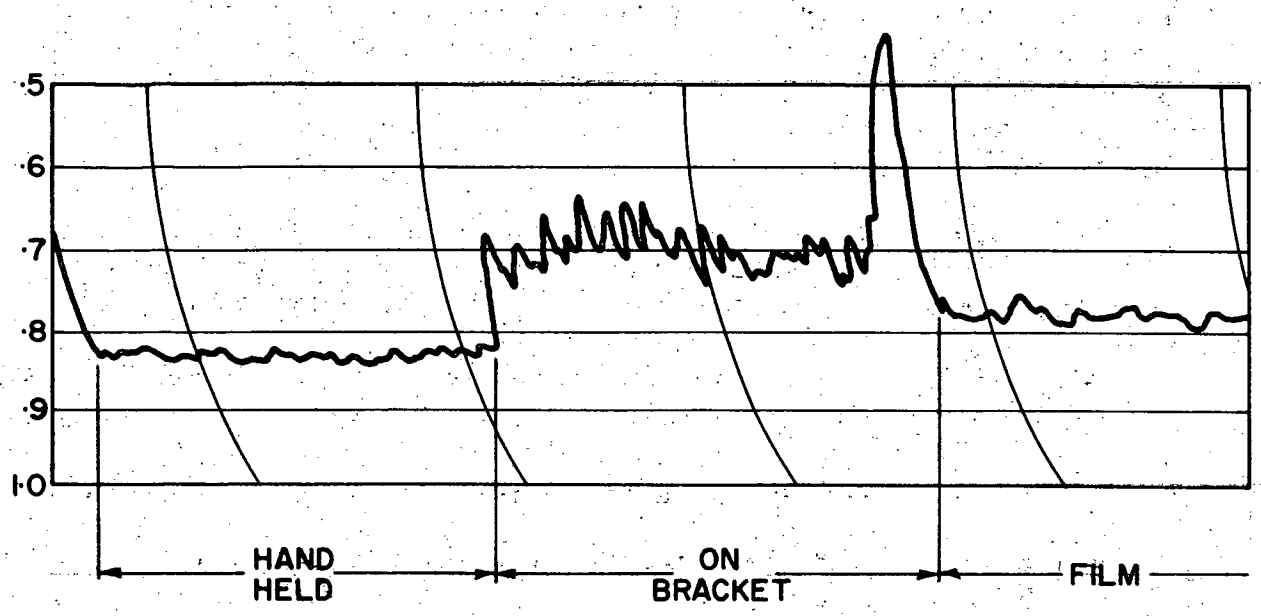


Figure 5
ART Trace Flight 1.3
Fluctuations Reduced by Introduction of Polyethylene Film and
by Holding Sensor Inside Cabin

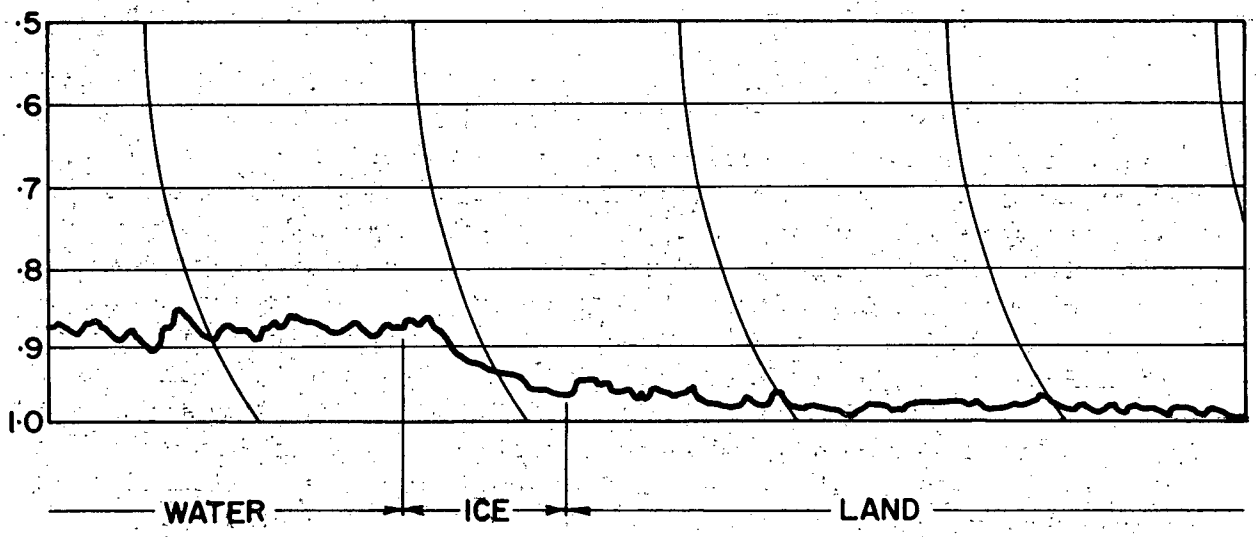


Figure 6
ART Trace Flight 1.4
Example of Trace over Water, Ice and Land
Fluctuations Reduced With Sensor Mounted 3-4 Inches Inside Cabin

Although the absolute temperatures obtained with the new mounting could not be checked the average reading of 0 to 1°C for open water with some ice floes present appeared realistic and the fluctuations were reduced to about two degrees. As indicated in Fig. 6 temperature variations from open water to ice to land were quite distinct.

3. Phase Two - Air-Ship Trials

The second phase of the test and evaluation program consisted of a series of flights in co-operation with the research vessel "Porte Dauphine". As indicated earlier, these trials were designed:

(1) to check the ART water temperature readings against the ship's water temperature observations;

(2) to find an optimum height for flying ART surveys;

(3) to make full scale surveys of a lake and check these against the ship's surveys;

(4) to assess the environmental errors of the instrument with the end in view of making corrections based on meteorological conditions. This latter problem is to be the basis of an M.A. thesis by R. W. Shaw, (Meteorology - University of Toronto), and will not be dealt with in this report.

The aircraft's program was to fly over the ship (upwind and downwind) at altitudes of 300, 500, 1000, 1500 and 2000 feet above lake level and then to proceed on a pre-planned survey of the lake. The surveys were designed to criss-cross the lake to provide a double check on ART temperatures at the cross points. In-flight in-cabin instrument calibration checks using a well mixed water bath were also planned for each flight. Eventually such spot checks were scheduled for each leg of each survey. Instrumentation and mountings remained the same as in the final flight of Phase I (Flight 1.4) except that beginning with the second flight of Phase II (Flight 2.2) the Esterline-Angus recorder was replaced by a Honeywell as previously noted. Eight hours of flying time were available on a charter basis for these tests and in all 6 flights were made.

The ship's program was one of taking simultaneous water temperature observations by the conventional bucket thermometer and for two flights by a second IRT based on the bridge. In addition, of regular meteorological observations the ship on three occasions also took micro-profile measurements of the atmosphere to 1000 feet by means of its meteorological boom and wiresonde facility. These latter observations were in support of the study of environmental errors.

The air-ship trials were held in conditions of no precipitation, cloud base above 2000 feet, visibility 3 miles or better and, because of the wire-sonde flights, surface winds of 10 mph or less. This latter restriction was most difficult to adhere to and several operations were made in higher winds in order to complete the program.

Flight 2.1 (March 25, 1965)

The first flight of Phase II consisted of a full program of 10 passes over the research vessel situated seven miles south of Toronto followed by a three-hour survey of Lake Ontario. The data from the fly-over are tabulated in Table I. The route of the aircraft and the results of the survey are shown in Fig. 7. The absolute temperature values of the surface water isotherms were deduced from corrections indicated in Table I.

As would be expected in the early spring the ART survey revealed low temperatures and a flat gradient in the isotherm pattern. However, both temperatures and gradient were consistant with a limited survey of eastern Lake Ontario taken by the ship on the same day (Fig. 7).

Flight 2.2 (May 3, 1965)

The second flight of Phase II was delayed until early May in order to obtain a greater range in surface water temperatures. The results warranted the delay as near-shore waters showed temperatures. The results warranted the delay as near-shore waters showed temperatures 7 to 8°C warmer than three to four miles offshore (Figs. 11, 12).

The same routine was followed as in Flight 2.1. The fly-over data are tabulated in Table II, the ART survey of Lake Ontario is shown in Fig. 8.

TABLE I

AIRCRAFT AND SHIP'S OBSERVATIONS

FLIGHT 2.1 : 25 MARCH 1965

AIRCRAFT DATA			WATER TEMPERATURE (°C)				
HEIGHT (FT.) above lake	HEADING	AMBIENT AIR TEMP. °C	ART aircraft	BUCKET TEMP. ship	DIFFERENCE ART-BUCKET	IRT ship	DIFFERENCE ART-IRT
300	West	--	1.2	1.7	-0.5	--	--
300	East	--	1.2	1.7	-0.5	--	--
500	West	--	1.7	1.7	0.0	--	--
500	East	--	1.7	1.7	0.0	--	--
1000	West	--	1.0	1.6	-0.6	--	--
1050	East	--	0.9	1.6	-0.7	--	--
1500	West	--	0.9	1.6	-0.7	--	--
1550	East	--	0.3	1.6	-1.3	--	--
2000	West	--	0.3	1.6	-1.3	--	--
2000	East	--	0.3	1.6	-1.3	--	--

SHIP'S WEATHER

CLOUDS : 4/8 of Altostratus at 8,000 ft. and 4/8 of Cirrostratus
VISIBILITY : 15 miles
AIR TEMPERATURE : 0°C
DEW POINT : -1°C
WIND : 110° at 19 knots
WAVE HEIGHT : 1 to 2 feet

TABLE II

AIRCRAFT AND SHIP'S OBSERVATIONS

FLIGHT 2.2 : 3 MAY 1965

AIRCRAFT DATA			WATER TEMPERATURE (°C)				
HEIGHT (FT.) above lake	HEADING	AMBIENT AIR TEMP. °C	ART aircraft	BUCKET TEMP. ship	DIFFERENCE ART-BUCKET	IRT ship	DIFFERENCE ART-IRT
350	West	16	4.5	2.5	2.0	--	--
350	East	16	4.7	2.5	2.2	--	--
450	West	18	5.4	2.5	2.9	--	--
450	East	18	4.8	2.5	2.3	--	--
1000	West	21	6.0	2.5	3.5	--	--
950	East	21	6.1	2.5	3.6	--	--
1550	West	20	5.8	2.5	3.3	--	--
1550	East	20	5.9	2.5	3.4	--	--
2050	West	20	5.8	2.5	3.3	--	--
2050	East	20	5.8	2.5	3.3	--	--

SHIP'S WEATHER

CLOUDS : 3/8 of Cirrus
VISIBILITY : 15 miles
AIR TEMPERATURE : 8°C
DEW POINT : 5°C
WIND : 210° at 11 knots
WAVE HEIGHT : Less than 1 foot

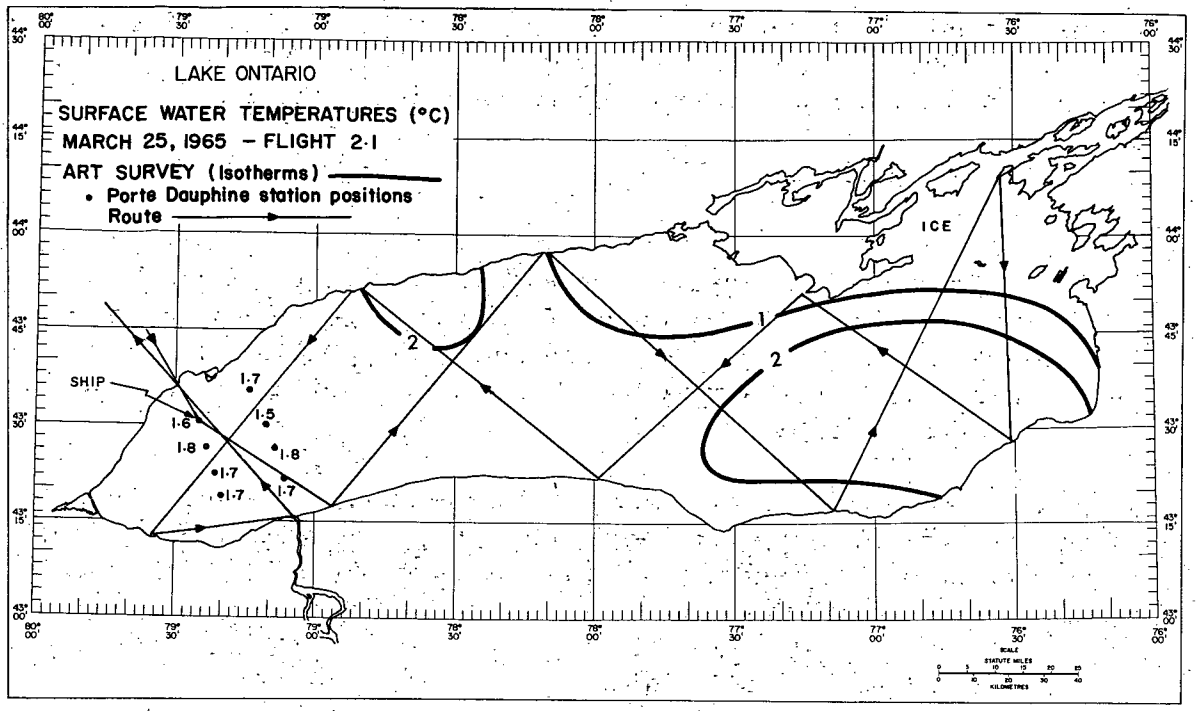


Figure 7
ART Survey, Lake Ontario, March 25, 1965
Showing Flat Temperature Gradient Typical of Early Spring
Limited Porte Dauphine Survey in Figures °C

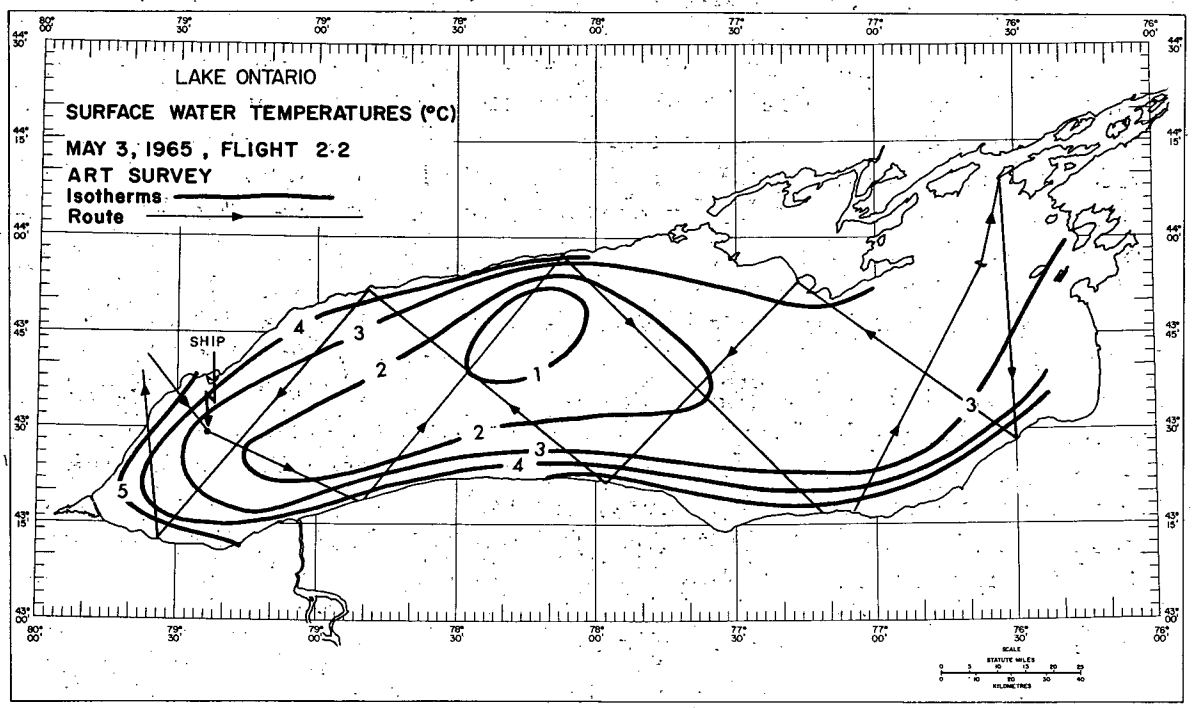


Figure 8
ART Survey, Lake Ontario, May 3, 1965
Showing Shoreline Warming

There were no "Porte Dauphine" temperature surveys to directly compare with this flight but ship's surveys of April 26-29 (Fig. 9) and May 17-20 (Fig. 10) show a similarity in pattern to the ART survey and the absolute temperatures appear entirely consistant.

Flight 2.3 (August 11, 1965)

All the remaining flights of Phase II were planned to assist the study of environmental errors inherent in the ART technique. To this end simultaneous wire-sonde flights were made from the ship to obtain profiles of temperature and humidity up to 1000 feet. The same program of passes over the ship was carried on but the subsequent surveys were reduced in length.

Flight 2.3 made contact with the Porte Dauphine 6 miles south of Toronto and after the program of fly-overs proceeded on a track to the mouth of the Niagra River and return to Toronto. Results of the fly-over are in Table III.

Flight 2.4 (August 24, 1965)

This flight was aborted within 30 miles of a planned rendezvous with the ship in western Lake Erie because of a recorder failure, - the result of one poor solder connection.

Flight 2.5 (August 25, 1965)

The fifth flight of Phase II was also made to Lake Erie with the ship stationed five miles north of Ashtabula, Ohio, where despite gusty winds a series of wire-sonde flights were completed. Data from the fly-over are in Table IV. Although not shown, a limited ART survey of Lake Erie compared favourably with a ship's survey of August 23-26.

Flight 2.6 (September 2, 1965)

The final flight of Phase II was made in Lake Ontario with the ship situated south of Prince Edward Point in an area of strong, but subsiding winds. One wire-sonde flight was completed before the instrument was damaged by gusty winds. A complete set of fly-over data is in Table V. After the rendezvous with the ship the aircraft flew to the mouth of the Niagara River and thence to Toronto.

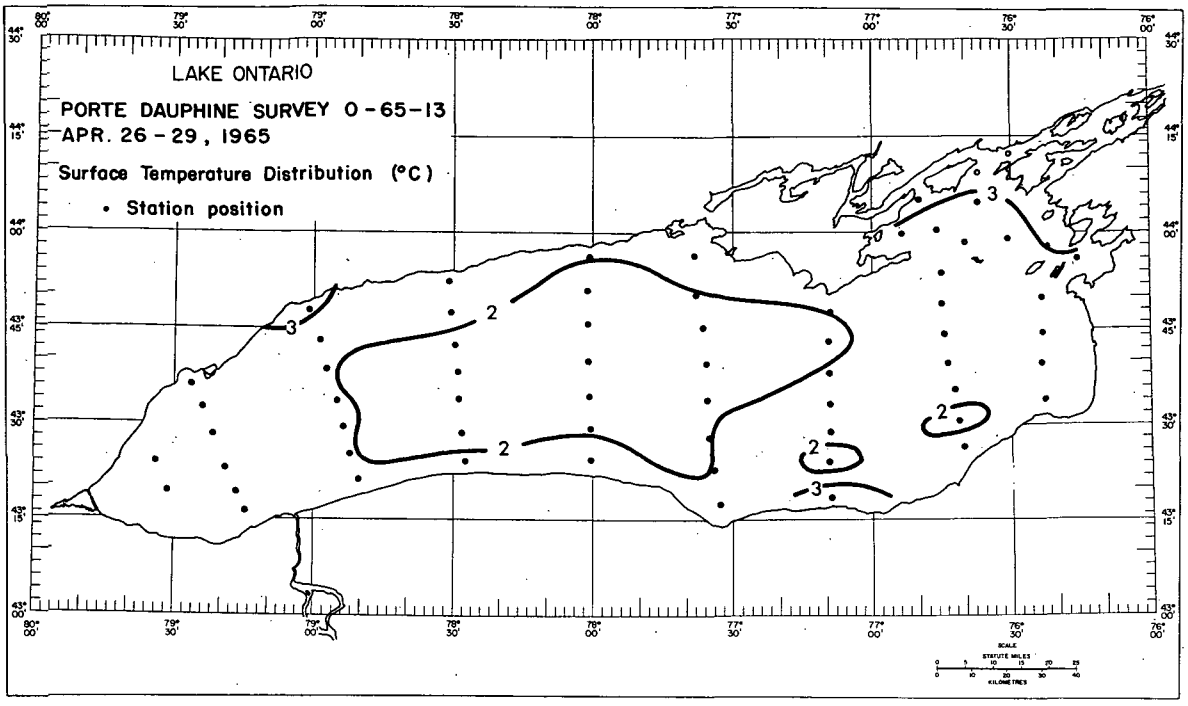


Figure 9
Porte Dauphine Survey, Lake Ontario, April 26-29, 1965
(Courtesy Great Lakes Institute, University of Toronto)

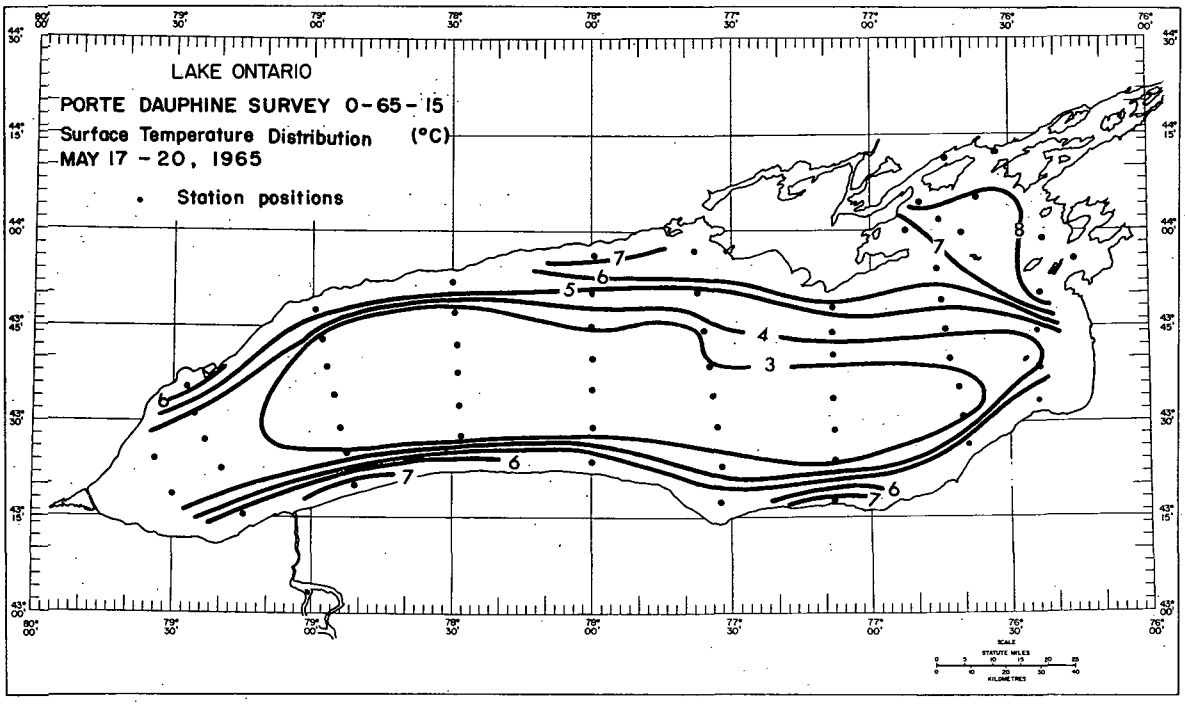


Figure 10
Porte Dauphine Survey, Lake Ontario, May 17-20, 1965
(Courtesy, Great Lakes Institute, University of Toronto)

TABLE III

AIRCRAFT AND SHIP'S OBSERVATIONS

FLIGHT 2.3 : 11 AUGUST 1965

AIRCRAFT DATA			WATER TEMPERATURE (°C)				
HEIGHT (FT.) above lake	HEADING	AMBIENT AIR TEMP. °C	ART aircraft	BUCKET TEMP. ship	DIFFERENCE ART-BUCKET	IRT ship	DIFFERENCE ART-IRT
350	West	15	15.3	15.0	0.3	14.6	0.7
350	East	15	15.4	15.0	0.4	14.5	0.9
500	West	14	16.0	15.1	0.9	14.8	1.2
500	East	15	15.7	15.1	0.6	14.7	1.0
1000	West	13	16.0	15.1	0.9	14.7	1.3
1000	East	14	16.0	15.1	0.9	14.7	1.3
1500	West	13	15.7	15.2	0.5	14.9	0.8
1500	East	13	15.5	15.2	0.3	15.0	0.5
2000	West	12	15.9	15.2	0.7	14.8	1.1
2000	East	12	15.7	15.3	0.4	14.7	1.0

SHIP'S WEATHER

CLOUDS : 1/8 of Cumulus at 1500 ft. and 1/8 of Cirrus
VISIBILITY : 15 miles
AIR TEMPERATURE : 18°C
DEW POINT : 11°C
WIND : Calm
WAVE HEIGHT : Less than 1 foot

TABLE IV

AIRCRAFT AND SHIP'S OBSERVATIONS

FLIGHT 2.5 : 25 AUGUST 1965

AIRCRAFT DATA			WATER TEMPERATURE (°C)				
HEIGHT (FT.) above lake	HEADING	AMBIENT AIR TEMP. °C	ART aircraft	BUCKET TEMP. ship	DIFFERENCE ART-BUCKET	IRT ship	DIFFERENCE ART-IRT
350	West	19.5	21.0	21.7	-0.7	--	--
350	East	19	20.7	21.7	-1.0	--	--
450	West	19	20.7	21.9	-1.2	--	--
450	East	19	21.0	21.9	-0.9	--	--
950	West	20	20.4	21.9	-1.5	--	--
950	East	19.5	20.6	21.9	-1.3	--	--
1500	West	20	20.7	21.9	-1.2	--	--
1500	East	20	20.6	21.9	-1.3	--	--
2000	West	18.5	20.7	21.9	-1.2	--	--
2000	East	18.5	20.4	21.9	-1.5	--	--

SHIP'S WEATHER

CLOUDS : 2/8 of Altocumulus at 8,000 ft. and 2/8 of Cirrostratus
VISIBILITY : 6 miles (Haze)
AIR TEMPERATURE : 20°C
DEW POINT : 14°C
WIND : 060° at 3 knots
WAVE HEIGHT : Less than 1 foot

TABLE V

AIRCRAFT AND SHIP'S OBSERVATIONS

FLIGHT 2.6 : 2 SEPTEMBER 1965

AIRCRAFT DATA			WATER TEMPERATURE (°C)				
HEIGHT (FT.) above lake	HEADING	AMBIENT AIR TEMP. °C	ART aircraft	BUCKET TEMP. ship	DIFFERENCE ART-BUCKET	IRT ship	DIFFERENCE ART-IRT
300	West	17	18.1	18.9	-0.8	18.1	0.0
350	East	17	18.1	18.9	-0.8	18.4	-0.3
550	West	16	18.1	18.9	-0.8	18.7	-0.6
550	East	16	17.8	18.9	-1.1	18.9	-1.1
1000	West	14.5	17.3	19.0	-1.7	18.7	-1.4
1000	East	14.5	16.8	19.0	-2.2	18.7	-1.9
1550	West	13	17.3	19.0	-1.7	18.7	-1.4
1550	East	13	16.8	19.0	-2.2	18.7	-1.9
2050	West	11.5	17.1	19.0	-1.9	18.6	-1.5
2000	East	11.5	16.9	19.0	-2.1	18.5	-1.6

SHIP'S WEATHER

CLOUDS : 2/8 of Stratocumulus at 2500 ft.
VISIBILITY : 15 miles
AIR TEMPERATURE : 19°C
DEW POINT : 12°C
WIND : 280° at 12 knots (gusty)
WAVE HEIGHT : 1 to 2 feet

Two rather dramatic changes in water temperature were noted on the flight. One was across an area of upwelling in north central Lake Ontario (Fig. 14), the other at the mouth of the Niagara River (Fig. 13). The latter change was accompanied by an abrupt change in colour from brown to greenish blue, and was presumably due to the outflow of the Niagara.

4. Discussion

Sensor Mounting

The results of the first part of the test and evaluation program indicate that the mounting and exposure of the sensor is critical and a review of the literature indicates that there is likely a different requirement for each type of aircraft. It is of utmost importance that there should be a gentle outflow of air with a minimum of small scale turbulence at the opening through which the sensor views the water. It is also important that all units be properly shock-mounted.

For the Lockheed 14 aircraft the high frequency fluctuations (or "noise") of the ART trace were reduced to an acceptable $\pm$ 1°C by mounting the sensor 3 to 4 inches inside the cabin and viewing the water through a streamlined pipe designed as an air diverter. A polyethylene film introduced between the sensor and the opening reduced the "noise" but added 2 to 3°C to the required correction.

Temperature Comparisons

In comparing ART readings and ship's water temperatures it is necessary to keep in mind that the infra-red thermometer senses the temperature of the "skin" or micro-surface of the water, whereas, the ship's bucket thermometer is more likely to read the average temperature of the top 6-12 inches of water. Recent studies (6) have reported an average difference between skin and bucket temperatures of 0.6°C. To check on this difference, an IRT was installed on the Porte Dauphine for flights 2.3 and 2.6. A comparison of 20 readings showed the IRT readings to be on the average 0.4°C lower with individual differences ranging from 0.8°C to zero. More extensive studies of this phenomenon are planned for a later date. However, for the purposes of this report, all further comparisons will be between the ART and the conventional ship's bucket temperatures.

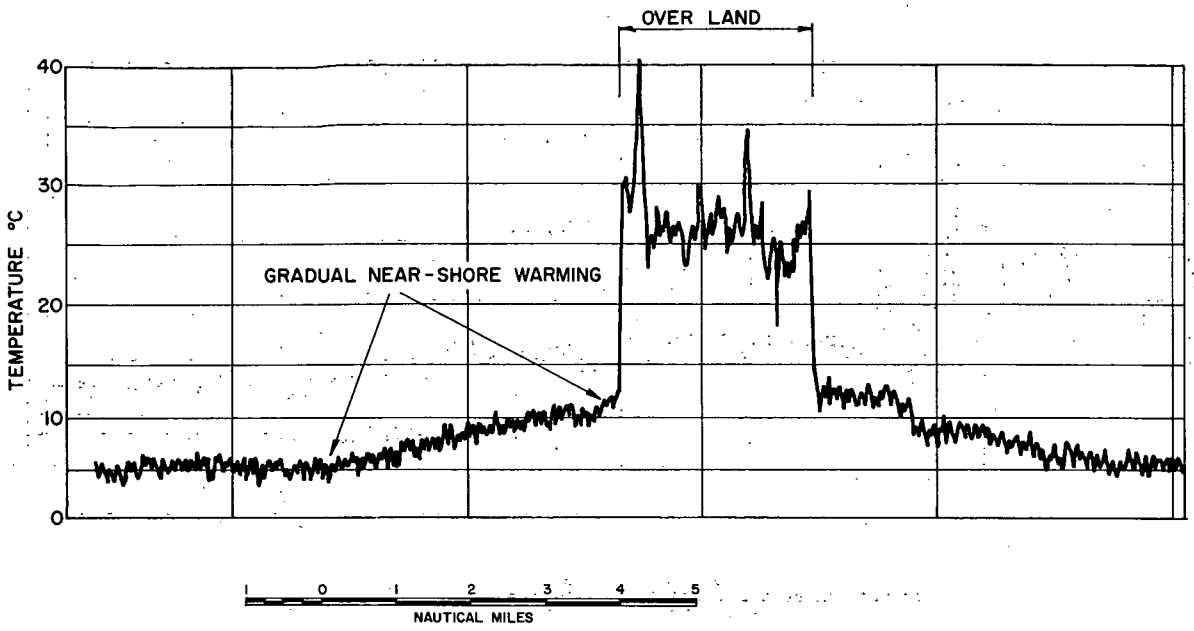


Figure 11
ART Trace, Flight 2.2, May 3, 1965, From 500 Feet
Example of Gradual Warming Towards Shore

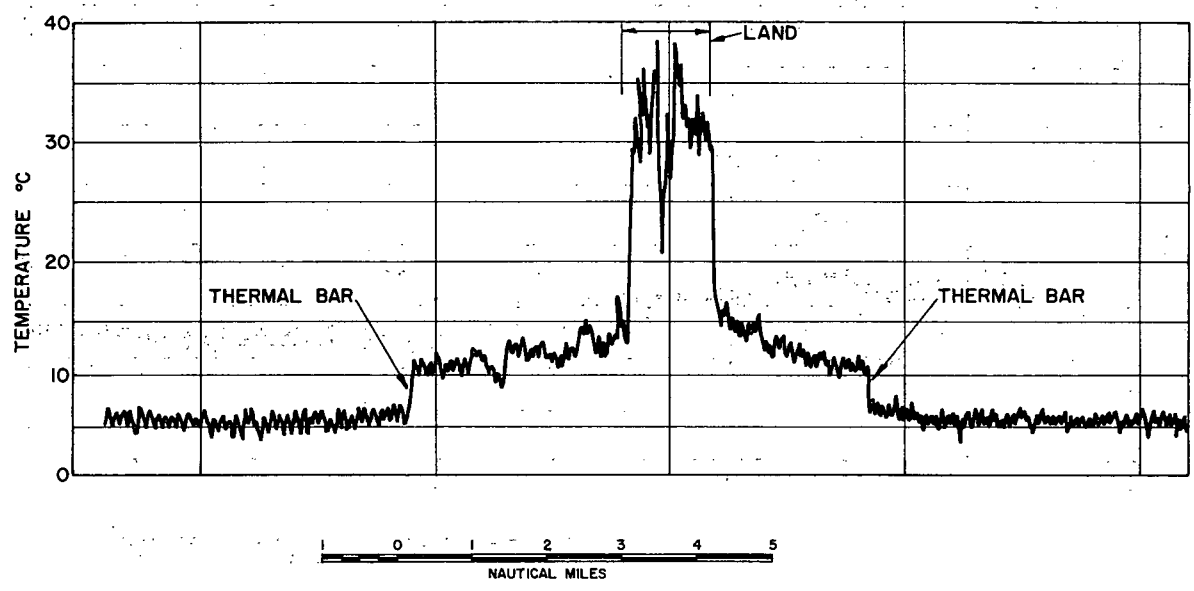


Figure 12
ART Trace, Flight 2.2, May 3, 1965, From 500 Feet
Example of Abrupt Temperature Change Near Shore, - The "Thermal Bar"

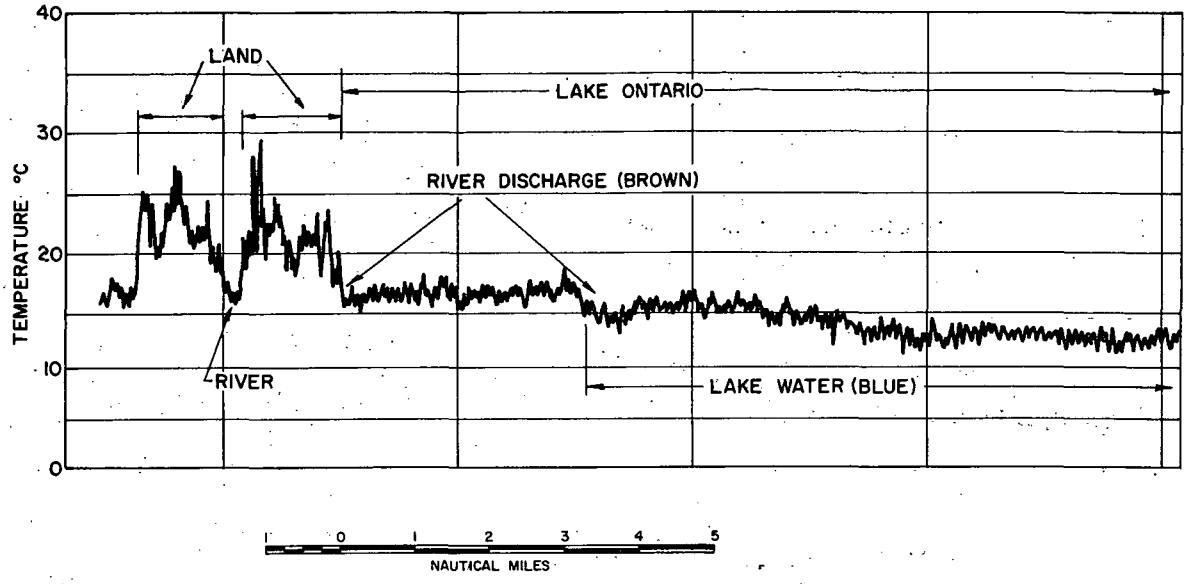


Figure 13
ART Trace, Flight 2.6, September 2, 1965, From 1000 Feet
Showing Warming in Lake Ontario at Outflow of Niagara River

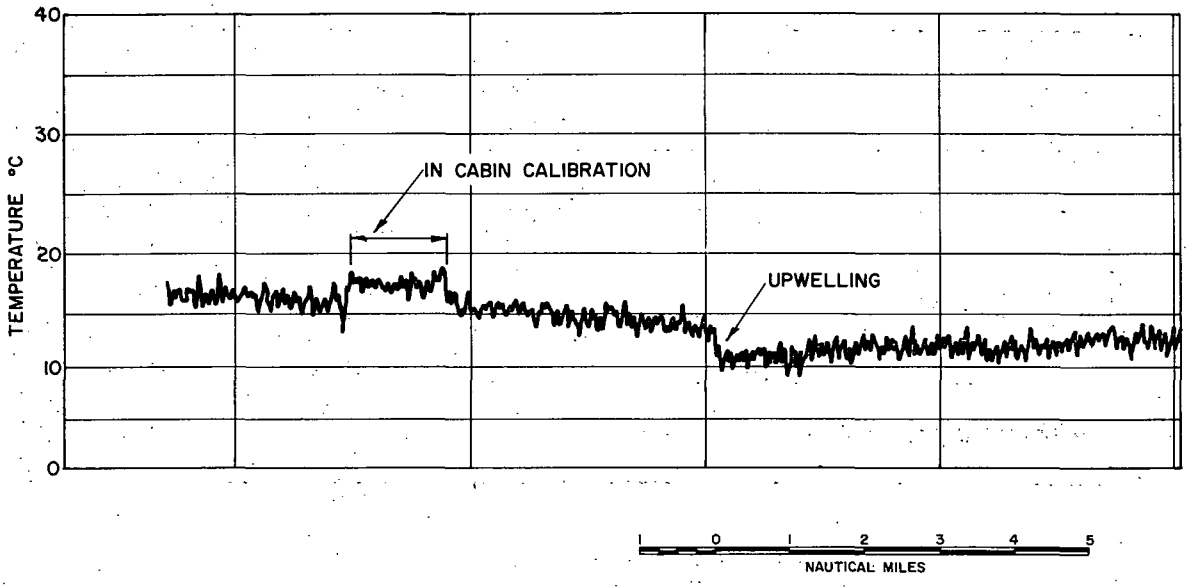


Figure 14
ART Trace, Flight 2.6, September 2, 1965, From 1000 Feet
Example of Upwelling Cold Water Lake Ontario

From Tables I and V it may be seen that the ART-ship's bucket temperature differences varied from -2.1°C to +3.6°C. It is also evident that these differences are related to the height of the aircraft and to day-to-day changes in the atmosphere. As a strictly empirical approach once the necessary correction to the ART has been found by flying over a known water temperature at a planned survey height, it is assumed that the technique will provide meaningful temperatures provided there are only small changes in the atmosphere between the aircraft and the water during the period of flight. Since the flights are at low altitudes and over periods of only a few hours the assumption appears warranted.

Optimum Flying Height

The summary of average temperature differences between the ART and the ship in Table VI indicates a "best" or optimum height for ART flights of 300 to 500 feet with an average difference of about 1°C within a range of -1.2°C to +2.9°C.

Flights at one to two thousand feet show larger average differences and a greater range of differences. However, the indicated corrections are small enough that flights at these heights appear feasible if safety or crew comfort dictates a higher altitude.

TABLE VI

TEMPERATURE DIFFERENCES WITH HEIGHT
(ART - Ship's Bucket)

Aircraft Height (feet)	Average Difference °C (regardless of sign)	Range of Difference °C	
		Negative	Positive
300	0.9	-1.0	2.2
500	1.0	-1.2	2.9
1000	1.7	-1.5	3.6
1500	1.6	-1.7	3.4
2000	1.7	-2.1	3.3

Environmental Errors

For consistent results the ART should be used in good visibilities, with no precipitation during or prior to the flight and with no cloud below the aircraft.

The relative differences found between the ART and the ship's temperature on each of the five flights of Phase II are shown in Table VII. For any given aircraft height there is a close relationship between the temperature difference (ART - ship) and the temperature of the air column through which the sensor was viewing.

TABLE VII

EFFECT OF AIR TEMPERATURE ON ART READINGS

Flight	Temperature Differences (ART-ship)	Air Temperature (Relative to Water)	Lapse rate	Visibility (miles)
2.1	small negative	air colder than water	estimated unstable	15
2.2	large positive	air much warmer	marked inversion	15
2.3	small positive	air a little warmer	slightly unstable	15
2.5	negative	air a little colder	unstable	6
2.6	negative	air and water about same	very unstable	15

In general terms it may be stated that the ART reads lower when the air column is colder than the water and conversely reads higher when the air column is warmer than the water.

The subject of environmental errors is a very large and important one which also involves water vapour absorption, aerosal scattering, surface emissivity, reflected radiation and sky cover above the sensor. The data collected from the Phase II ship-aircraft program are currently under study and as stated earlier, will form the basis of a M.A. thesis. Further comment will be withheld pending the results of the study.

Calibration

For best results the infra-red thermometer requires fairly frequent laboratory calibration checks.

Until more is learned of the environmental errors inherent in the ART technique an in-flight calibration check over a known water temperature is required preferably prior to, and after each survey.

Frequent in-flight in-cabin water bath calibration checks are advisable although a drift in excess of 0.5°C was detected on only one flight.

A monitor of the power input to the ART is also advisable to guard against errors introduced by frequency changes to which the instrument is extremely sensitive.

Temperature Surveys

Two complete surveys (Flight 2.1, Fig. 7; Flight 2.2, Fig. 8) and three limited surveys (Flights 2.3, 2.4, 2.6) produced realistic isotherm patterns of surface water temperatures. As discussed earlier, when compared to ship's surveys at or near the same time (Figs. 7, 9, 10) the tentative conclusion has been reached that with fly-over and in-cabin calibrations the isotherms have an absolute accuracy of about 1.0°C and a relative accuracy (between isotherms) of the order of 0.5°C or less.

With these accuracies the ART provides a fast and satisfactory technique for making lake water temperature surveys.

Small Scale Variations

The ART traces from the survey flights of Phase II have revealed some good examples of the detection of surface water temperatures changes over short horizontal distances.

Fig. 11 (Flight 2.2, May 3) shows the gradual near-shore warming typical of Lake Ontario in the spring.

Fig. 12 (Flight 2.3, May 3) shows two abrupt changes of upwards to 5°C with the "thermal bar" as described by Rodgers (8).

Fig. 13 (Flight 2.6, September 2) shows the temperature of the Niagara River and follows the outflow of the river three miles into Lake Ontario. A colour photograph taken on the flight confirms a sharp change in colour and texture of the water at the point of temperature change.

Fig. 14 (Flight 2.6, September 2) shows a 7°C temperature change in north-central Lake Ontario deemed due to an upwelling characteristic of the lake and the time of year.

The relative accuracy of these traces are thought to be within 0.5°C making the ART an excellent tool for the detection of small scale horizontal gradients in surface water temperatures.

5. Conclusions

Although the exposure of the sensor is critical, the ART, when used in suitable weather and with proper calibration checks, provides a good technique for making fast and reliable water temperature surveys of the Great Lakes.

The optimum height for such surveys appears to be 500 feet or lower although, if necessary, flights at one to two thousand feet appear feasible with proper calibration.

With the present instrumentation and installation the absolute accuracy appears to be of the order of 1.0°C with a relative accuracy within 0.5°C.

The accuracy may be increased with an improved understanding of the environmental errors involved. This requires a further study for which data have been collected and which is already in progress.

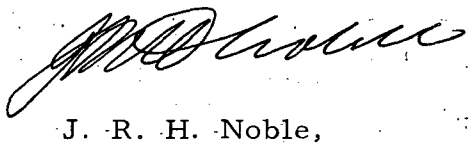
The experience gained with the instrumentation and the aircraft has been invaluable and the results confirm the usefulness of the ART technique for both research and operational purposes in the Great Lakes area. As a result, it is planned to operate monthly ART flights in 1966 over Lakes Ontario and Erie with occasional flights over Lakes Huron and Superior. In addition, preliminary plans call for a program of monthly surveys of all the Great Lakes bordering on Canada in 1967.

6. Acknowledgements

This program could not have been carried out without the splendid co-operation of the University of Toronto Great Lakes Institute's technician staff aboard the Department of Transport's research vessel C.C.G.S. "Porte Dauphine". A special acknowledgement is due to Chief Technician Mani Aesma who, at times managed wire-sonde flights under very trying conditions.

In addition to the help received from the literature as noted in the References, the authors also wish to acknowledge assistance obtained in private communications from Prof. Robt. Ragotzkie, Department of Meteorology, University of Wisconsin and Dr. John Tully, Fisheries Research Board of Canada, Nanaimo. Within the Meteorological Branch Mr. W. R. Smith of the Instrument Division was responsible for installation and maintenance of the equipment, Messrs. E. J. Truhlar and J. R. Latimer of the Research and Training Division provided advice and assistance in the theoretical (infra-red radiation) aspects of program, and finally, Phase I of the program was made possible through the co-operation of the Ice Observing Section, Basic Weather Division.

APPROVED,



J. R. H. Noble,
Director,
Meteorological Branch.

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