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Green Sheet Project: Dye Sheet Evolution

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A 300-kHz Acoustic Doppler Current Profiler (ADCP) was used aboard the USNS Bartlett as part of the Green Sheet 91 experiment during June 1991 in the Gulf of Mexico. The purpose of the experiment was to lay out a sheet of dye at the bottom of the mixed layer for later sampling by an airborne LIDAR system.

Ship's tracks relative to targeted depths were calculated that reconstructed the dye deployment and sampling process. During the practice deployment, termed "Dress Rehearsal", a small front was found between the second and third leg which adversely affected the location and geometry of the dye sheet. During the first LIDAR test, termed "Flight One", currents rotating strongly in depth and weakly in the horizontal also adversely affected the character of the final dye sheet.

A shear-Advection model was developed, using ADCP data and concurrently recorded navigation data, to predict the dye sheet evolution. The results of the model helped understand the evolution of dye sheets and were in agreement with the results of the LIDAR sampling during Flight One.

For future Green Sheet experiments the ADCP should be used to provide real-time ship's tracks relative to a given water depth to aid dye deployment. The Shear-Advection model should be used in near-real-time to aid the vectoring of the plane over the evolved dye sheet.

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GREEN SHEET PROJECT: DYE SHEET EVOLUTION

I   INTRODUCTION

The Green Sheet project concerns using a thin two-dimensional sheet of dye to analyze the internal wave field in the upper ocean. This sheet is formed by laying fluorescein dye in a series of parallel streaks, following isotherms, in the seasonal thermocline. These streaks, acted upon by the local vertical shear, are then kinematically spread out into wide thin patches that overlap to form an continuous sheet of dye. This sheet is then examined with an airborne LIDAR system to obtain a two-dimensional picture of the internal wave field. For a more detailed description of the process see "Green Sheet Engineering/Ambient test plan" (Dugan, et al, 1992).

There are several specific assumptions made about the velocity and shear fields, at the depths which the dye is dispersed, that need to be reasonably met for the Green Sheet dye deployment scheme to work: One; the velocity field needs to be consistent over the approximate three by five kilometer area of water used in order for the dyed water to advect as a unit and retain some sort of simple geometry. Two; the shear field needs to be consistent along the streaks and perpendicular to the streaks in order to maximize the kinematic spreading of the dye streaks into patches. Three; the shear field also needs to be fairly consistent over a period of twelve to twenty hours to allow the sheet to mature.

A basic oceanographic assumption is that the shear along an isotherm (isopycnal) surface is more constant than along a constant depth surface. This is felt to be a reasonable assumption and is one of the reasons why the dye is laid down along isotherms. The assumption that the shear will remain constant, or at least spatially consistent, over a twelve to twenty hour period is a little less reasonable but is felt to be workable.

The Green Sheet experiments have involved several groups of investigators. NRL's participation has been mainly concerned with the recording and analysis of Acoustic Doppler Current Profiler (ADCP) data taken during the experiments. There have been two experiments testing the Green Sheet concept. One in 1989 and the other in 1991. This report will be concerned with the ADCP data taken during the second experiment, 1991, and how these data can be used to describe the dye deployments and support the basic Green Sheet assumptions. A simple model will be developed to see how ADCP data taken during the dye deployment can be used to predict the evolution of a dye sheet.

Some environmental data taken during the 1991 experiment will also be discussed.

The basic conclusions drawn are that the dye deployment scheme is valid, that the ADCP data is vital to understanding the conditions present, and that an ADCP predictive model developed with the Green Sheet 91 data might be a definite asset in future experiments. These conclusions are temporized by the knowledge that the basic assumptions about the consistency of the velocity and shear fields were not very well met in the 1991 experiment. It is hoped that future experiments will be conducted in areas that are more in line with these assumptions.

In this report section II will discuss the equipment used to produce the data discussed. Section III will present the basic ideas behind the shear-advection model developed from this data. Sections IV and V will present the data from the two dye deployments, termed "Dress Rehearsal" and "Flight One". These two deployments were chosen for comparison and contrast because the first fit the Green Sheet concept the best and the second had successful flights. The procedures used on these two deployments were also used on the "Flight Two" data but the results will not be discussed in this report as they do not add anything of value. Then section VI will discuss the ADCP data in terms of the Green Sheet and shear-advection model. Section VII will then summarize the results and discuss how ADCP data and the shear-advection

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model can be used in future Green Sheet experiments.

II   EQUIPMENT USED AND EXPERIMENT SUMMARY

The equipment used by NRL consisted of a RD Instruments 300 kHz Acoustic Doppler Current Profiler (ADCP), a Trimble 10X GPS/LORAN navigation receiver, a Sea-Bird Seacat portable CTD (model SBE 19-03), and a borrowed Biospherical Instruments Multi-Channel Spectral Radiometer (model MER-1010). The ship used for the dye deployment was the USNS Bartlett. The ship was loaded in Key West, Florida from May 27th to 29th. Some tests were run near Key West on May 30th. The Bartlett returned to Key West on May 31st for fueling and departed for the main operations area in the northern part of the Gulf of Mexico that afternoon.

The RD Instruments 300 kHz ADCP was located in a midships transducer well. Data was collected continually, except for a few times when the equipment jammed. Its sampling period was set at 0.6 seconds and it sampled the velocity field in 75 depth bins, each of 2.1 m, from 9.7 to 163.8 m. The data were excellent and were reduced to one-min-average profiles for analysis. The pure ADCP data provides estimates of the ship and water velocities relative to a defined reference layer. Navigation estimates of absolute ship's motion are necessary to estimate absolute water velocities. The ADCP also provided a rough estimate of acoustic backscatter intensity and of the temperature inside the transducer (located at a depth of 4.5 m). The temperature data, since it's from inside the transducer, has a time constant of 5-10 minutes.

The ADCP data acquisition system also recorded data from the Trimble 10X GPS/LORAN receiver about every 8 seconds. The GPS coverage was quite good (95% of the time) and the Air Force Signal Availability was not in effect so the data was excellent. For those periods when the GPS was not available (insufficient satellites visible) the LORAN data was used. The one-minute-average ADCP data were combined with the navigation data to

provide estimates of absolute water velocities.

The Sea-Bird CTD and the radiance meter were used on a fairly regular basis to provide some estimate of the water characteristics in the area. The CTD was hand lowered to 60 m and the data plotted with Sea-Bird software on a PC. The data quality of the CTD was sufficient, but not excellent. Some profiles will be shown later in this report. The radiance meter was not the preferred instrument for measuring the optical properties of the water column. A transmissometer would have been better but one was not available. The radiance meter measured the decay of sunlight with depth and the optical absorption was calculated from this data. Since it measured solar radiance it could only be used during daylight hours with a fairly clear sky. The data was useful during operations but will not be used in this report.

All data are collected by the ADCP, CTD and radiance meter are available to other researchers working on this project.

The main operations area was in the Gulf of Mexico between latitudes 26 dN and 28 dN and longitudes 84 dW and 86 dW (Figure 1). The first couple of days were spent doing an large scale survey attempting to find an adequate dye deployment area. There were three dye deployments in the operations area. A practice deployment, termed the Dress Rehearsal, was made during the morning of June 5, with shipborne assessments made that afternoon and evening. Weather conditions for this deployment were nearly ideal. A storm came up on June 6 and conditions for the rest of the experiment were rougher than the dye deployment system was designed for. The second deployment, termed Flight One, was made in the morning hours of June 8, with shipborne assessments made that afternoon and evening. The airborne LIDAR arrived in the early hours of June 9 to sample the sheet. The third deployment, termed Flight Two, was made during the morning of June 10, with shipborne and airborne assessments following. The conditions for Flight One were bad and during Flight Two worse. The data used in the rest of this report come from the Dress Rehearsal and

Flight One.

Figure 2 shows the operation area with the positions of the CTD casts and optical casts shown. Also shown are the ship's tracks during the three dye deployments.

III SHEAR-ADVECTION MODEL

A simple model has been developed to predict how the current field will advect and disperse a dye line deployed during a Green Sheet experiment. It must be emphasized that this model is simple and can only be used as a first approximation. A more complicated model is possible but this one is designed not only to give a first approximation of the dye dispersal during post-experiment analysis but also as a near-real-time approximation to help vector the plane over a sheet. Therefore it is felt that it is as sophisticated as should be.

The basic idea behind the Green Sheet concept is that a line of dye, deployed in a tube, about 1 to 2 m thick, will be sheared into a patch and that several parallel patches will merge into a sheet. It is felt that turbulent diffusion will maintain the thickness of the patch but it is mainly vertical shear that will disperse the dye in the horizontal direction.

The model consists of isolating a period of ADCP data representing a dye leg, usually about 15 minutes in length. The latitude/longitude position and times of each end point are noted along with the average absolute velocity profile for the leg. A depth bin is selected and two velocities are associated with each end point; one an average of the selected bin and the one above it and the other of the selected bin and the one below it. One can imagine this as a vertical ribbon of water 2.1 m high (one ADCP bin) stretching from the first lat/lon position to the last. With the top of the ribbon is associated the shallower velocity and with the bottom the deeper. Some later time is selected and the four corners of the ribbon are advected to a set of lat/lon positions reflecting the effect of mean advection and a 2.1 m

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shear.

Figure 3 shows an example of model parameters for a Green Sheet dye leg (Dress Rehearsal, leg #11). The top part of the figure presents the average U and V absolute velocity profile over the thirteen minutes of the leg. The lower left portion lists the input parameters to the model (bin/depth, start time, and end time) and the lower right corner lists the model parameters found from the data (start and end positions, and shallow and deep velocities). In the upper velocity profiles the depth range of the dye ribbon is indicated with a vertical bar.

Figure 4 then shows the result of the model. The first line (lower-left portion) indicates the track of the dye line as it was laid down from 1811 UTC to 1823 UTC (JD 156). Each of the eight patches to the upper right of the dye track represent the model prediction of the horizontally sheared and advected dye line in two hour increments from 156:2000 UTC to 157:1000 UTC.

Note, in Figure 4, that the successive patches move steadily towards the northwest. This is because the advection velocity is frozen at the average value found during the dye leg. This is a not a strong assumption but is defensible. Longer records of the data were examined to see if there was any consistent inertial or tidal rotation in the currents; none was evident. Also note that the direction of the main advection is unimportant. The dye legs could advect in any direction and maintain a simple dye sheet geometry, as long as the advective velocities of all the legs are consistent.

Again referring to Figure 4, note that the geometry of the spreading patches remains similar in that the edges of all the patches are parallel to each other. This is again the result of freezing the shallow and deep advective velocities at the average value found during the dye leg. This assumption is weaker in that what is being represented here is the shear and small variations in the mean velocity, while not strongly affecting the overall advection, can affect the shear vectors quite a bit. Evidence was found in some of the data for an inertial like

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rotation of the shear vectors.

Now note that the orientation of the shear vector is quite important. Ideally, the shear vector should be perpendicular to the dye leg. This will result in a maximum horizontal spreading of the dye patch and will maximize the likelihood that the various patches will overlap and form a continuous dye sheet. If the shear vector is parallel to the dye leg then there will be little or no spreading.

The previous paragraphs discuss the two basic oceanographic assumptions of the model and their weaknesses. The basic character of these assumptions is that the time variability in the ocean can not be accounted for and that it is therefore ignored. Another oceanographic assumption made is that the current field is constant along a dye leg and can be represented by an average profile. This also is a weak assumption but is constrained by the character of estimating absolute velocities from ADCP and navigation data. The weak link in this process is the navigation estimates of ship speed relative to the Earth. This process is noisy and usually must be smoothed in time to obtain a resolution comparable to the ADCP estimates of ship's velocity relative to the water. The navigation taken during Green Sheet 91 was excellent in that GPS was available most of the time, but it still needed to be smoothed over a ten-minute period. In the future this will worsen as the Air Force has since implemented an intentional Signal Availability that puts a time varying slew on the GPS signal which degrades calculated positions by as much as 100 m. This variation has a time constant of about 30 minutes and can result in a 15 minute error in calculating ship's velocity of over 50 cm/s. Therefore relying on absolute velocity variations within a dye leg will be chancy.

An assumption made that depends on the character of the ADCP data is to limit the modeled depths to ADCP bins and a set shear depth interval. The ADCP data taken during Green Sheet 91 was taken in 2.1 m bins. The average profile over a dye leg could be

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interpolated to any depth but that would be pushing the ADCP data. The shear interval used is also 2.1 m and basically represents a central difference in ADCP estimates taken about the designated bin applied to one-half the central difference depth interval. To do more would also push the quality of the ADCP data.

Then there are the assumptions that are taken that do not comply with the Green Sheet concept. Taking one bin to represent the depth of the dispersed dye contradicts the assumption that the dye is dispersed following isotherms. The isotherms can vary in depth by as much as ten meters over the deployment, as will be shown later, and the model does not take this into account. The dye is dispersed this way partially under the assumption that the velocity and shear field will be more constant along an isopycnal surface than along an isobaric surface. This is a basic weakness of the model that needs to be addressed, but it is felt at this time that to adjust the velocities to the varying depths of the dye dispenser would push the quality of the ADCP data beyond it's present capability. Remember this model is a first approximation as to how the dye sheet evolves and it is the LIDAR system data that is the key instrument of the Green Sheet experiments

This model will be applied to the Dress Rehearsal and Flight One dye deployments later in this report where its value can be evaluated.

IV DRESS REHEARSAL

On the morning of June 5th (JD 156) the procedures for deploying the dye started with a CTD cast at 1000 UTC (0600 LT). Then the Arete Fish was put over the side and dye was deployed for 6.5 hours from 1420 UTC to 2050 UTC. Weather and sea conditions were nearly ideal and the dye deployment went well.

Figure 5 shows the results of the CTD cast and the average absolute velocity profile for the entire dye-dispensing period. The CTD cast shows a two tier mixed layer with the thermocline

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located near 30 m. The average velocity profile shows a fairly constant shear with depth in a uncomplicated profile. The dye was dispensed approximately on the 23 dC isotherm. While this isotherm was near 30 m during the CTD cast it was at about 38 m during the dye deployment.

Figure 6 shows fish data provided by Arete. The top portion of this plot shows the depths at which the dye was dispersed as a function of time. The depth range of 29 to 45 m is shown on the left hand axis and the depths of the ADCP bins 11 to 18 are indicated on the right side. The middle portion of this plot shows the times of the designated ADCP legs (defined while discussing Figures 7 and 8). The bottom portion shows three-second-average temperatures recorded by the three sensors on the fish during the deployment. The first thing to note is that there is no dye deployed during the first ADCP leg. Therefore leg one should be discarded from this analysis, particularly if there was a flight associated with this deployment. It was decided to leave it in because it helps discussing the results of the shear-advection model described in section III. The next thing to notice is that the dye was dispersed quite well as the temperature recorded on the middle thermistor remains fairly constant at about 23 dC. The depth trace shows that the 23 dC isotherm did not remain at a fairly constant depth. It ranged from about 35 to 43 m and varied during legs as well as between legs. This variability is designed into the Green Sheet concept. Also shown is the effect of the turns on the depth of the fish particularly at 1515 when the fish was not turned off during a turn. The fish rose up to quite a shallow depth (<29 m - note that the depth trace was capped at 29 m in this plot as was the temperature trace at 24 dC) and the temperature rose accordingly.

The variation of the isotherm depths points out the basic weakness of the shear-advection model. By using one ADCP depth bin to describe the velocity and shear field for the entire deployment some error is inherent. The selection of ADCP bin 15 (depth 38.8 m) is somewhat arbitrary but seemed the best choice.

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Figure 7 shows the track of the ship relative to the Earth using navigation data. The deployment started at the west end and moved towards the east-north-east in 18 north-south legs. The ocean current was towards the northeast so the early tracks were moving toward the ship during the 6.5 hours of the deployment. This is shown in Figure 8 which shows the track of the ship relative to the water at 38.8 m (average depth of dye dispersal). Here the legs are closer together reflecting the fact that the current and ship motion were in the same general direction. The deployment pattern was designed to result in a certain spacing of the legs relative to the water. Figure 8 is the important one in that it shows how the dye was laid down in the water. In both Figure 7 and Figure 8 the straight segments are emphasized. These segments form the ADCP legs for use in the model. The data taken during the turns were ignored partly because absolute velocity estimates are poorer during turns but mainly because the dye dispensing was turned off during turns as the fish could not maintain proper depth.

In Figure 8 it is evident that the first few legs were put down on top of each other. This is partly due to the fact, to be shown later, that there was a small velocity front found in the water between the second and third legs.

Figure 9 shows waterfall plots of the leg-average velocity component and the shear magnitude profiles. The scales are as shown with the consecutive velocity profiles offset by 13.33 cm/s and the consecutive shear magnitude profiles offset by .033 1/s. The velocity profiles support the basic simplicity of the velocity field. If the first two profiles are examined they indicate that a small front was crossed after the second leg. The shape of these two profiles are similar to the others but the offsets indicate that the overall absolute velocity did change. The shear magnitude profiles indicate that shear field is irregular and that the only strong shear is near 30 m for legs three through nine. The shear at 38.6 m, the average depth of the dye deployment, shows some energy but little consistency.

The directions for the shears are not shown in this waterfall
form as the plots become confusing.

Figure 10 is like Figure 8 in that it shows the ship's track
relative to the water at 38.8 m. Figure 10 is different in that
it covers a longer period of time which includes the early
assessment period. After the dye was dispersed the fish was
brought back aboard the ship and reconfigured to assess the dye
field. For this assessment there were three dye sensors on the
fish. Only one of these sensors worked properly, sensor #3. The
track shown in Figure 10 starts at JD 156, 1420 UTC and goes to
2400 UTC. Where the dye sensors were collecting data the ship's
track is emphasized. Where the dye sensor noted dye an x is
placed upon the ship's track. There has been no effort made to
check the depth of the sensor during dye hits. The lack of a dye
hit does not mean that dye was not in the area, the dye sensor
could have been above or below the dye sheet when the sensor was
the "right" spot. The presence of a hit when the ship track
crosses a location where the ADCP indicates dye should be present
is an encouraging sign that the ADCP tracking of the ship
relative to a given water depth is a valid procedure.

Figure 10 shows that 38.8 m is a good estimate of the
average dye dispensing depth and that the ADCP tracking is
working as all the dye hits are near locations where the ADCP
track indicates there should be dye and that no dye is found
where the ADCP track indicates there shouldn't. Figure 11 shows
twelve plots showing ship's tracks, in the same way as described
in Figure 10, for sequential depth bins ranging from 26.3 m to
49.2 m. This figure is not very exciting in that it confirms
earlier statements about the consistency of the shear profiles.
In this case the depth ascribed for the average dye dispensing
depth is not too critical. If the dye had gone down at 26.3 m
then the first panel indicates that there would be some problem
with using the ADCP data in this manner but the pictures for
depths 32.6 m through 49.2 m are not too different. This will
not be the case for the Flight One data to be discussed later.

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Figures 12 and 13 show the leg positions relative to 38.8 m, as in Figure 8, with the leg-average velocity vectors (Figure 12) or leg-average shear vectors (Figure 13) attached to the mid-point of each leg trace. The velocity and shear vectors were calculated for 38.8 m (the shear was calculated as a central difference about 38.8 m). Figure 12 shows the leg-average velocities were fairly consistent for legs three through eighteen but were quite different for legs one and two. The bulk of the dye sheet will move off to the northeast while the first two legs will move off to the southeast. The leg-average shear vectors (Figure 13) do not show a great deal of consistency except for perhaps the last eight legs.

The data described in Figures 12 and 13 are entered into the shear-advection model and the results for the selected time of JD 157, 0700 UTC are shown in Figure 14. The initial dye leg positions are indicated by the group of eighteen north-south lines in the western one-half of the figure. The advected and sheared patches of dye are shown in the eastern one-half of the figure. Patches from legs three through eighteen group into what appears to be an acceptable sheet. The patches from legs one and two appear lost off to the south of the main sheet. The variability of the shear field is demonstrated by the shapes of the individual patches. Where the shear was perpendicular to the leg, like in the last few legs, the patch is basically rectangular and the patches have the greatest likelihood of forming a continuous sheet. There are a few legs where the shear is basically parallel to the legs and the patch ends up a longer line instead of a rectangle.

V   FLIGHT ONE

Between the Dress Rehearsal and Flight One there was a significant storm and the resulting conditions were much worse than planned for or that the Arete Fish could handle properly. The Flight One deployment went ahead anyway, after a one day

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delay, on June 8th (JD 159) because the plane was scheduled and it was necessary to proceed. Again the deployment started with a CTD cast at 1000 UTC (0600 LT). Dye was dispersed from 1418 UTC to 2005 UTC.

Figure 15 shows the results of the CTD cast and the average ADCP absolute velocity profile averaged over the dispersal period. Here it is obvious that the storm affected the mixed layer by creating a well mixed layer from the surface to 40 m. Also the mixed layer has developed a strong velocity compared to the rest of the water column with a "jet like" character at the bottom of the mixed layer. It is not too obvious in the Figure but the shear at the bottom of the mixed layer has the character of a downward propagating inertial wave in that the shear direction rotates clockwise with depth over the shear zone. This figure can be compared to Figure 5 to show the differences between the conditions during the Dress Rehearsal and Flight One.

Arete tried to disperse the dye, as best as conditions would allow, on the 24.4 dC isotherm which again was generally at the ADCP depth of 38.8 m.

Most of the figures presented in this section have a parallel figure for the Dress Rehearsal in section IV.

Figure 16 shows the data from the Arete Fish taken during the dye dispersal with the ADCP legs (defined in Figures 17 and 18) shown. The depth of the fish started off at about 33 m and shifted to about 39 m by the seventh leg where it remained. The extreme ship motion did not allow the fish to follow an isotherm as well during Flight One as it did during the Dress Rehearsal so the temperature traces are very noisy and generally can not be distinguished from each other.

Figures 17 and 18 show the ship's track, for the period JD 159, 1418-2005 UTC, both relative to the Earth (Figure 17) and relative to the water at 38.8 m (Figure 18). The ship proceeded from SE to NW during the dispersal and the current was generally in the same direction. The ADCP legs are again defined as straight sections of the ship's track and are emphasized in the

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figures. The horizontal pattern of dye dispersal was superior in Flight One than the pattern in the Dress Rehearsal (Figure 8) but the depth control of the dye dispersal relative to the isotherm was not.

Figure 19 shows the waterfall plot of the leg-averaged velocity component profiles and the shear magnitude profiles. The velocity profiles show the strong mixed layer current with a strong, rotating, shear to the deeper currents. The shear magnitude profiles show strong, dominant, shear maxima that are fairly steady at -35 m, just above the dye dispersal depth. No front is apparent in this plot but it is apparent from the velocity profiles that the directions of the shear maxima rotate during the dispersal. This rotation is significant and will be shown later.

Figure 20 shows the ship's track relative to 38.8 m for the dispersal and early assessment period (to 2330 UTC). The process of returning to the dye sheet for assessment was not as successful here as during the Dress Rehearsal and only five minutes were isolated during which dye was measured. There was a long period during which the sensors were turned on that did not show dye activity that this plot shows there shouldn't have been any, so the ADCP tracking again appears to have worked fairly well.

Figure 21 shows the danger of dispersing dye in a water column whose velocity rotates with depth. This figure should be compared to Figure 11. If the dye had gone out at 28.4 m the resultant ·rea covered would have been aligned nearly east-west while if it had gone out at 38.8 m or deeper it would have been aligned nearly north-south.

Figures 22 and 23 show the positions of the ADCP legs relative to the water at 38.8 m, with average velocity vectors (Figure 22) and average shear vectors (Figure 23) calculated at 38.8 m. The average velocities are fairly constant with a slight clockwise rotation with time. It is not certain whether the rotation is temporal or spatial. The shear vectors show a strong

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rotation with time, about 110 degrees in about 6 hours. The inertial period at this latitude (27.6 dN) is 25.9 hours. This is not a perfect match so there is probably spatial rotation as well as temporal for this shear.

The use of the model for this deployment has the added attraction that there is some LIDAR data to compare the model to. When comparing the LIDAR data to the ADCP data it must be remembered that three separate navigation systems were used during Green Sheet. The Arete buoys were using LORAN receivers, the ADCP system was using a combined GPS/LORAN system, and the plane was using an inertial system. At no time were the three systems calibrated to each other. This would have been difficult because the offsets were unlikely to be constant, but it wasn't done. The procedure used was for the ship to maintain position at what was thought was one end of the sheet with an estimate, using the LORAN buoys, of its orientation. Then the plane would fly over the ship on a heading given to it by the ship.

Figure 24 shows the model result advected and sheared to JD 160, 0227 UTC. This is about 14 hours after the dye dispersal started and about 6.5 hours after it ended. The velocity rotation noted in Figure 22 has distorted the geometry of the sheet so that it has a crescent shape rather than a rectangular shape. Also on the plot is a large asterisk that denotes the GPS/LORAN position of the ship at that time. Then the flight path of the plane is shown as a line extending from the start to the end lat/lon positions of the run according to its inertial system. The hypothesis made here is that the plane flew over the ship so the line should be moved to overlay the asterisk. The time during the flight when it saw dye can not be estimated as the along path offset is unknown.

It is apparent that the model does show a viable plane path as it would hit the right hand edge of the modeled sheet. One feature of the LIDAR data that is confirmed by the model is that the plane only saw dye for about 1 km along the path, not the 5 km expected. Figures 25 and 26 show the model plus flight paths

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for two additional LIDAR runs at 0235 UTC and 0243 UTC. Both show the plane passing near to the right hand side of the modeled sheet with the 0235 pass missing by about 1 km and the 0243 pass again hitting the right hand edge.

Figures 27, 28, and 29 repeat the model for the 0243 pass using three different depths. This is done to reiterate the problem shown in Figure 21 concerning the rotation of the velocity vector with depth. Figure 27 assumes the dye went down a 43.0 m (4.2 m below the "best" depth used in Figures 24, 25 and 26). Here the shear is less, indicated by the smaller patches, and the crescent shape more pronounced. Here also the plane misses the sheet. Figure 28 shows the model for a depth of 34.7 m (4.1 m shallower than "best" depth) and patches are larger and the plane hits more towards the middle of the sheet. Figure 29 then shows the model at 30.5 m (8.3 m shallower than "best") and here the sheet is distorted some more. There is no real way to decide, from these figures, which of these depths is best. Figure 21, using the early assessment data would be the best vehicle for picking the best depth (if only one is being used) as it should show believable dye hits. Looking at the four figures concerning the 0243 plane pass together (26-29) it is apparent how sensitive the model can be to the depth of the dye sheet. In a near-real-time use of the model, when the actual depth of the dye is not certain, models of the sheet at several depths bracketing the estimated depth could be used to guide the plane.

VI DISCUSSION

The environmental conditions during the Green Sheet 91 experiment were less than ideal. Satellite imagery, not shown, indicate that the operations area was in a broad area of horizontal temperature gradient with evidence of smaller scale variability. Several CTD casts were taken in the operations area but attempts to combine these into a overall picture of the operations area environment proved impossible as the variations

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in the density field were on smaller space and time scales than the sample spacing. This large scale survey was not very helpful other than to find the right operational "ballpark".

The storm that came up on June 6 ruined the surface smoothness that was required for successful dye dispensing operation.

The two deployments, described previously, show that the current variability, within the three by five kilometer dye dispensing area, can cause definite problems. Some such variability is inevitable. What was not done in the past, mainly due to time constraints, which should be done in the future is to do a close-order environmental assessment in the dye dispersal area. The ADCP could do this by having the ship steam over the area once or twice looking for fronts and velocity variations. Several CTDs or some sort of simple Tow-Yo CTD system would be invaluable.

The tracking of the dye sheet is mainly done with the use of drogued navigation buoys. Ideally four buoys are used, one on each corner of the proposed sheet. The initial CTD is used to identify the isotherm of interest and its depth. The buoys are then drogued to that depth. The buoy radios navigation data and temperature data at the drogue depth to the ship. The dye is then dispensed along the isotherm representing the average of the temperatures actually present at the drogues. The buoys are designed to be advected by the mean current and be used to track the dye sheet and define its geometry. For flights the ship positions itself at one end of the sheet and vectors the plane over the ship in the direction of the sheet. The basic assumption that this procedure makes is that the velocity field is basically constant over the dye dispersal area.

The presence of small fronts in the dye sheet area will give the operators on the ship a incorrect idea of the dye sheet geometry. Figure 14 shows the shear-advection model results for the Dress Rehearsal. It is obvious that if there were four buoys placed at the four corners of the dispersal area, then the two

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western ones would have advected south relative to the bulk of the sheet. Any attempt to fly a plane over the area defined by the four buoys would therefore have missed most of the sheet.

Even if the four buoys are all drogued at the depth of the desired isotherm they will stay at that depth, not on the isotherm. This is not a big problem as the buoys are tracking the average velocity and not the shear, but it does detract from the value of deploying and measuring a dye sheet on an isothermal layer rather than a isobaric layer.

If a buoy is drogued at an incorrect depth in a rotating shear zone, as in the Flight One deployment, then the buoy positions will give an incorrect estimate of the dye sheet location and orientation. This is best prevented with a careful selection of an operations area.

Finally, if one or more buoys send faulty data to the ship then they will also result in a poor estimate of the dye sheet geometry. This was a problem with the LORAN receivers used in the past, but should not be a problem if GPS receivers are used.

Some effort has been made in this report to show how the ADCP data can be used to track the ship relative to the dye sheet and predict the basic location and geometry of the resultant dye sheet. It must be stated firmly that it is not proposed that the ADCP can do a better job than the drogued navigation buoys. It is felt that the buoys are the best way to track the dye sheet, but that the ADCP can provide some help and backup. The main weakness of using the ADCP data is that a ship's track relative to the dye dispersal lines assumes that the velocity field, at a given depth, is constant over time and the area that the ship uses. The buoys at least will not be adversely affected by time variations, though they are prone, as is the ADCP, to problems caused by spatial variations. The strength of the ADCP is that it estimates and records water velocity at several, regularly spaced, depths that can be used to estimate shear fields. Ship's tracks relative to the water, as shown in Figures 8 and 18, provide information that would be extremely helpful to the team

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operating the ship during the dye deployments and assessments. In the past these plots have not been available in real time; in the future they should be.

The buoys most probably provide the best form of experimental control (tracking and diagnosing the dye sheet) but the ADCP is a helpful partner. Both systems have some strengths and weaknesses, together they should provide excellent experimental control.

The shear-advection model discussed in section III was made in an attempt to compare the ADCP data to the airborne LIDAR data. It is not meant to be a overly sophisticated model because of the basic limitations of the data. The model does do a adequate job of describing what occurred during Green Sheet 91 but it's main strength is probably its use, during future experiments, as a near-real-time predictor of the dye sheet evolution. If implemented in this manner it could provide another invaluable aid to the experimental guidance of the plane.

The shear-advection model depends not on the main product of the ADCP (shear or water motions relative to each other) but on derived estimates of absolute velocity. Therefore, the ADCP data need to be combined with navigation data (for estimates of the ship motion relative to the Earth), which need to be of comparable precision. In the past navigation has been the weak link in the process of estimating absolute velocities. Now, with the GPS network nearly operational, the capability exists to obtain navigation data of sufficient quality. Unfortunately GPS data have been intentionally degraded with SA (Selective Availability) that results in the estimated positions varying about the true position by 100 m (RMS) with time scales up to about 30 min. There are two basic ways of sidestepping this problem. Either borrow, from the military, a classified system that decodes the P-CODE signal and estimates the best position correctly or use a Differential GPS (DGPS) system that involves two GPS receivers, one at a fixed site ashore and one aboard ship, with a radio interface to correct the ship positions.

This author has collected regular GPS data at a fixed site, here at NRL, and found the apparent velocities to be daunting. During an experiment off Cape Hatteras in June of 1993 both regular and differential GPS data (the differential receiver was borrowed from the Coast Guard) were collected and analyzed. The differential data were definitely superior. The only real problem with differential GPS is that it's only usable within radio range of a broadcasting station.

VII SUMMARY AND FUTURE PLANS

The ADCP has provided excellent data sets for understanding the velocity conditions present during past experiments. It has done an excellent job of reviewing the deployment procedures and reconstructing the dye sheet evolution. It is felt that these features alone justify the presence of an ADCP during future experiments.

Calculating ship's tracks relative to a given water depth is fairly straightforward. These plots have been very helpful in recreating the actions of the ship during dye deployments. In the past this capability has not been available in real time. With the recent purchase of a new data-acquisition system it is felt that this real time capability is attainable and should be developed for future experiments.

The concept of using drogued navigation buoys is good and should be used, with GPS receivers, in a full suite of four. The ADCP estimates of ship's track relative to the water, if made available to the experimental control group, would be a very helpful addition to the buoy data.

The shear-advection model developed to compare ADCP data with LIDAR data was successful and also should be used in future experiments. A valuable addition to future experiments would be to apply the model in near-real-time to further aid the experimental control group. About six hours is used to lay down the dye sheet. Then a period of about six hours is used to allow

the shear field to defuse the dye lines into a continuous sheet. Finally the plane arrives and collects the primary data. During the period after the dye is dispersed and before the plane arrives the ADCP data can be analyzed to produce model parameters for various depths. The model results can be made available for use in vectoring the plane to the dye sheet. The buoy data should still be the primary input to this vectoring process but the model results could play an important part.

During the Green Sheet 91 experiment the ADCP collected data every 0.6 seconds in 2.1 m depth bins. For future experiments data will be collected every 0.4 seconds in 1 m depth bins from about 10 to 100 m. The increased sampling rate will increase the precision of velocity estimates. The smaller bin size will reduce velocity precision but increase vertical resolution.

The navigation system available now is the same one used in Green Sheet 91. Efforts will be made to upgrade this system into one that can avoid the intentional degradation of the GPS satellite data. This will be a critical step if the shear-advection model is to be employed in near-real-time.

NRL is presently developing a simple Tow-Yo CTD package. This system would be invaluable for mapping a targeted isotherm in the three by five kilometer box designated for the dye deployment. Adding an optical sensor to the CTD could also help future experiments. This system would be smaller and easier to deploy than the Arete fish and the two systems should compliment each other.

A general CTD capability, to be used on the large scale survey prior to the deployment site selection will also be available.

REFERENCES:

1. Dugan, J, M. Lents, W. Martin, W. Morris, and K. Vierra, 1991. Green Sheet Engineering/Ambient Test Plan. Arete Associates Report No. ARE-199-056-TR. P.O. Box 16297, Arlington, VA, 22215. 81 pp.

Gulf of Mexico
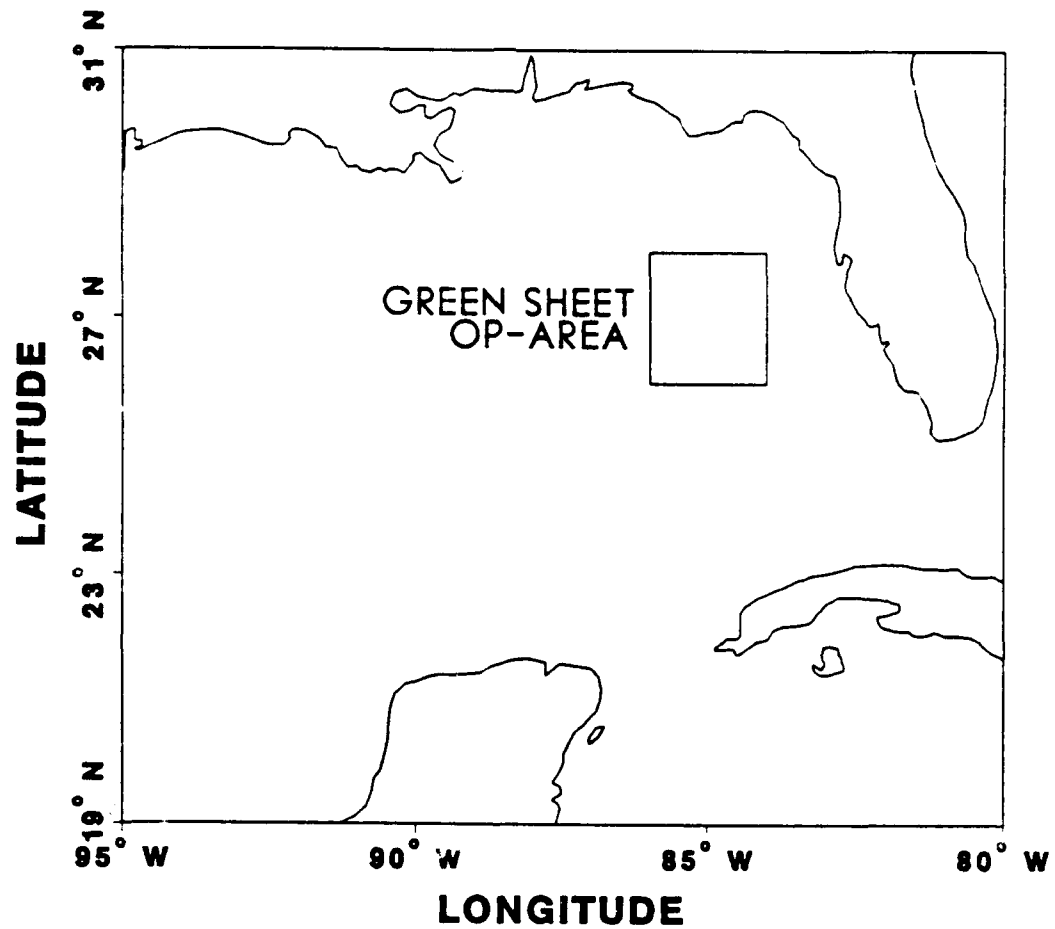
FIGURE 1   Map of Gulf of Mexico showing the Green Sheet operations
area.
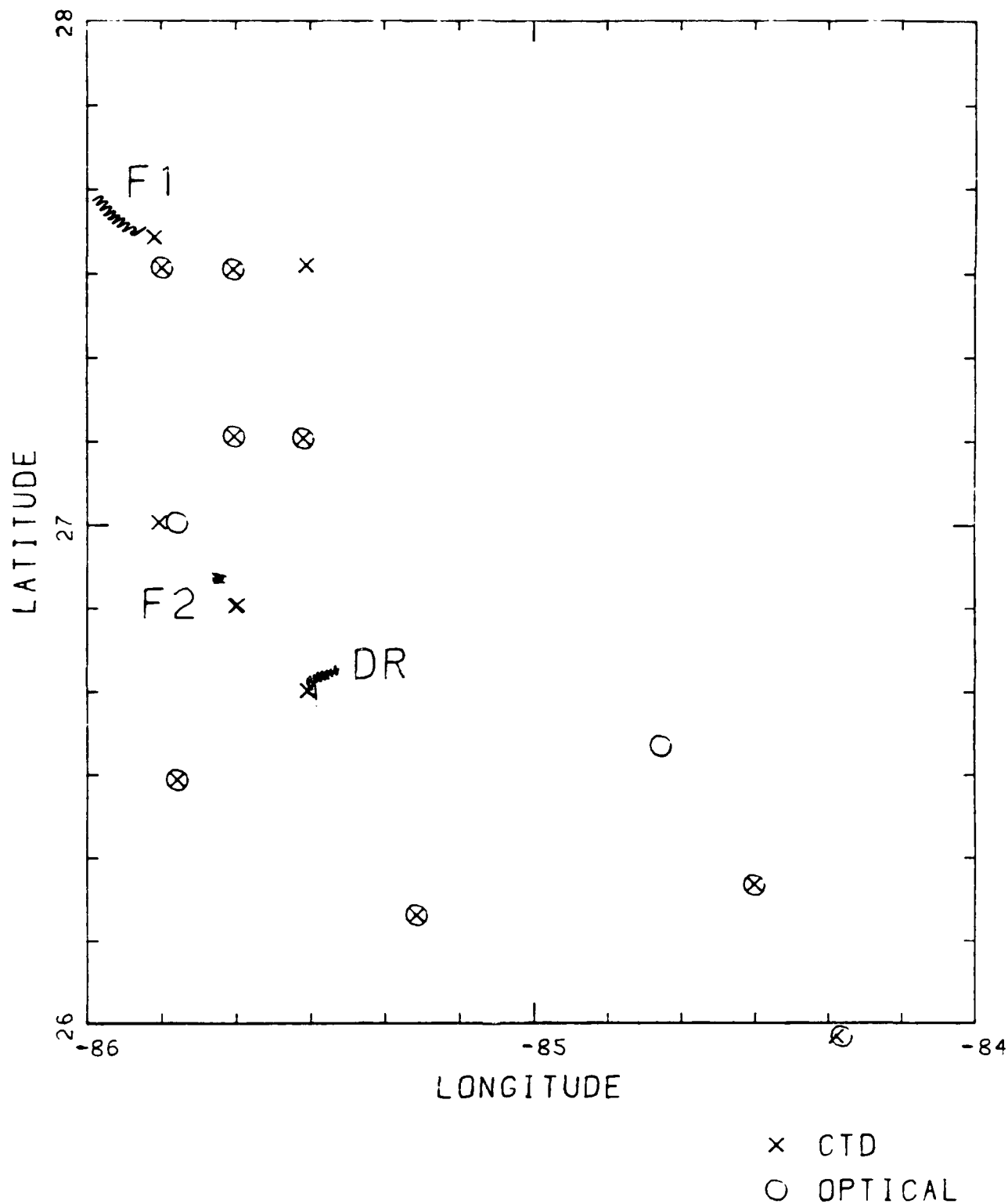
FIGURE 2 Green Sheet operations area showing locations of CTD casts (X), optical casts (O), and ship's track during the three dye deployments (labeled DR for Dress Rehearsal, F1 for Flight One, and F2 for Flight Two).

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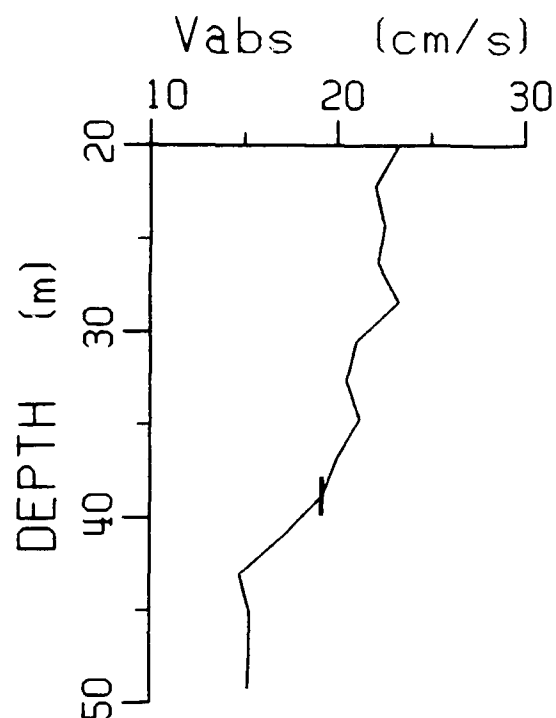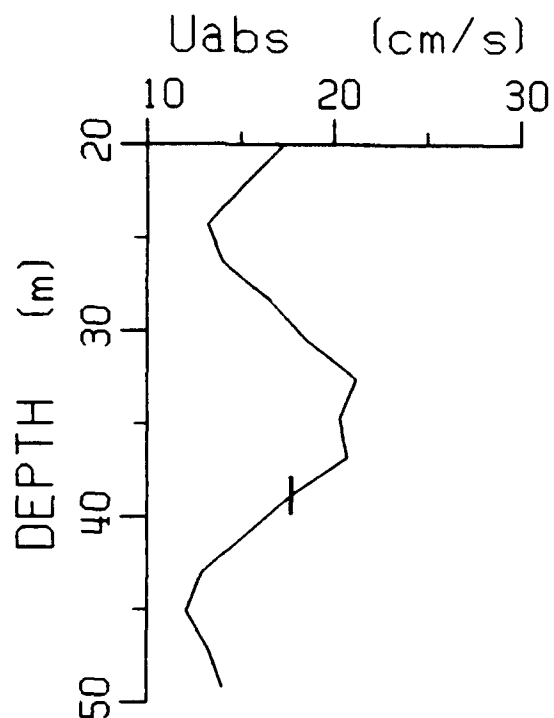
INPUT PARAMETERS

BIN   = 15
DEPTH = 38.3 m
TIME 1 = 1811
TIME 2 = 1823

MODEL PARAMETERS

LAT 1 = 26.706 dN
LON 2 = 84.528 dW
LAT 1 = 26.690 dN
LON 2 = 84.529 dW
U sh = 19.2 cm/s
U dp = 16.5 cm/s
V sh = 19.6 cm/s
V dp = 17.7 cm/s

FIGURE 3   Average profile and shear-advection model parameters
associated with one dye leg of the Dress Rehearsal
deployment. See text for explanation.
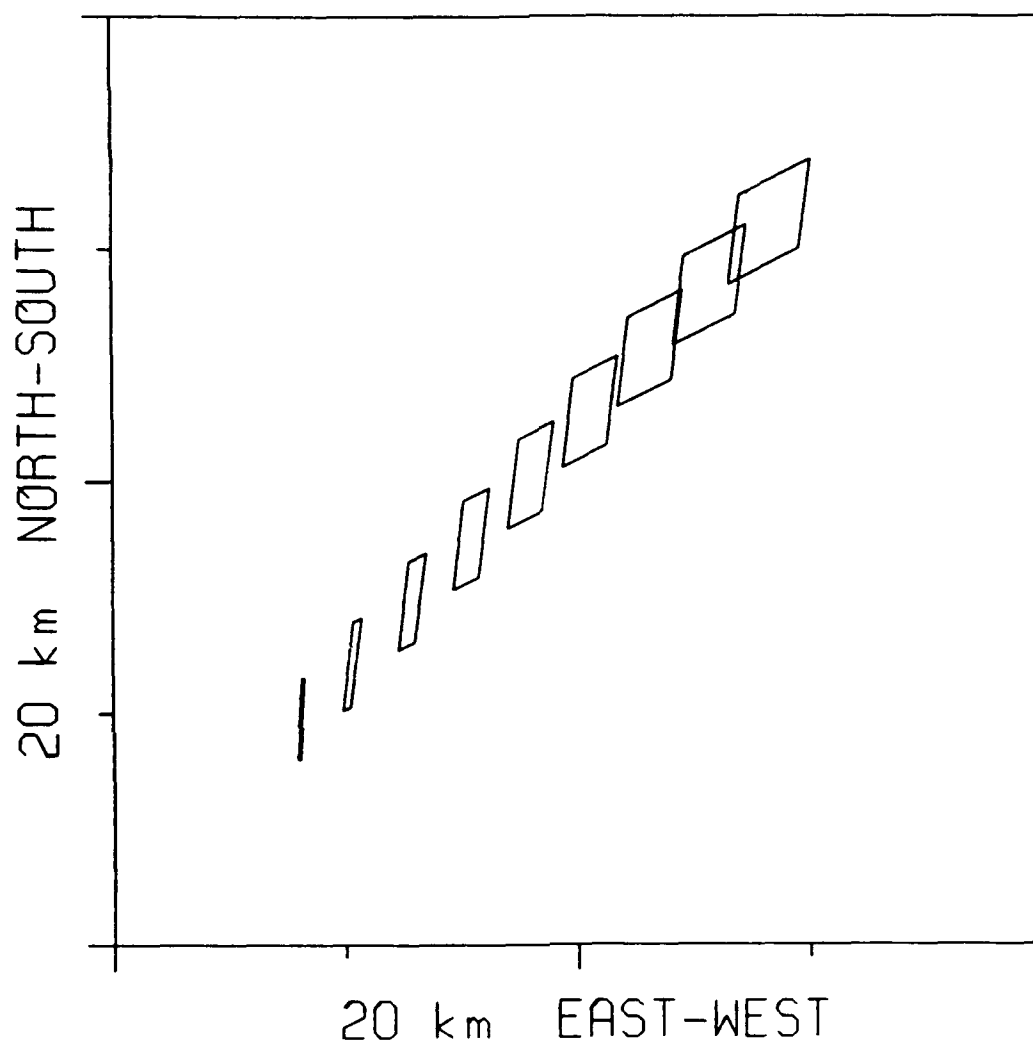
FIGURE 4   Effect of model on dye line described in Figure 3 in
eight two-hour increments starting at JD 156, 2000 UTC.
See text for explanation.
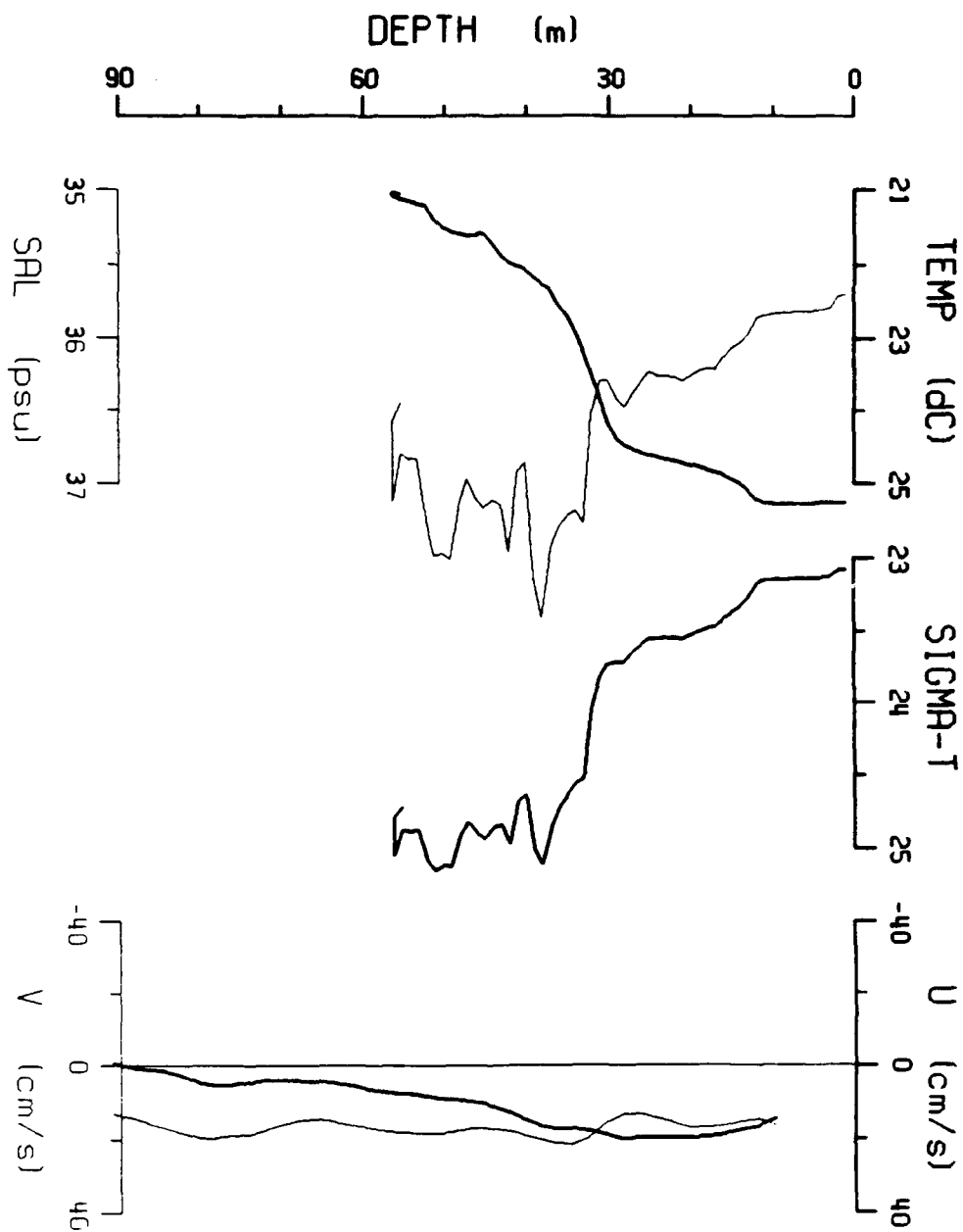
FIGURE 5   Water column data taken during Dress Rehearsal on June 5th. The CTD cast was made at 1000 UTC and the velocity profile is an average over dye deployment period (JD 156, 1420-2050 UTC).
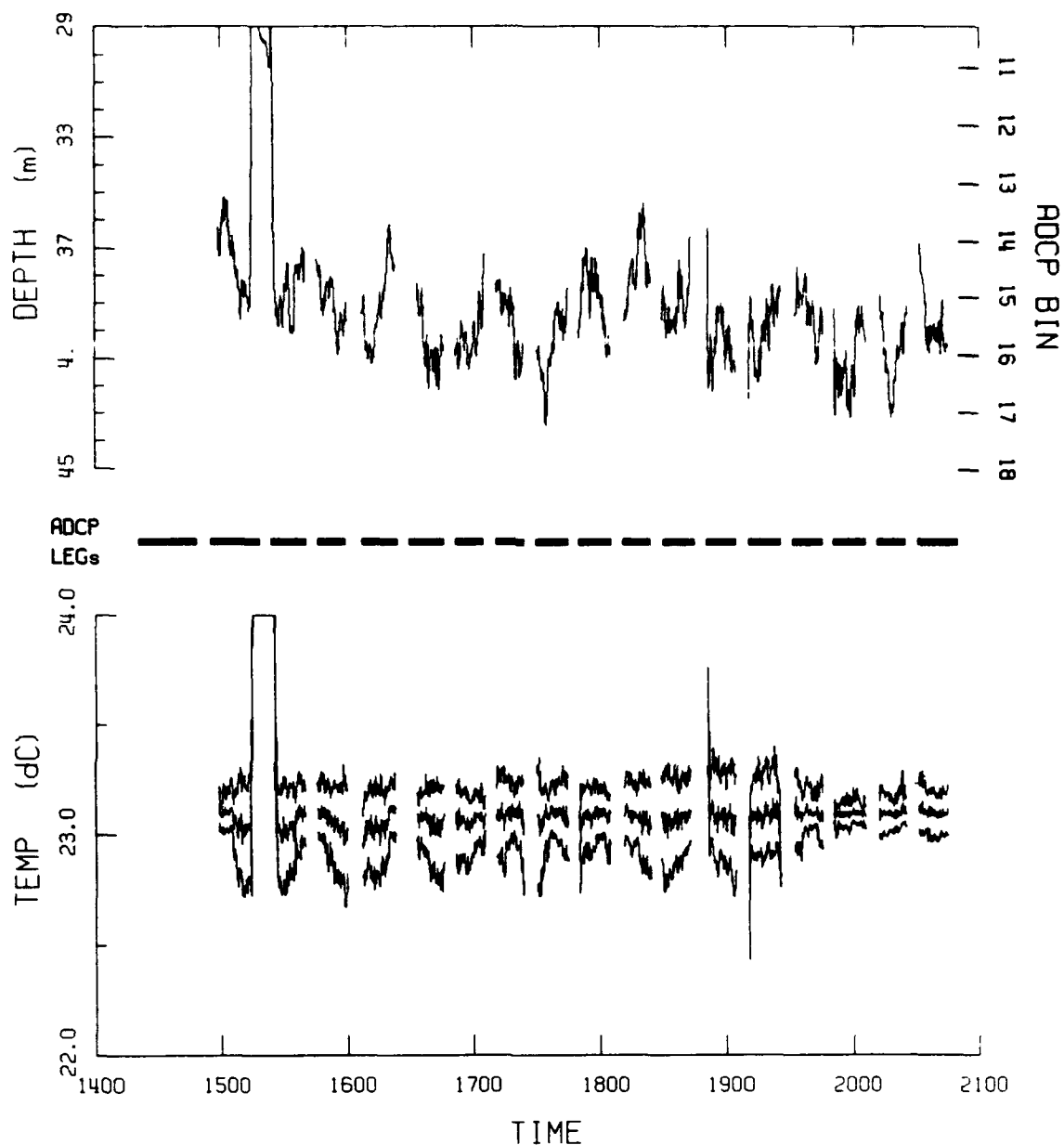
FIGURE 6   Display of Arete Fish data for Dress Rehearsal deployment
period.   Top portion shows depths at which dye was dispersed
as a function of time   Depths in meters and depths of ADCP
bins are indicated on sides.   The middle portion indicates
times of the ADCP legs (defined in the text).   Bottom
portion displays three-second average temperatures
recorded on the three fish sensors.

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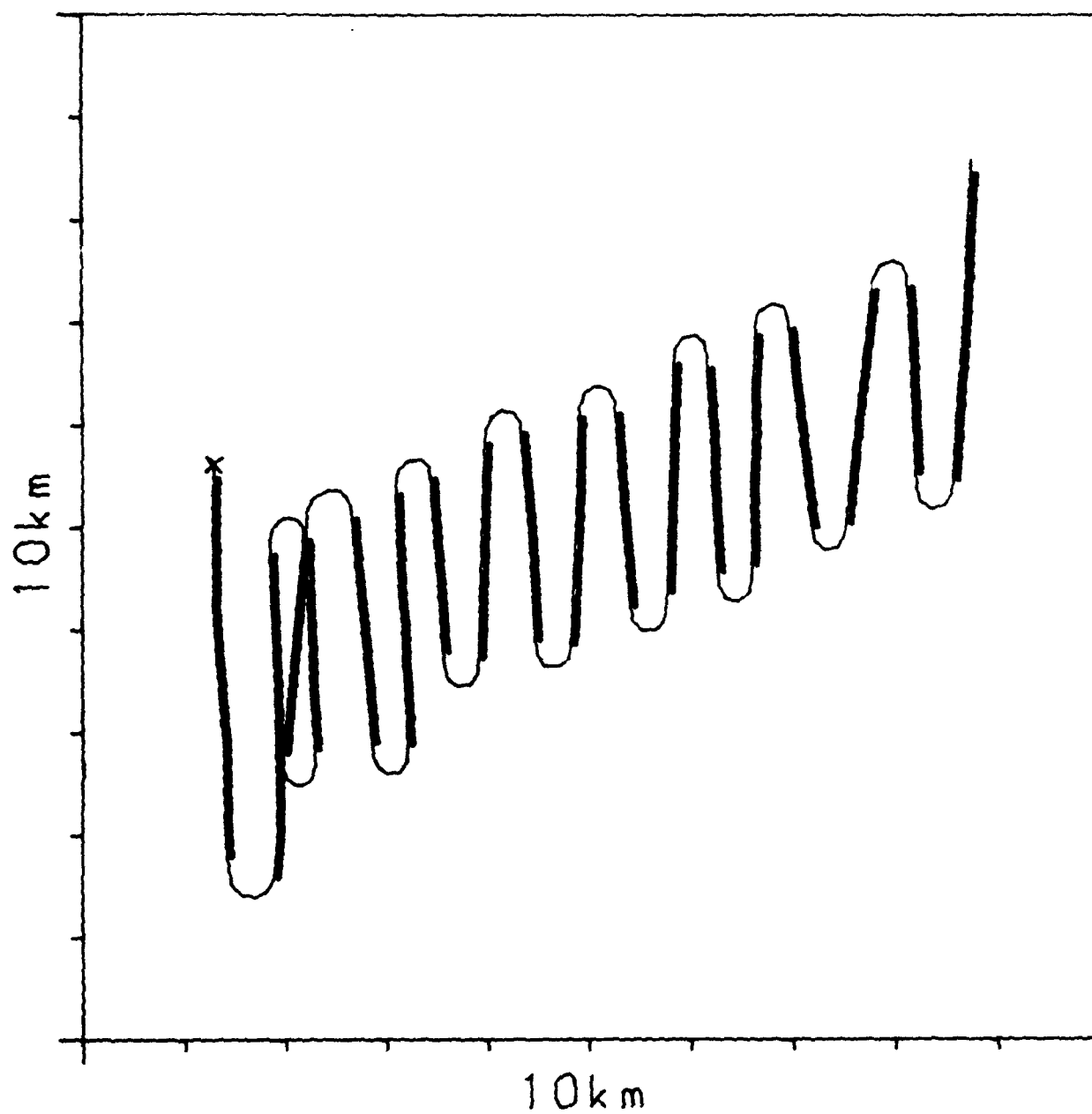
× START

FIGURE 7 Ship's track relative to the Earth for the Dress Rehearsal
deployment period (JD 156, 1420-2050 UTC). An asterisk
denotes the start position and emphasized segments denote
the ADCP legs (defined in the text).

10km

10km

× START
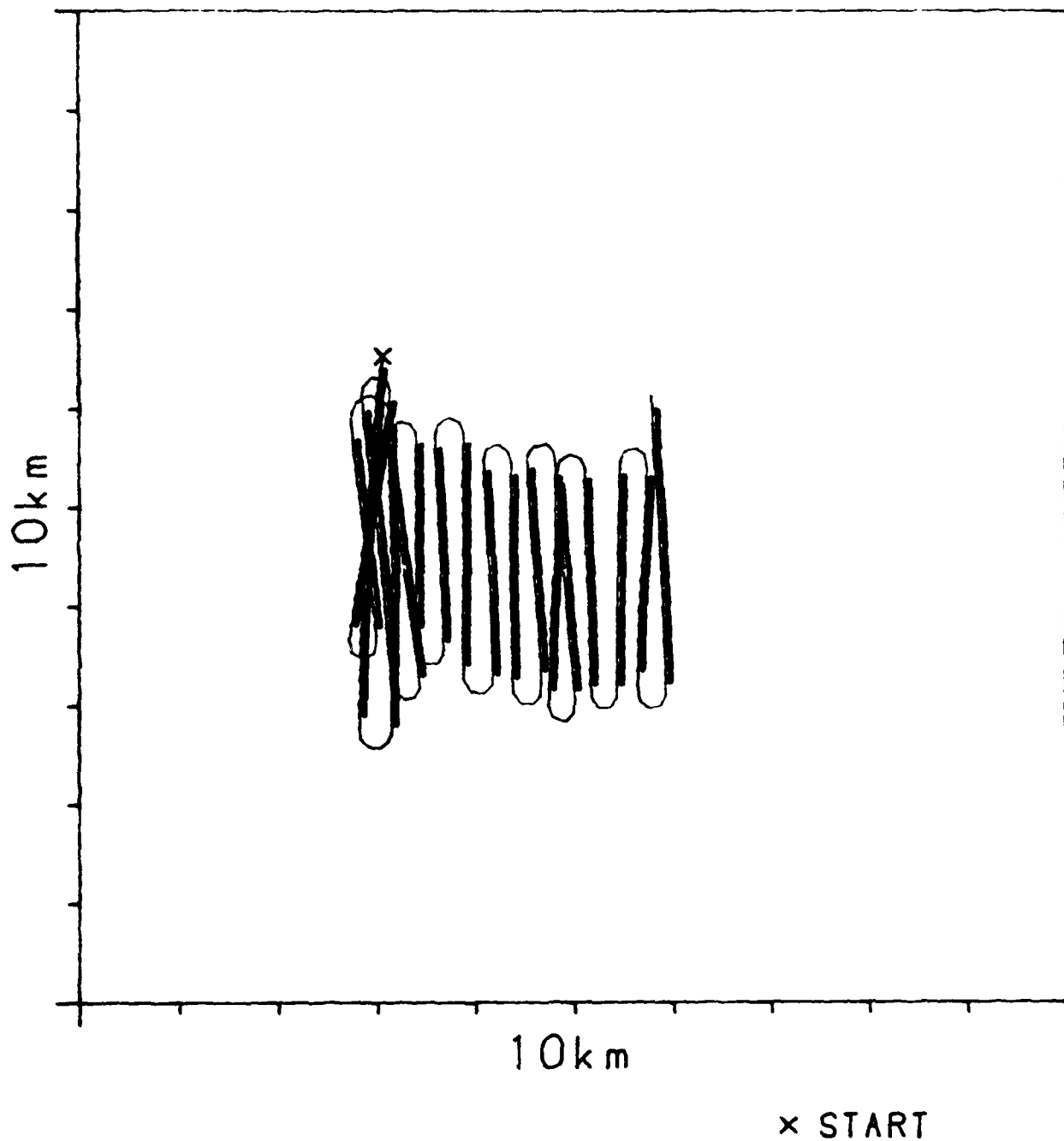
FIGURE 8   Ship's track relative to water at depth 38.8 m for the Dress
Rehearsal deployment period (JD 156, 1420-2050 UTC).   This
figure is similar to Figure 6 except the track is relative
to a water layer instead of to the Earth.
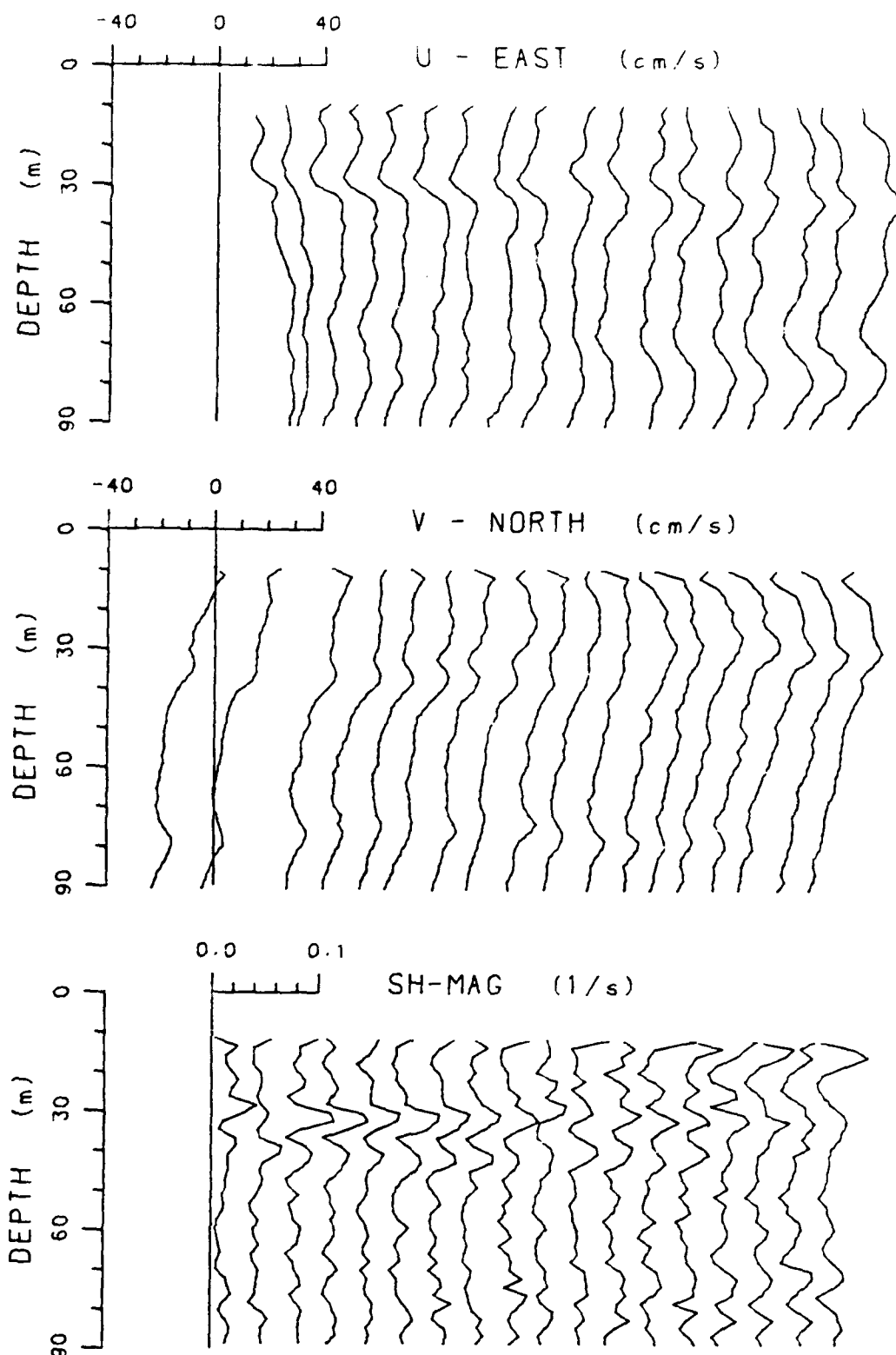
FIGURE 9 Waterfall plot of leg-average velocity and shear-magnitude profiles for Dress Rehearsal deployment period. Each velocity component profile is offset from the previous one by 13.33 cm/s and each shear profile is offset by .033 1/s.

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SHIPs TRACK wrt WATER AT 38.8m

10km

10km

× START
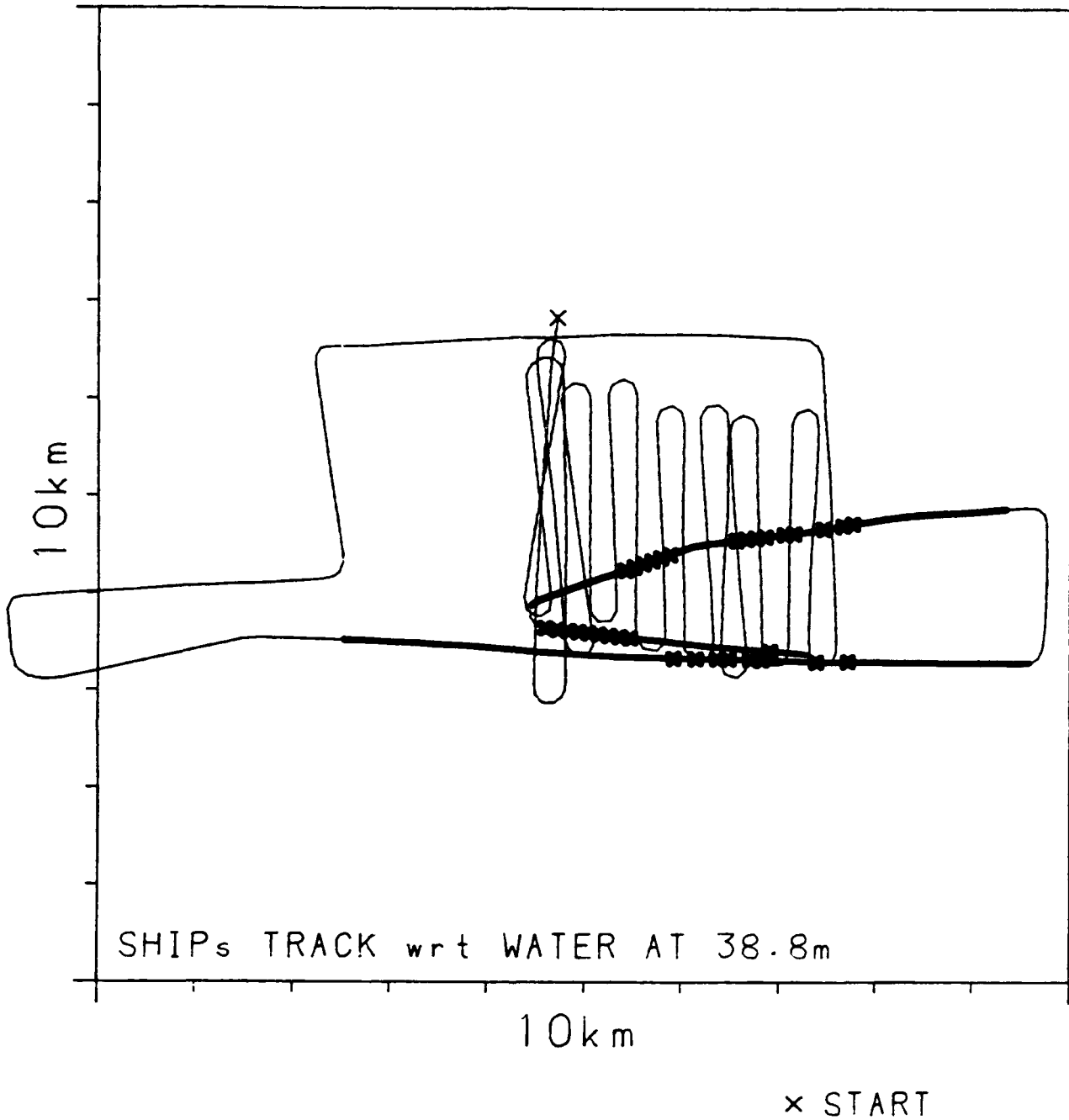
FIGURE 10   Ship's track relative to water at depth 38.8 m for the
             Dress Rehearsal deployment plus early dye assessment period
             (JD 156, 1420-2400 UTC). The ship's track is emphasized
             during periods when assessment data were collected and x's
             mark minutes when dye was noted on sensor #3.

FIGURE 11   Multiple versions similar to Figure 10 showing ship's tracks relative to the water at twelve depth bins starting at 26.3 m and moving in 2.1 m intervals to 49.2 m. Dye hits on sensor #3 are denoted by x's.

SHIPs TRACK wrt WATER AT 38.8m

10km

10km

50 cm/s
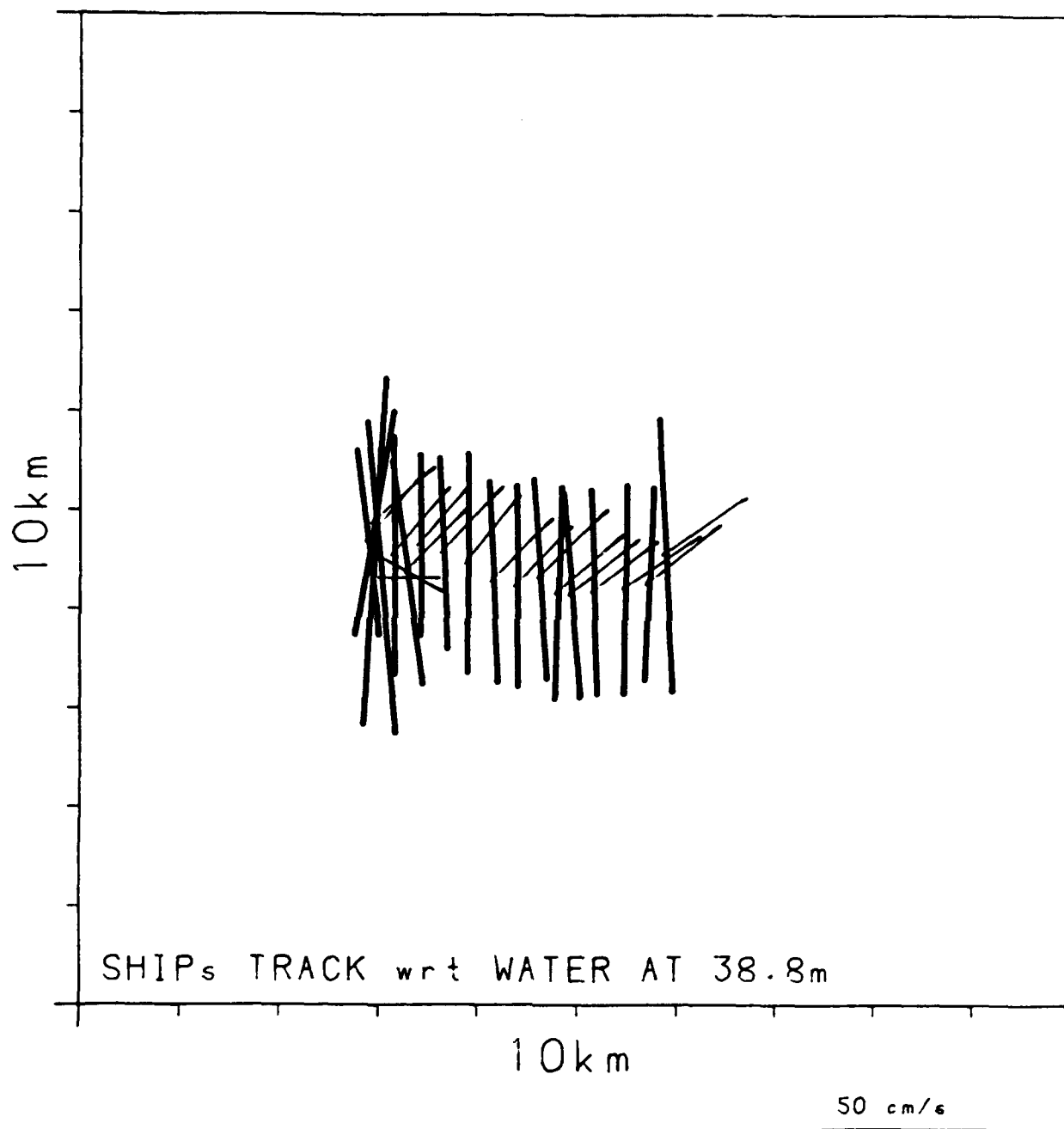
FIGURE 12   Initial positions of each ADCP leg for Dress Rehearsal
             deployment relative to the water at 38.8 m. At the center
             of each leg is a vector denoting the absolute velocity at
             38.8 m averaged over the entire leg. A speed scale is
             located in the lower right corner of the plot. North is
             toward the top of the page.
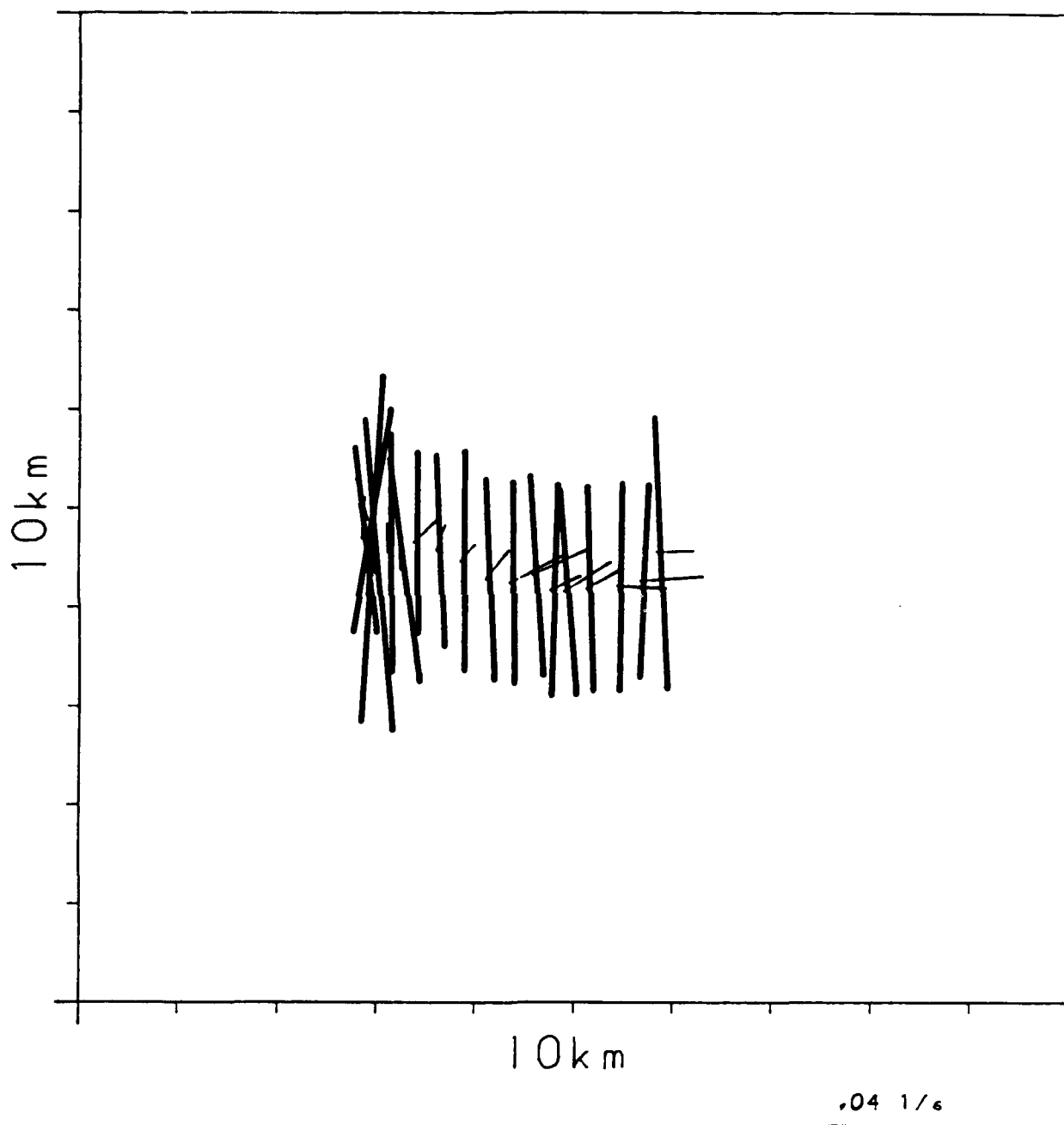
FIGURE 13 Like Figure 12 except the average shear at 38.8 m is shown.
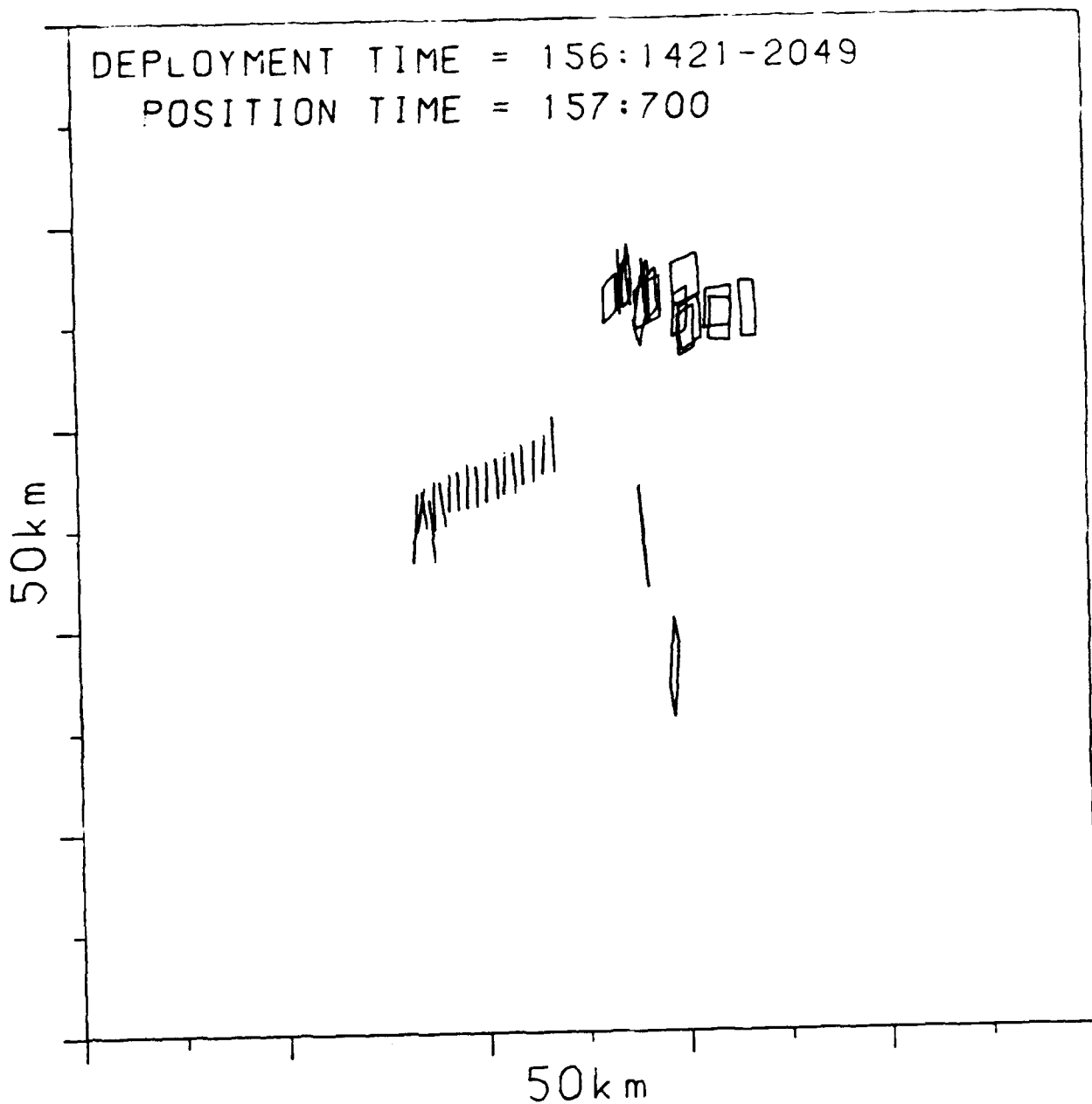
FIGURE 14   The result of the shear-advection model on the Dress
             Rehearsal dye sheet.   This Figure is explained in the text.
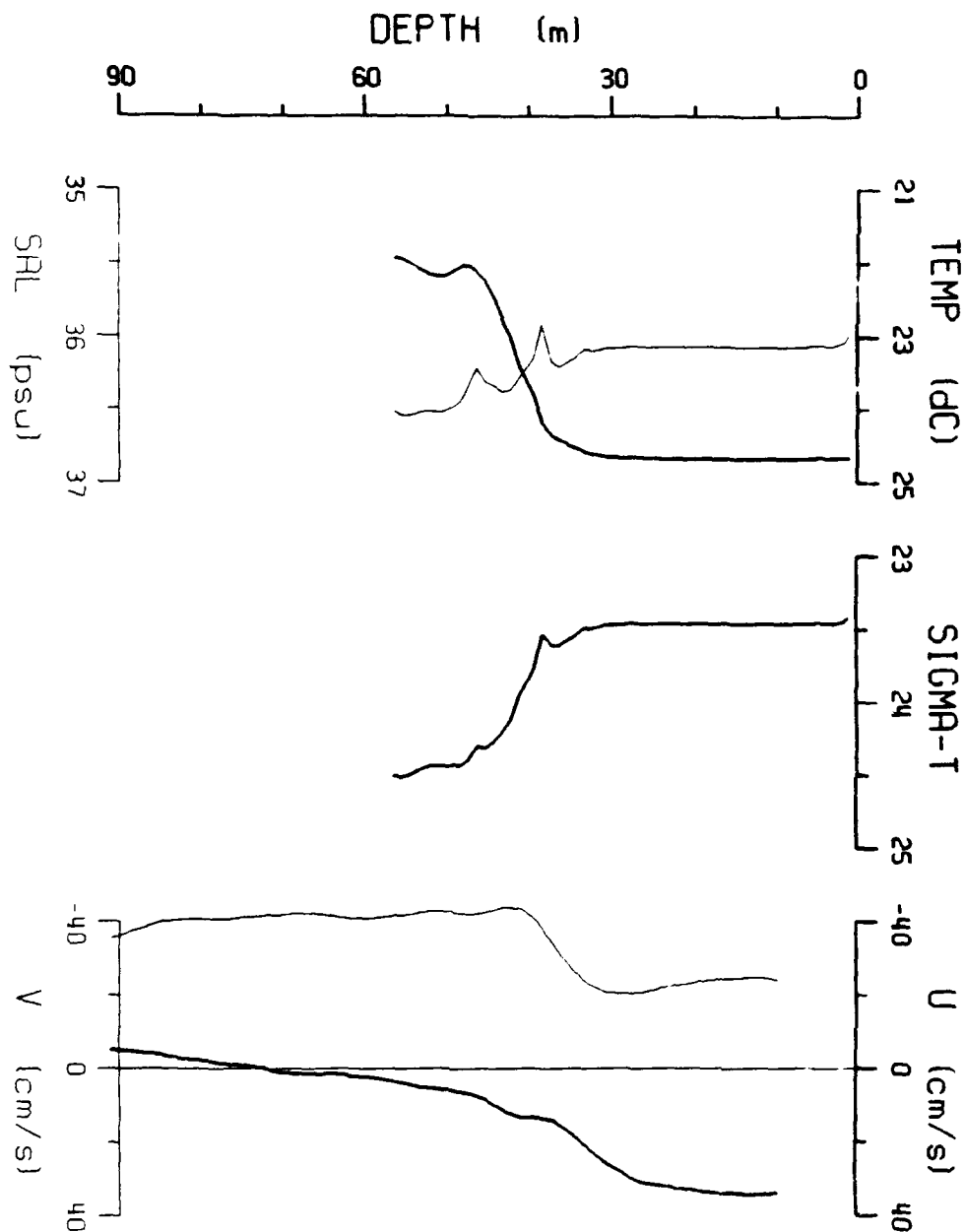
FIGURE 15 Water column data taken during Flight One on June 8th. The CTD cast was made at 1000 UTC and the velocity profile is an average over dye deployment period (JD 159, 1418-2005 UTC).
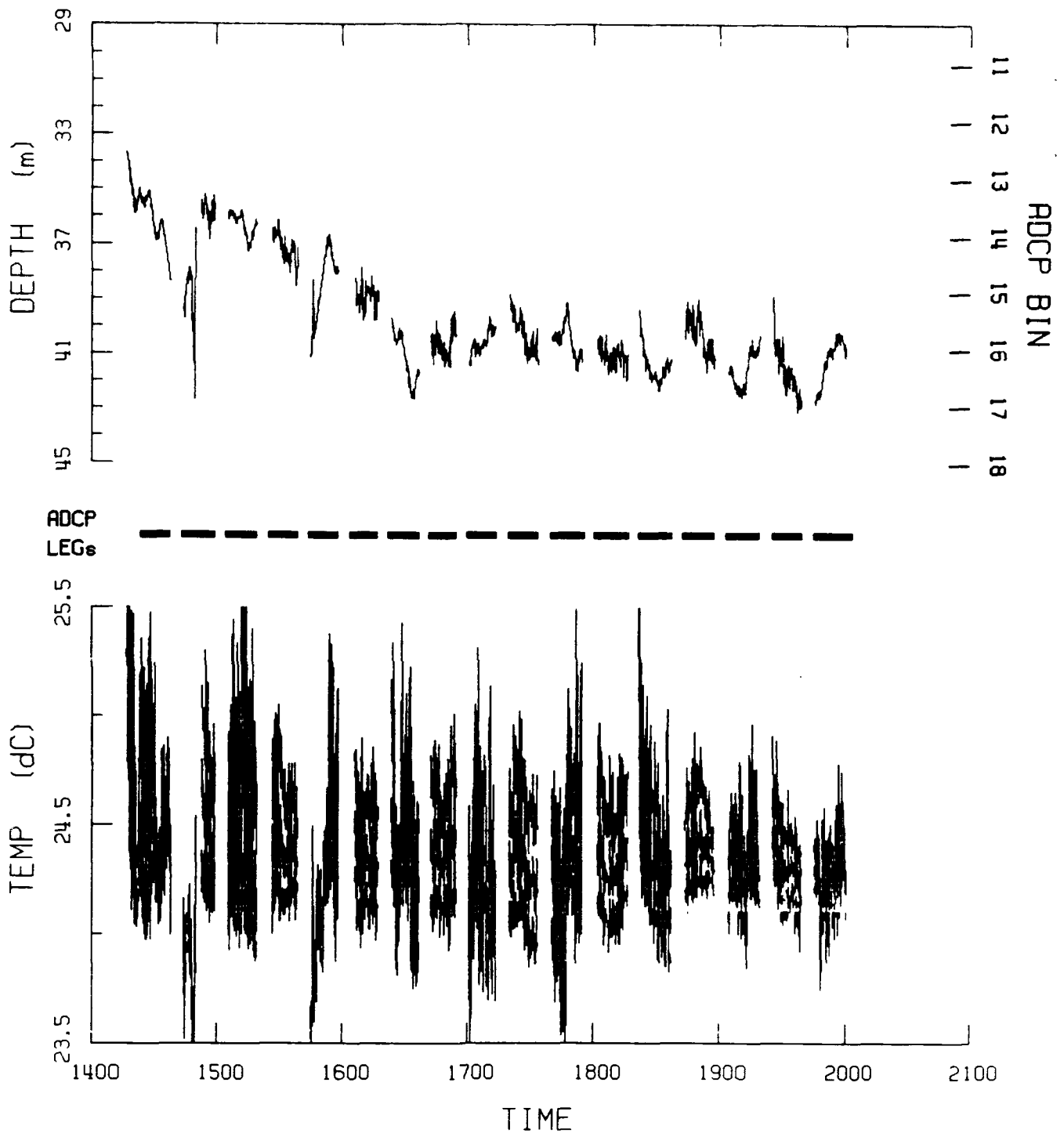
FIGURE 16   Display of Arete Fish data for Flight One deployment
            period.   Top portion shows depths at which dye was
            dispersed as a function of time.   Depths in meters and
            depths of ADCP bins are indicated on sides.   The middle
            portion indicates times of the ADCP legs.   Bottom portion
            displays three-second average temperatures recorded on
            the fish sensors.
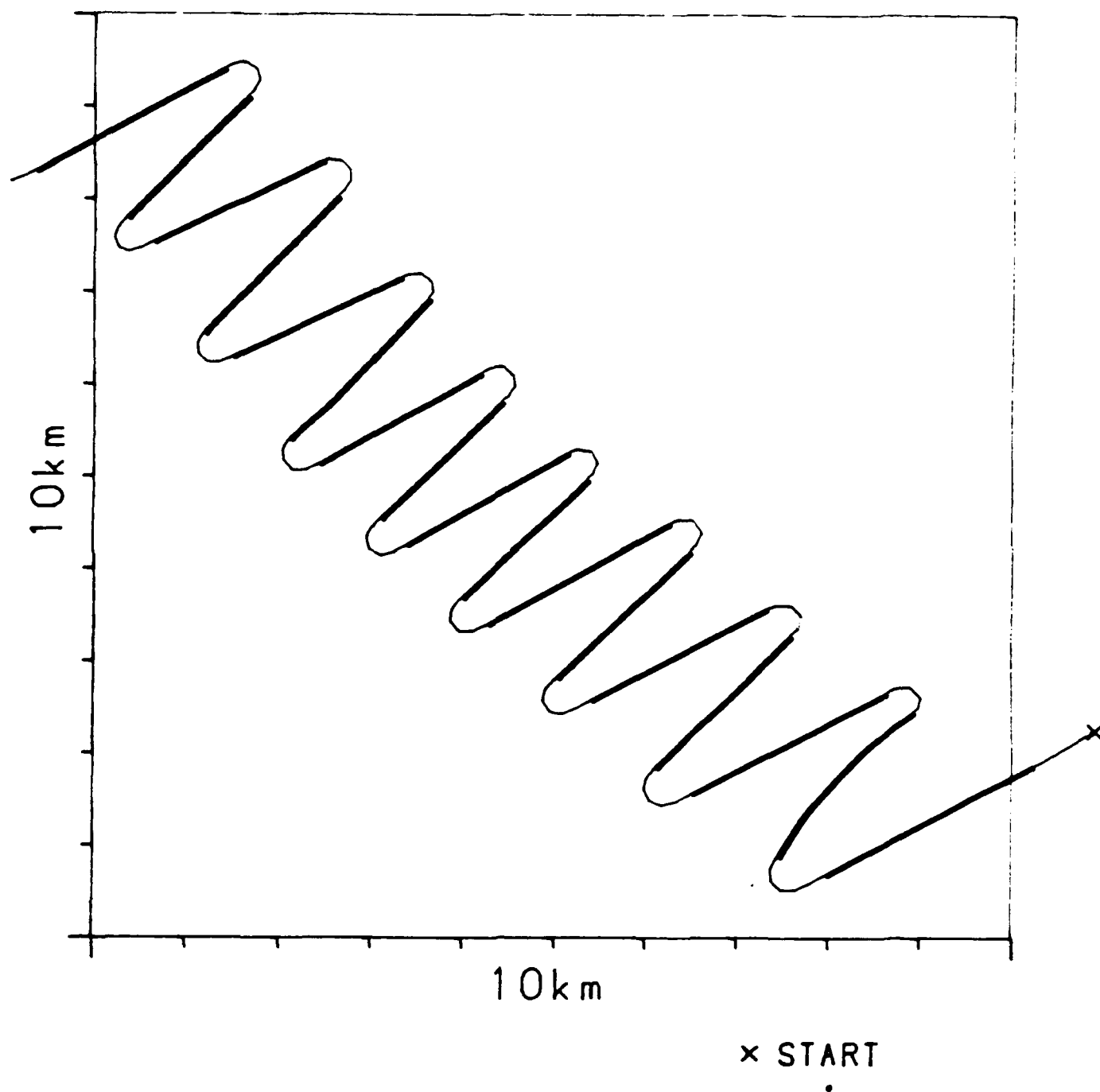
× START

FIGURE 17   Ship's track relative to the Earth for the Flight One
             deployment period (JD 159, 1418-2005 UTC). An asterisk
             denotes the start position and emphasized segments denote
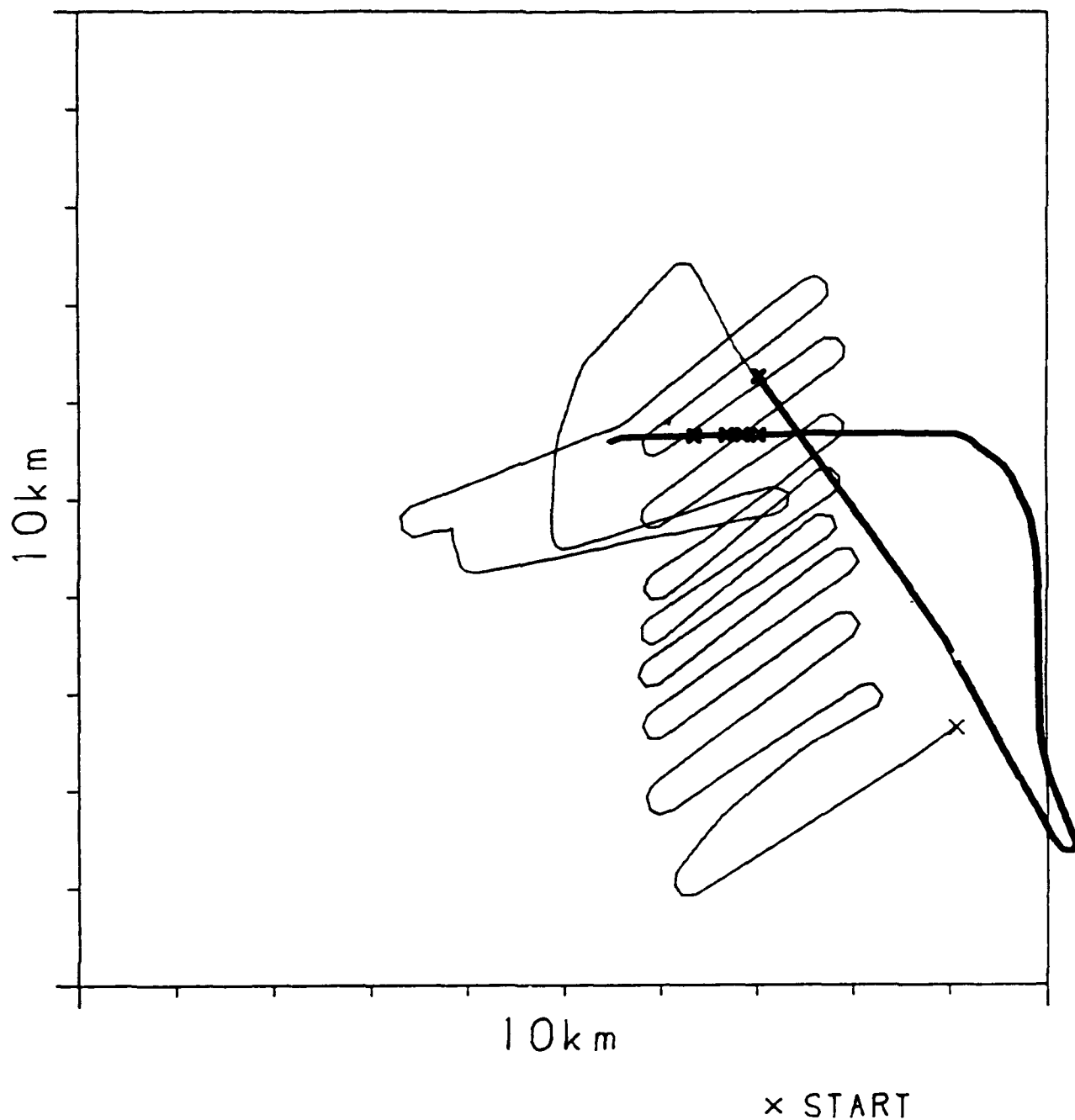   the ADCP legs.

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x START
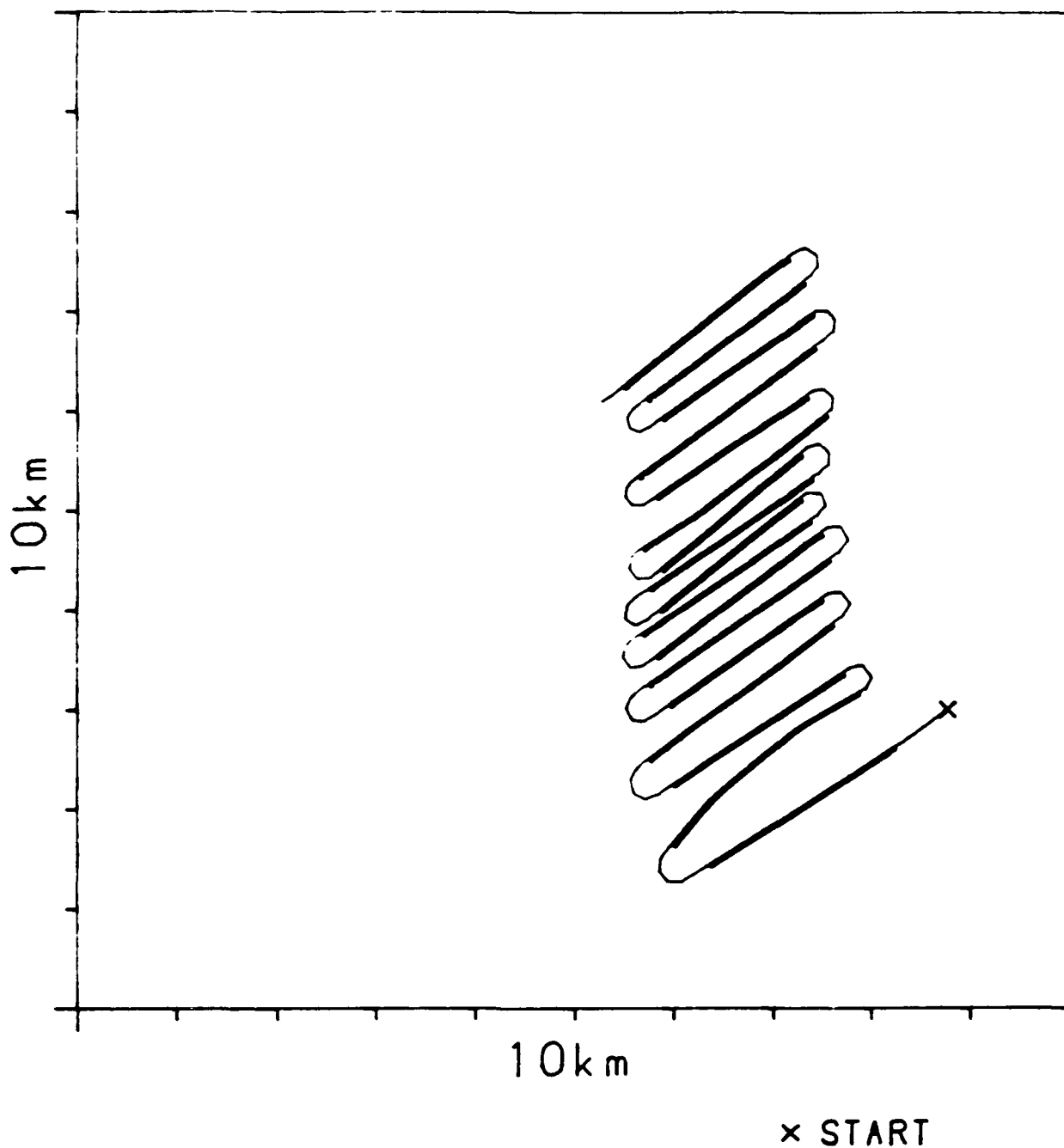
FIGURE 18   Ship's track relative to water at depth 38.8 m for the
             Flight One deployment period (JD 159, 1418-2005 UTC). This
             figure is similar to Figure 17 except that the track is
             relative to a water layer instead of to the Earth.
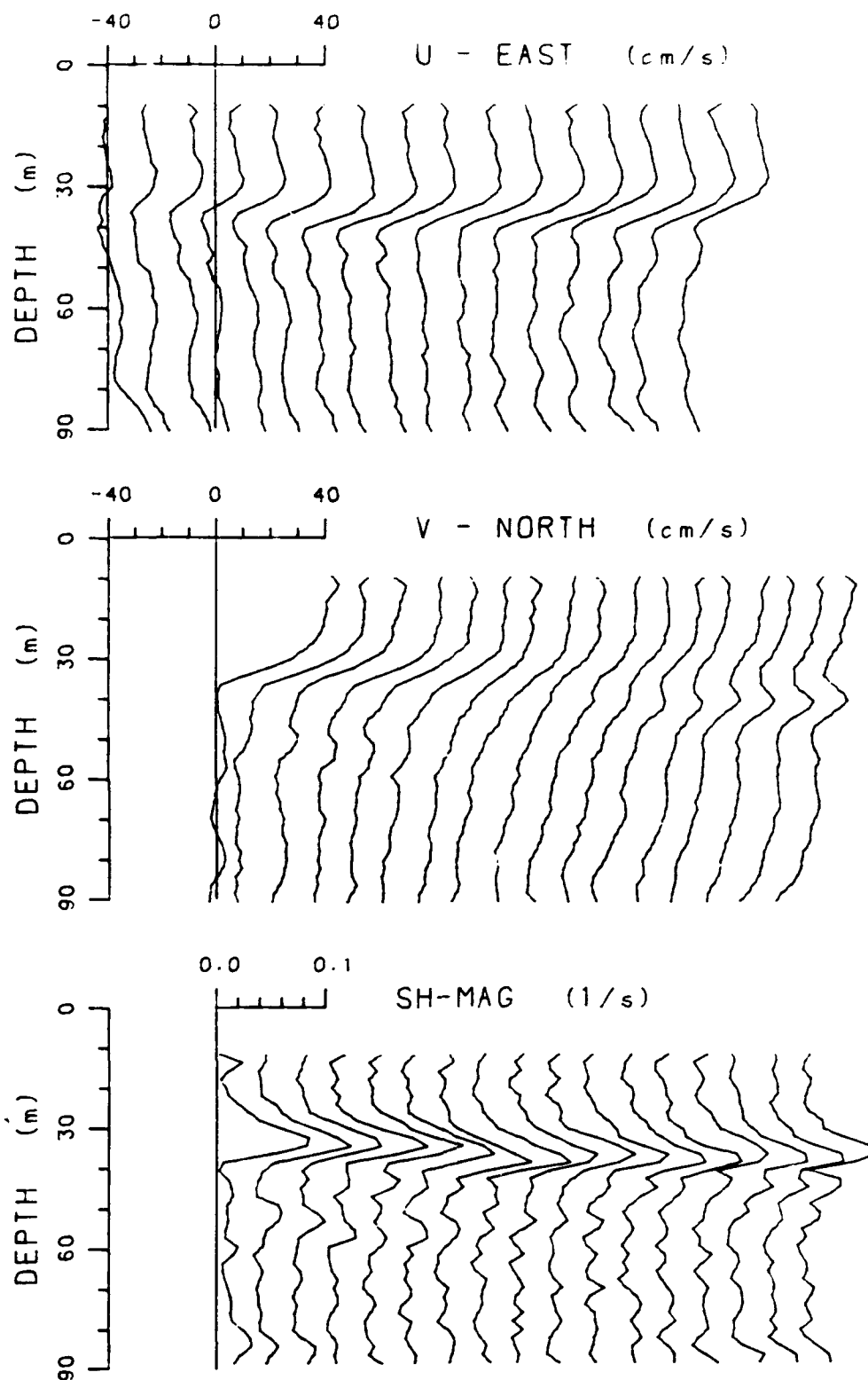
FIGURE 19   Waterfall plot of leg-average velocity and shear-magnitude
profiles for Flight One deployment period.   Each velocity
component profile is offset from the previous one by
13.33 cm/s and each shear profile is offset by .033 1/s.

41

× START

FIGURE 20   Ship's track relative to water at depth 38.8 m for the
             Flight One deployment plus early dye assessment period
             (JD 156, 1418-2330 UTC).   The ship's track is emphasized
             during periods when assessment data was collected and
             x's mark minutes when dye was noted on sensor #3.
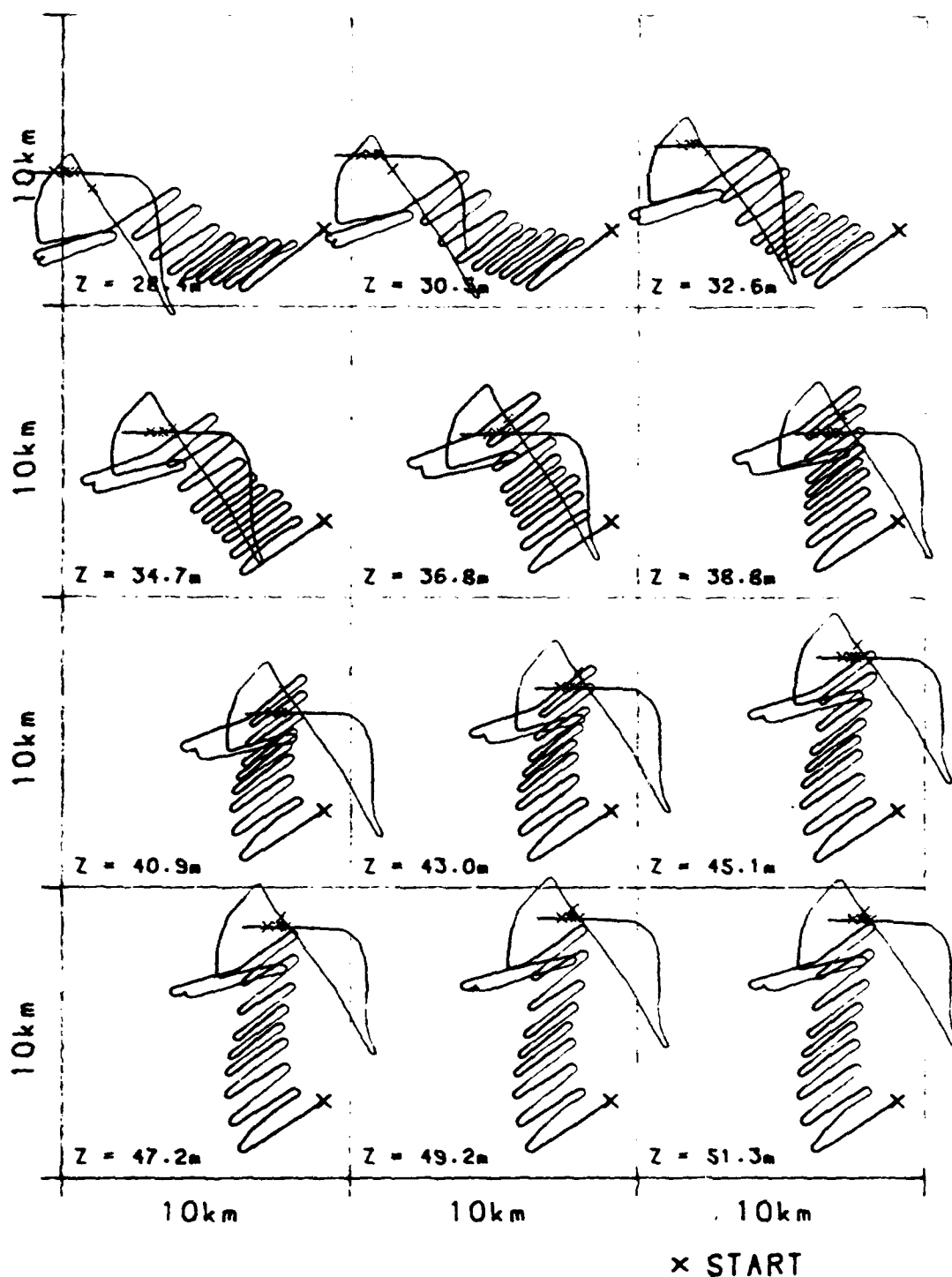
FIGURE 21 Multiple versions of Figure 20 showing ship's tracks
relative to the water at twelve depth bins starting at
28.4 m and moving in 2.1 m intervals to 51.3 m. Dye hit:
on sensor #3, are denoted with x's.
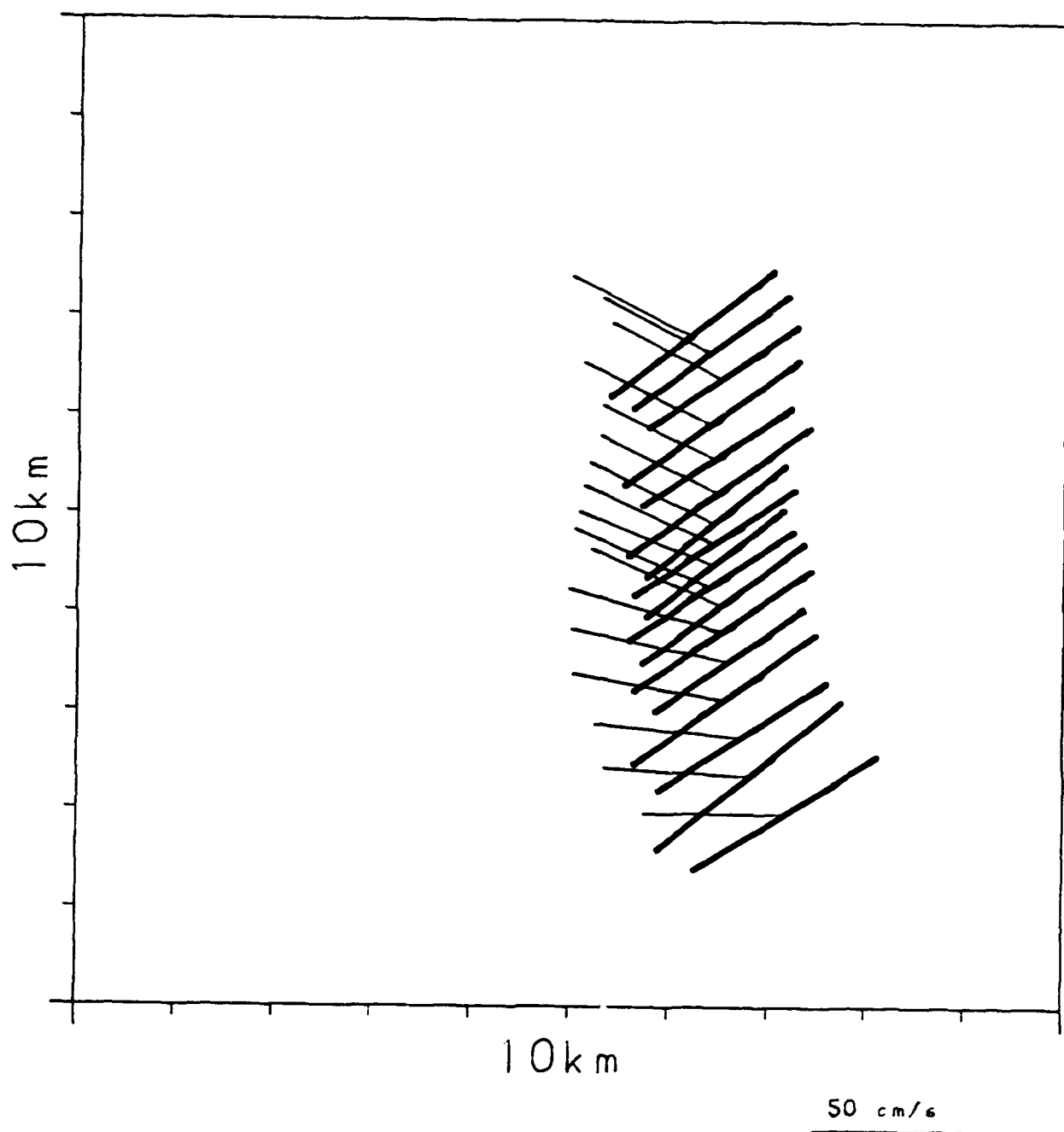
FIGURE 22   Initial positions of each ADCP leg for Flight One
deployment relative to the water at 38.8 m.   At the center
of each leg is a vector denoting the absolute velocity at
38.8 m averaged over the entire leg.   A speed scale is
located in the lower right corner of the plot.   North is
toward the top of the page.
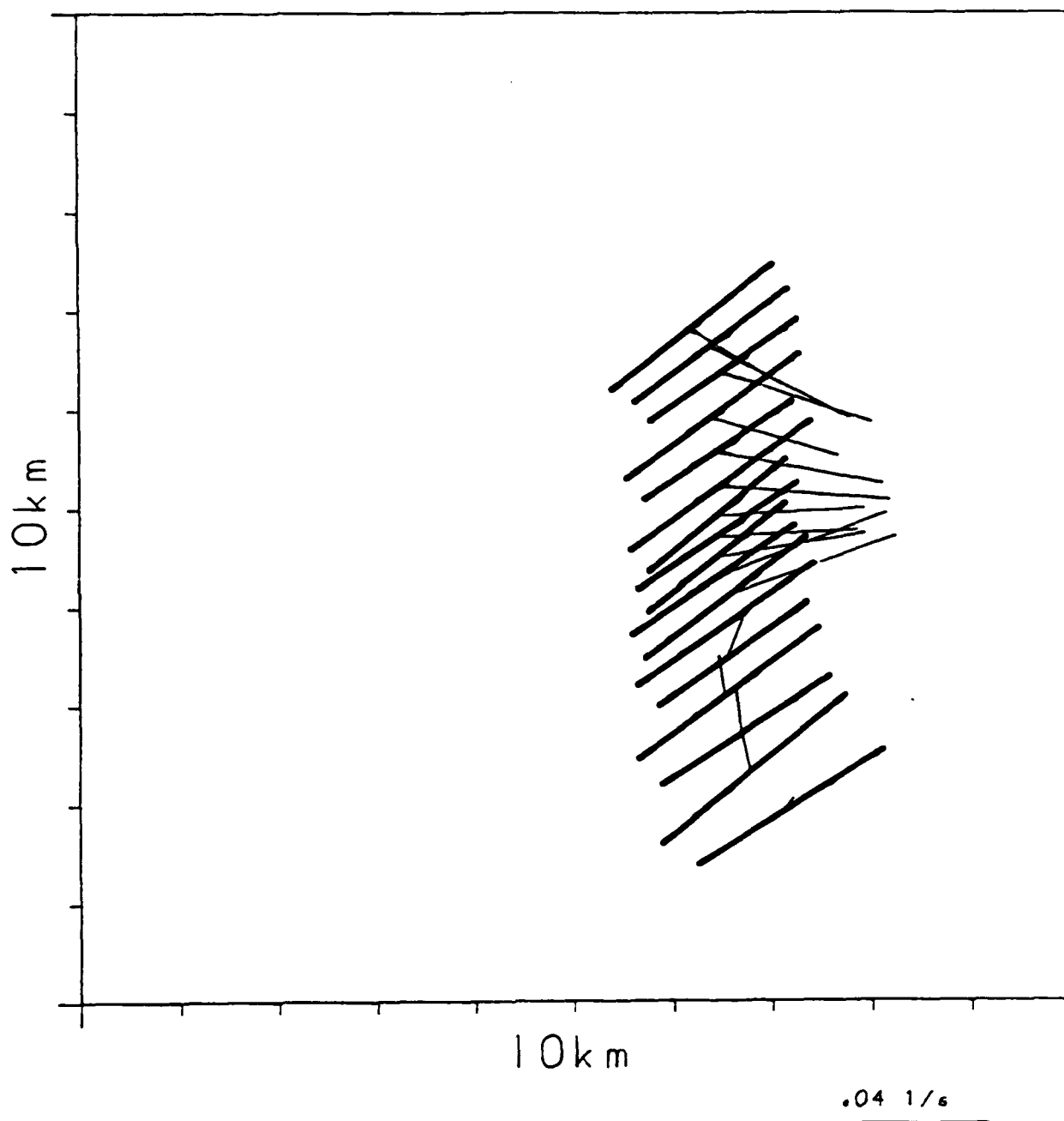
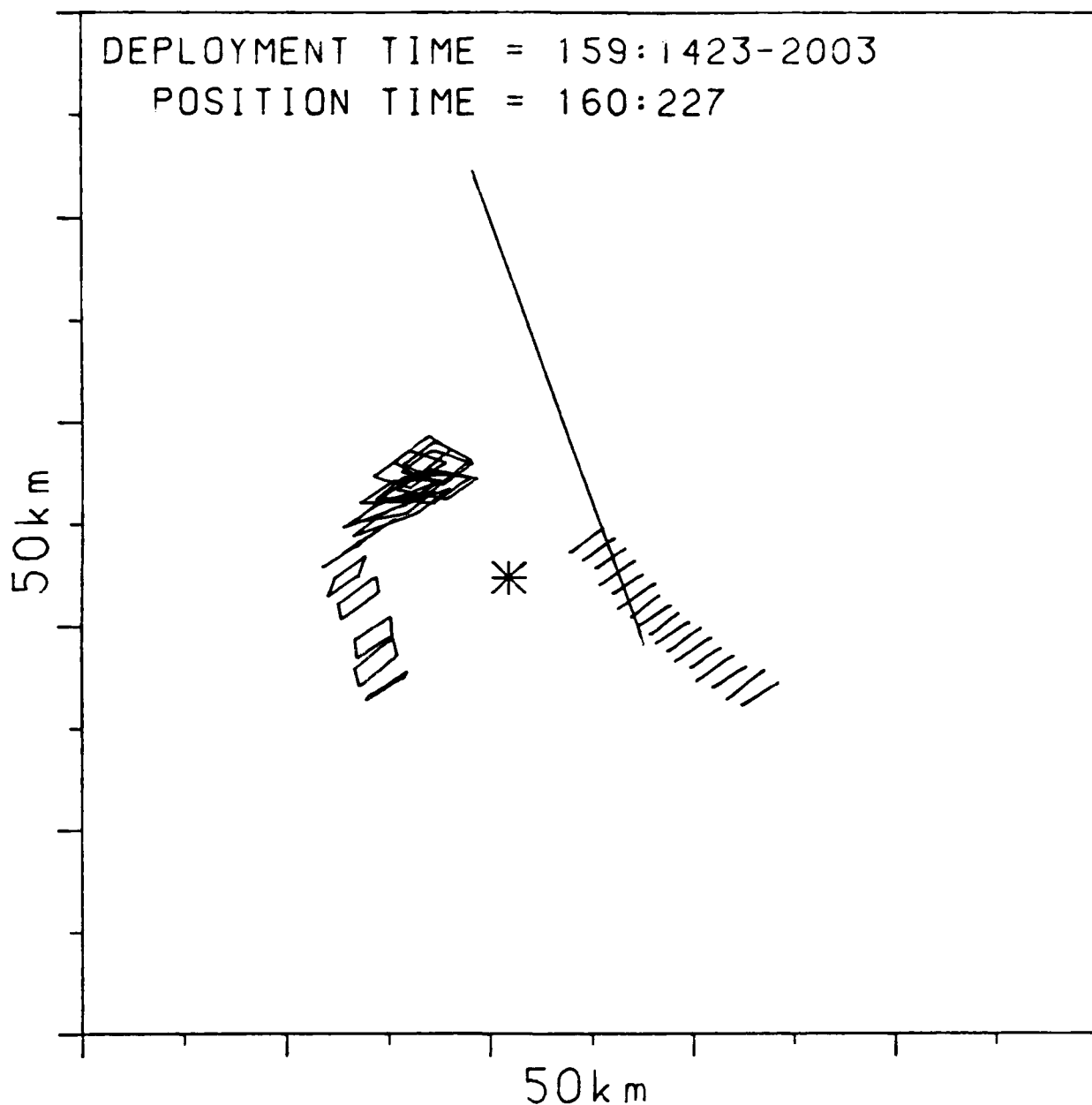FIGURE 23   Like Figure 22 except the average shear at 38.8 m is shown.

FIGURE 24   The result of the shear-advection model on the Flight One
dye sheet at the time of LIDAR pass 240 (JD 160, 0227 UTC).
Model applied to depth bin 15 at 38.8 m. Ship's position
at that time is indicated by asterisk. The flight path,
according to plane's inertial navigation, is indicated by
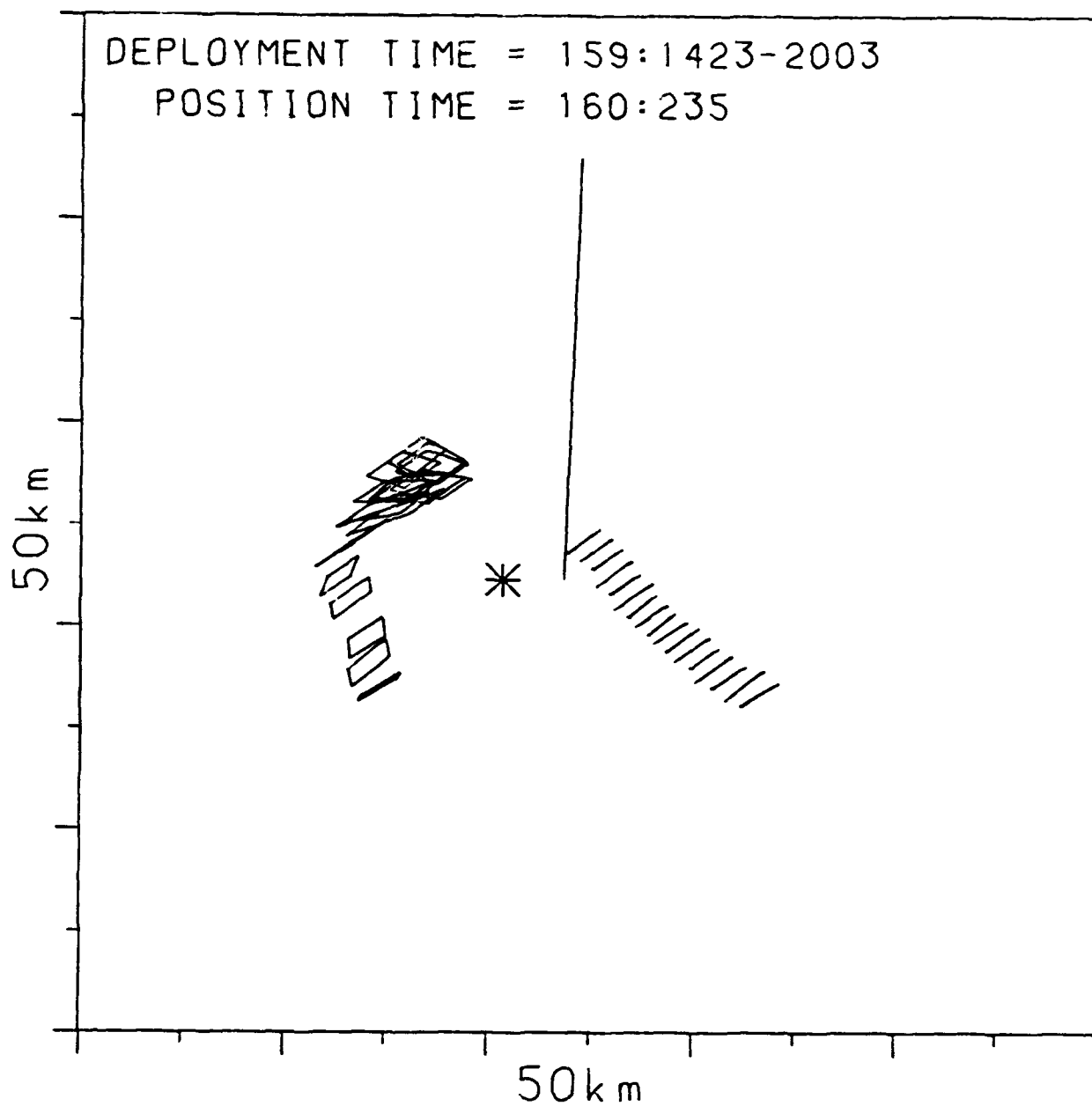the straight line. See text for more detail.

DEPLOYMENT TIME = 159:1423-2003
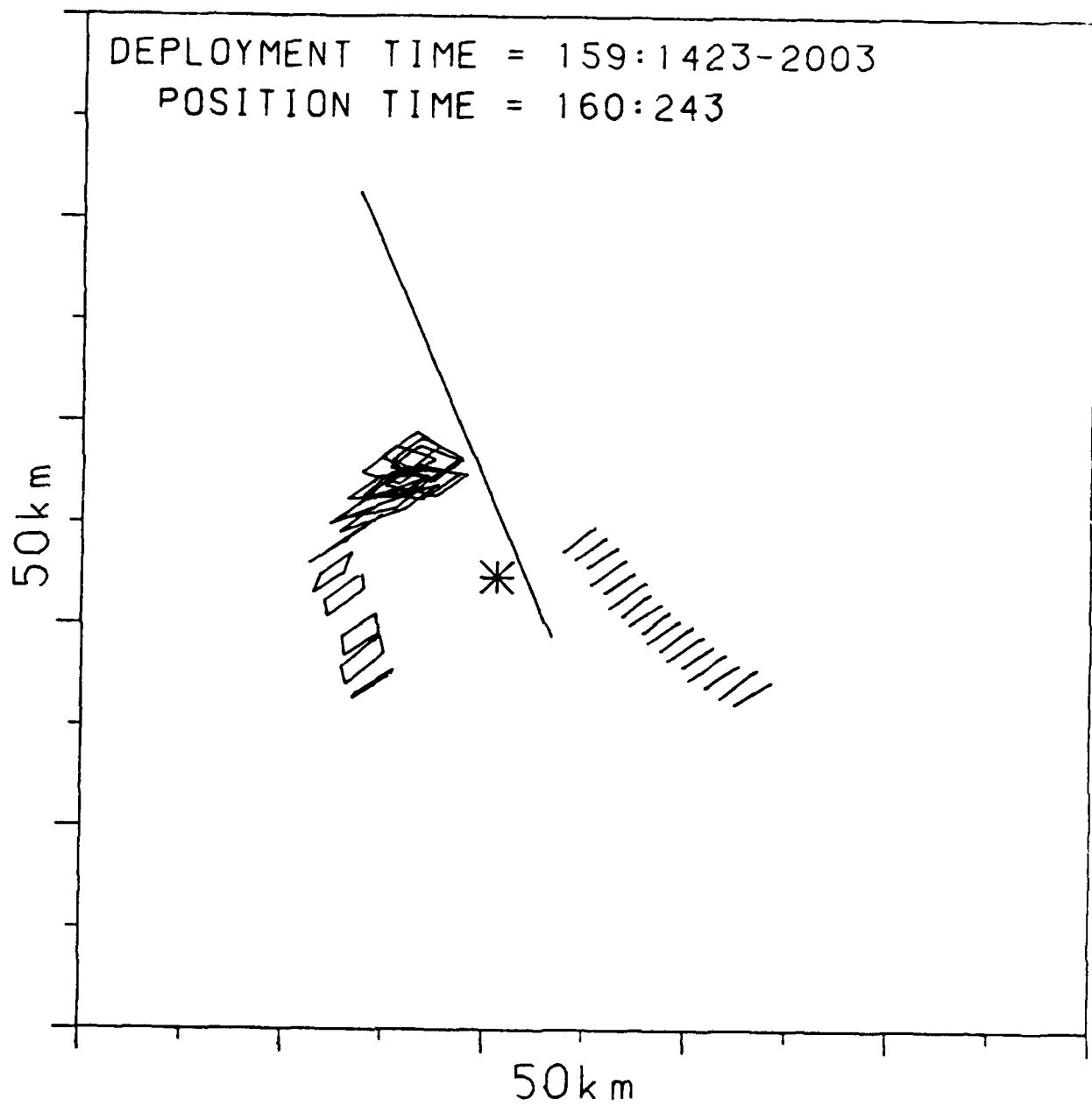 POSITION TIME = 160:235

FIGURE 25   Same as Figure 24 except for time of LIDAR pass 241
             (JD 160, 0235 UTC).   Depth model applied to is 38.8 m.

FIGURE 26   Same as Figure 24 except for time of LIDAR pass 242
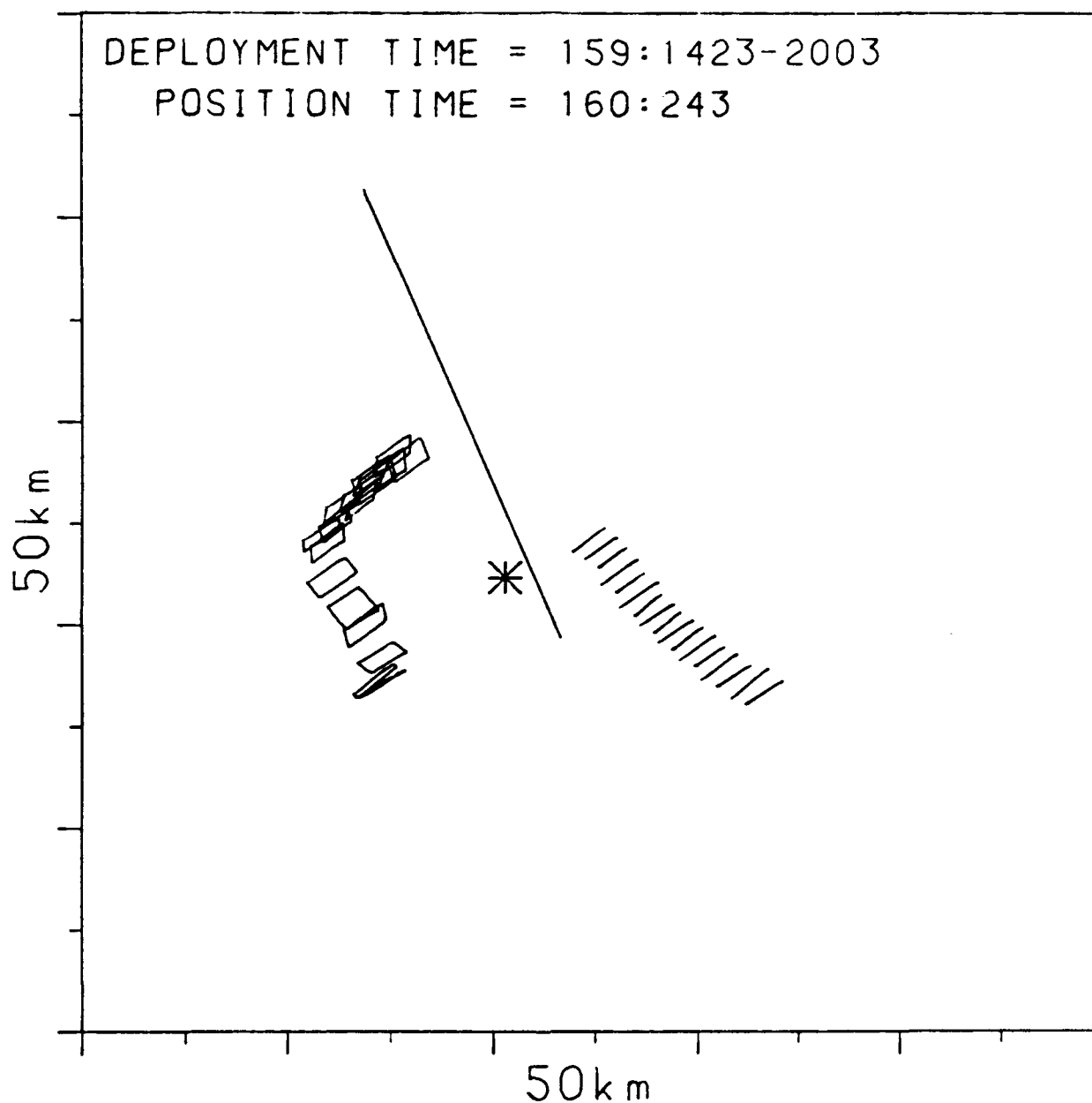(JD 160, 0243 UTC).   Depth model applied to is 38.8 m.

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DEPLOYMENT TIME = 159:1423-2003
   POSITION TIME = 160:243

50km

50km

FIGURE 27   Same as Figure 26 except depth model applied to is 43.0 m.
Time is still that of LIDAR pass 242 (JD 160, 0243 UTC).
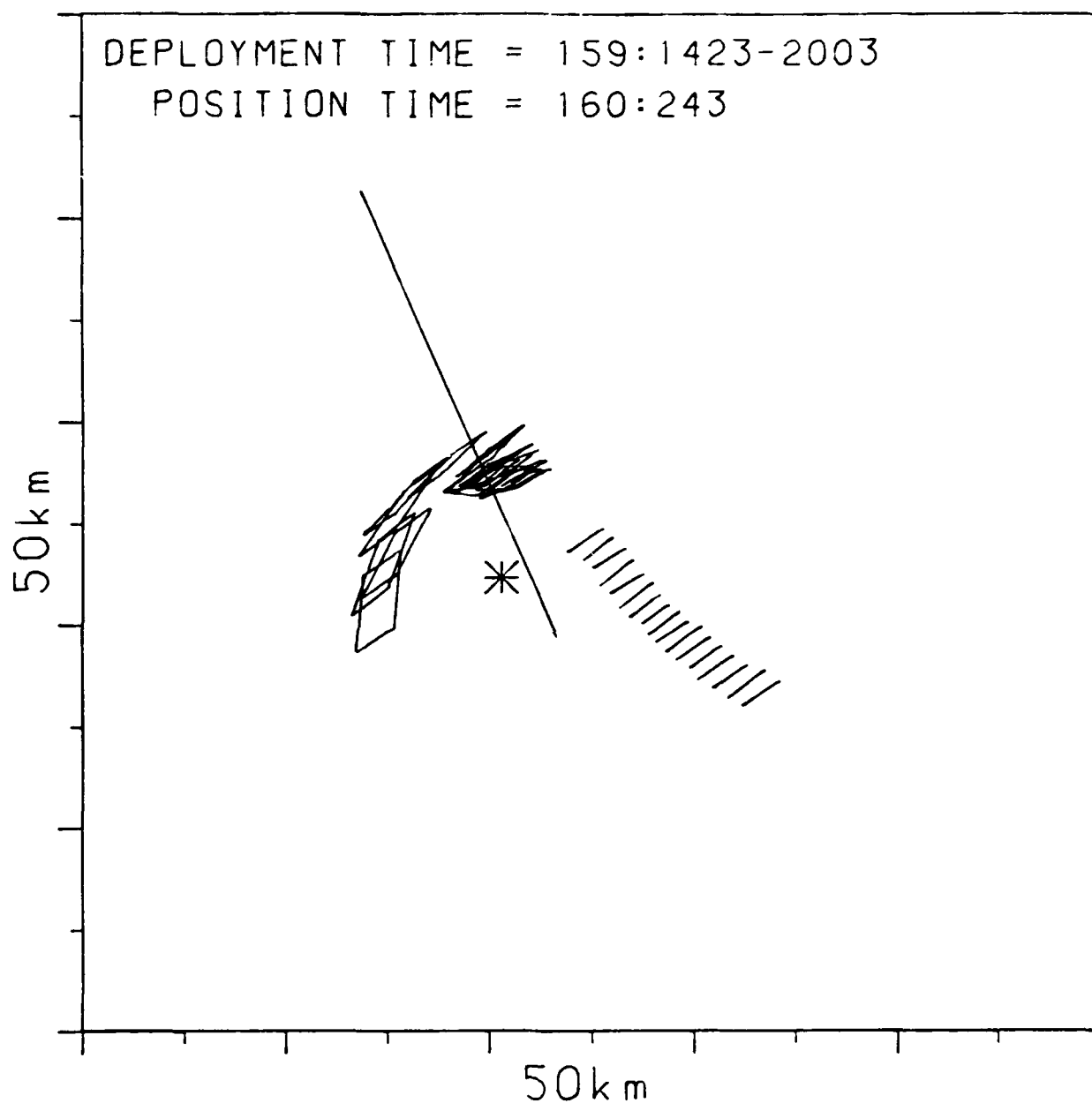
DEPLOYMENT TIME = 159:1423-2003
POSITION TIME = 160:243

50 km

50 km

FIGURE 28 Same as Figure 26 except depth model applied to is 34.7 m. Time is still that of LIDAR pass 242 (JD 160, 0243 UTC).

DEPLOYMENT TIME = 159:1423-2003
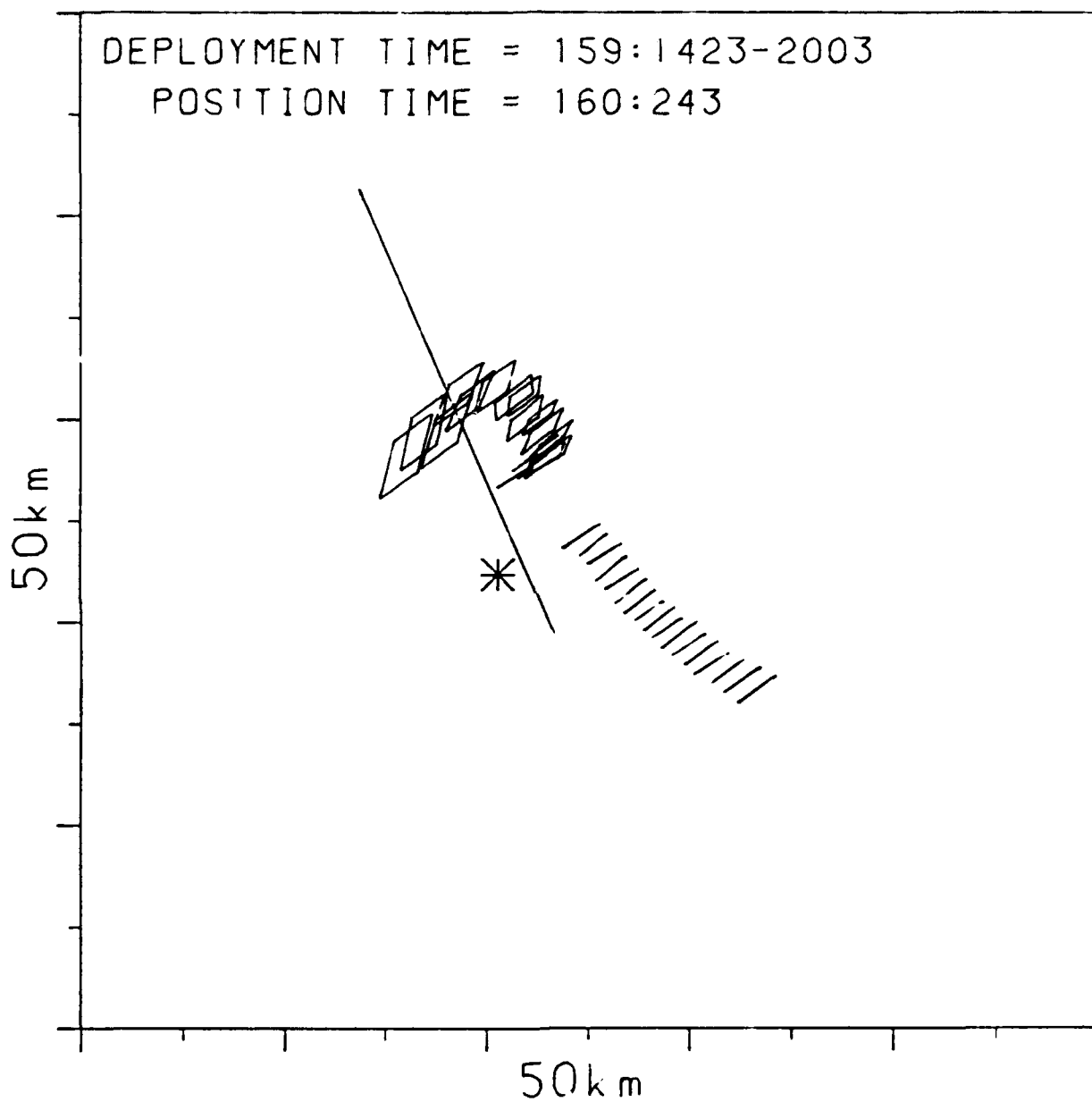POSITION TIME = 160:243

50km

50km

FIGURE 29   Same as Figure 26 except depth model applied to is 30.5 m.
Time is still that of LIDAR pass 242 (JD 160, 0243 UTC).

51