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TESTING OF A TECHNIQUE FOR REMOTELY MEASURING WATER SALINITY IN AN ESTUARINE ENVIRONMENT

by

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TESTING OF A TECHNIQUE FOR REMOTELY MEASURING WATER SALINITY IN AN ESTUARINE ENVIRONMENT

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ABSTRACT

An aircraft experiment was flown on November 7, 1973 to test a technique (Thomann, 1973) for remote water salinity measurement. Apparent temperatures at 21 cm and 8-14 μm wavelengths were recorded on eight runs over a line along which the salinity varied from 5 to 30 $^{0}/oo$. Boat measurements were used for calibration and accuracy calculations. Overall RMS accuracy over the complete range of salinities was 3.6 $^{0}/oo$. Overall RMS accuracy for salinities greater than 10 $^{0}/oo$, where the technique is more sensitive, was 2.6 $^{0}/oo$. Much of this error is believed to be due to inability to exactly locate boat and aircraft positions. The standard deviation over the eight runs for salinities $\geq$10 $^{0}/oo$ is 1.4 $^{0}/oo$; this error contains a component due to mislocation of the aircraft also. It is believed that operational use of the technique is possible with accuracies of 1-2 $^{0}/oo$ under conditions specified in the paper.

Thomann, G.C. (1973). "Remote Measurement of Salinity in an Estuarine Environment," Remote Sensing. Environment 2, pp. 249-259.

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INTRODUCTION

Since 1971, the Earth Resources Laboratory (ERL) has been engaged in experimental research to remotely determine water salinity from measurements of upwelling radiation at 21 cm wavelength. The methods used and the theoretical basis for the dependence of apparent temperature at L-Band frequencies upon water salinity have already been discussed by Thomann (1973). Earlier investigative work was also done by Paris (1969).

The instrument used for the ERL experiments has been the Multifrequency Microwave Radiometer (MFMR) which is located on the NP3A, a NASA Earth Resources Program aircraft. The MFMR has a total of four bands, of which only the L-Band Channel near 1.42GHz is used for salinity measurement. Recently a separate radiometer obtained by ERL has been used in boat and helicopter tests, but the results of these experiments are not complete and will not be presented here.

The MFMR has been previously tested on several occasions at ERL (Thomann 1973; 1973a). From the results of these experiments, a recommendation was made to Johnson Space Center (JSC) that the L-Band portion of the radiometer be modified to improve its sensitivity and stability. The modifications were subsequently accomplished and the instrument tested again in November of 1973. The results of the November experiment are presented here. A single flight line was used in this experiment. The NP3A flew the line eight times consecutively to test both the accuracy and repeatability of the salinity measuring technique. The flight line used is shown in Fig. 1. The flight line is just south of the Mississippi Gulf Coast. It extends from the upper part of Lake Borgne near the Rigolets into the Gulf water south of Ship Island. It is an excellent line of salinity testing because a salinity gradient exists along it during all but exceptional environmental conditions. The water near the west end of the line is relatively fresh (about 5 ^{o}/oo during the November experiment) due to the flow from the Pearl rivers and from Lake Pontchartrain. The middle part of the line extends over water slightly more saline (about 10 ^{o}/oo at the time of the experiment) and the eastern end of the line extends into the Gulf of Mexico where the salinities approach more closely oceanic values (about 30 ^{o}/oo in November). Three boats were located along the flight line at the circled positions and a fourth boat traversed the line taking measurements of salinity and water temperature at the numbered points shown in the figure.

REMOTE MEASUREMENT OF SALINITY

The relationship between 21 cm apparent temperature and water salinity is shown in Fig. 2 for several water temperatures (Thomann 1973). The radio astronomy band near 21 cm wavelength is a reasonable choice for salinity studies because there is little interference in this quiet band, because the apparent temperature variation with salinity is not as marked at shorter wavelengths, and because at longer wavelengths the antennas become intractable. Two things about the

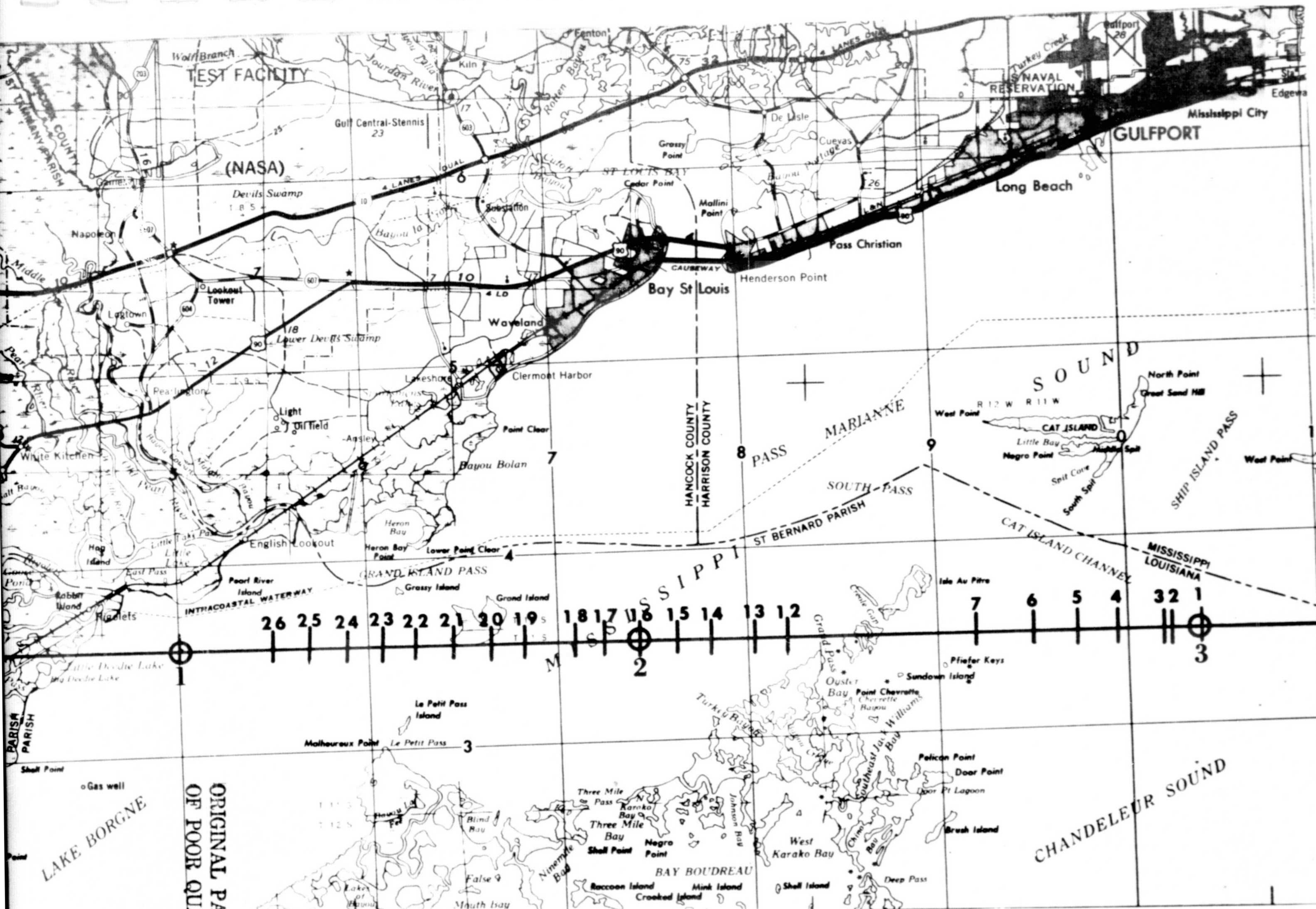

Figure 1. Flight line and position of stationary boats.

(circles) and moving boat (hash marks).

remote sensing technique are evident from Fig. 2. First, the sensitivity is not as good at low thermodynamic water temperatures as it is for warmer ones. Secondly, for fresh water there is reduced sensitivity as compared to that in more saline waters. Basically, the technique is for use in fairly warm areas with good salinity accuracies (1 - 2 $^{0}/oo$) to be expected for salinities $\geq$ 5 to 10 $^{0}/oo$, with the low end of the salinity range being somewhat dependent upon water temperature.

The ERL procedure for remote salinity measurements consists of the following steps:

1. Measurement of the apparent temperature of the sea surface at 21 cm and 8-14 μm wavelength.

2. Correction of perturbations in the 21 cm and 8-14 μm data.

3. Determination of salinity using a table look-up procedure. (A look-up procedure employed by the computer in which a salinity value is located which will give the indicated 21 cm and 8-14 μm apparent temperature.)

The accuracy obtained is limited by the sensitivity of the instruments and the extent to which required corrections to the measured radiometric temperature can be made. Errors in the 8-14 μm region occur usually because of instrument offset and atmospheric effects. These errors are eliminated by a simple offset adjustment with a surface measured temperature supplying the required calibration.

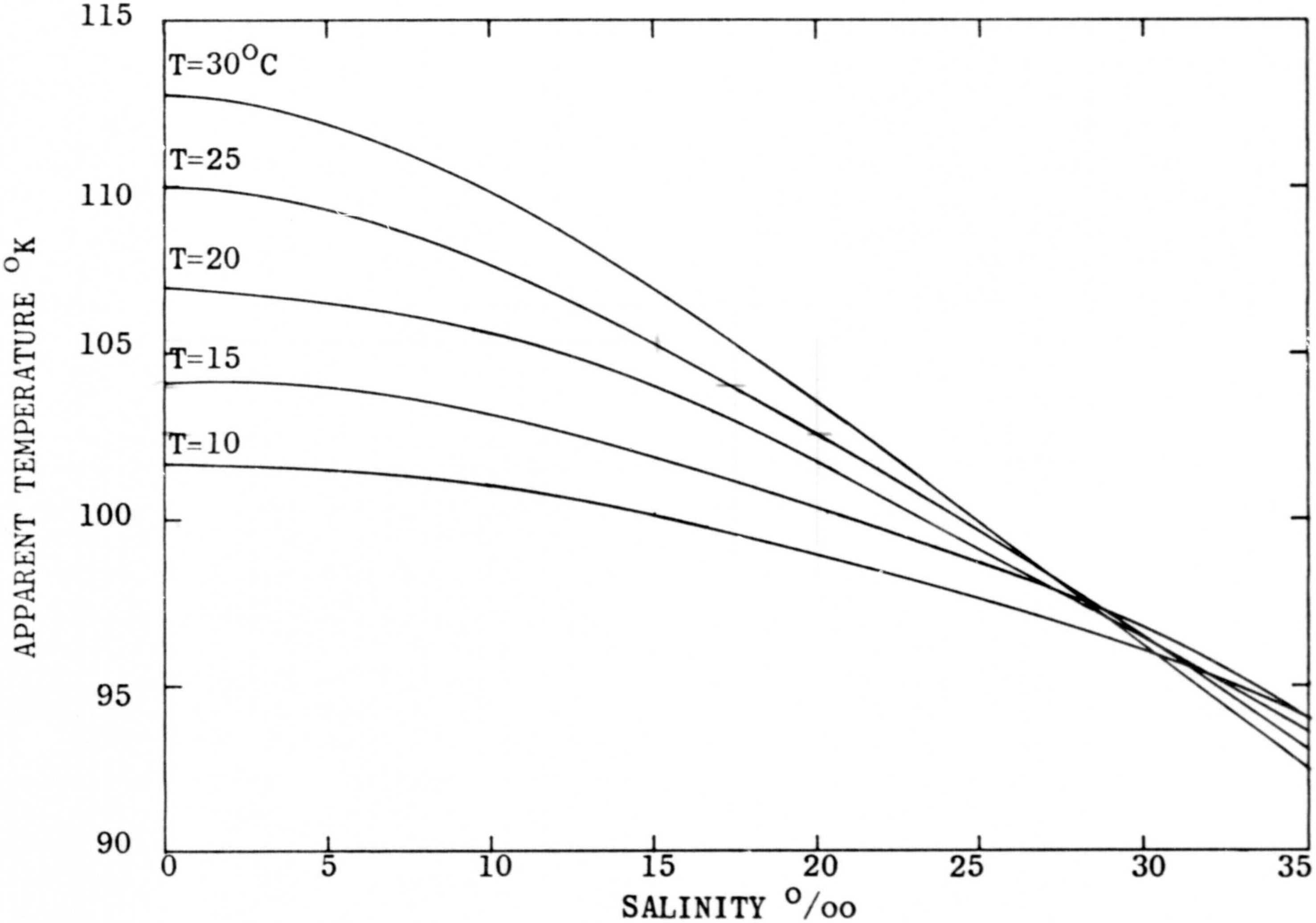

Figure 2. Apparent sea surface temperature as a function of salinity and water temperature for 21.1cm wavelength, 9.3° incidence angle, vertical polarization.

Significant errors in the 21 cm data are potentially more numerous and are caused by instrument offset and gain variations, reflected galactic radiation, atmospheric attenuation and emission, and surface emissivity changes due to sea state changes along the flight line. If the instrument gain is well known, all corrections can be done by a simple offset since the multiplicative errors such as atmospheric absorption are small. Unfortunately, in the past, the MFMR gain function did not seem stable over any but the shortest lengths of time and a linear correction of the 21 cm data was necessary. This required two surface calibration points at stations substantially different in 21 cm apparent temperature.

The data from previous experiments using the two point calibration ranged from very good to completely unusable. The very good data produced accuracies of 2 $^{o}/oo$; at other times, the remote data seemed to bear little relation to ground measurements. The instrument was apparently unstable and would operate well for one experiment, poorly for another.

Some of the best results were obtained from an experiment conducted on August 25, 1972. The same line shown in Fig. 1 was flown six times at an altitude of 800 ft. The comparison between remote and surface measurements is shown in Fig. 3. A separate two point linear correction was made for each of the six runs of remote data from surface measurements collected at stationary boat positions 1 and 3. The accuracy was evaluated by comparison of the remote values on each line with the

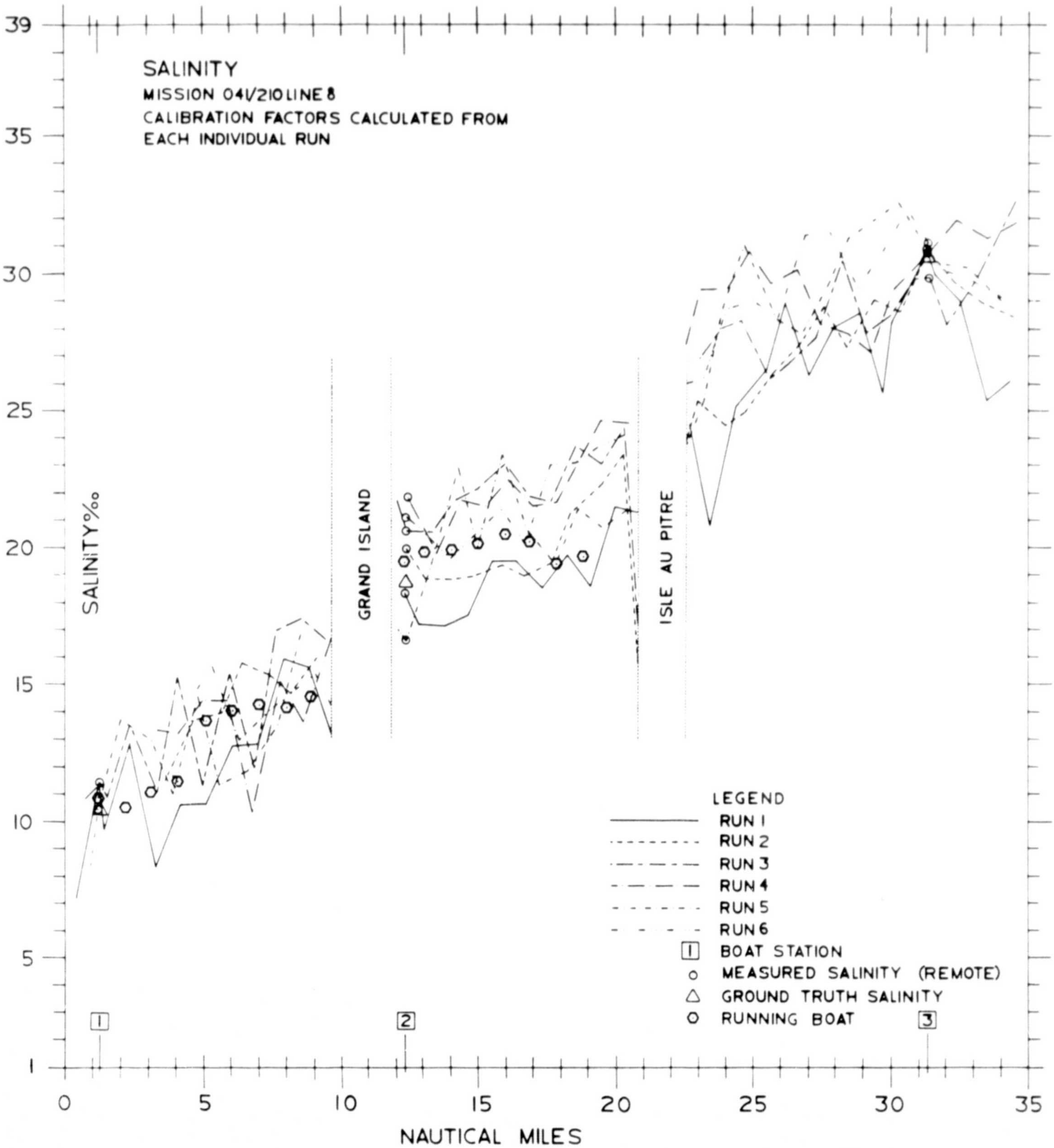

Figure 3. Remote and ground truth measurements of salinity, each run calibrated from measurements at positions 1 and 3.

values measured by stationary boat 2, and the values found by the running boat (indicated by hexagons). The overall RMS accuracy for the six lines was about 2 $^{o}/oo$, and with a single set of two ground truth points used to calibrate all six runs, the accuracy was about 2.5 $^{o}/oo$.

Despite the quite good accuracies obtained with the MFMR in the August 25, 1972 experiment, it was thought the instrument should be reconditioned in an attempt to improve its stability and sensitivity, and such a recommendation was made to Johnson Space Center.

MFMR MODIFICATIONS

The modifications to the instrument were done at the Johnson Space Center and will not be discussed extensively here; they are documented by Reid (1973). The MFMR is a four-channel Dicke receiver. Problems had been experienced with the antenna, the receiver electronics, the noise reference sources, and the calibration procedures. All of these problems were addressed in the modification; a new antenna was procured, the receiver was rebuilt and the instrument recalibrated.

NOVEMBER 7, 1973 EXPERIMENT

The line shown in Fig. 1 was flown eight times, four times in each direction, at an altitude of 800 feet. The MFMR antenna was pointed 15° forward of vertical and only the vertical component of the upwelling radiation was sensed. A PRT-5 was used to measure water temperature at 8-14 μm wavelenth; it was pointed straight down.

KA-62 cameras with color and color-IR film were used to locate boats and land crossings and to delineate differing water masses. The flight began at 11:30 a.m. and ended at 2:00 p.m. CST. The sea surface was fairly smooth, with only a small amount of whitecaps occurring. Isolated patches of fog occasionally made sighting of the ground truth boats difficult from the aircraft and, as a result, some sharp turns were necessary to ensure that the aircraft passed directly over the boats. The aircraft banking associated with these turns caused a change in the pointing angle of the antenna and, therefore, some remote salinity determination errors. These errors will be discussed later in the paper.

DATA PROCESSING AND RESULTS

Preliminary examination of the data indicated that it was good, except for some cyclic interference in the L-band data consisting of spikes of about 2-4° K occurring every 10 secs. The interference occurred most strongly at the western end of the line and became much less severe at distances from the western end of the line, no matter which direction the plane was headed. The interference was subsequently traced to an aircraft detection radar located near Lake Pontchartrain. The radar operates near 1300 MHz, transmitting a peak power of 3.5 Mw in a 2 μ sec pulse. It scans at a 6 rpm rate. Considering that the MFMR is sensitive to radiation between 1400 and 1427 MHz and that the bandwidth of a pulse modulated waveform is nominally equal to the reciprocal of the pulse length it appears unreasonable that this radar could interfere with the MFMR. Apparently, however, this radar has a reputation of being exceptionally dirty, i.e., it transmits radiation over a wide spectral band, and from this fact and the other characteristics of the interference, it is believed to be the interference source. Processing was first done without these spikes removed.

The remote data obtained after processing, stationary boat ground truth values, and running boat ground truth values for each of the eight lines are shown in Figs. 4 through 11. The data was first averaged over ten second blocks. An offset was added to the 21 cm data so the apparent temperature was correct at boat 3 on run number one. This same offset was then used for processing all eight runs of data. As can be seen from the eight graphs, the correlation between the remote and running boat surface data appears quite good near the eastern (saline) end of the line, but poor near the western (fresh) end of the line. These results are what might be expected, because theoretically the sensitivity is much poorer in fresh waters than in saline waters. This is especially true with fairly cold water; during this experiment the water temperatures were about 20°C. Another factor which probably influenced the accuracy on the western end of the line is the close proximity of land to the flight line. In fact, land areas virtually encircle the line near stationary ground truth boat 1. At 21 cm wavelength the land is radiometrically much hotter than the water and any land seen by the antenna will raise the apparent temperature and lower the resulting calculated salinity. It is felt that these

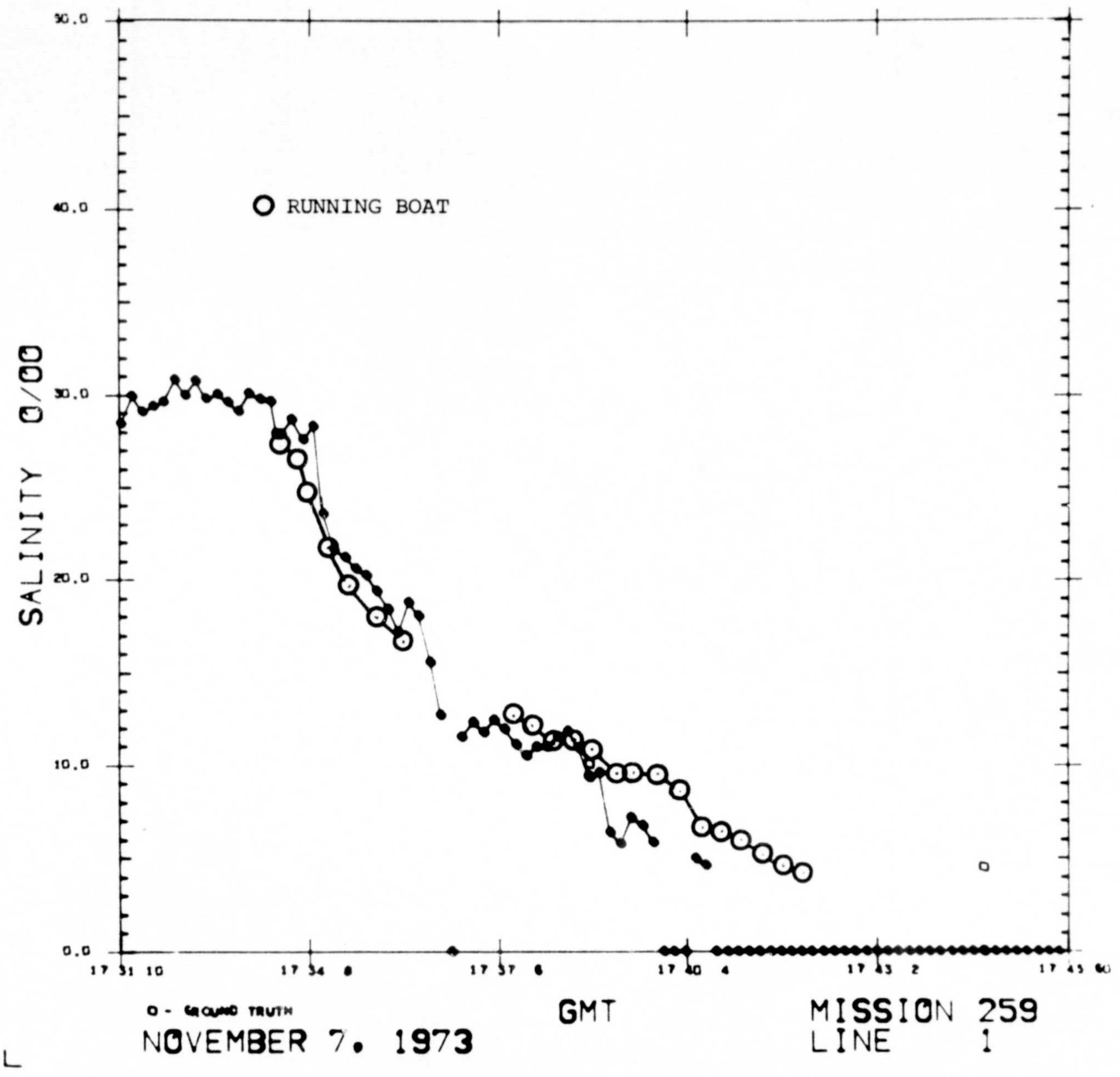

Figure 4. Remote and surface measured salinity values for run 1.

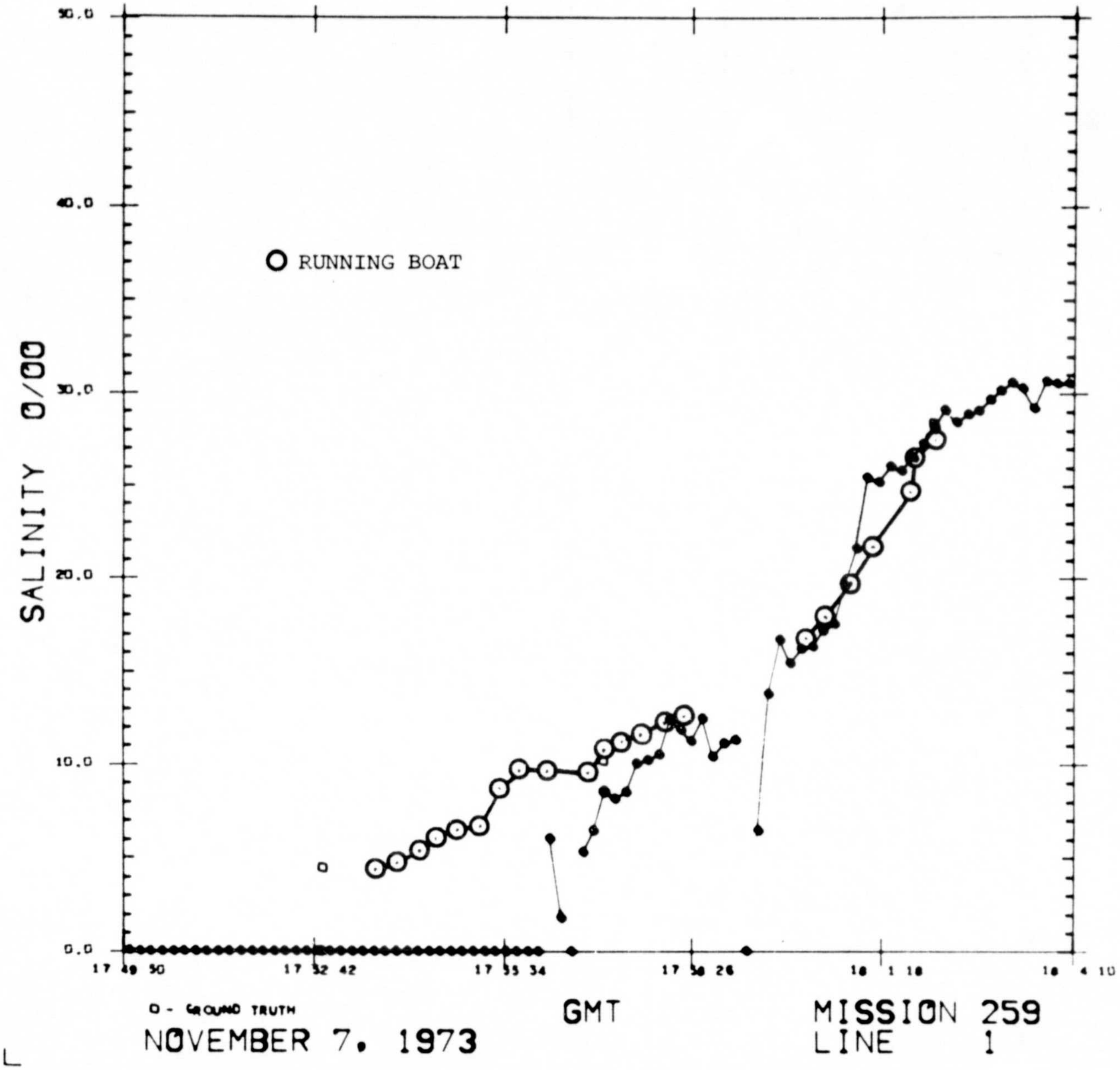

Figure 5. Remote and surface measured salinity values for run 2.

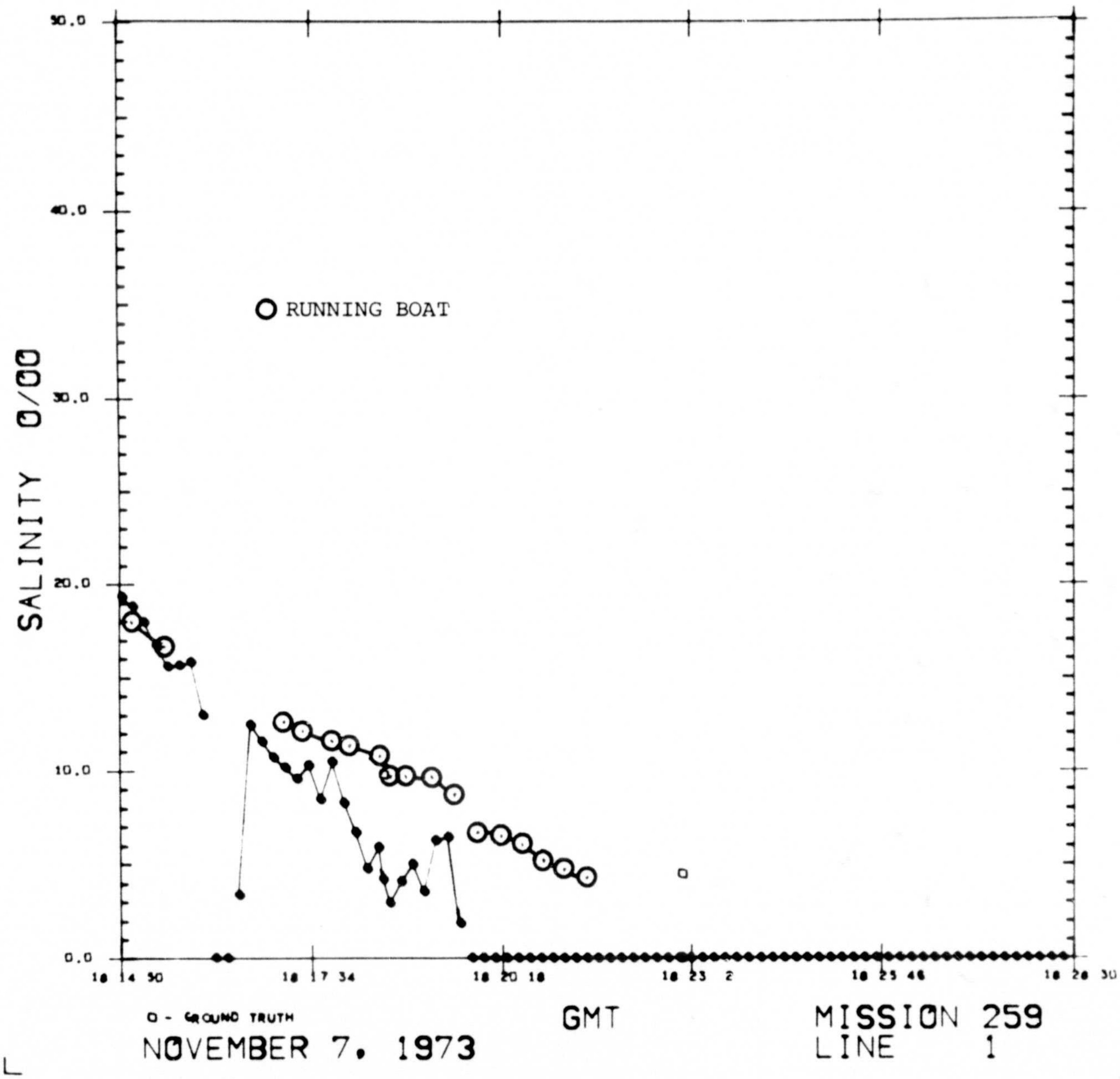

Figure 6. Remote and surface measured salinity values for Run 3.

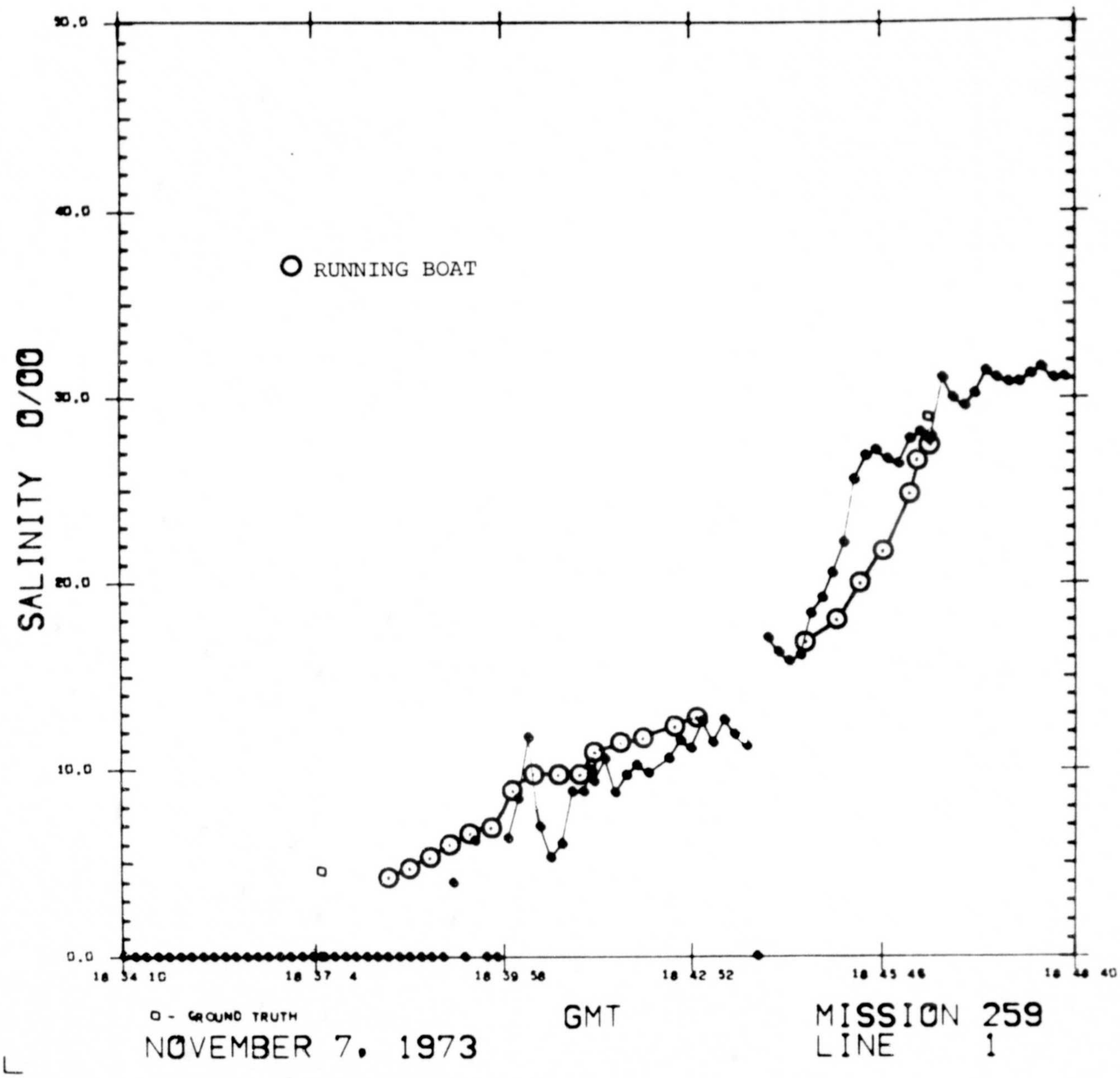

Figure 7. Remote and surface measured salinity values for Run 4.

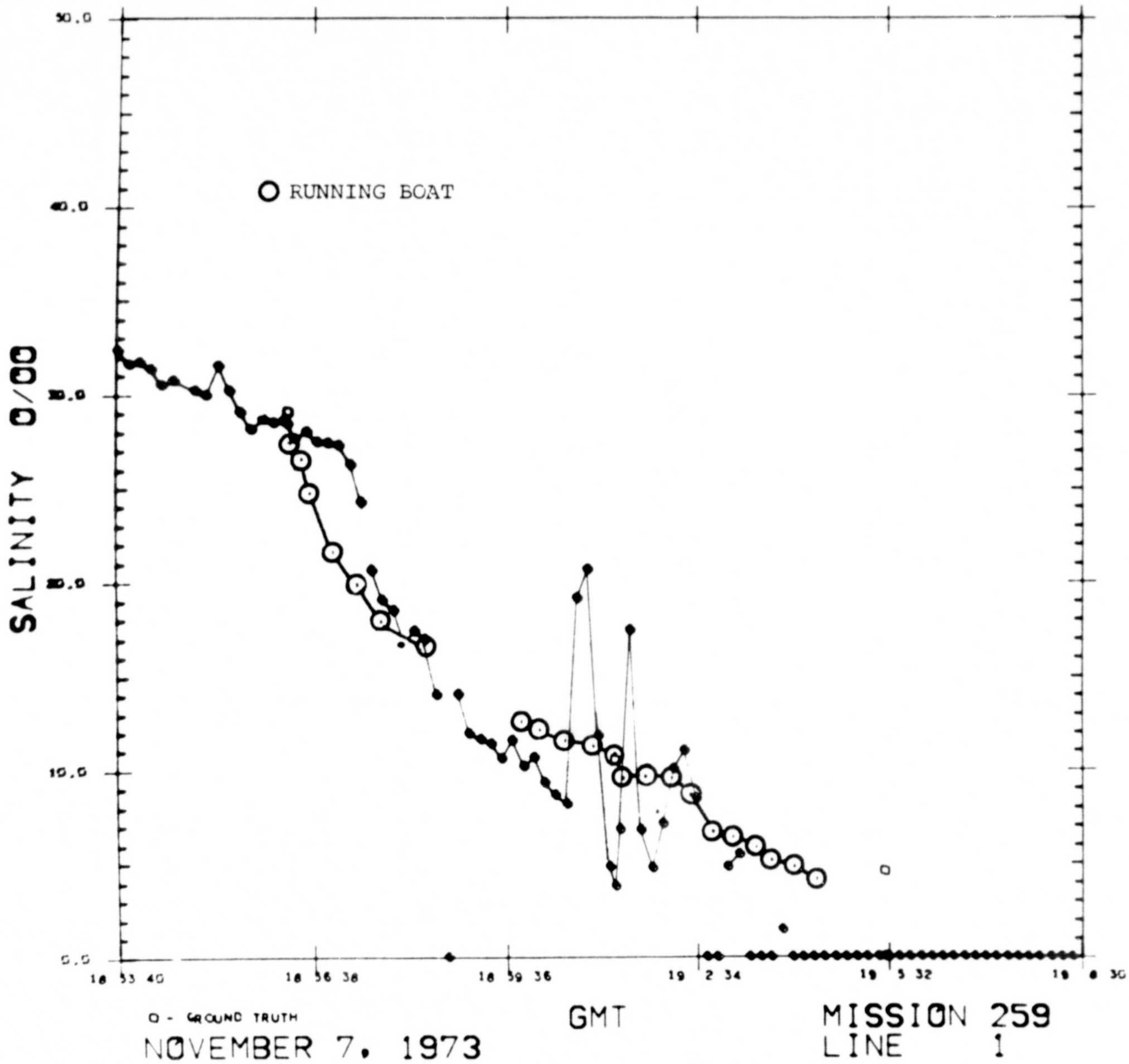

Figure 8. Remote and surface measured salinity values for Run 5.

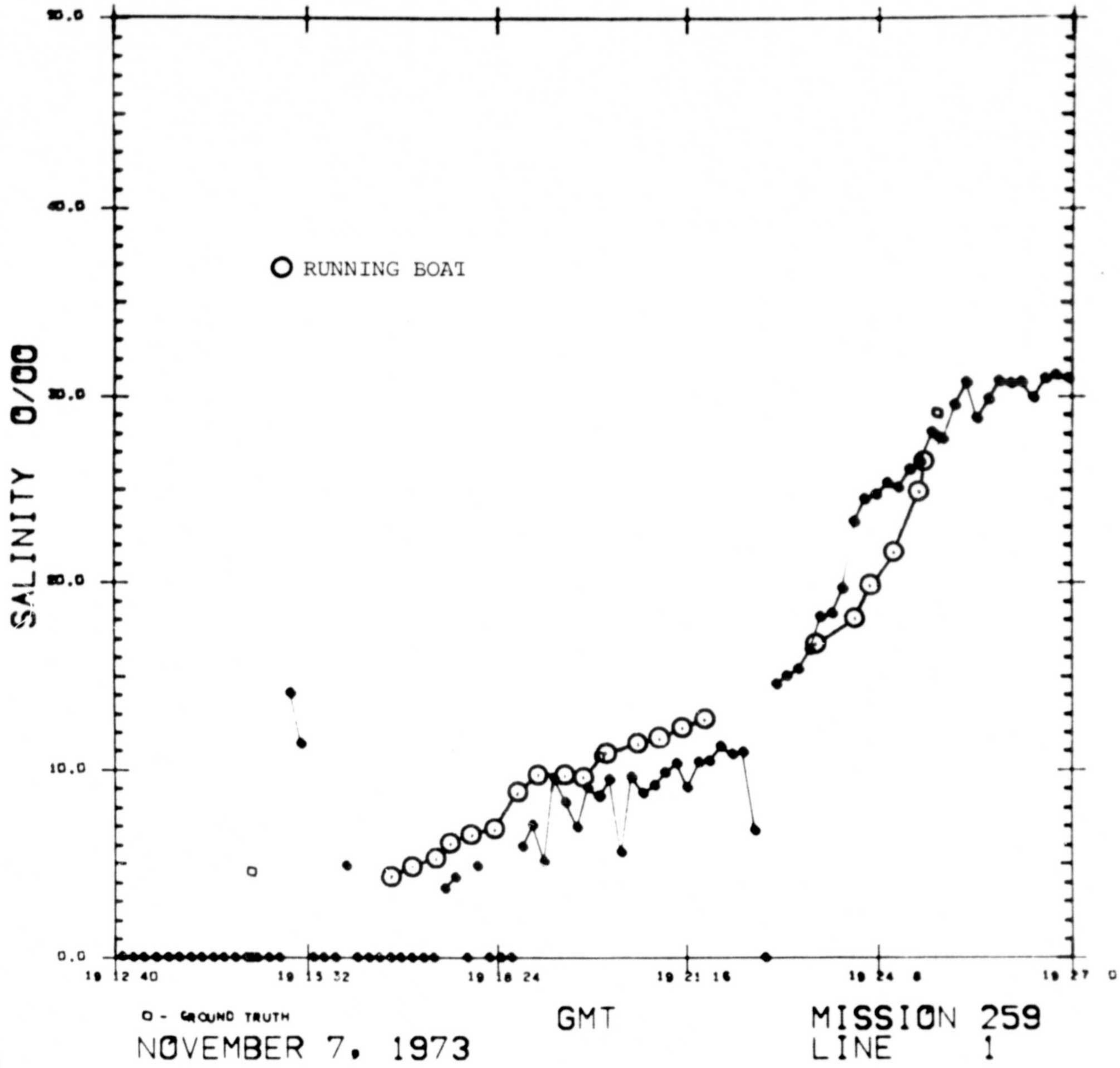

Figure 9. Remote and surface measured salinity values for Run 6.

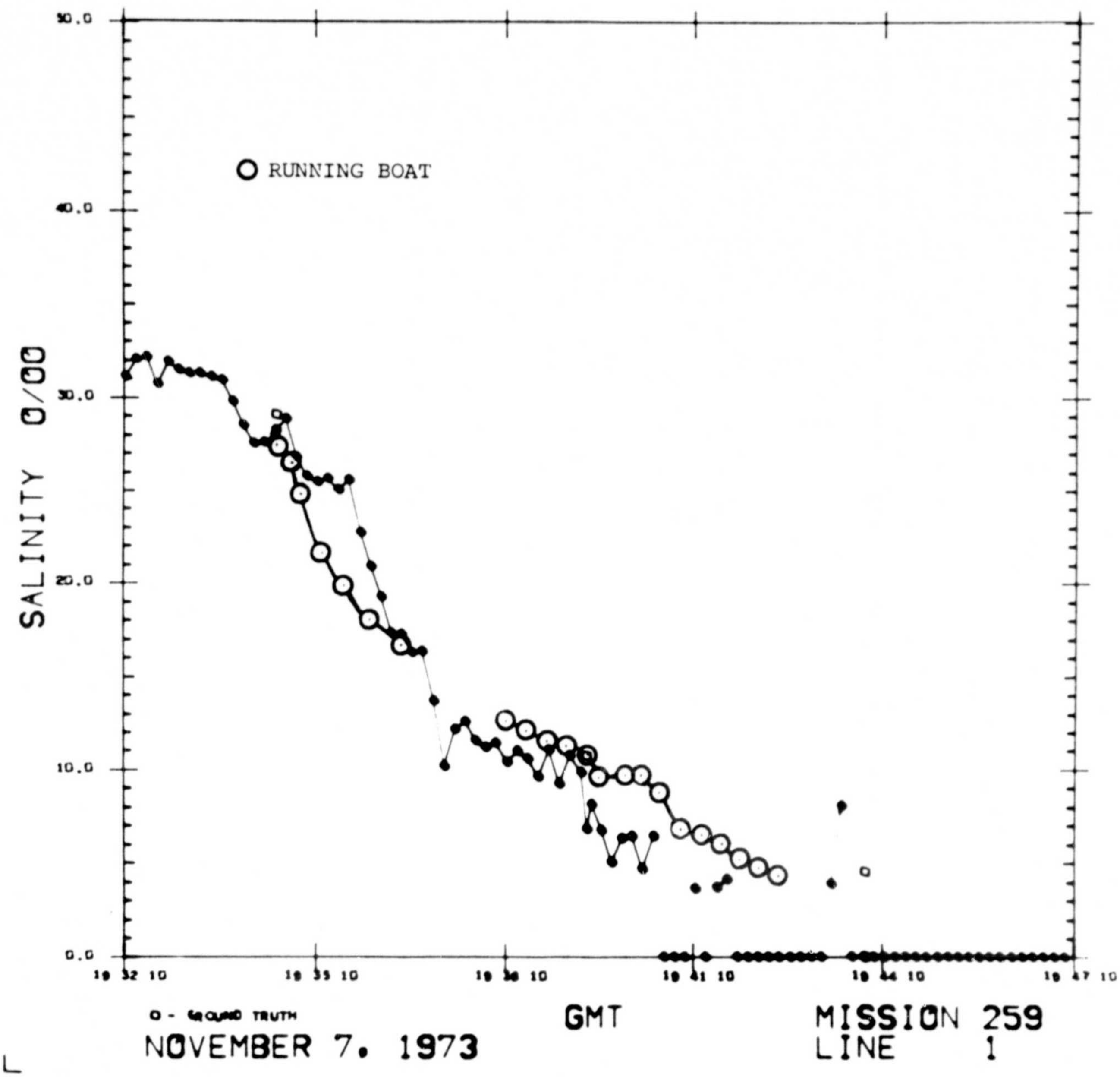

Figure 10. Remote and surface measured salinity values for Run 7.

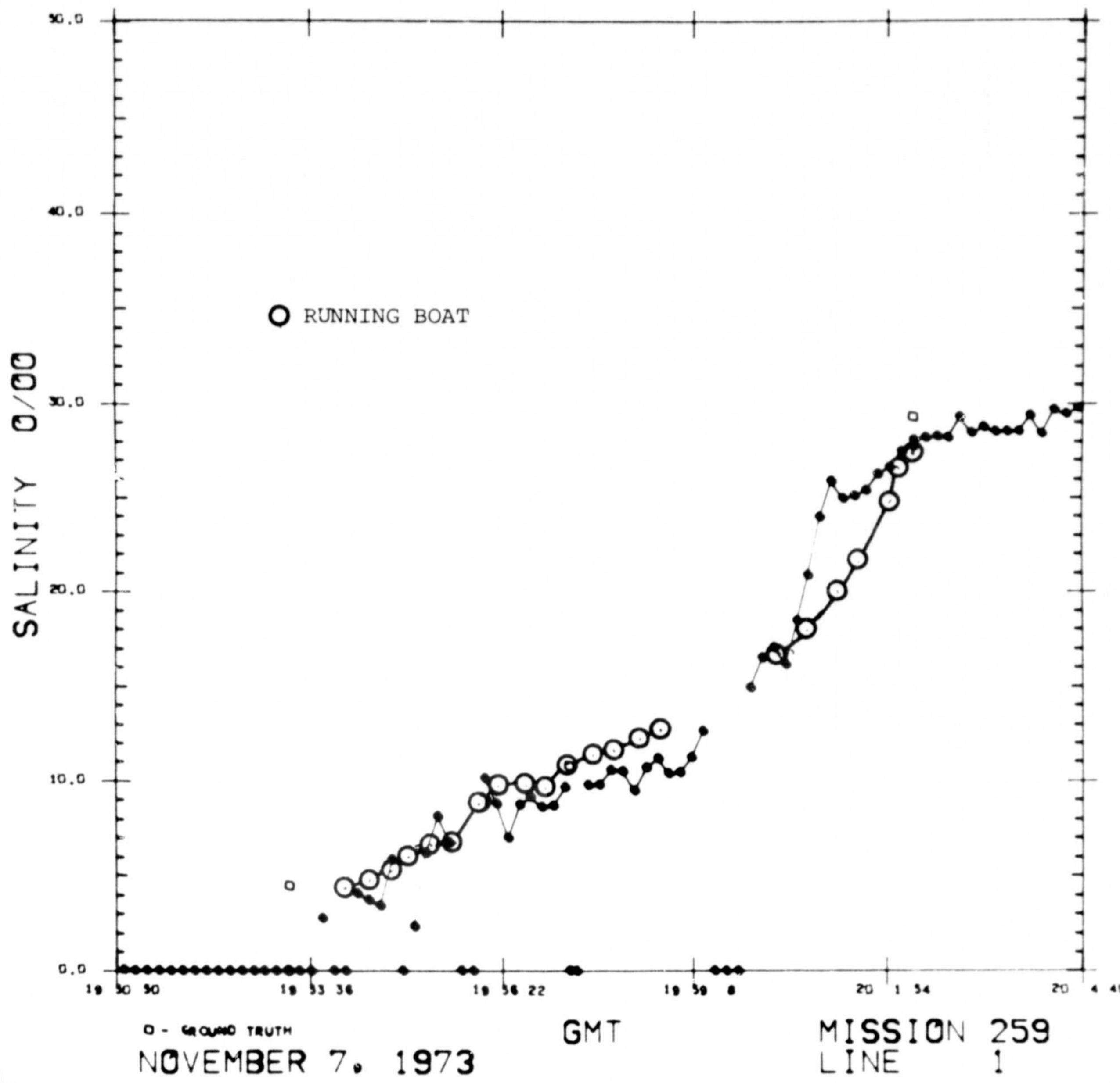

Figure 11. Remote and surface measured salinity values for run 8.

two factors, the lower sensitivity and land proximity account for the numerous poor salinity readings at the western end. There are also some zero salinity readings which occur in the line at the points when the plane overflew Grand Island and Isle au Pitre, as would be expected.

A running ground truth boat started at the eastern end of the line and proceeded along the line, making salinity and temperature measurements approximately every mile along the line. These boat positions are shown in Fig. 1. These measurements were used to evaluate the accuracy of the remote measurements. The RMS accuracy for each line and number of ground truth points used for each calculation are shown in Table 1.

RUN	NUMBER POINTS	RMS ERROR $^o/oo$
1	20	3.62
2	20	4.28
3	15	4.28
4	20	3.49
5	20	4.10
6	20	2.84
7	20	3.23
8	20	2.34

TABLE 1. RMS salinity error of each of the eight runs.

As can be seen from Fig. 1, the running boat took measurements at 22 stations. However, two of these, numbers 20 and 21 were too near Grand Island and were not used. On run 3, the PRT-5 data was unaccountably lost for part of the line and only 15 points were available. The overall RMS accuracy of the experiment was 3.56 $^{0}/oo$. This appears to be a rather poor accuracy but, it must be remembered, the low salinity end of the line contributes heavily to the error. Consider, as an alternate the RMS error over those parts of the line where the salinity was $\geq$ 10 $^{0}/oo$. The values recorded by the running boat are shown in Table 2.

Station	1	2	3	4	5	6	7	12
Salinity	27.4	26.6	24.8	21.7	19.9	18.0	16.8	12.7
Station	13	14	15	16	17	18	19	
Salinity	12.1	11.6	11.3	10.9	9.6	9.7	9.7	
Station	20	21	22	23	24	25	26	
Salinity	8.8	6.8	6.5	6.0	5.2	4.8	4.3	

TABLE 2. Salinity values at each running boat position.

The RMS error for S $\geq$ 10 can then be obtained from the ground truth stations 1 through 16. If this is done, the composite error for each line is shown in Table 3.

RUN	NUMBER POINTS	RMS ERROR
1	12	1.39
2	12	1.97
3	7	2.83
4	12	2.87
5	12	4.21
6	12	2.28
7	12	2.51
8	12	2.73

TABLE 3. RMS salinity errors for each run for salinities $\geq$ 10 ^{o}/oo.

These accuracies are considerably better, as would be expected, since the sensitivity is better for the higher salinities. The overall accuracy is 2.70 ^{o}/oo. However, the values in Table 3 do not, it is believed, reliably reflect the accuracy of the remote measurements. This is due to obtaining ground truth by a running boat. The aircraft passes directly over the three stationary boats on each run and since photography is taken along with the other data, the time of overpass over the three boats is precisely known; in addition, the data taken by these three boats is taken at exactly the time of the overpass. Unfortunately, because of various areas of shallow water, it is impossible for the running boat to stay exactly on the flight line, and even when it is overflown by the aircraft, it is not usually at the time the boat is taking one of its ground truth samples. In addition, the navigational equipment on the boat will not allow location of its position to a better accuracy than about one-quarter mile. It is also impossible to exactly locate the aircraft position versus time. Thus, for most of the running ground truth boat measurements, accurate alignment of the ground truth and remote data is difficult. In areas of rapidly changing salinity, position offset can result in a considerable salinity difference. Since in this case the salinity changes markedly along the line, these position inaccuracies undoubtedly contribute to the RMS errors calculated in Tables 1 and 3.

There is one area of particularly sharp salinity change near the east end of the line which shows in the graphs as the rapid change from salinities of about 27 $^{o}/oo$ to those of about 20 $^{o}/oo$. It is interesting to compare the ground and remote measurements in this region. These are shown on Table 4.

BOAT POSITION

	1	2	3	4	5	6	7
RUN 1	27.9	28.0	27.6	22.6	20.9	19.4	18.8
2	28.1	26.8	26.6	25.6	23.6	17.6	16.2
3	--	--	--	--	--	18.8	15.6
4	27.9	27.9	27.9	26.9	26.2	20.5	16.1
5	28.6	27.9	28.0	27.4	25.3	19.0	17.4
6	27.7	27.1	26.5	25.2	24.6	19.7	16.4
7	28	27.6	26.8	25.6	25.3	20.9	17.3
8	27.8	27.0	26.6	25.3	25.4	20.9	17.1
AVERAGE	28.0	27.5	27.1	25.5	24.5	19.6	16.9
GROUND TRUTH	27.4	26.6	24.8	21.7	19.9	18.0	16.8
DIFFERENCE	.6	.9	2.3	3.8	4.6	1.6	.1

TABLE 4. Remote and ground truth salinities at boat positions 1 through 7 and difference between ground truth and average remote measured values for each boat position.

On both sides of the abrupt salinity drop the difference between the running boat salinities and the average of the remote salinities is quite small, while in the area of sharp salinity change, which is near boat positions 4 and 5 the difference is quite marked.

It is thus reasonable to suspect that the difference might be due to inaccuracies in the boat and aircraft positions. This conclusion is somewhat supported by an examination of Figs. 4 through 11 in which the remote data experiences the same sharp drop in salinity that the ground truth data does. If part of the data in this area is dropped from consideration, say points 4 and 5 and another accuracy calculation made, the results for the salinities $\geq$ 10 $^{o}/oo$ are shown in Table 5.

RUN	NUMBER POINTS	RMS ERROR
1	10	1.47
2	10	1.32
3	7	2.83
4	10	1.75
5	10	3.89
6	10	[illegible]
7	10	1.75
8	10	1.54

TABLE 5. RMS deviation between remote and ground truth measurements for ground truth salinities $\geq$ 10 $^{o}/oo$ and points 4 and 5 dropped from consideration.

These values are much better; the composite accuracy is 2.16 $^{0}/oo$ which is respectable. Of course, this value cannot be taken as the accuracy of the remote measurement since the worst two values have been removed. However, removal of points 4 and 5 is done with some cause and the resulting values in Table 5 should be treated with some consideration.

It is interesting to note that the values in Table 5 are similar except for the large errors in runs 3 and 5. Line 5 was examined in more detail to see if the reason for its large error could be determined. As mentioned earlier during this experiment, there were patches of fog which made sighting of the three stationary boats difficult and at times maneuvering was necessary to pass directly over them. Examination of the sun glitter patterns in the photography of line 5 showed some very sharp aircraft turns. These turns, with their resulting aircraft tilt, change the antenna pointing angle and hence the measured radiometric temperature. It was discovered that some of the salinities on line 5 were calculated at places where the aircraft was turning and that the large errors in line 5 are undoubtedly due to these measurements. These values are not going to be dropped and accuracy calculations made; if we continue in the same vein that resulted in Table 5, there will probably be eventually no points at all for accuracy calculations. However, what has been demonstrated is the difficulty in evaluating the accuracy of the remote sensing technique. Not only must the aircraft (or satellite) position be known precisely, the fidelity of the ground truth must be unquestionable.

There are some points at which the remote measurement accuracy can be evaluated, namely at the three stationary ground truth boats which are directly overflown and hence, precisely located in time. Unfortunately, boat 1 is in very fresh water where the sensitivity is not good. The salinity at boat two is 10.9 $^{0}/oo$ and at boat three 27.4 $^{0}/oo$. One of the runs over boat 3 was used for calibration so it was not used for error analysis. If the other passes are listed, the results are as shown in Table 6.

RUN	STATION 2	STATION 3
1	9.4 $^{0}/oo$	Calibration
2	8.5	28.2 $^{0}/oo$
3	4.2	No data
4	10.0	27.7
5	3.8	28.4
6	8.6	27.8
7	6.8	28.3
8	0.0	28.1

TABLE 6. Remotely measured salinity values over stationary boats 2 and 3.

The composite accuracy over station 3 is .7 $^{o}/oo$, which is encouraging and 5.5 $^{o}/oo$ over station 2, which is very discouraging.

Station 3 is not near land, and since the salinity at the point is the same as that where the radiometer was calibrated, good accuracies would be expected. The values over station 2 show a wide variation and for the same reasons considered above, it is not felt they offer a reliable estimate of the accuracy of the remote sensing techniques. It is interesting to note that runs 1, 2, and 4 show good accuracies. The low value from run 5 is because this is the boat over which the quick turn was made which is discussed above. The reasons for the poor readings on the other runs is presently not understood. It is also interesting to note that at station 2 all values which differ markedly from the correct salinity are low, which might suggest the occurrence of some outside mechanism other than instrument accuracy.

The relative accuracy, or precision, of the remote measured salinity values can be determined without recourse to the ground truth, by calculating the deviation between the eight runs at various points along the flight line. This was done at the positions 1 through 16 shown in Figure 1 where the water salinity was greater than 10 $^{o}/oo$. The deviation at each of the 12 positions was calculated from the following formula:

$$\hat{\sigma}_j = \left(\frac{1}{N_j - 1} \sum_{i=1}^{N_j} x_{ij}^2 - \bar{x}_j^2 \right)^{1/2}$$

$\hat{\sigma}_j$ - standard deviation at j_{th} point

N_j - number of data points (runs) at j_{th} point.

x_{ij} - remotely measured salinity on i_{th} run at the j_{th} point.

$\bar{x}_j$ - sample mean at j_{th} point.

The values obtained are shown in Table 7.

Position	1	2	3	4	5	6	7	12	13	14	15	16
$\bar{x}_j$	28 $^o/oo$	27.6	27.2	25.6	24.6	19.6	16.9	10.8	10.6	10.1	10.8	8.2
$\hat{\sigma}_j$	.3	.5	.7	1.6	1.8	1.2	1.0	.5	.8	.9	4.0	1.8

TABLE 7. Estimated means and standard deviations of the remotely measured values for the eight runs at positions 1 through 16.

The estimated standard deviations are quite good, the average for the twelve points being 1.3 $^o/oo$. Part of this error is due to the inability to exactly locate the aircraft's position and errors due to aircraft banking. The large estimated standard deviation at boat position 15 is undoubtedly due to the error induced by banking. In addition to the above mentioned sources of error, Table 8 reflects the repeatability and sensitivity of the measurements for salinity values $\geq$ 10 $^o/oo$. If the remote measurement technique is assumed to be an unbiased statistical estimator of water salinity, then Table 7 indicates the measurement accuracy, since the moving ground truth boat has been eliminated, although the errors due to uncertainties in the aircraft location and roll still cloud the results somewhat.

An attempt was also made to remove the radar interference spikes from the 21 cm data. To do this, a section of the radiometer data suffering from interference was Fourier transformed. The resulting power spectrum clearly showed the fundamental and first three harmonics of the radar pulse interference. The fundamental and the three harmonics were subsequently removed from all the original data. Water salinities were then recalculated from the corrected data. The RMS salinity error for each of the eight runs is shown in Table 8.

RUN	NUMBER POINTS	RMS ERROR
1	20	3.58
2	20	3.71
3	15	4.91
4	20	3.38
5	20	4.05
6	20	2.92
7	30	2.99
8	30	3.51

TABLE 8. RMS salinity errors for each of eight runs with interference from radar pulses removed.

These values should be compared to those in Table 1. Comparisons of the two tables indicates some difference, but nothing substantially in favor of the values in the later table, and apparently, the radar interference does not significantly affect the remote measurement technique.

SUMMARY AND CONCLUSIONS

The remote measurements were not very good for salinities below 10 $^{o}/oo$; this is to be expected because of the fairly low water temperature (20°C), the proximity of land areas, and the inherent lack of sensitivity of the technique in low salinity environments. The accuracies were quite good for areas where the water salinity was greater than 10 $^{o}/oo$; it is believed from examination of the calculations that accuracies of 1-2 $^{o}/oo$ were obtained. Furthermore, it is believed that the measurement technique is ready for operational use and capable of 1-2 $^{o}/oo$ accuracies under the following conditions.

1. Ground truth calibrations about every hour at locations well removed from land contamination (a mile or two).
2. Operation in warm (20-30°C) fairly saline (above 5-10 $^{o}/oo$) water with decreasing accuracy expected for colder or fresher water. The low salinity limit of the technique is not exactly specified because it is temperature dependent.
3. Insurance that all data used was taken when the aircraft was flying level.

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