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Remote Sensing of Surface Water Temperature on the Great Lakes and off the Canadian East Coast

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Abstract

Surface water temperature data for the Great Lakes and Canadian east coast waters are derived from infrared radiation detected by sensors on board NOAA polar-orbiting satellites and transmitted in digital form to a receiving station, where the data are recorded on magnetic tape and subsequently processed. The temperature data can be corrected for atmospheric effects and surface reflection by two methods, a direct atmospheric correction method or a linear algorithm of the relationship between true and indicated temperatures at different wavelengths (two-channel method). The direct method requires input of local radiosone data, and thus its use is restricted to inland and coastal waters. Temperatures derived by the atmospheric correction method, for small zenith angles (<45°), were found to have a root-mean-square difference of 0.6° C from buoy temperature measurements. Less reliable results were obtained by the two-channel method, due to amplification of instrumental noise in the algorithm and contamination of the 3.8 μm infrared data by reflected solar radiation.

Introduction

Surface water temperature is an important parameter in air-water interaction and in the physical and biochemical processes occurring within the water mass. Assessment and monitoring of these processes require accurate and preferably regular synoptic-scale temperature data from both large and small water masses. During the past three decades, intensive environmental research programs of various kinds were carried out on the Laurentian Great Lakes system, with concomitant demand for surface water temperature data. The Hydrometeorology Division of the Atmospheric Environment Service (AES) of Canada conducted a program of airborne radiation thermometer (ART) surveys of the Great Lakes bordering Canada during 1966–80. The surveys were conducted at approximately monthly intervals during the ice-free season (Richards *et al.*, 1969; Irbe, 1972). The ART water temperature data were used by many investigators for diverse applications.

In the early 1970's, polar-orbiting sun-synchronous satellites, operated by U. S. National Oceanic and Atmospheric Administration (NOAA), provided the opportunity for acquisition of truly synoptic water temperatures with full spatial resolution over large areas. The feasibility of extracting surface temperatures for the Great Lakes from the NOAA satellite infrared data was first investigated by the National Environmental Satellite Service (NESS) of NOAA (Strong, 1974). In 1975, The NOAA-NESS Environmental Products Group started issuing maps of Great Lakes water temperatures derived from the satellite data.

The Aerospace Meteorology Division of AES has maintained a satellite data-receiving station since the mid-1960's. Recording of digital data from NOAA satellites began in 1974. By 1977, the Aerospace Meteorology and the Hydrometeorology Divisions had developed a cooperative program for retrieving water temperatures from digital satellite radiation thermometer (SRT) data. Consequently, analyses of Great Lakes water temperatures commenced in 1977. Since 1980, analyses have been done for the Great Lakes and the Bay of Fundy-Scotia Shelf regions at intervals of 2–3 weeks. In addition, water temperatures of other water bodies (e.g. Lake Winnipeg and Hudson Bay) are monitored in support of other programs or by special request.

SRT temperatures for the Great Lakes were compared with buoy and ART measurements from 1977 and 1979-80 data, in order to assess the accuracy of the extraction methods. This paper contains the results of these comparisons, together with descriptions of the methods employed, the main structure of the computer program, and the output format of temperature data.

NOAA Satellites

The orbital characteristics, sensor types and data transmission modes of the NOAA satellites are described briefly below. Complete information on the satellite systems is given in NOAA Technical Memoranda: NESS 60 by Fortuna and Hambrick (1974), and NESS 95 by Schwalb (1978).

Orbital characteristics

The satellites operate in sun-synchronous near-polar orbits at an altitude of 883 $\pm$ 90 km. Orbital inclination is between 98° and 99°, and the orbital period is about 102 min. The satellites orbit the earth 14 times per day, overflying the mid-latitude regions twice in a 24-hr period.

Sensors

The pre-TIROS-N satellites carried a sensor in the visual and one in the infrared regions of the spectrum. The TIROS-N and NOAA-6 satellites carry four Advanced Very High Resolution Radiometers (AVHRR), operating in the following spectral regions (channels):

Channel No.	Range (μm)
1	0.55 – 0.68
2	0.725 – 1.10
3	3.55 – 3.93
4	10.5 – 11.5

NOAA-7 carries an additional infrared channel (No. 5) centered at 12 μm.

The sensors scan continuously at 360 lines per minute while rotating about an axis aligned in the direction of travel of the satellite. The field of view of the sensors is 1.3 milliradians. The radiation detected over the earthward portion of a scan is split into 2,048 elements (pixels). A pixel comprises the radiation intensity from a km^2 area of the earth's surface at satellite sub-point. Away from the sub-point, pixels represent progressively larger rectangular areas.

Data transmission

Data are transmitted in 10-bit digital format. At the AES receiving station, selected blocks of data from an orbital pass are recorded on magnetic tape. The data are processed by the Hydrometeorology Division on a MODCOMP mini-computer.

Data Processing

Temperature extraction methods

Surface water temperatures can be processed from SRT data by two methods. The first method is designated as the Atmospheric Correction Method (ACM) and the second as the Two-Channel Method (TCM). The latter is the simplest variant of the multichannel method and has been used successfully with NOAA-6 data by McClain (1980). However, the method has yielded unsatisfactory results at AES (for reasons that are discussed later), and practically all routine temperature analyses have been performed using ACM. The ACM and TCM options are available in the same data-processing program. Use of the ACM option involves a lengthier procedure which requires imput of additional information generated beforehand by a separate atmospheric correction program.

The MODCOMP system

The system hardware components are: 128K memory words floating point hardware, RAMTEX GX-100B graphics display unit, 25 megabyte disk drive, VERSATEC printer/plotter, magnetic tape drive, and CRT terminals.

Data-processing program

The main program is structured such that the analyst can utilize any one of a set of routines. Each routine performs certain operations on a blcok of SRT data that have been transferred from magnetic tape to a disk file. The available options include:

1. Display data — displays earth-curvature-corrected data from a specified channel on the RAMTEX CRT.
2. Color slicing — allows arbitrary assignment of colors to radiation intensity levels, thus helping to discriminate details in the displayed scene.
3. Point location — calculates, from latitude and longtitude, the location of a point on earth in terms of pixel and scanline number within the data block and the zenith angle of the point with respect to the orbital track.
4. Calibration — calibrates digital count *versus* temperature (channels 3, 4 or 5) or percent albedo (channels 1 or 2) from data of a given block of scanlines; atmospheric correction values can be input to obtain digital count *versus* corrected temperature for data from channels 4 and 5.
5. Two-channel calibration — calculates, from the digital count *versus* temperature calibrations of channels 3 and 4, the surface temperature, using the relationship

$$T_s = a + T_4 + b\,(T_3 - T_4)$$

where a and b are constants.

6. Process data for printing — a block of data is processed and stored for printing, the specifications being size and location of data block, range

of temperature or albedo, spatial resolution and map scale of output data, resolution of the temperature or albedo field and digital count cutoff for channels 1 or 2 data if either of these channels is used to mask land surfaces in the temperature field.

Print program

The block of processed data is output in alphanumeric character code on the appropriate scale. Figure 1 illustrates sample output of a 2×2 pixel averaged field on a 1:1,000,000 scale of the Bay of Fundy area. Starting with the character □ for temperature at the warm end of the range, the characters represent stepwise decreases in temperature toward the cold end of the range (Table 1). To facilitiate analysis of the temperature field, the printout also contains unique symbols that replace certain grouped characters.

Data analysis

The temperature field (Fig. 1) is hand-analyzed and the results are transferred to a standard map, such

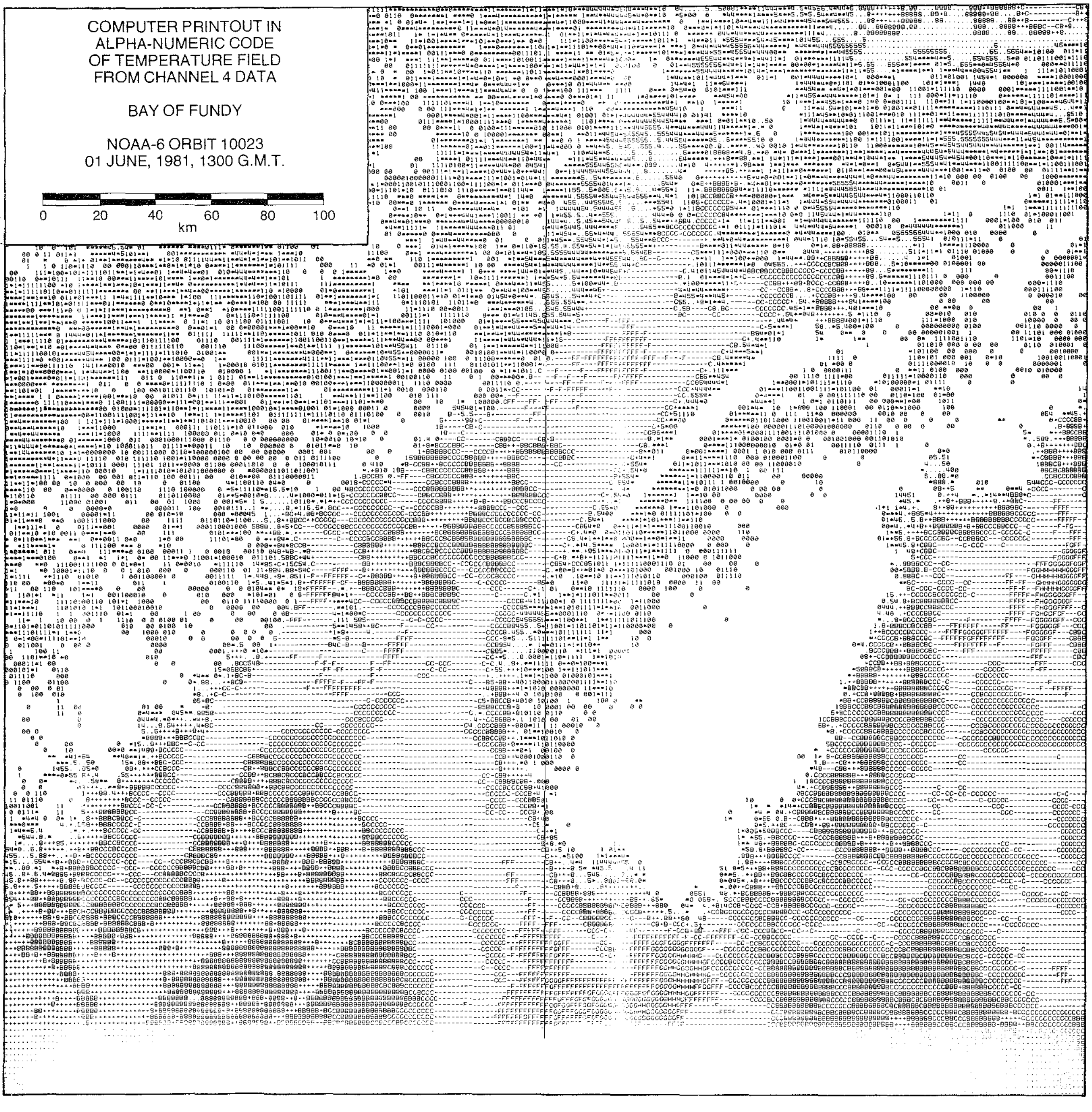

Fig. 1. Computer illustration in alpha-numeric code of the temperature field in the Bay of Fundy region from channel 4 data of NOAA-6 (orbit 10023) at 1300 GMT on 1 June 1981.

TABLE 1. Alpha-numeric codes and corresponding indicated and corrected temperatures (°C) for the computer illustration in Fig. 1.

Code character	Channel 4 indicated temperature	ACM corrected temperature
□	⩾12.2	⩾14.2
ϕ	11.8	13.7
1	11.3	13.2
*	10.9	12.7
*	10.4	12.1
4	10.0	11.6
5	9.5	11.1
•	9.1	10.6
•	8.6	10.0
8	8.1	9.5
+	7.7	8.9
+	7.2	8.4
B	6.7	7.8
C	6.3	7.3
—	5.8	6.7
—	5.3	6.2
F	4.9	5.6
G	4.4	5.0
H	3.9	4.4
@	⩽3.4	⩽3.9

as that illustrated in Fig. 2 for the Bay of Fundy. Both the indicated and ACM-corrected temperatures are listed in Table 1. Although the data have been rectified for earth curvature and rotation and for map projection, minor distortions of the data field, caused by orbital perturbations, remain in the printed scene. The distortions are adjusted for with the aid of land-water boundaries when the analyzed data are transferred to the map.

Atmospheric Correction Method

Development of the method

This method calculates the net atmospheric contribution to radiation measured from aircraft or satellites in the "window" regions of the infrared portion of the spectrum. The windows are located in the vicinity of 900 waves/cm (11 μm) and 2,650/cm (3.8 μm). Attenuation by water vapor and gases is relatively small in these regions of the spectrum and reflection by surface water is also minimal. Hence, water temperature can be

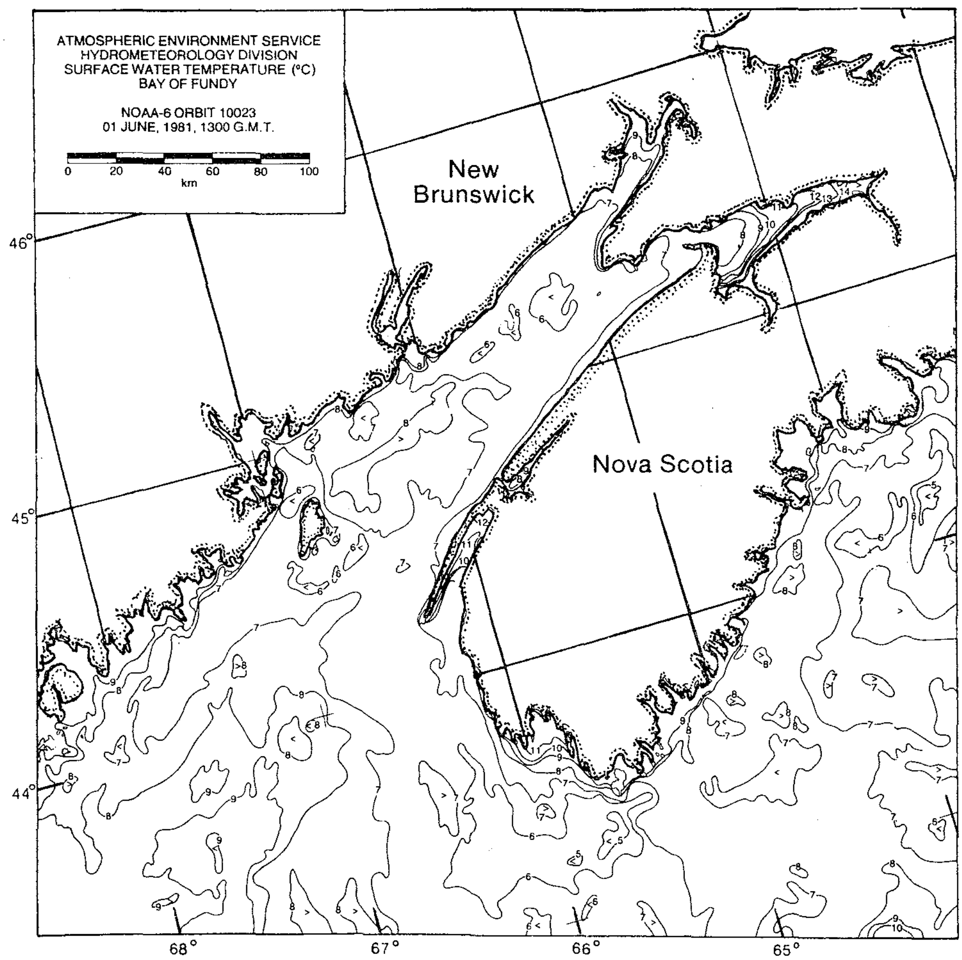

Fig. 2. Surface water temperature contours (°C) for the Bay of Fundy region, derived from NOAA-6 (orbit 10023) at 1300 GMT on 1 June 1981.

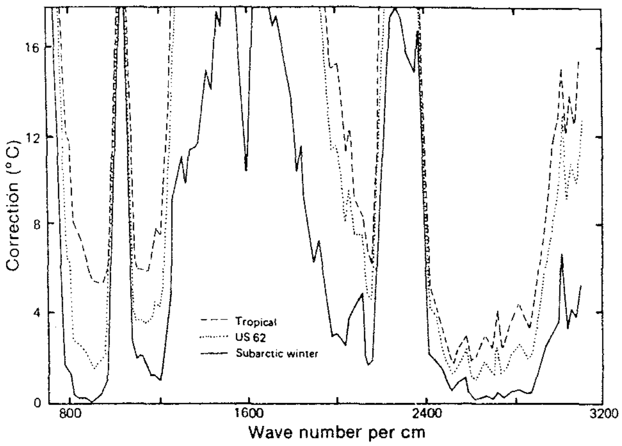

Fig. 3. Atmospheric correction as a function of wave number between 800 and 3,200 per cm.

determined by Kirchhoff's Law and the Planck function. Likewise, the atmospheric effects can be expressed in terms of temperature (Fig. 3).

In order to use ACM, the distribution of several gaseous attenuators and water vapor must be quantified over the atmospheric pass length. Water vapor accounts for most of the attenuation and it is also the most variable component. Other lesser attenuators (carbon dioxide, nitrogen, ozone, etc.) can be assumed to have a slowly changing global distribution. Therefore, the distribution of these gaseous attenuators can be reasonably defined by use of standard model atmospheres, but realistic estimates of water vapor distribution through the atmosphere require input of local radiosone (RAOB) data.

ACM is based on concepts similar to those proposed by Wark *et al.* (1962). A similar approach was used to develop a method for correcting surface water temperatures measured by an airborne sensor (Shaw and Irbe, 1972). The method was used with good results (root-mean-square error of 0.5° C) in the ART program for the Great Lakes (Irbe, 1972). The ACM now in use was developed by combining the Shaw method with the LOWTRAN (Low Resolution Transmission) model of Selby *et al.* (1976).

The ACM program

The atmospheric correction computer program calculates corrections for surface water temperatures derived from SRT data provided by channels 4 and 5.

Input data. Pressure, temperature and humidity data from RAOB ascents are input at the beginning of the program. The RAOB data from stations nearest to the water mass being studied and closest in time to the satellite pass are selected, data from several stations being used in the case of large water masses. The program merges the data to produce an "average" temperature-humidity profile for the atmosphere over the survey area. Usually the lowest RAOB levels are adjusted prior to input to account for (i) average surface air conditions in the survey area at the time of the satellite pass, as indicated by hourly observations at stations in the area, and (ii) modification of the air mass by the water mass itself. Further adjustments are required if the RAOB ascents penetrate cloudy layers, indicated by spikes in the humidity profile. Since surface temperatures can be evaluated only for cloud-free areas, the cloudy layers are eliminated from the RAOB data by smoothing out the humidity spikes.

Atmospheric transmission model. The program uses the LOWTRAN 3B (updated version) transmittance model developed by Selby *et al.* (1976). The model is versatile in that atmospheric transmittance can be calculated over a range of 0.25 to 28.5 μm for vertical, horizontal and slant paths through the atmosphere and for aircraft as well as satellite heights. The model contains transmittance functions for water vapor, uniformly mixed gases and ozone, and absorption coefficients for the gaseous elements and aerosols. Model atmospheres for water vapor and ozone (6), aerosols (5) and haze (2) are also provided.

Program functions. The radiation intensity detected by a sensor through a spectral band-pass filter can be expressed as a function of radiation emitted and reflected by the target, attenuation and emission by the intervening atmosphere, and transmittance efficiency of the filter-optics system. Starting with a given pressure-temperature-humidity profile, (from RAOB data) and a given distribution of gaseous constituents and aersols (from LOWTRAN model atmospheres), the program uses the radiative transfer equation to calculate the upward intensity of radiation transmitted progressively through 10-millibar layers of the atmosphere and finally through the filter-optics systems. Contributions from the different terms are evaluated for small wave-number intervals and then integrated over the filter band-pass range. The net detected radiance is equal to the sum of three terms that correspond to surface emitted radiation, reflected radiation and radiation emitted by the atmosphere. The radiative transfer equation is as follows:

$$N(Z,u) = \frac{1}{\pi} \int_{V_1}^{V_2} \emptyset(V)\, \epsilon(V)\, B_V(T_0)\, t_V(0,Z;u)\, dV$$

$$+ \frac{1}{\pi} \int_{V_1}^{V_2}\int_{0}^{Z} \emptyset(V)\, [1-\epsilon(V)]\, t_V(0,Z;u)\, B_V[T(z)]\, \frac{\partial t_V(0,z;u)\, dz\, dV}{\partial_z}$$

$$+ \frac{1}{\pi} \int_{V_1}^{V_2}\int_{0}^{Z} \emptyset(V)\, B_V[T(z)]\, \frac{\partial t_V(z,Z;u)\, dz\, dV}{z}$$

where N = detected radiance

θ = zenith angle

u = $\cos\theta$

Z = radiometer altitude

V = wave number

$\phi(V)$ = filter function such that $\phi(V) = 0$ outside the interval $[V_1, V_2]$

$B_v(T)$ = Planck function at absolute temperature T

$\varepsilon(V)$ = emissivity of the radiating surface

T_o = surface temperature (Kelvin)

$t_v(z_1,z_2;u)$ = transmittance of the layer located between altitudes z_1 and z_2 for incidence θ

$$= \exp\left[-\frac{1}{u}\int_{z_1}^{z_2} K_v(z)\,dz\right]$$

where K_v is the total absorption coefficient per meter which is equal to the sum of the aerosol and molecular absorption coefficients.

The atmospheric correction program finds the value of the true temperature for an indicated temperature and zenith angle by iterative calculation with different target temperatures until the equation is balanced to a specified residual error. Program output is an array of indicated *versus* corrected temperatures for zenith angles of 0° to 50°. This array is used later in the calibration routine for the main data-analysis program.

Two-Channel Method

The two-channel (or multi-channel) method for obtaining surface water temperatures is based on the fact that, after some simplification and approximation of the radiative transfer equation, the error introduced in radiometric temperature measurements by the atmosphere is proportional to a wavelength-dependent absorption coefficient. The method has received the attention of several investigators, including Deschamps and Phulpin (1980), who showed that surface temperature can be obtained from the linear relationship

$$T_o = a_o + \sum_{i=1}^{n} a_i T_i$$

where T_o = surface temperature,

a_o = constant term accounting for surface reflection and emission of CO_2

T_i = radiometric temperature at wavelength λ_i

a_i = coefficient dependent on the absorption coefficient at wavelength λ_i

Using a set of diverse RAOB temperature and humidity profiles, McClain (1980) calculated atmospheric corrections for various combinations of radiometrically-derived surface water temperatures from all of the AVHRR channels aboard the NOAA-6 satellite. From these calculations, he developed a workable algorithm that gives surface temperatures from channels 3 and 4 data, as follows:

$$T_s = 1.28 + T_4 + 1.42\,(T_3 - T_4)$$

where T_s = surface temperature

T_3 = channel 3 radiometric temperature

T_4 = channel 4 radiometric temperature

This algorithm is used in the two-channel calibration routine of the main data analysis program.

As mentioned before, TCM was found to give unsatisfactory results in most of the cases when it was tried at AES, the main problem being the high noise level in the temperature field. Deschamps and Phulpin (1980) showed that the instrumental noise is amplified in a multi-channel algorithm, and they proposed instrumental noise limits for successful application of the method. In addition, the use of channel 3 data in TCM limits application of the method to nighttime passes because of contamination by reflected solar radiation and sun glitter in the 3.8 μm window. It is hoped that the two thermal infrared channels (4 and 5) aboard NOAA-7 will give better results with TCM and obviate the use of channel 3.

Temperature Comparisons

When AES decided to undertake systematic monitoring of surface water temperature in the Great Lakes from SRT data, it became necessary to assess the accuracy of the temperature measurements. The ART survey program for the Great Lakes was continued on a reduced scale until 1980, in order to compare temperatures obtained by the two radiometric methods. In addition, the SRT temperatures were compared with those measured at meteorological buoys operated by the Canada Centre for Inland Waters.

Certain unavoidable difficulties were encountered when effecting comparisons of SRT temperatures with more conventional temperature measurements. The problems have been discussed fully by Morcrette and Irbe (1978) and Irbe *et al.* (1979). Briefly, the problems arise due to inaccuracies in matching data points, large differences in data resolution and sensor-related differences in the definition of "surface water temperature".

Data-point location errors are common to SRT and ART measurements. Errors in SRT data registration are caused by orbital perturbation and the roll and yaw of the satellite. Inaccurate determination of flight tracks introduces errors in ART data point location. Furthermore, SRT and ART data collection times may differ by several hours, in which cases diurnal variation in surface temperature becomes a factor.

Comparisons have doubtful validity in regions of strong surface temperature gradients, due to disparities in data resolution (1 km^2 at best for SRT and 10^{-4} km for ART data) and point measurements for buoy temperatures. Significant vertical temperature gradients can occur in the upper few centimeters of the surface water layer. Whereas SRT and ART data pertain to the radiative temperature of the water surface and buoy measurements are taken by an immersed sensor, the differences in measured temperature can be real.

In view of the several unknown factors, there simply is no standard against which SRT measurements can be assessed. The three data sets can be compared only in a relative sense (i.e. closeness of agreement), recognizing that each has unique properties and intrinsic errors. Therefore, the term "r.m.s. (root mean square) difference" rather than "r.m.s. error" is used in this discussion.

The first comparisons of SRT data from NOAA-5 with other temperature measurements were based on observations obtained in 1977 and reported by Morcrette and Irbe (1978) and Irbe *et al.* (1979). The results indicated a r.m.s. difference of about 1.5°C between SRT and buoy measurements and about 1°C between SRT and ART measurements.

For the second set of comparisons in 1979 and 1980, the SRT temperatures were obtained from the TIROS-N and NOAA-6 data. Comparisons were also attempted by applying the two-channel algorithm to data from channels 3 and 4 of NOAA-6 in the few instances where the resultant temperature field appeared to be relatively noise-free. The results of the eight comparisons between SRT (channel 4) and ART measurements are given in Table 2. In the case of the observations on 14 July 1980, it is suspected that the SRT data were contaminated by very light fog over the lake. Excluding that comparison, the r.m.s. difference is 2.25°C for indicated (uncorrected) and 1.19°C for temperatures corrected by ACM. These differences agree closely with those reported earlier by Irbe *et al.* (1979). No conclusions can be drawn from the three comparisons of two-channel temperatures with those from ART except to say that the temperatures appear to be less reliable.

Comparisons of SRT (channel 4) and buoy temperatures for Lake Erie were possible from data provided by 35 satellite orbits. The buoys were located over deep water no less than 10 km from shore, so that there was no problem with large near-shore temperature gradients which were encountered by Morcrette and Irbe (1978). Since routine lake temperature analyses are not normally undertaken during periods when a very hot, humid and hazy air mass occupies the region, SRT temperatures from five orbits when such conditions prevailed were excluded from the final statistics (Table 3). The remaining 30 cases were grouped by zenith angle to investigate the effect of atmospheric path length on reliability of SRT measurements, the

TABLE 2. Comparison of surface water temperatures measured by airborne radiation thermometer with satellite radiation thermometer measurements from channel 4 and from channels 3 and 4 combined. (r.m.s. = root-mean-square; PTS = number of ART point-temperature values compared with SRT data.)

	Satellite (SRT)				Aircraft (ART)				r.m.s. temperature difference SRT 4 *vs* ART		r.m.s. temperature difference
Lake	Orbit	Date	GMT	Zenith angle	Date	GMT	Time diff. (hr)	PTS	Ind.	Corr.	SRT 3+4 *vs* ART
Geo. Bay	TIROS-N 4230	9 Aug 79	1000	48°	9 Aug 79	1500	5.0	91	2.63	0.73	
Ontario	NOAA-6 922	31 Aug 79	1300	40°	31 Aug 79	1430	1.5	94	2.73	1.41	
Erie	TIROS-N 4786	17 Sep 79	1930	47°	17 Sep 79	1500	4.5	31	1.31	0.44	
Erie	NOAA-6 1264	24 Sep 79	1430	53°	24 Sep 79	1530	1.0	94	3.67	0.67	
Ontario	NOAA-6 3680	12 Mar 80	1300	31°	12 Mar 80	1600	3.0	113	1.28	0.42	1.74
Erie	NOAA-6 4192	17 Apr 80	1300	25°	17 Apr 80	1600	3.0	129	2.00	0.92	
Huron	NOAA-6 4881	5 Jun 80	0000	53°	4 Jun 80	1600	8.0	175	1.36	1.89	3.43
Erie	NOAA-6 5443	14 Jul 80	1230	60°	14 Jul 80	1600	3.5	131	6.15[a]	4.74[a]	1.07
					Average r.m.s. (excluding last comparison)				2.25	1.19	

[a] Suspected light fog over lake at time of satellite pass.

TABLE 3. Comparison of surface water temperatures on Lake Erie measured from buoys with temperatures obtained from satellite channel 4 data.

Zenith angle (°)	Number of cases	Root-mean-square (r.m.s.) temperature difference		Average ATM correction (°C)
		Uncorrected	Corrected	
0-20	6	2.18	0.64	2.3
21-40	7	2.58	0.51	2.4
41-60	15	3.90	2.03	1.8
≥61	2	4.26	2.21	2.1
0-44	14	2.57	0.60	2.4
≥45	16	3.93	2.10	1.7
All angles	30	3.37	1.59	2.0
All cases[a]	35	3.38	1.65	2.4

[a] Includes cases with very humid atmosphere, where corrections were greater than 3.5° C.

result being a r.m.s. difference of 0.6° C between buoy and SRT temperatures for zenith angles smaller than 45°. For larger zenith angles, the r.m.s. increased sharply to 2.1° C. Therefore, in order to avoid the probability of large errors in SRT measurements, data analyses should be limited to dry and clear atmospheric conditions, and data should be selected from orbits where the zenith angle is smaller than 45°.

Applications

There is a continuing demand for surface water temperature data for many diverse applications. Within AES specifically, SRT synoptic water temperatures of coastal zones and large lakes are useful in general meteorological forecasting as well as in predicting ice conditions on marine shipping routes. Furthermore, it is necessary to accumulate a temperature data base for studies of local and regional climatic regimes.

The program of monthly retrieval of surface temperatures for Bay of Fundy and Nova Scotia coastal waters, initiated in 1980, is given as an example of climatological application of a water temperature data base. The seasonal distribution of SRT temperature at three selected points in the Bay of Fundy (Fig. 4) is shown in Fig. 5. The meager data base is beginning to define the seasonal temperature regime at these locations. With increased input in the future, the curves will be defined with increasing precision and analysis of temperature variability will be possible.

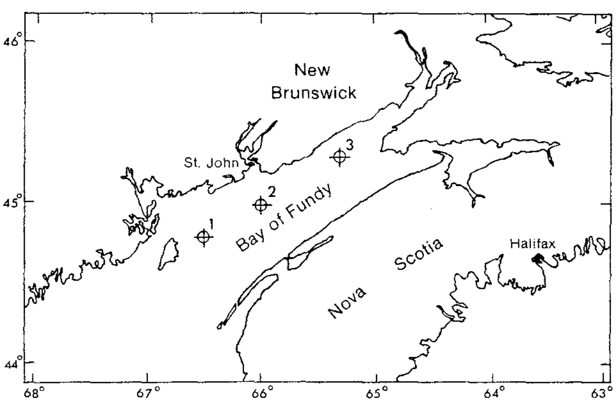

Fig. 4. Location of selected stations in the Bay of Fundy. (No. 1 at 44.8° N, 66.5° W; No. 2 at 45.0° N, 66.0° W; No. 3 at 45.3° N, 65.3° W.)

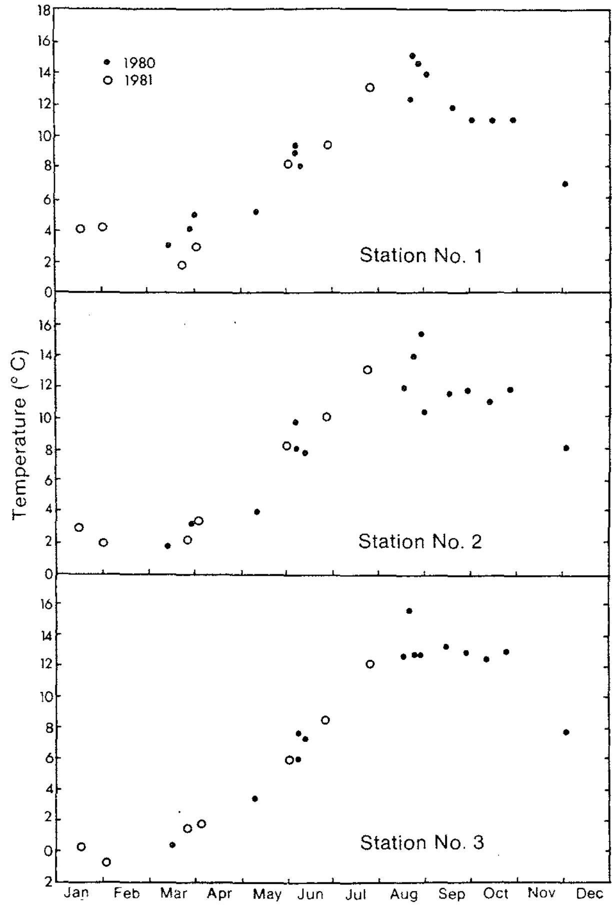

Fig. 5. Surface temperatures at three selected stations in the Bay of Fundy, 1980-81. (See Fig. 4 for station positions.)

References

DESCHAMPS, P. Y., and T. PHULPIN. 1980. Atmospheric correction of infrared measurements of sea-surface temperature using channels at 3.7, 11 and 12 μm. *Boundary-Layer Meteorology*, **18**: 131-143.

FORTUNA, J. J., and L. N. HAMBRICK. 1974. The operation of the NOAA polar satellite system. NOAA Technical Memorandum NESS 60, Dept. of Commerce, Washington, D. C., 127 p.

IRBE, J. G. 1972. An operational program for measuring surface water temperature by airborne radiation thermometer (ART) survey. Proc. 1st. Canadian Symposium on Remote Sensing, Feb. 1972, Ottawa, Ontario, p. 183-200.

IRBE, J. G., J. J. MORCRETTE, and W. D. HOGG. 1979. Surface water temperature of lakes from satellite data collected for atmospheric attenuation. Canadian Climate Centre, Downsview, Ontario, Rep.

No. 79-7, 58 p.
McCLAIN, E. P. 1980. Multiple atmospheric-window techniques for satellite-derived sea surface temperature. *In* Oceanography from space, J. F. R. Gower (ed.), Plenum Press, New York, p. 73-85.
MORCRETTE, J. J., and J. G. IRBE. 1978. Atmospheric correction of remote measurements of Great Lakes surface temperature. Proc. 5th Canadian Symposium on Remote Sensing, Aug. 1980, Victoria, B. C., p. 579-585.
RICHARDS, T. L., J. G. IRBE, and D. G. MASSEY. 1969. Aerial surveys of Great Lakes water temperatures, April 1966 to March 1968. Canada Dept. Transport, Meteor. Branch, Toronto, Ont., Climat. Studies No. 14, 55 p.
SCHWALB, A. 1978. The TIROS-N/NOAA A-G satellite series. NOAA Technical Memorandum NESS 95, Dept. of Commerce, Washington, D. C., 75 p.
SELBY, J. E. A., E. P. SHETTLE, and R. A. McCLATCHEY. 1976. Atmospheric transmittance from 0.25 to 28.5 microns. Supplement to LOWTRAN 3B, AFGL-TR-76-0258, Envir. Res. Paper 587, Bedford, Mass., 109 p.
SHAW, R. W., and J. G. IRBE. 1972. Environmental adjustments for airborne radiation thermometer measuring water surface temperature. *Water Resources Res.*, **8**: 1214–1225.
STRONG, A. E. 1974. Great Lakes temperature maps by satellite. Int. Assoc. Great Lakes Res., Proc. 17th Conf. Great Lakes Res, p. 321–333.
WARK, D. Q., G. YAMAMOTO, and J. H. LIENESCH. 1962. Methods of estimating infrared flux and surface temperature from meteorological satellites. *J. Atmos. Sci.*, **19**: 369–384.