REMOTE SENSING OF SALINITY

By Gary C. Thomann, NASA/JSC, Earth Resources Laboratory
Bay St. Louis, Mississippi

ABSTRACT

The complex dielectric constant of sea water is a function of salinity at 21 cm wavelength, and sea water salinity can be determined by a measurement of emissivity at 21 cm along with a measurement of thermodynamic temperature. Three aircraft and one helicopter experiments using two different 21 cm radiometers were conducted under different salinity and temperature conditions. Single or multiple ground truth measurements were used to calibrate the data in each experiment. RMS deviations of between 2 and 3°/oo were found between remote and ground truth boat measurements. Part of this deviation is attributed to position mislocation between the aircraft and boats. It is inferred from these experiments that accuracies of 1 to 2°/oo are possible with a single surface calibration point necessary only every two hours if the following conditions are met--water temperatures above 20° C, salinities above 10°/oo, and level plane flight. More frequent calibration, constraint of the aircraft's orientation to the same as it was during calibration, and two point calibration (at a high and low salinity level) rather than single point calibration may give even better accuracies in some instances.

INTRODUCTION

In a previous paper (Thomann 1973), the variation of the dielectric constant of sea water versus salinity at 21 cm wavelength was investigated. The remote radiometric and ground truth calibration measurements necessary to remotely determine sea water surface salinity were discussed, along with the results of some initial aircraft experiments. Perturbating influences, which limit the salinity measurement accuracy which can be attained with this technique were also covered. This report presents the results of several additional aircraft and helicopter experiments which have been done since 1973. A very brief description of the measurement technique will be given before the experiments are discussed. A reader wishing a more detailed account of the technique itself can consult the above reference.

The dielectric constant of a sea water solution can be approximated by a Debye equation

$$\varepsilon_c = \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\lambda_s^{1-\alpha}/\lambda} + \varepsilon_\infty + \sigma / i\omega\varepsilon_o \qquad (1)$$

in which ε_c is the complex dielectric constant of the solution. ε_s is its low frequency value, and ε_∞ its high frequency value (both real). λ_s is the relaxation wavelength, α is a spread parameter used to make slight adjustments to the value of ε_c, λ and ω are wavelength and radian frequency, σ is the ionic conductivity of the solution, and ε_0 is the permittivity of space. λ_s, ε_s, σ, and α are functions of salinity and temperature.

For a complex solution such as sea water, the parameters (except for the conductivity σ) have not been known as a function of salinity and temperature and values obtained from a NaCl solution are usually substituted. Since the salt content of normal sea water is 78% NaCl this substitution results in a fairly accurate approximation, especially since the sea water conductivity, which is known, has the major effect upon the change in ε_c as salinity and temperature vary. In our experiments, the actual conductivity of sea water is used and values derived from NaCl solutions are used for the other parameters. Recently, direct measurements of the dielectric constant of sea water have been made (Ho, 1974), but these results have not been incorporated into the Earth Resources Laboratory (ERL) equations.

The last term in Eq. (1) determines the frequency range in which the salinity of sea water can be measured. At frequencies above about 3 GHz, the term is inconsequential (for this purpose). As wavelengths become longer, another factor enters; very large antennas are required to obtain any pointing ability. A radio astronomy band exists from 1.400 to 1.427 GHz, which is in the required frequency range and is also fairly free from man-made radiation. As a result, it is a good choice for remote salinity sensing and is used in our experiments. At this frequency, an antenna about one meter square is required to obtain a 15° half power bandwidth.

The apparent temperature of the water at 21 cm wavelength can be determined from its emissivity for any thermodynamic water temperature. Fig. 1 shows the variation of 21 cm apparent temperature versus salinity for several water temperatures. The emissivity used to construct this figure was derived from the dielectric constant using the Fresnel equation for reflection from a plane surface. The possible salinity measurement accuracies can be determined from this graph; the best accuracies are obtained for higher salinities and higher temperatures with little sensitivity available at salinities below 10‰ except perhaps at the higher water temperatures. A reasonable goal turns out to be a 1-2‰ accuracy measurement for salinities above 10‰ and water temperatures above 20°C.

A remote system for measuring salinity requires a measurement of apparent temperature at 21 cm wavelength (or some nearby wavelength) and a measurement of the thermodynamic temperature. This second measurement can be done in any region where the dielectric constant is known; in the ERL experiments the measurements are done at 8-14 μm, but measurements in other regions could be done as well.

Because of the 1-2‰ sensitivity of this technique, it would appear doubtful to be of use in the deep oceans where usually only small salinity changes occur. For anomalous larger changes, this would not necessarily be the case. Because of the large salinity changes which normally occur along coasts, the technique is more suited to these regions. Since land is radiometrically much hotter than water at 21 cm wavelength and because antenna beamwidths are limited by the combination of long wavelength and feasible antenna size, low altitudes are usually dictated. Most ERL experiments to date have been flown at 800 ft. The 21 cm antenna is pointed from 5 to 15° forward of vertical incidence in the ERL experiments. Fig. 1 is for a 9.3° incidence angle, which happened to be the angle used in one of the earlier ERL experiments. Larger sensitivities actually exist for larger incidence angles. For instance, at 30°C water temperature, the difference in 21 cm apparent temperature between water of 0‰ salinity and 35‰ salinity is 30°K for a 55° incidence angle, and is 25°K for a 30° incidence angle. For zero degree incidence angle, the difference for the same salinity range is only 23°K. However, at the larger incidence angles, the variation of 21 cm apparent temperature with antenna incidence angle is much greater than at the smaller angles and variations in the pointing angle of the antenna can cause significant errors. As an example, at a supposed 30° incidence angle, a pointing angle error of one degree will cause a salinity calculation error of 1.3‰. At 10° incidence angle, the same error will effect the salinity by a .4‰ and at 5° the error will be only .2‰.

Another problem with large incidence angles is that the area being sensed is not directly under the aircraft, which is the area most other instruments sense. For these reasons, temperature measurements for salinity are usually not made at extreme incidence angles.

For a different reason, incidence angles of zero degrees are also usually not used. At zero degrees, the reflection of the hot aircraft off the sea surface would be seen by the 21 cm antenna. A large plane with, for instance, a wingspan of 100 feet might raise the apparent temperature by about 3°K if the antenna had a 15° beamwidth and the aircraft altitude was 800 ft. If the reflection of the plane could be considered to emanate from a large number of independent statistical emitters of comparable amplitude on the surface of the sea (much as many area extensive targets are treated in certain types of scattering problems) then the post detection bandwidth provides enough averaging to allow only a small variance and the 3°K offset would be removed in the calibration. However, it is not certain that the aircraft's reflection behaves in this manner. Random motions of aircraft orientation and the non-smooth surface of the sea might cause variations of a slow enough nature that they would not be filtered. Because of this possible reflection problem, the antenna is tilted far enough forward (in our case 5-15° angles have been tried) to remove most of the aircraft reflection from the antenna in the ERL experiments. With a smaller aircraft, the reflection would not be as severe and operation directly under the plane might be optimum.

The vertical component of the upwelling radiation is the only component sensed for salinity calculations, because the horizontal component is much more susceptible to variation with wind speed than the vertical (Paris, 1971). For this reason, Fig. 1 shows variation for vertically polarized radiation.

Some superfluous radiation always enters the radiometers; galactic radiation and solar radiation reflecting off the sea surface are the main outside sources of error for the 21 cm measurement, while the atmosphere is the main problem with measurements in the thermal infrared. Instrument offsets are always a problem in both bands. The errors in the radiometric measurements are corrected from one or more ground truth measurements. A simple offset correction obtained from one position usually suffices for the 8 - 14 μm measurement. An offset correction will also suffice for the 21 cm measurement if the gain of the 21 cm radiometer is trusted, since the other errors appear mainly as an offset. If the radiometer gain is not trusted, which was the case during the first ERL experiments, then a two-point correction is required which involves both an additive and multiplicative adjustment to the data. During later ERL experiments, only a single offset correction was used for the 21 cm data.

After corrections are applied to the data from the calibration points, the raw data is converted to salinity by matching the measured emissivity at 21 cm and measured thermodynamic temperature to a matching salinity.

Flight Line for Aircraft Experiments

The flight line shown in Fig. 2 was selected for the aircraft experiments. This line is off the Gulf Coast of Louisiana and Mississippi and extends at the west end, from waters near Lake Pontchartrain where considerable fresh water flows into the Gulf, eastward into the Gulf outside the barrier islands where the salinity more closely approaches that of oceanic values. Because most of the fresh water input in this area of the Gulf is at the western end of the line, and because of the mixing influence of the tides, there usually exists a fairly constant salinity gradient along the line, although the absolute salinity value may vary quite markedly according to recent precipitation and river level conditions. Except for the presence of quite a few land masses near the western end of the line, this line was originally thought to be ideal for testing. Unexpectedly, the fairly constant salinity gradient has caused problems, which will be discussed below.

August 25, 1972 Aircraft Experiment

On this date, the line in Fig. 2 was flown six times, three in each direction by the NP3A NASA Earth Resources aircraft. The altitude was 800 ft (244m). The antenna incidence angle was 10°; only vertical polarization radiation was received. The experiment was flown between 1645 and 1800 CDT. The L-band channel of the Multi-Frequency Microwave Radiometer (MFMR) a four channel NASA radiometer, measured the apparent temperature of the sea surface at 21 cm and a PRT-5 measured apparent temperature at 8-14 μm. Surface salinities varied from about 10‰ at the western end of the line to about 30‰ at the eastern end. These salinities are somewhat high for this line and are due to the dry conditions which had been experienced during the time preceding the experiment. Stationary boats were located at the three circled positions shown in Fig. 2. On each run the aircraft flew directly over each of these three boats to provide time markers on the photography which was taken coincidentally with the radiometric data. A moving boat traversed the line during the experiment and took ground measurements at approximately one mile intervals. The sampling positions were located as closely as possible using a LORAN system. The running boat was to traverse the entire line, but darkness halted it at position 17. Water temperatures were quite warm, about 30°C. In 1972, there was little confidence in the MFMR as an instrument and two ground truth points were used to correct each run of the 21 cm data before salinity processing. That is, both a translation and a rotation of the data plotted two dimensionally as amplitude versus time was made.

Fig. 3 shows the remotely measured salinity for each of the six runs, the salinities measured by the three stationary boats and the salinity values measured by the moving boat. Stationary boats 1 and 3 were used to calibrate each remote measurement run individually. The accuracy obtained using stationary boat 2 and the values from the moving boat for error calculation was about 2‰. Processing was also done using the scale factors calculated for line 3 to process data from the complete mission. The accuracy in this case was about 2.5‰. A more complete discussion of this experiment is given by Thomann (1973a).

November 7, 1973 Experiment

Experiments previous to the August 25, 1972 experiment had shown that MFMR yielded quite variable results and the operation of the radiometer during the August 25 experiment was much better than had been experienced before. For additional information on previous results obtained from the radiometer see

Thomann (1973). Previous to the November 7 experiment, ERL requested that the L-Band channel of the MFMR be upgraded to improve its sensitivity and stability. The instrument was overhauled by Johnson Space Center engineers. Improvements included a new antenna, and improvement of the receiver electronics, the noise reference sources and the calibration procedures. The improvements to the L-band channel of the MFMR are documented by Reid (1973).

On November 7, the line, shown again in Fig. 4, was flown eight times, four times in each direction at an altitude of 800 ft. (244 m). The antenna was pointed 15° forward of vertical; only the vertical component of radiation was received. The PRT-5 was used to measure water temperature. The experiment started at 1130 and ended at 1400 CST. Three stationary boats were located at the positions shown in Fig. 4. A moving boat took ground measurements at the positions 1-26; the measurements at positions 20 and 21 were later thrown out because they were too close to Grand Island, a small grass island and the 21 cm data was contaminated at these points. The water temperature at the time of the experiment was about 20°C, which is near the lower limit for effective remote measurement of salinity, so reduced sensitivity could be expected and very poor performance in the 0 to 10^{o}/oo range could be expected.

More confidence in the MFMR existed after the modifications and for this experiment only an offset was added to the 21 cm data. This offset was calculated from a measurement at stationary boat 3 as the NP3A passed over it on run 1. The remotely measured values of salinity, the measurements at the stationary boats, and the measurements taken by the moving boat are shown in Fig.'s 5 - 8 for runs 1, 4, 6, and 8, which are representative of the eight runs. By the time of this experiment, a computer program had been written to generate the graphs instead of hand drawing them as was previously done. All information except the position and measured salinity values obtained by the running boat are computer plotted. The moving boat information was still plotted by hand.

The overall RMS accuracy for the experiment was 3.6^{o}/oo, which was at first glance disappointing. However, much of the error occurs along the parts of the line where the salinity is low and poor accuracies would be expected. In addition, it is believed that some land interference may be occurring along the western end of the line, which would cause the numerous zero salinity readings seen in Fig.'s 5 - 8. If the accuracy is calculated only along the section of the line where the salinity was 10^{o}/oo, the composite accuracy is 2.7^{o}/oo, which is considerably better.

One problem in calculating the accuracy of the remote measurements is uncertainties in the aircraft position. It is always impossible to locate exactly the position of the plane with time. Internal navigation systems are not as accurate as required and photography only provides time-marks at landfalls and over the stationary boats. Also, it is impossible to locate the position at which the moving boat made measurements with an average accuracy much better than about a quarter of a mile. Along a line with a constantly changing salinity, the result is that each mislocation between the aircraft and ground truth position contributes (statistically, at least) to the calculated RMS error. One particular place during this experiment where such a possible discrepancy can be noticed is the sharp drop in salinity from about 30^{o}/oo to about 20^{o}/oo which can be seen in the figures. In this area there is a marked difference in the remote and ground truth salinity even though the salinity variation follows the same pattern. This marked difference could be caused by a displacement in the estimated positions of the aircraft and the boat. If this area of very rapid change is removed for the error calculations, the overall accuracy comes out to be 2.2^{o}/oo, which is respectable.

As mentioned previously, the aircraft attempts to fly directly over the stationary boats on each pass to provide time markers on the plane's location. On November 7, there was considerable fog and often some rather quick turns had to be made to pass over the boats. As discussed before, the apparent temperature of the sea surface depends upon incidence angle and the banking during turns thus resulted in a change in the remotely sensed salinity. Examination of the photography sun glint patterns were made to determine the times at which the aircraft banked; the difference between the remote and ground truth salinities at these times were examined. Large errors at these times were found, which undoubtedly contributed to the overall RMS accuracy attributed to the experiment. No attempt was made to remove that data taken at the time the plane was turning and recalculate the error. It was felt that continuation in this vein was going to eventually disqualify all data taken. It is important to point out these problems which cause errors in the remotely sensed salinity because they can often be corrected with careful planning. In this case, they arise simply because it is being attempted to evaluate the technique, and very high fidelity "truth" data is needed which will not be needed in large quantities with operational use of such a system after it has been proven.

As a final accuracy check, without recourse to the ground truth data, the remote data standard deviation was calculated at each boat position where the salinity was greater than $10^{o}/oo$. The salinity changed very little during the experiment, hence the remote measurement should be the same at each point on each run. If it is assumed that the remote measurement is an unbiased statistical estimator of the salinity, then the standard deviation can be considered to be the RMS error. The average standard deviation was $1.3^{o}/oo$, which is quite good. One contributing effect still not removed from this error figure, however, is the fact that it is impossible to precisely locate the plane on each run and hence the standard deviation was not calculated at the exact same points on each run.

Several conclusions were drawn from this experiment. The first was that it is impossible to exactly determine the remote measurement accuracy using for a test area a line with a nominally constant salinity gradient, because ground truth and aircraft location problems contribute too much intrinsic error to the experiment. The type of line that is needed for an evaluation experiment is one where the salinity changes in unit steps and stays constant between these impulse changes. Such conditions are unfortunately hard to find in natural circumstances. Another testing method would be to use a large number of stationary boats and fly directly over them using the coincident photography to determine the passover time. Unfortunately, such types of experiments are expensive.

Despite the inability to exactly determine the remote accuracy, it was felt that the experiment did provide enough accuracy data to make a definite statement about operational use of the technique. It was felt that operational remote salinity measurement with an accuracy of $1 - 2^{o}/oo$ was possible if the following conditions were observed:

1. Ground truth calibrations about every two hours at locations well removed from land contamination (a mile or two).

2. Operation in warm (20-30°C) fairly saline (above $5\text{-}10^{o}/oo$) 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.

If desired, a more detailed discussion of the November experiment is given by Thomann (1975).

June 4, 1974 Aircraft Experiment

The June experiment was conducted virtually identically to the one that preceding November. Unfortunately, this experiment was conducted before the data from the November experiment was processed, so the same measurement difficulties are inherent in the experiment, i.e., the problems of plane and boat position alignment and aircraft banking were still experienced. In addition, there was a considerable overall salinity change in the test area during the course of the experiment which adds a further error to the remote salinity accuracy determination. The aircraft takes several measurements at each point, while the moving boat has time during the experiment to run the line only once and the values it measures must be used during the entire time of the experiment. As a result, ground truth taken by the moving boat gradually loses its fidelity for evaluating the remote measurement, the loss being proportional approximately to the difference in time between the remote and aircraft measurement.

This experiment was conducted from 1630 to 1845 CDT. The flight line, the positions of the stationary boats, and the positions where measurements were taken by the moving boat are shown in Fig. 9. To demonstrate the salinity change that occurred during the experiment, the salinity dropped from 22.4^{o}/oo to 20.0^{o}/oo at stationary boat 3 during the course of the experiment, from 10.4^{o}/oo to 8.9^{o}/oo at boat 2, and from 2.3^{o}/oo to 1.8^{o}/oo at boat 1. This change was unexpected since during the previous experiments along this line the salinity change was rarely over $.1^{o}$/oo during the entire experiment.

The line shown in Fig. 9 was flown eight times, four times in each direction. The first run was from east to west, with subsequent runs in alternate directions. The incidence angle of the 21 cm antenna was 10°, with vertical polarization received. The water temperatures were warm at this time of the year, running about 30°C. The water was quite fresh, varying from virtually fresh water at the west end of the line to about 20^{o}/oo at the eastern end. The running boat started at the western end of the line at the beginning of the experiment and took measurements at positions 1-24 shown on Fig. 9. Although the seas were calm at the beginning of the experiment, surface conditions deteriorated as the experiment progressed and the moving boat was forced to quit at position 24 before the complete line was traversed. This was unfortunate since it is the eastern measurements which are most important for the experiment since this is the more saline end of the line.

Representative plots of the remotely calculated salinity, the measurements by the stationary boats and the moving boat are shown in Fig.'s 10, 11, 12, and 13, for runs 1, 4, 5 and 8. As before, the remote salinity values and the stationary boats' positions and measured salinity value are computer plotted; the positions and salinity values measured by the moving boat are hand drawn. Calibration was established at a single point, as the aircraft passed over boat 3 on run 4, which was the midpoint of the mission. The overall accuracy for the complete experiment was 3.64^{o}/oo. Most of this error occurs at the western end of the line, where the fresh water occurs and also where there are numerous land areas near the flight line. The numerous zero salinity readings occurring both during this experiment and the November 7, 1973 experiment at the western end of the flight line lead to the suspicion that with the new antenna mounted in the aircraft some side lobes exist which affect the system performance when the plane is oriented unfavorably to an adjacent land mass. Since land virtually encircles the aircraft at the western end of the line, it is not possible to tell which orientation this is. For that matter, it is also impossible to form more than a suspicion about the side lobes of the antenna since the water at the western end of the line is so fresh that little sensitivity is expected anyway. When not in the aircraft, the antenna pattern supposedly shows no anomalies, but the pattern of the antenna mounted inside the nose of an aircraft can be quite different than it exhibits on an isolated mounting.

As for the November experiment, the accuracy improves markedly when only the higher salinities are considered. For salinities greater than 9^o/oo, the overall accuracy for the eight lines is 2.3^o/oo. This error figure includes the problem of locating the aircraft and moving boat exactly, some plane banking, the fact that the overall salinity changed during the mission which degrades somewhat the measurements taken by the moving boat which are used in the error calculation, and the fact that the water was unusually fresh so even at the saline end of the line the sensitivity was not as high as it would be on other experiments involving saltier water. Statistically, it is possible that all these factors would affect the error calculation favorably, but that is extremely unlikely, and it is felt that the actual remote measurement accuracy is somewhere between 1 and 2^o/oo.

Additional examination of the accuracy calculations yields more insight into possible accuracies. The calibration was done as the plane passed over boat 3 on run 4. Runs 2, 4, 6, and 8 were all in the same direction (west to east), while runs 1, 3, 5, and 7 were all east to west. The composite accuracy for the even numbered lines for salinities greater than 9^o/oo was 1.8^o/oo, while the composite accuracy for the odd lines 2.6^o/oo. This difference in accuracies would indicate that the best results will be obtained when the aircraft is flying in the same orientation that it was in when calibration was established. This is a reasonable result since, because the radiometer antenna is not pointed directly below the aircraft, differing amounts of galactic and solar radiation will be reflected into the antenna as the aircraft changes direction. In this instance, only four lines in each direction, no general statement can be made, especially since at this time a separate calibration has not been established for the odd lines to see if a corresponding accuracy with the even lines would result. In addition, because of considerable surrounding land masses, and possible side lobes in the antenna pattern, the east to west lines may simply provide less accuracy than the west to east lines because of land contamination.

The accuracy for line 4 was the best of all runs, 1.2^o/oo, which is again a reasonable outcome since it is the closest even numbered line to the calibration time. Again, no conclusion can be drawn since individual calibrations have not been established for each line to optimize them. In any case, even individual calibration might not provide any definitive basis for conclusions since the water salinity changed during the course of the experiment and the ground truth fidelity varies with time.

It is thought that the results of this experiment support closely those already listed after the November 7 experiment, and, consequently, lend more weight to them. The additional information gathered from this experiment is an indication that for best results the plane orientation should be kept the same as it was during calibration.

HELICOPTER EXPERIMENTS

The helicopter experiments were conducted with a separate radiometer purchased by ERL. The purposes of conducting experiments with another radiometer were to see if the results obtained with the MFMR on the NP3A could be duplicated and also eventually to install this newer radiometer on a smaller aircraft which would be an easier and less expensive aircraft to use. The ERL instrument is a Dicke type null balancing radiometer. The antenna is approximately one meter square and is capable of receiving only a single linear polarization at any one time.

The radiometer antenna was mounted beneath a NASA Bell Jet Ranger helicopter with the receiver mounted within the helicopter for the experiments.

April 16, 1974 Helicopter Experiment

The line shown in Fig. 14 was flown four times, twice in each direction. The line that was used for the aircraft experiments was not used with the helicopter because the limited range of the helicopter did not allow it. The helicopter altitude was 800 ft., the antenna incidence angle was 10° forward, and vertical polarization was received. The experiment was conducted between 1430 and 1600 CDT. Three stationary boats were located at the positions shown in the figure, which the helicopter was to pass directly over on each run, and a fourth boat moved between boats 2 and 3 taking salinity and temperature measurements as close to every mile as possible. The fourth boat could not run the entire line because of areas of shallow water between boats 1 and 2.

The overall accuracy for the experiment was 1.4^{o}/oo, with the accuracy being calculated from the measurements taken by the moving boat. The same problems which existed during the aircraft experiments, i.e, the inability to exactly locate the position of the helicopter and the moving ground truth boat also occurred during this experiment, but probably had little effect upon the data because the water through which the fourth boat moved was of fairly constant salinity, varying only from about 20^{o}/oo to 15^{o}/oo. The salinity did not change significantly during the experiment. A single calibration point was established for each line, as the helicopter passed over boat 3. The salinity plots for runs 1 and 4 are shown in Fig.'s 15 and 16, respectively. It is evident from these plots that in almost every instance, as the helicopter passes over one of the stationary boats the salinity drops precipitously, which is due to the fact that the boat is radiometrically much hotter than the surrounding water and its contribution raises the perceived 21 cm temperature and hence lowers the salinity. Because of this effect, the calibration of each run was not done using the radiometric data acquired directly over boat 3, but with data acquired to one side or the other of the boat which was not contaminated. This effect did not occur during the aircraft experiments because the aircraft velocity is much higher than that of the helicopter and the long post detection averaging time used filtered out the effect of the boat. The slower helicopter is over the boat long enough for its effect to be felt even after post detection averaging.

It can also be seen from the two figures that while the instrument gain is close to correct on run 4, the gain (voltage out vs. power in) of the radiometer is markedly off on run 1. The salinity is correct at boat 3 where the calibration was done (it has to be, by definition) but is quite high as the helicopter passes boat 2 (disregarding the boat induced spike which almost certainly is correct only by coincidence) and is about 10^{o}/oo high over boat 1. The same gain function is used throughout the experiment for calculating the salinities, so it is obvious that the gain of the radiometer has drifted during the experiment. This is not alarming--the radiometer itself was still very new and could still have had minor defects inherent within it which have not yet been corrected. Also, it had only recently been installed on the rather hostile helicopter environment. The gain problem might arise simply because the instrument was not properly warmed up when the experiment started, which would account for the poor performance on run 1 and the much better gain performance on run 4. Examination of runs 2 and 3 show a slight trend in instrument performance improvement with time, but not enough to state that the warm up problem is the cause. Whatever the cause of the gain drift, if the instrument were to be operated on the helicopter permanently, it would have to be solved if single point calibration were to be used. Since the helicopter was only a temporary platform for the radiometer, no solution to the drift problem was sought. After the radiometer is installed on a small aircraft, if gain drift problems continue, they will then have to be addressed. A two-point calibration could be done on run 1 to force the salinity to be correct at both boats 3 and 1. This was not done because it is not anticipated that two point calibration will be used with this radiometer in the future. As stated above, if any gain drift problems persist after aircraft installation, they will be addressed and solved. There is also a danger in using boat 1 for a calibration point because of its close proximity to land and the possibility of contamination from land radiation. This is often a problem with two point calibration; if the calibration is to be effective, the salinities of the two points must be markedly different, and it is often difficult to find a fresh water calibration point that is not near land.

A second helicopter experiment similar to the April 16 experiment has also been done, but the plots of the remote and surface salinity were not completed in time for this paper. The accuracies obtained in this second experiment were close to those of the April 16 experiment; in addition, the gain problem was not as noticeable during this second experiment.

DISCUSSION AND SUMMARY

The results of several aircraft and helicopter experiments have been presented. In most cases, single point calibration was used, using either a single calibration point for a whole experiment, or, in the helicopter experiment outlined, a single calibration point was used for each line. For the first aircraft experiment of August 25, 1972, two point calibration was used on each line, but this was before the MFMR was rebuilt, and later experiments showed that single point calibration gave quite good results after the MFMR improvement.

In the instances where ground truth was available over a considerable salinity range, the remote accuracies usually varied from 2 to 3$^{o}/oo$. Part of this error is due to the problems of matching aircraft and ground truth boat locations, so the actual error attainable remotely has been inferred to be between 1 and 2$^{o}/oo$. Fairly consistent results were obtained using two separate radiometers, one mounted on the aircraft and the other on a helicopter. Some gain problems were noted in the radiometer on the helicopter experiments, but it is felt that these problems are due to the newness of the radiometer and the fact that it was only recently installed on the helicopter for tests. In general, it is thought that the results obtained from the experiments with the two radiometers support each other in determining the accuracies obtainable remotely. It is presently felt that the following list describes accuracies and constraints for operational use of a remote salinity measuring system in the microwave region.

1. Accuracies of 1 to 2^{o}/oo with single point calibration about every two hours.

2. Water temperature above 20°C, and salinity levels above 10^{o}/oo with reduced accuracies for lower salinity levels.

3. Insurance that all data is taken with the aircraft flying in a level position.

In addition to these listed conditions, there are other situations which are assumed will be avoided, e.g., specular reflection from the sun, heavy sea states, very large clouds, and proximity to land. The effect of these conditions are treated more fully by Thomann (1973).

Slight improvements in accuracy should be obtained with some refinements in the measurement technique, although at the present time it is not possible to estimate what degree of accuracy improvement will result from each refinement. The more constrained conditions of operation are:

1. Hold the aircraft orientation to be the same as it was when the calibration was established.

2. Calibrate the remote data more frequently than once every two hours.

3. Use two point calibration in situations where it is applicable, that is, when homogeneous areas of markedly different salinity exist which are free from land or other contaminating factors.

REFERENCES

Ho, W.W. (1974), "Measurement of the dielectric properties of sea water at 1.43 GHz," NASA CR-2458, Rockwell International Corp., Downey, Calif.

Paris, J.F. (1971), "Transfer of thermal microwaves in the atmosphere," Texas A & M University, College Station, Texas.

Reid, S. (1973), "Multifrequency microwave radiometer (MFMR) L-Band modification," Lockheed Electronics Co., Houston, Texas.

Thomann, G.C. (1973), "Remote measurement of salinity in an estuarine environment," Remote Sensing of Environment 2, 249-259.

Thomann, G.C. (1973a), "Remote measurement of salinity: repeated measurements over a single flight line near the Mississippi Sound," ERL Report No. 079, Earth Resources Laboratory, Bay St. Louis, MS.

Thomann, G.C. (1975), "Testing of a technique for remotely measuring water salinity in an estuarine environment," ERL Report No. 118, Earth Resources Laboratory, Bay St. Louis, MS.

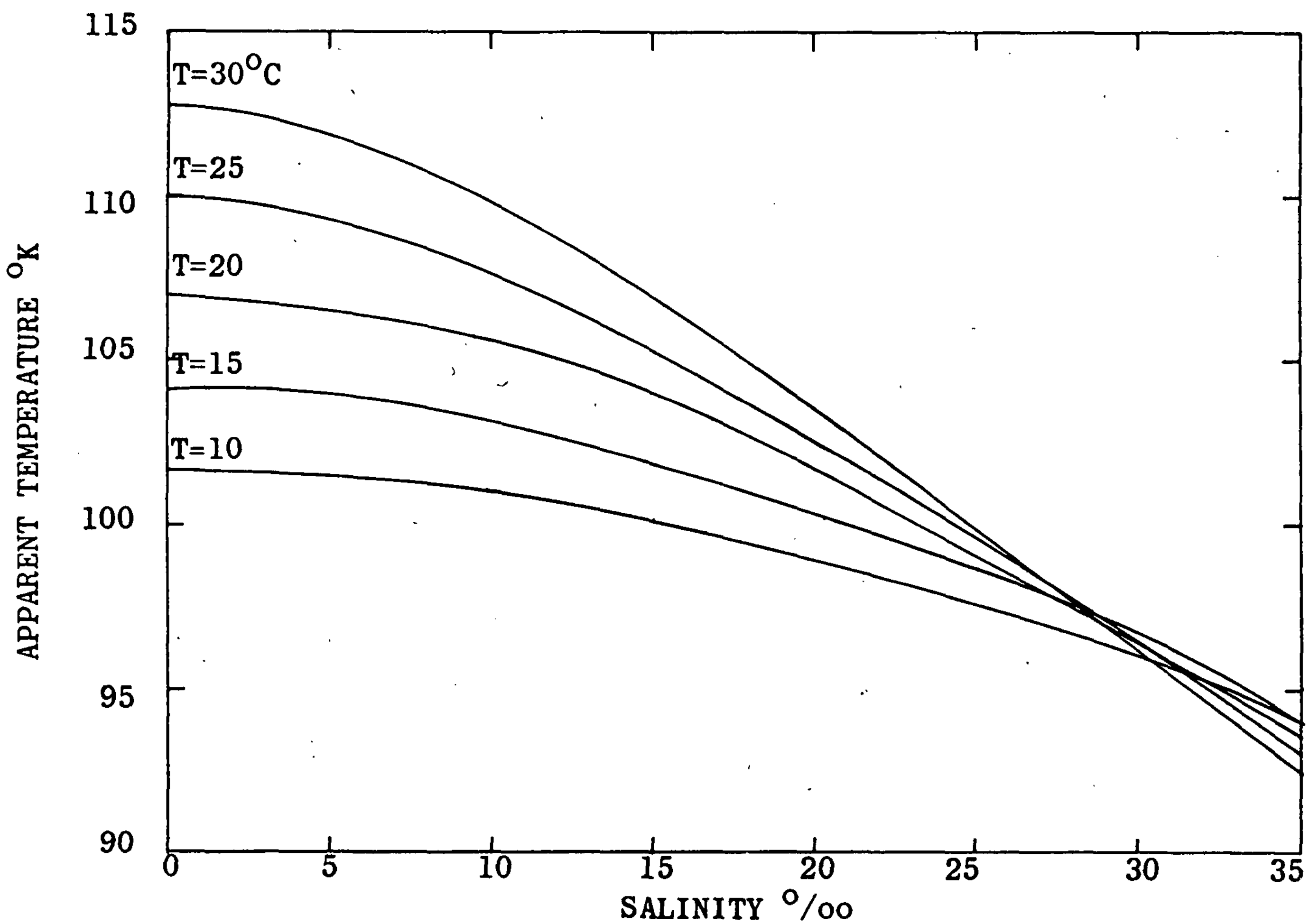


Figure 1. Apparent sea surface temperature at 21 cm wavelength as a function of salinity and water temperature--9.3° incidence angle, vertical polarization, plane sea surface.

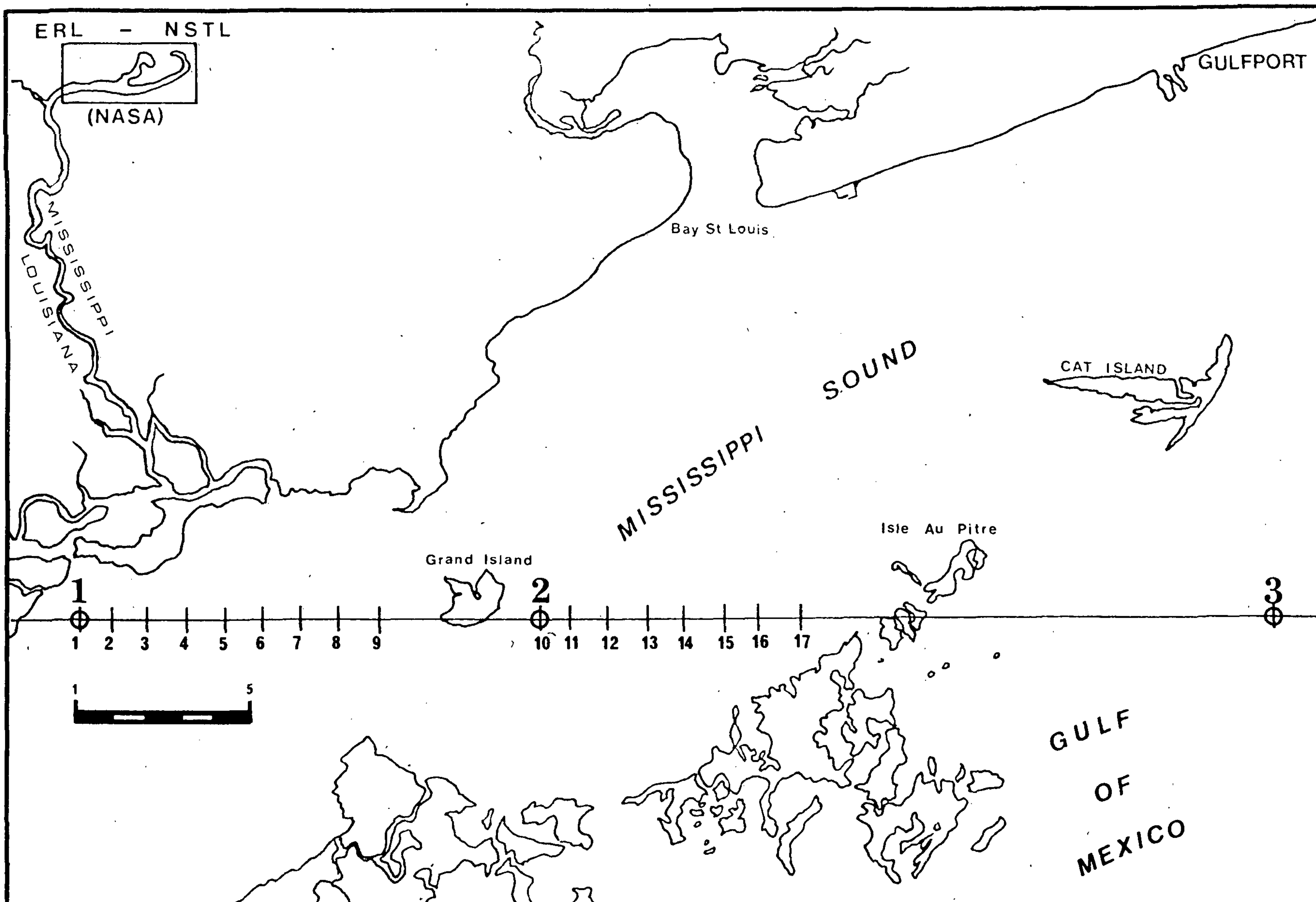


Figure 2. Flight line, stationary boat positions(circled), and moving boat measurement positions for August 25, 1972 experiment

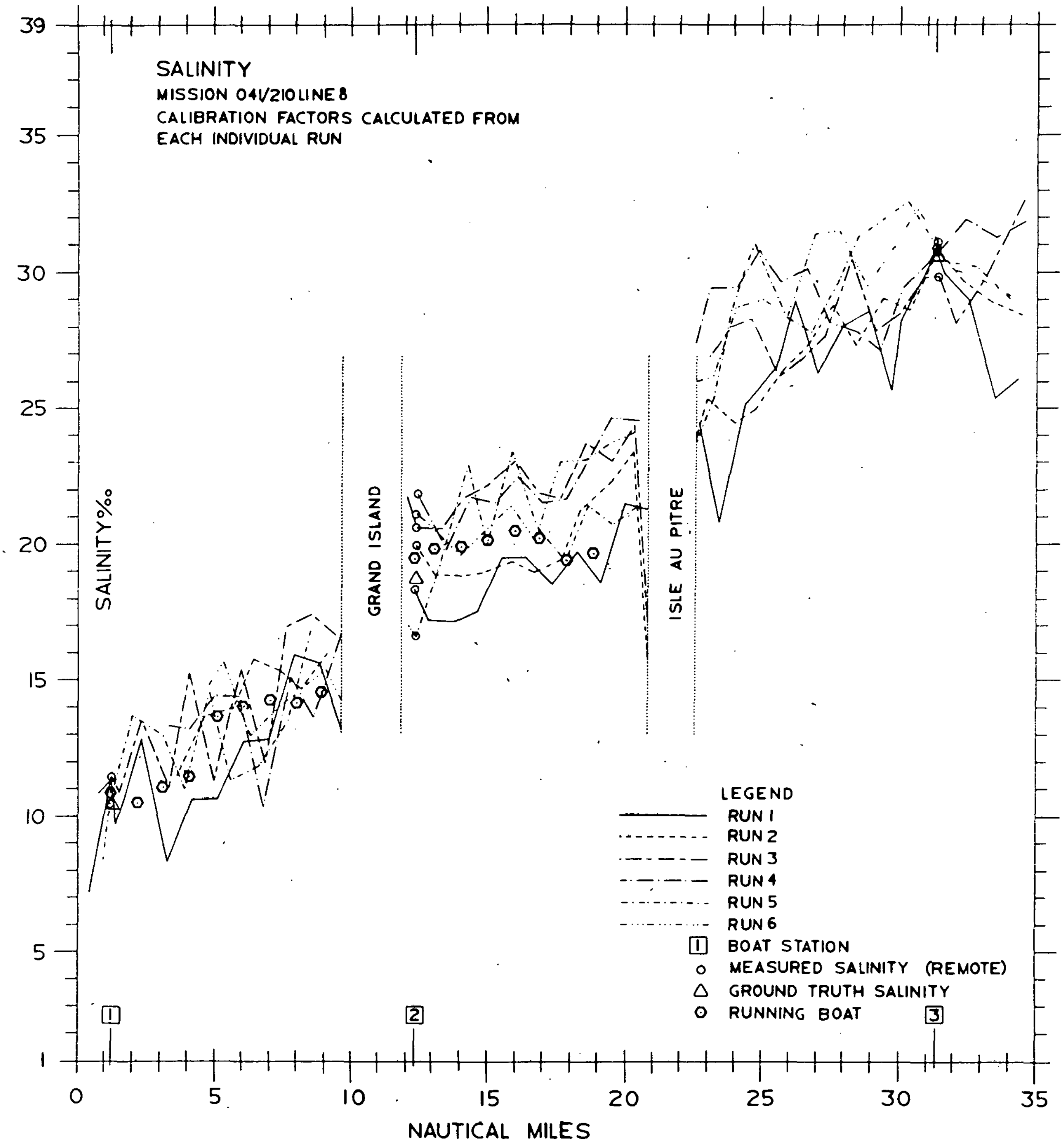


Figure 3. Remotely measured salinity values for the six runs, stationary boat and running boat measured salinity values for the August 25, 1972 experiment.

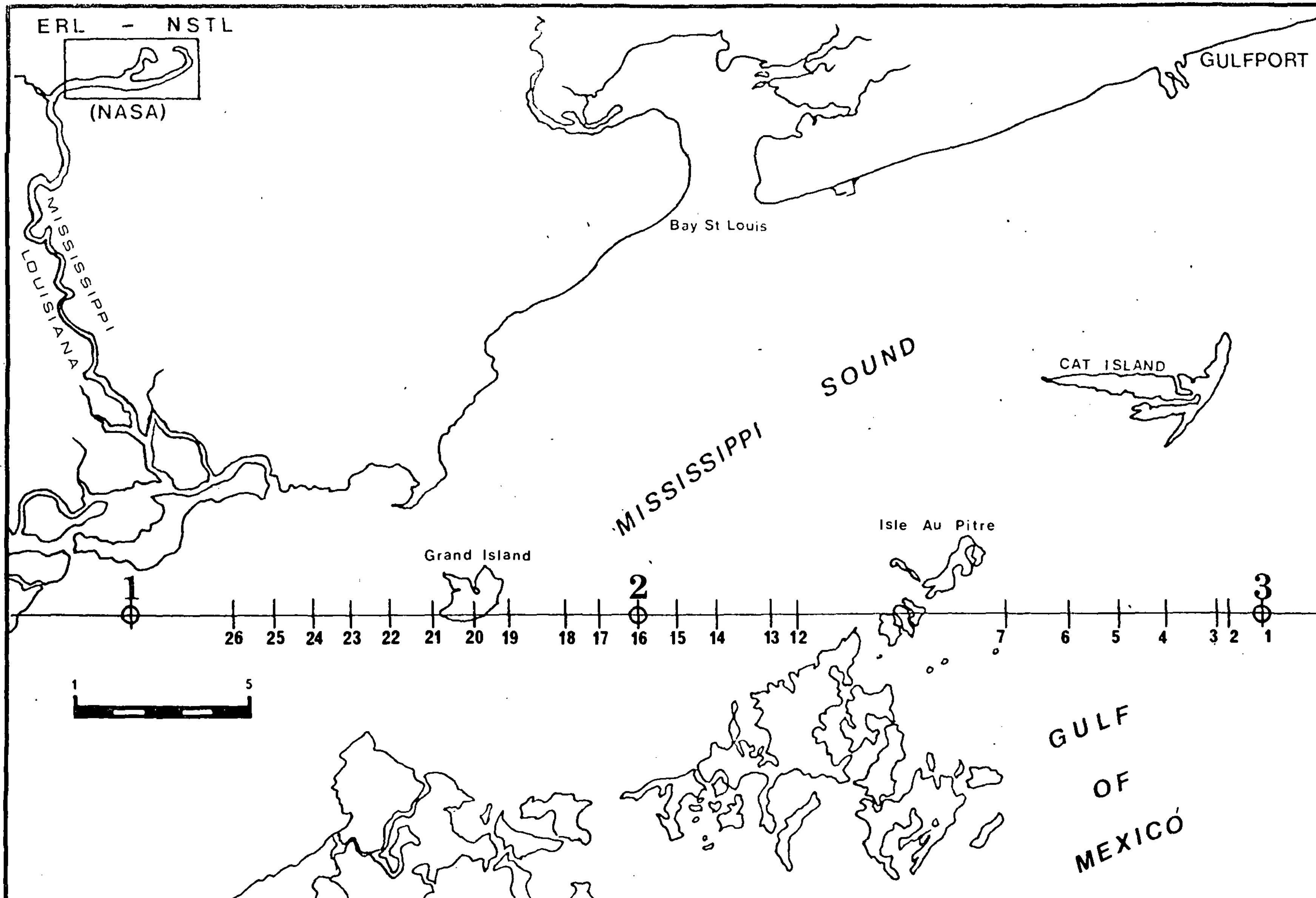


Figure 4. Flight line, stationary boat positions(circled), and moving boat measurement positions for November 7, 1973 experiment

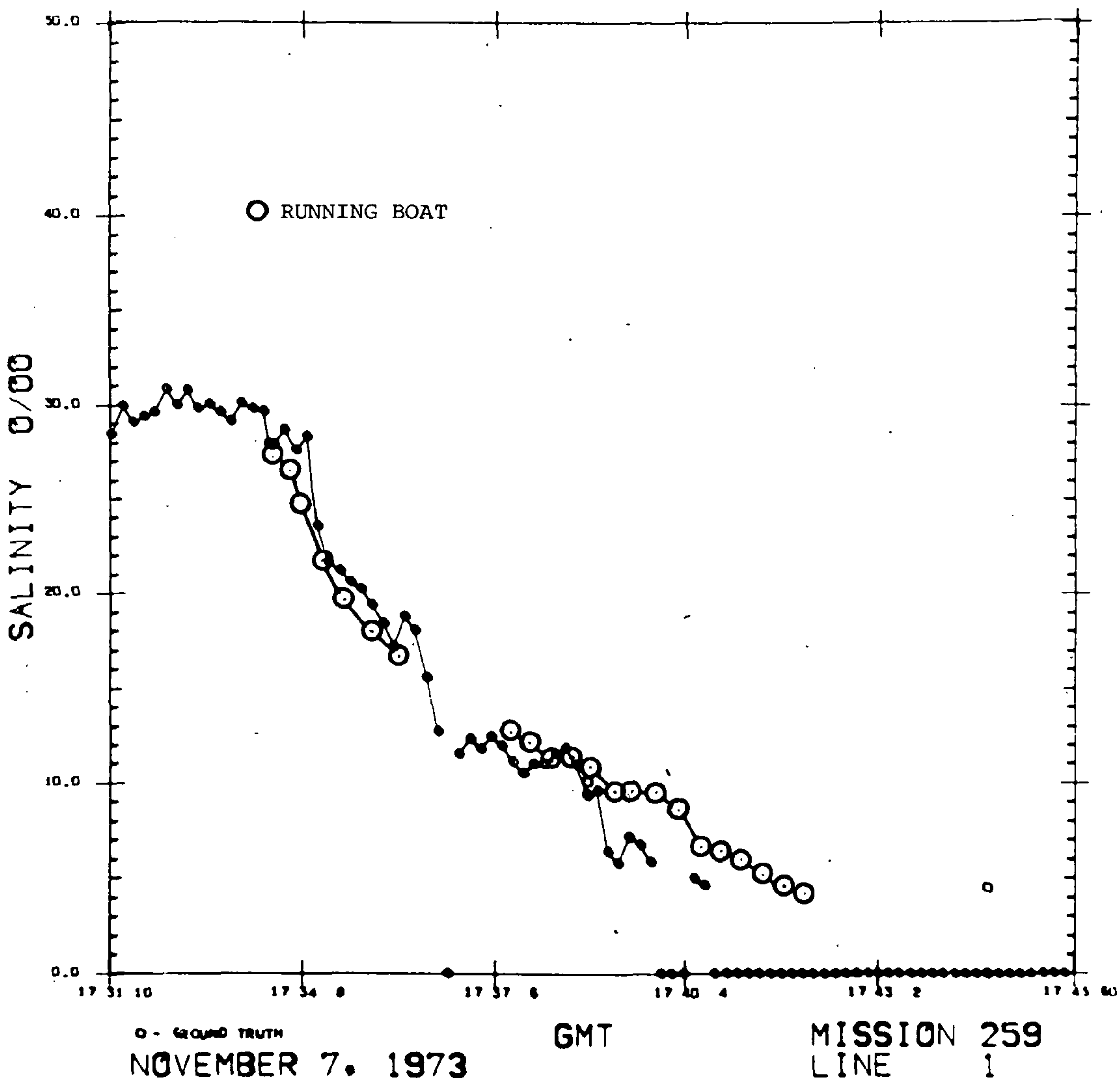


Figure 5. Remote and surface measured salinity values for run 1 of the November 7, 1973 experiment.

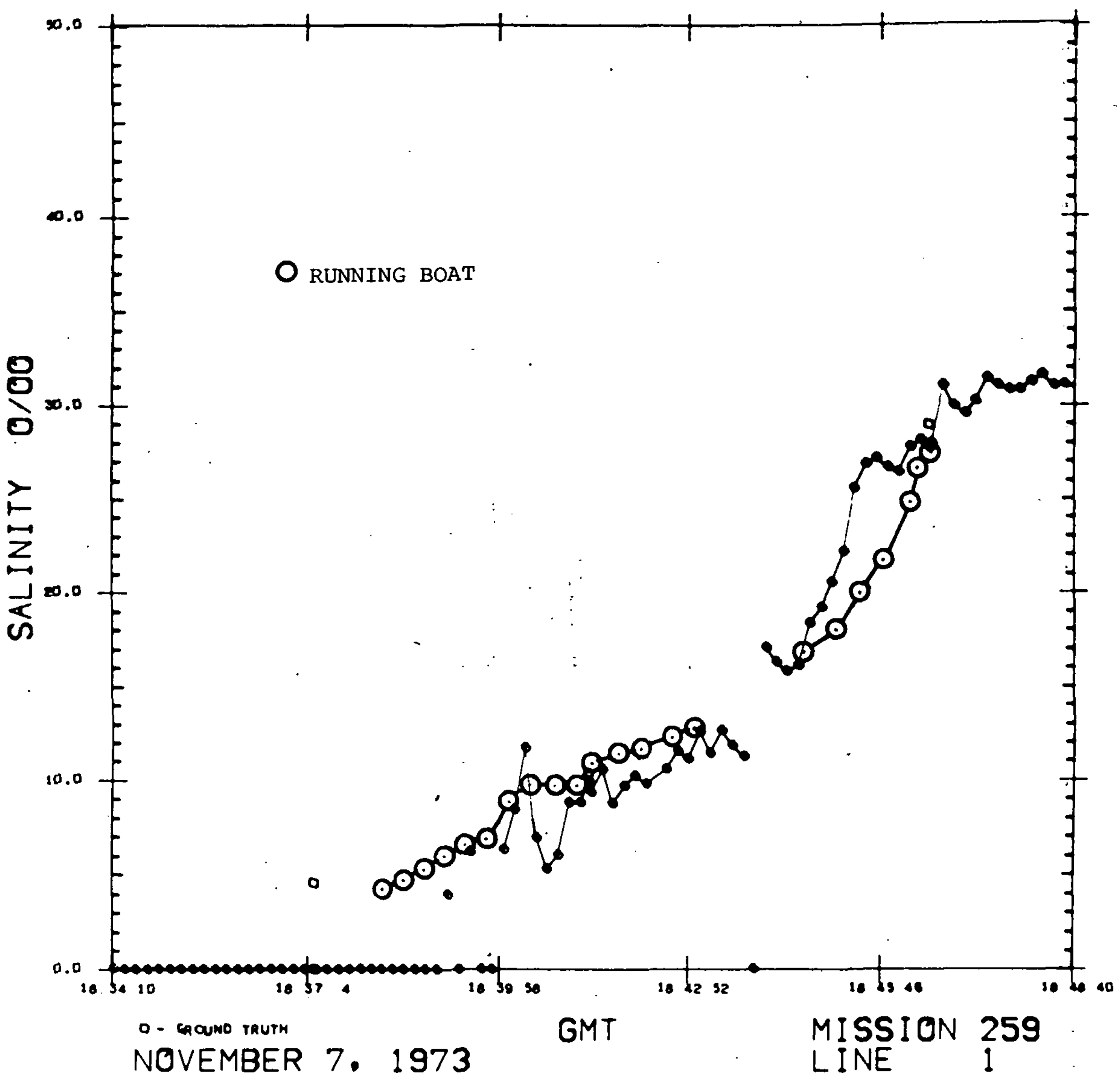


Figure 6. Remote and surface measured salinity values for run 4 of the November 7, 1973 experiment.

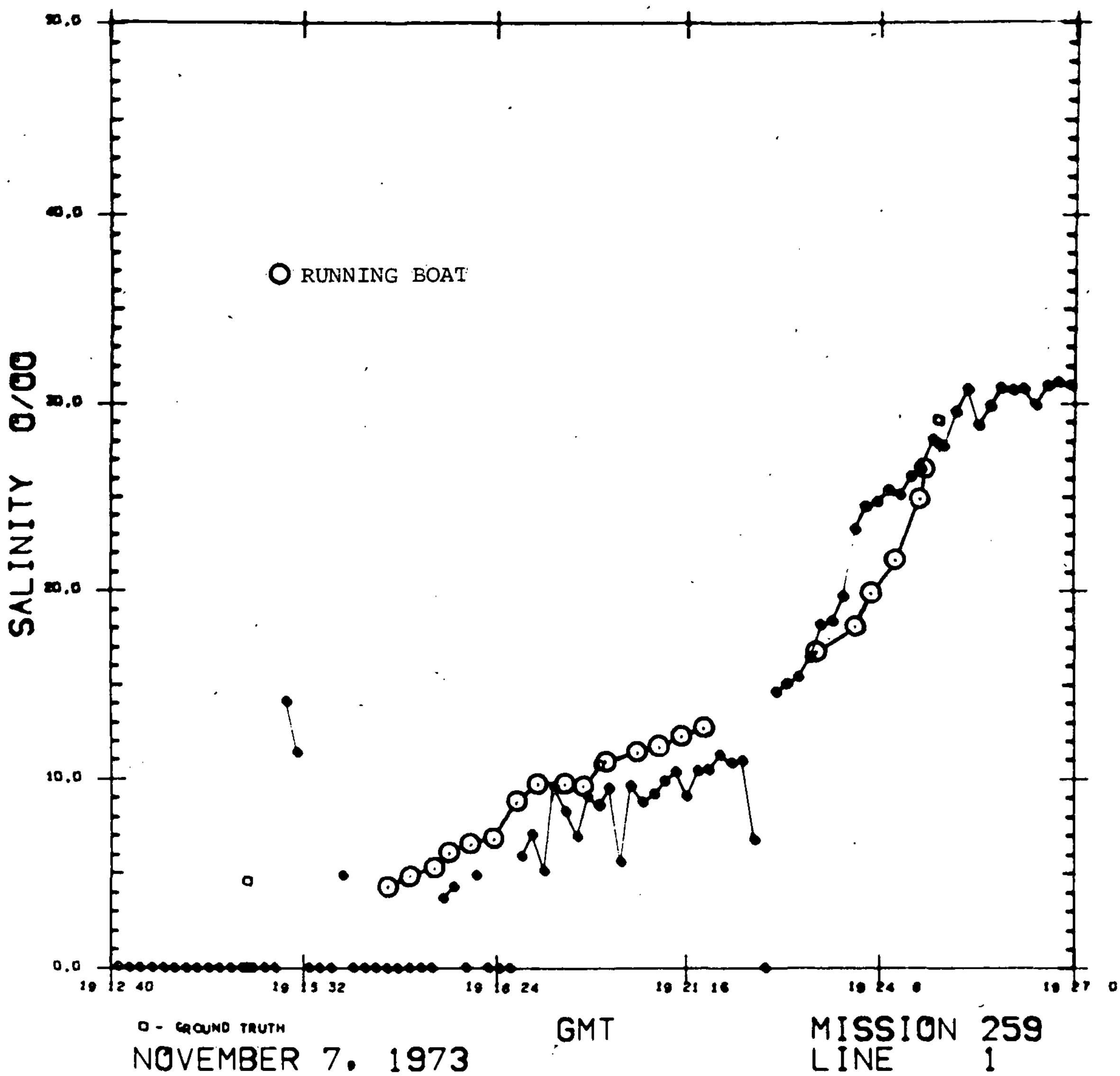


Figure 7. Remote and surface measured salinity values for run 6 of the November 7, 1973 experiment.

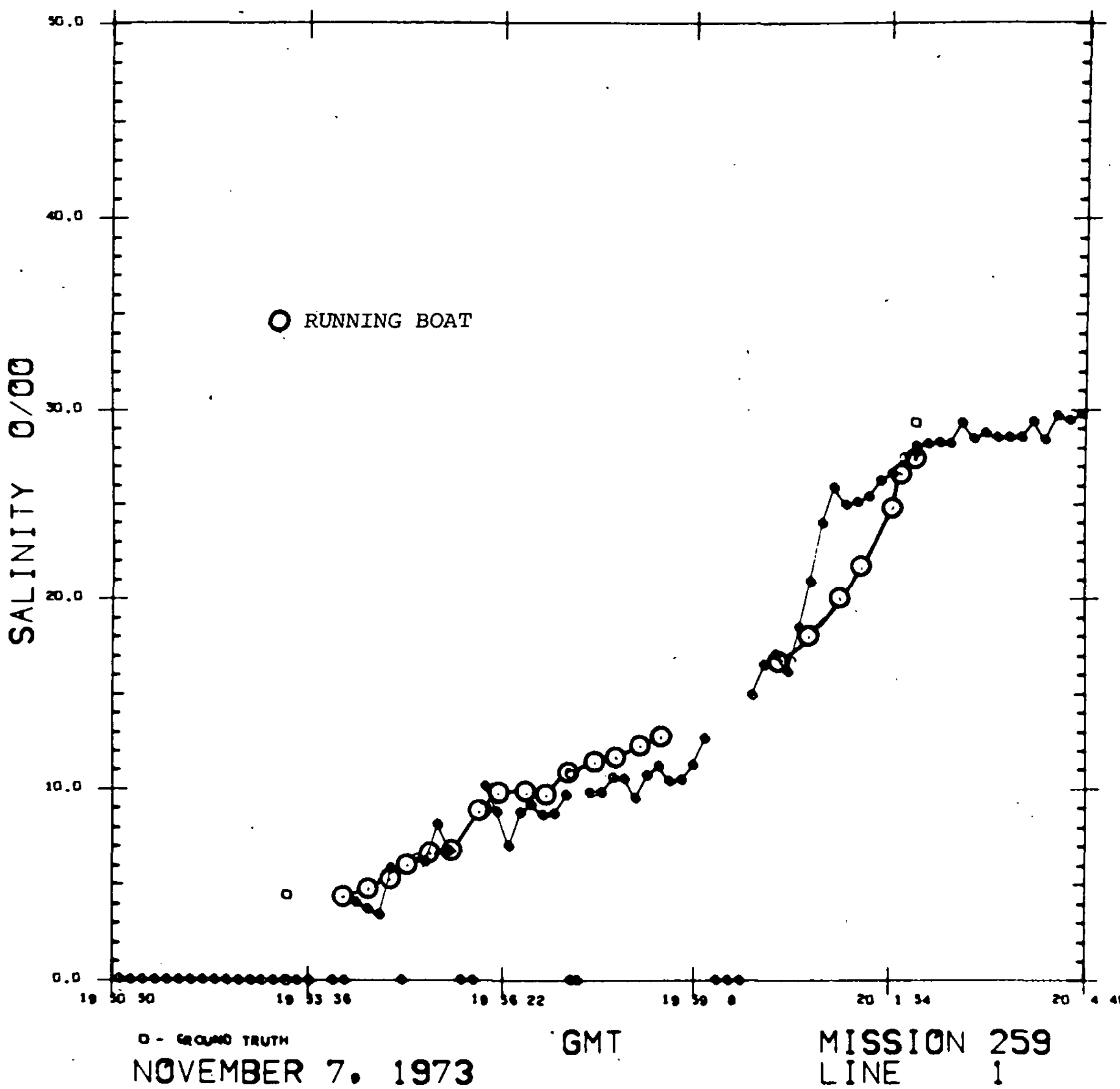
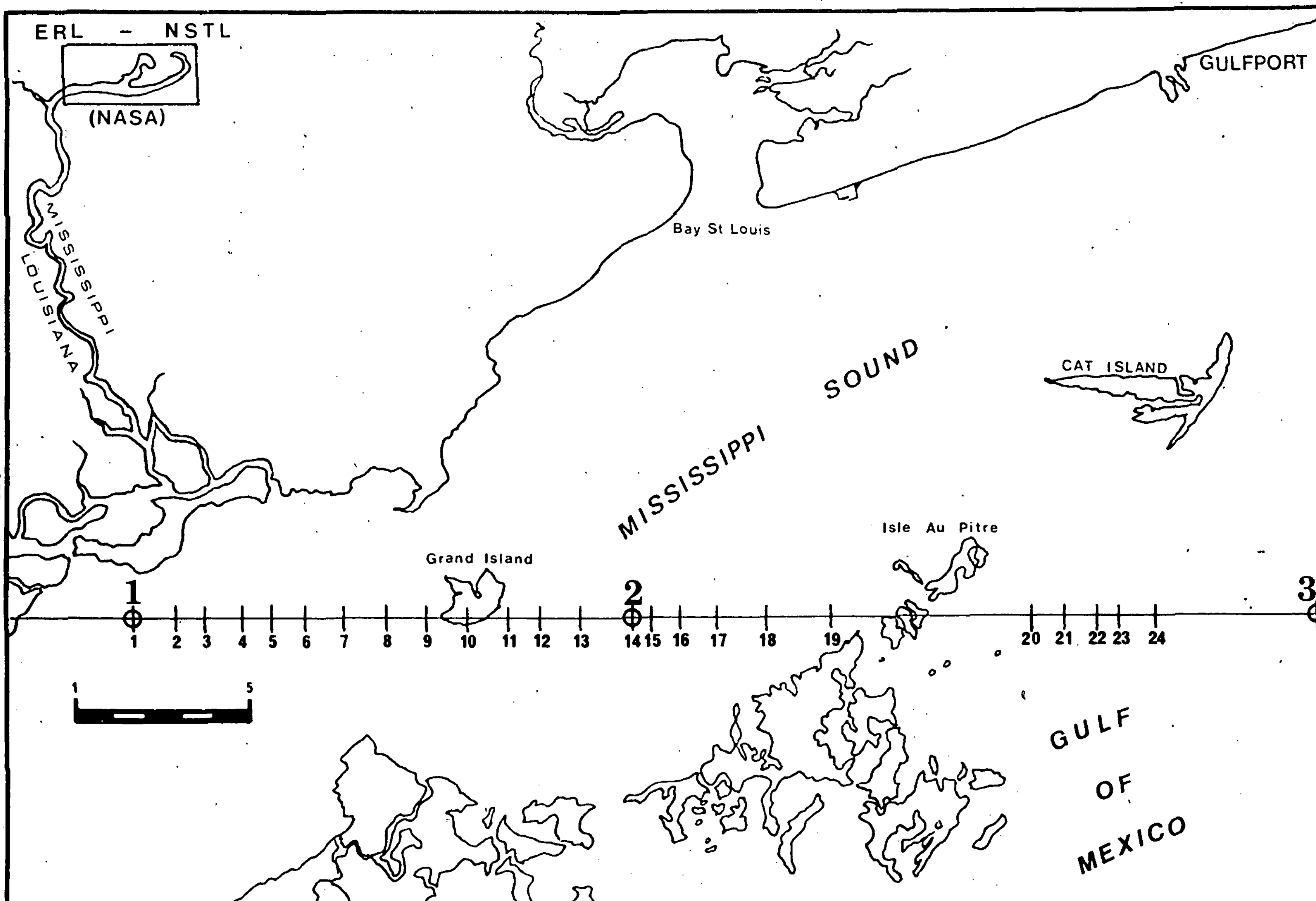


Figure 8. Remote and surface measured salinity values for run 8 of the November 7, 1973 experiment.



2119

Figure 9. Flight line, stationary boat positions(circled), and moving boat measurement positions for June 4, 1974 experiment.

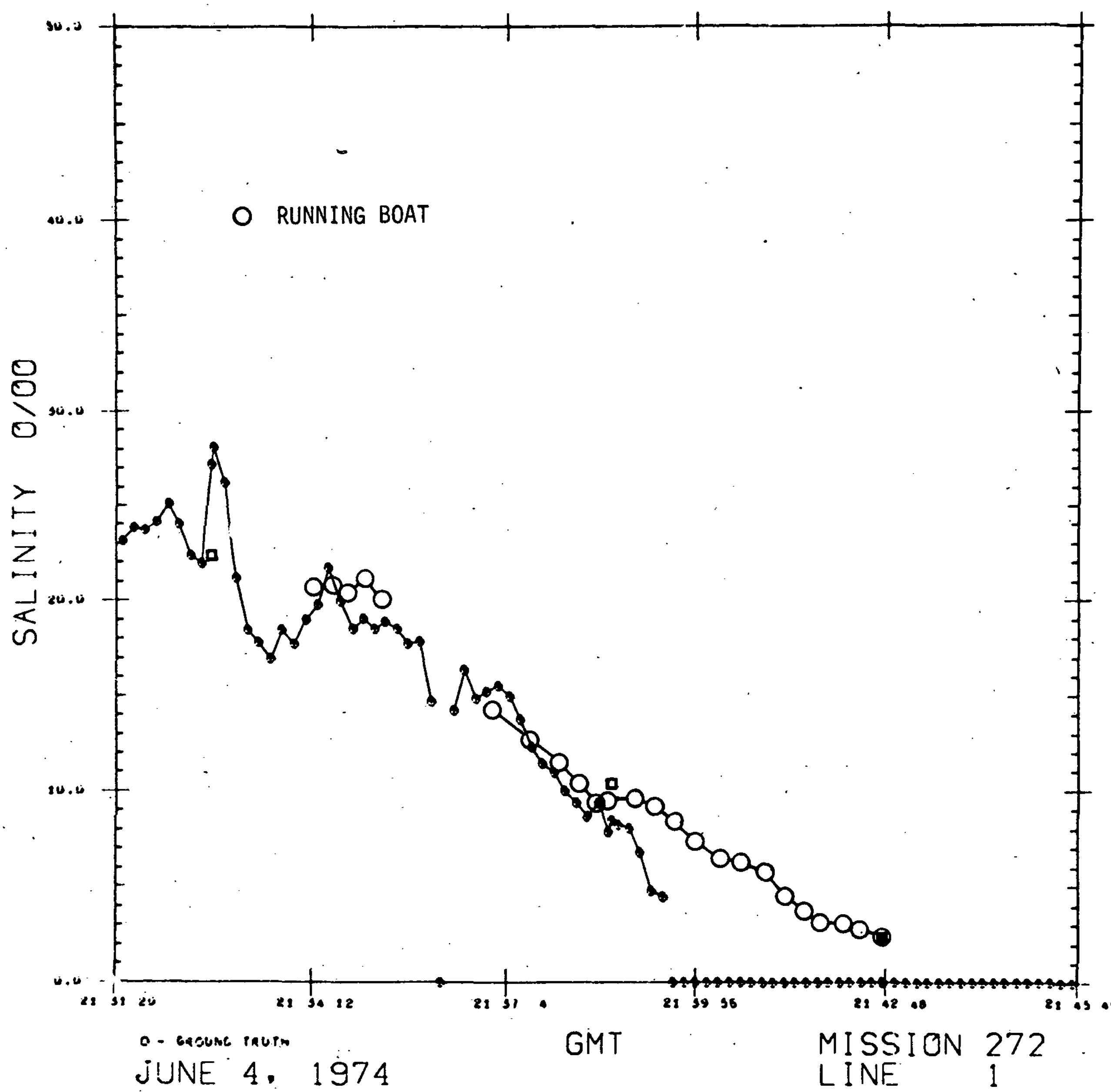


Figure 10. Remote and surface measured salinity values for run 1 of the June 4, 1974 experiment.

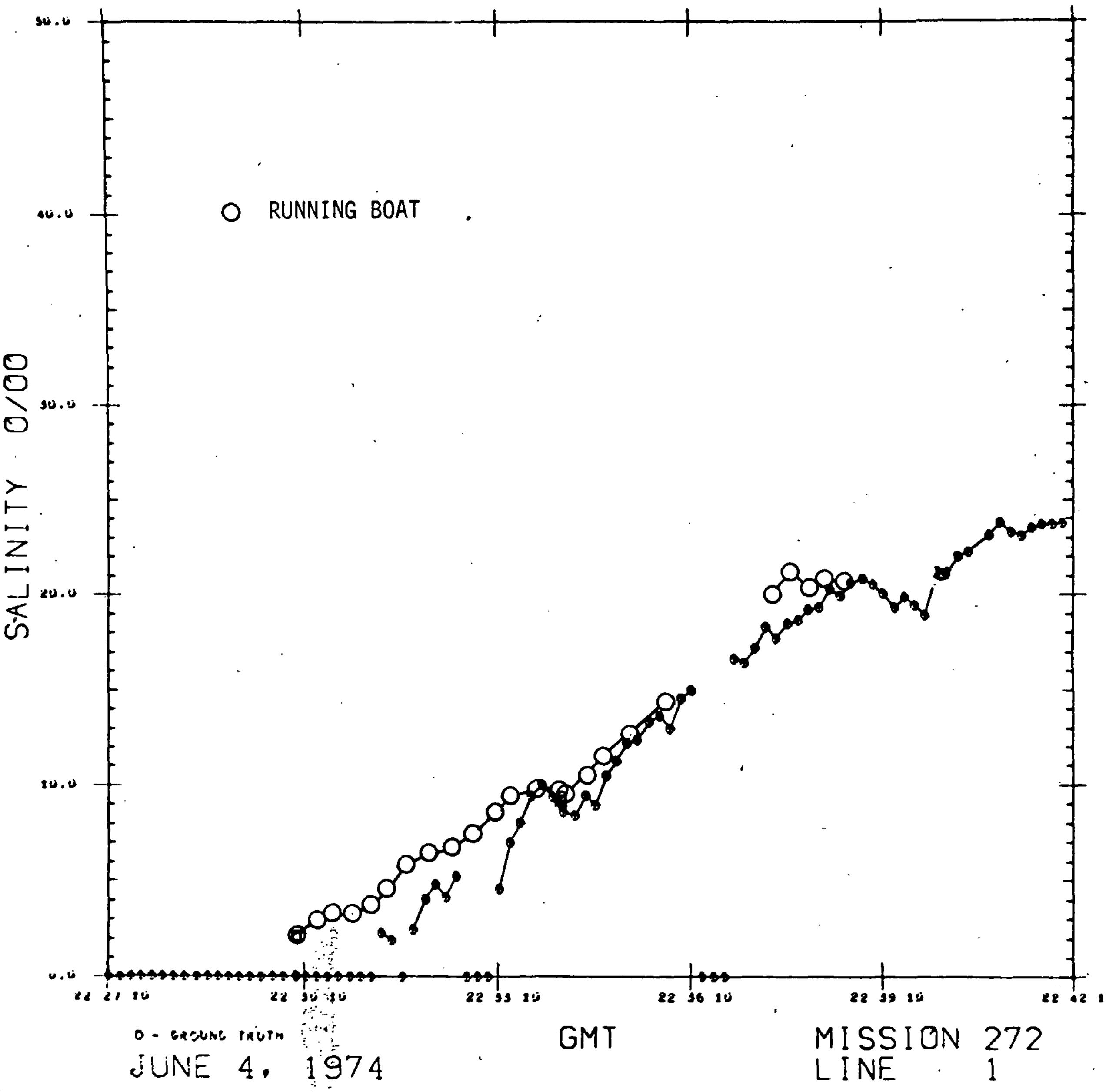


Figure 11. Remote and surface measured salinity values for run 4 of the June 4, 1974 experiment.

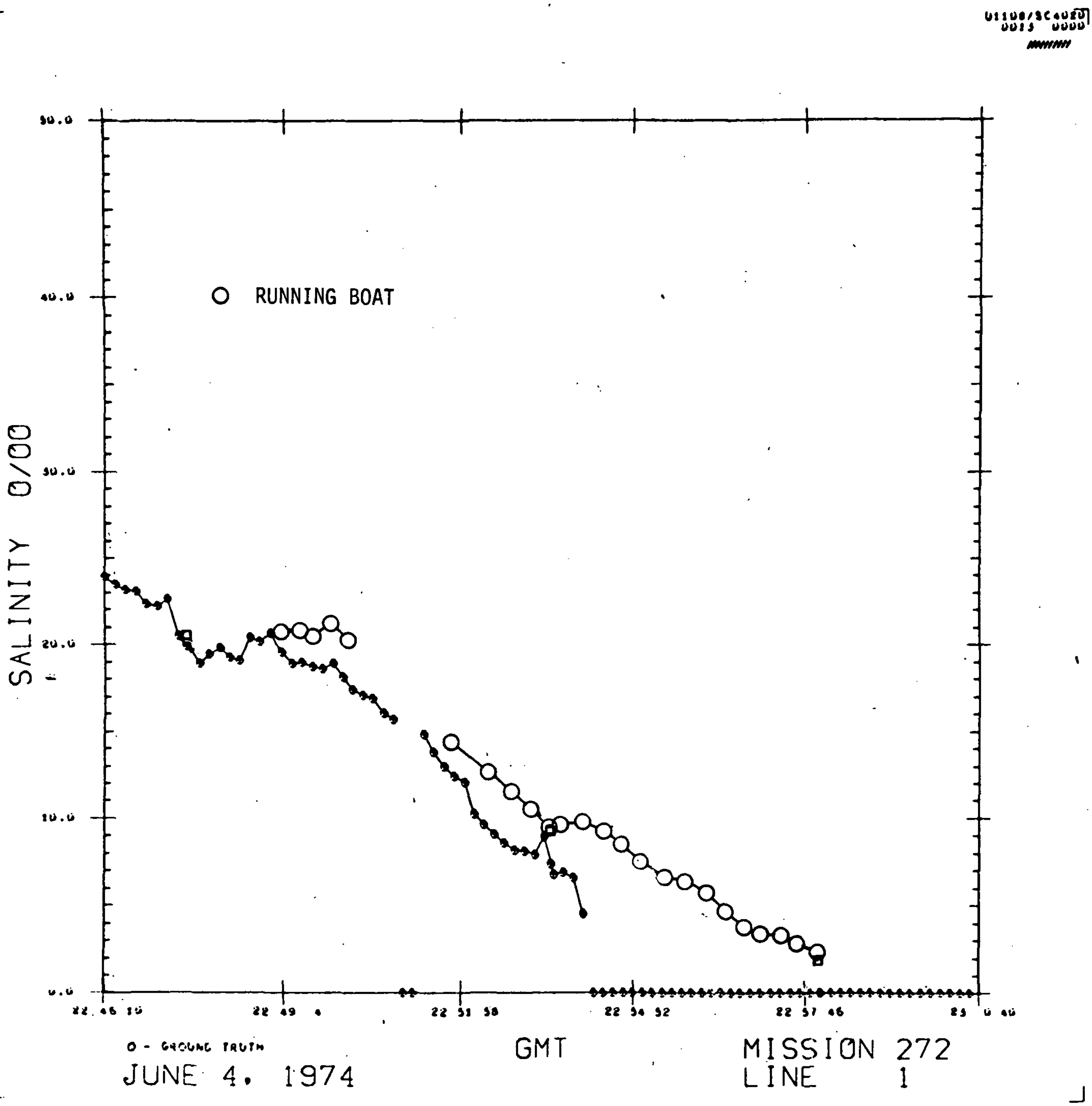


Figure 12. Remote and surface measured salinity values for run 5 of the June 4, 1974 experiment.

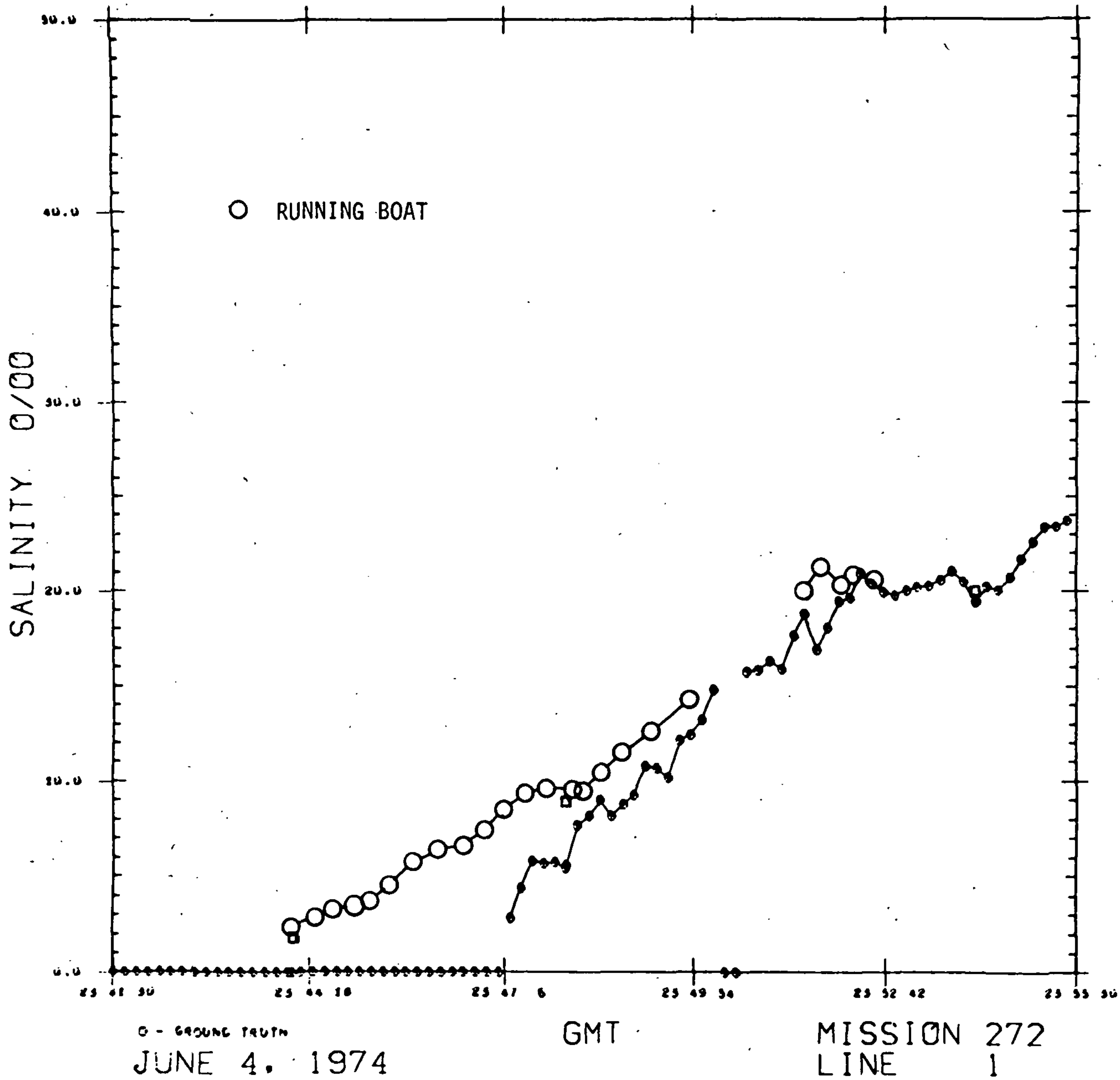


Figure 13. Remote and surface measured salinity values for run 8 of the June 4, 1974 experiment.

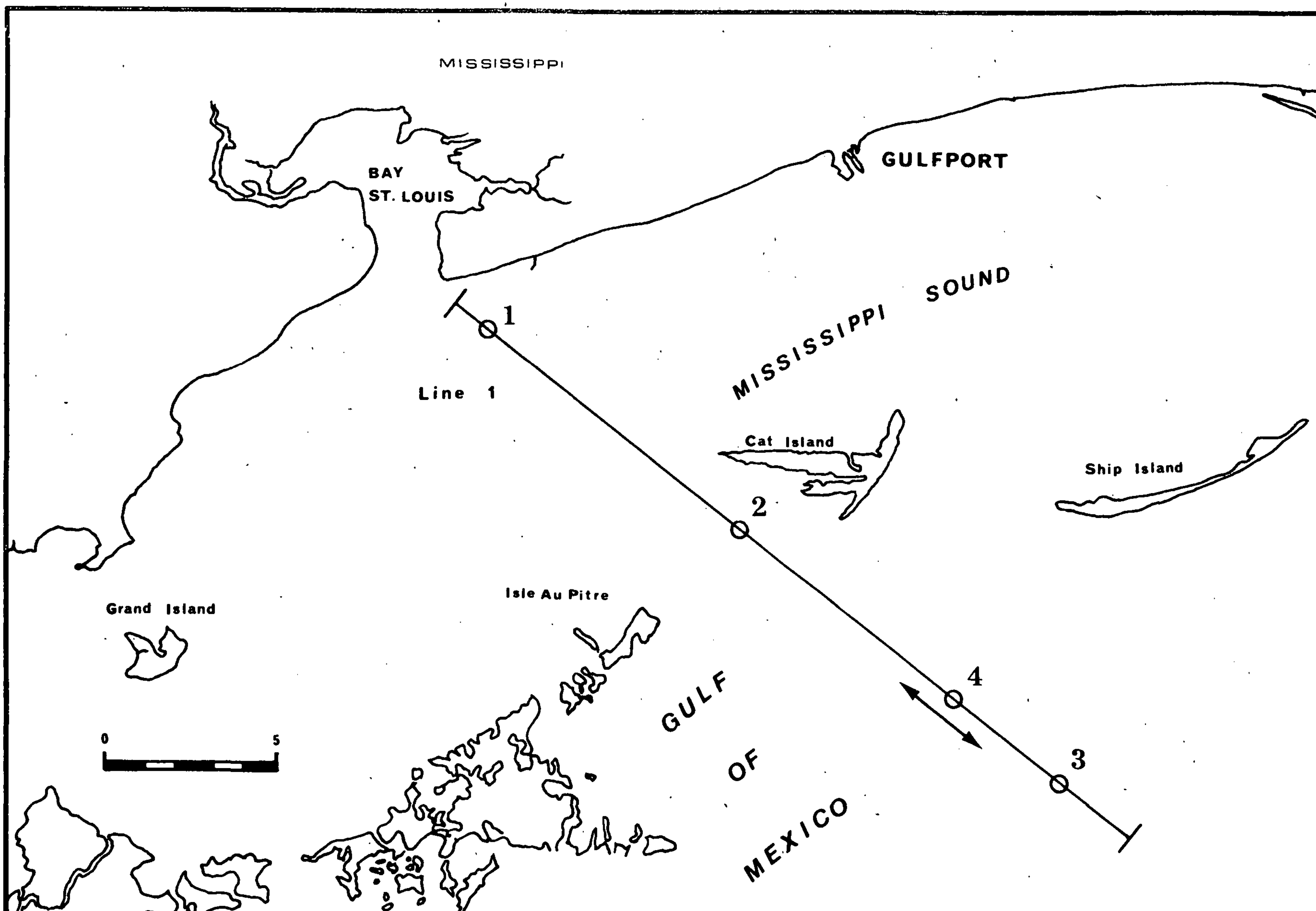


Figure 14. Flight line and stationary boat positions for the April 16, 1974 helicopter experiments.

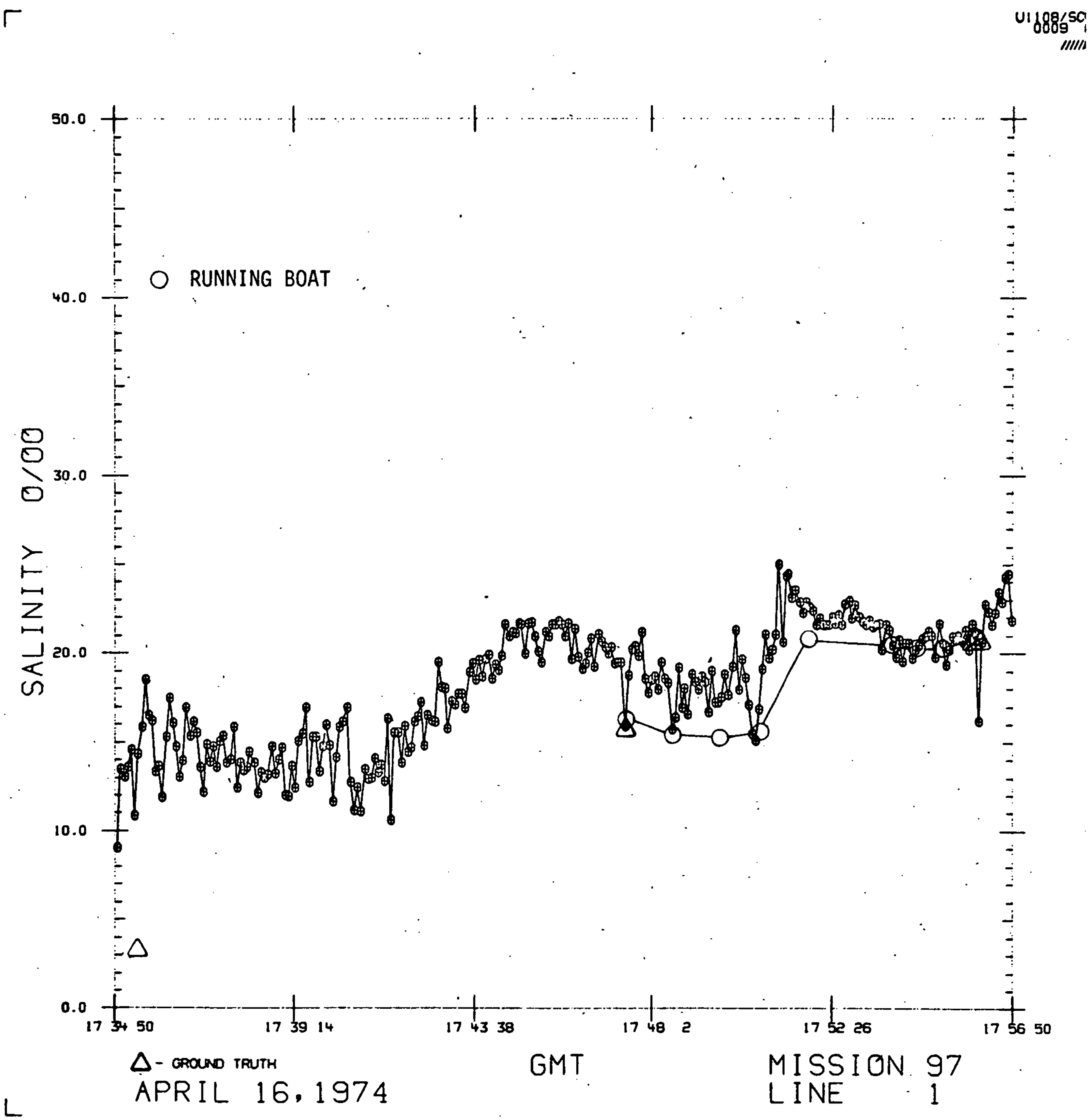


Figure 15. Remote and surface measured salinity values for run 1 of the April 16, 1974 helicopter experiment.

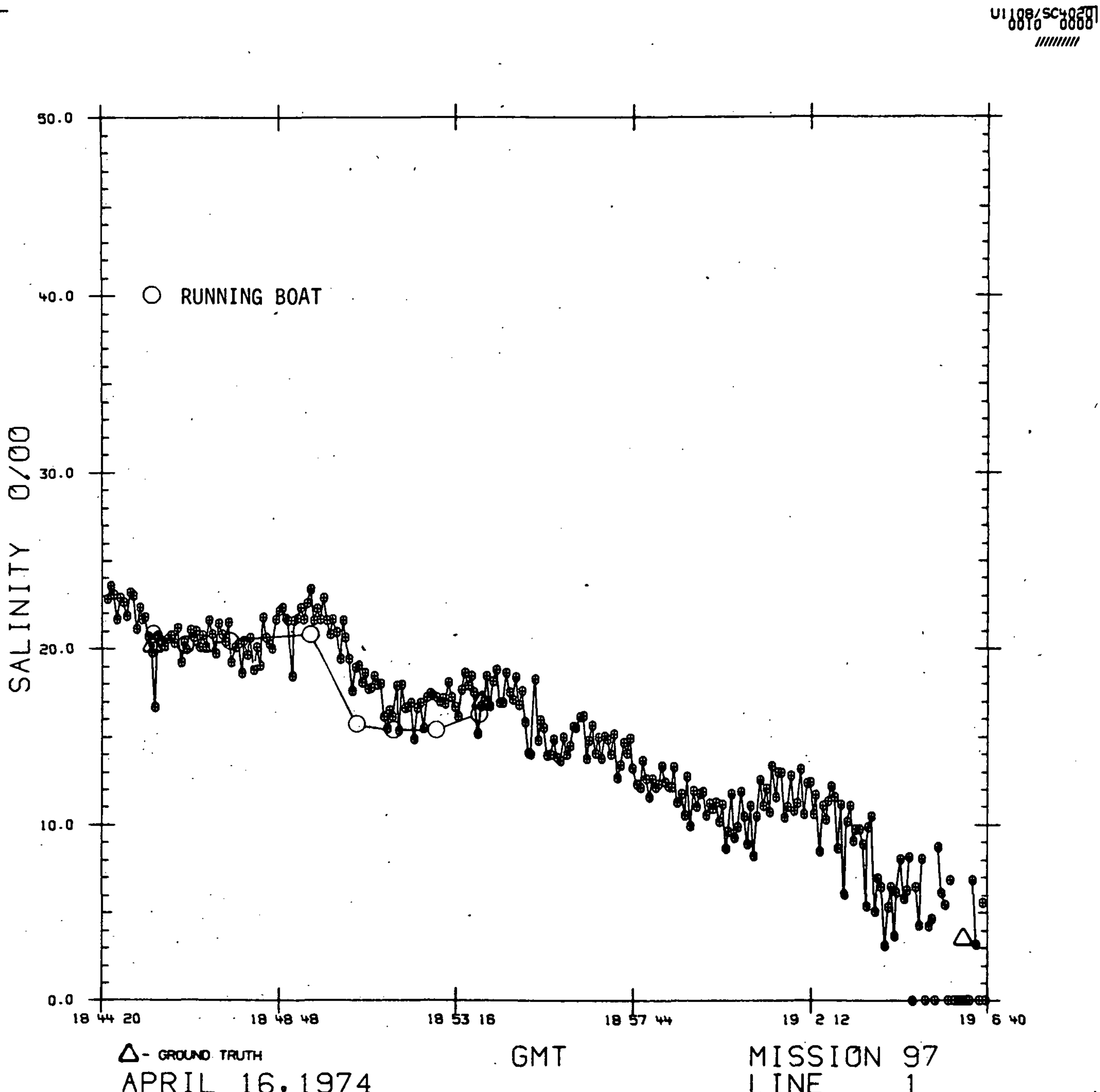


Figure 16. Remote and surface measured salinity values for run 4 of the April 16, 1974 helicopter experiment.