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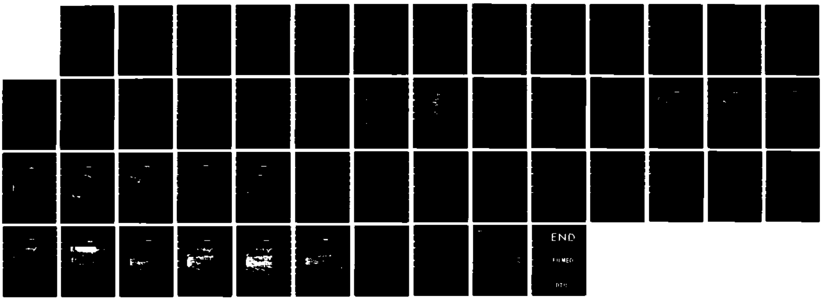

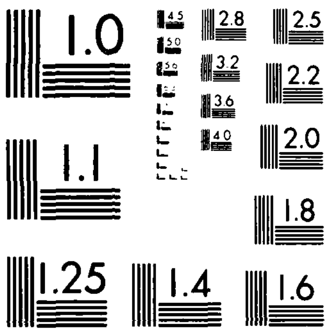

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NRL Memorandum Report 5573

A Processor for the Study of Ocean Fine-Scale Patches

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When a vertical array of temperature sensors is towed through the upper thermocline, patches of high temperature variance of considerable horizontal length can be observed. The Ocean Dynamics Branch at NRL has developed a towed thermistor array system which is extremely useful in obtaining finely detailed data on the horizontal/vertical structure of small-scale temperature fluctuations in the upper ocean. This report documents an algorithm for using towed thermistor array data to study these patches.

Briefly, the algorithm detrends the temperature data and computes the FFT of the windowed data for 16 second (≈ 40 m) data blocks. An estimate of the temperature variance is thus obtained within a user-selected band, typically 1 to 3 m. A normalization is generally performed to remove the effects of a changing vertical temperature gradient. Shades of gray plots are then used to display the patch structure.

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19. ABSTRACT (Continued)

The algorithm is applied to data from a 1981 Atlantic Ocean experiment near the Sargasso Sea. Many examples of "patch processor" output will be shown, along with other results. It will be seen that the patch processor algorithm provides an effective medium for the portrayal of high variance of ocean fine structure.

CONTENTS

A PROCESSOR FOR THE STUDY OF OCEAN FINE-SCALE PATCHES

INTRODUCTION

Overview

When a vertical array of temperature sensors is towed through the upper thermocline, patches of high temperature variances of considerable horizontal length may be observed. This report describes a processing algorithm developed to enhance the identification and analysis of the patchy structure and the physical processes responsible.

The study of fine-scale physical processes which occur in the ocean relies upon both measurements of ocean scalar structure and appropriate analysis and display techniques for the collected fine scale data. In recent years, as the detail required to analyze complicated processes has increased, instruments have been deployed to provide a two dimensional view of ocean turbulence. The data is obtained by recording temperature measurements from a large number of temperature-current meters, from a CTD (conductivity-temperature-pressure) profiler used in a yo-yoed vertical mode, or from a thermistor chain.

A real-time computer system is typically used to record and monitor data from the instrumentation. The data, usually on magnetic tape, is then returned to the laboratory where it is analyzed in detail in an effort to increase understanding of both the physical processes which operate to cause turbulence and the statistical distribution of temperature variability.

Background on the NRL Thermistor Chain

The Ocean Dynamics Branch of the Marine Technology Division at the Naval Research Laboratory (NRL) has developed over a period of years a

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towed thermistor array system which is extremely useful in obtaining finely detailed data on the horizontal/vertical structure of small-scale temperature fluctuations in the upper ocean. The system consists of a thermistor array, often referred to as a thermistor "chain", with 200 sensor locations spread over a 90 m vertical aperture. A pneumatically controlled constant tension device decouples the towed array from ship motion. Two Data General Eclipse series processors with a variety of peripherals perform all operations required to sample, store and display the data in real-time, as well as perform various diagnostic testing to assure the quality of the data. Figure 1a is a schematic illustration of the NRL towed thermistor array in a typical operational scenario. Over the depth range of interest in this report, the vertical sensor separation is very nearly 0.5 m (Fig 1b). An additional 20 sensor breakouts are used to obtain cable motion information, system noise estimates and conductivity measurements. Full detail of the towed thermistor system, as well as a detailed discussion of the history of towed thermistor chains, is contained in [1].

Background on the Fine-Scale Problem

The oceanographer uses such data as that provided by the thermistor chain both to statistically describe the distribution of energy in the ocean and to physically interpret the underlying phenomena behind energy changes. In describing the spatial distribution of energy in the ocean, it is useful to split the problem according to the length of the horizontal scale under consideration [2 and ref. cit.]. Scales greater than roughly 10 km are called mesoscale. Consideration of effects on the scale of tens of meters to 10 km can be called intermediate scale. From 1 m to 100 m the data can be considered fine-scale and below 1 m micro-scale. The use of the word "patch" in the literature is sometimes used in conjunction with the word turbulence [3,4,5]; however for this report "patch" shall be defined as regions of maximum temperature activity or "energy" for a given fine-scale wavelength band. There are many processes which produce temperature fluctuations. These include shear instabilities, small-scale internal waves, breaking internal waves, interleaving and double-diffusive convection.

In order to study fine-scale ocean structure, one would like to obtain a representation of energy within a two-dimensional cross section of the ocean (depth vs. horizontal distance) and have a method for displaying the energy variations. Since the main purpose of such an algorithm is to study patches of unusually high energy, such an algorithm will be referred to as a patch processor. Patch processor output can then be used both to study the statistics of ocean fine-scale patches and to develop greater understanding of the physical processes which occur to create these patches.

The patch processor documented in this report calculates temperature variance, normalized to remove vertical gradient effects, for a given (user selected) bandwidth, typically 1 m to 3 m. Shades of gray plots, where a shade of gray corresponds to a range of normalized variance, are then used to produce a snapshot of ocean energy. The section entitled "Processed Data" will apply the patch processor to a five hour twenty minutes long set of data collected using the NRL thermistor chain.

ALGORITHM DESCRIPTION

TEMDAT Data

The raw digital data tapes obtained from the thermistor chain contains data recorded at 20 Hz. These tapes are routinely reduced to digital tapes containing 4 Hz data in engineering units. The 4 Hz tapes, each containing 80 minutes of data, are referred to as "TEMDAT" Tapes. Patch processing uses the

TEMDAT tapes as the starting point for data processing (Fig. 2). In the discussion that follows, channel refers to any specific thermistor on the chain. For plots whose x-axis displays time, time can be converted to distance by using 1 minute = 150 m.

In addition to the patch algorithm, two other operations are performed on the TEMDAT data. One-dimensional contour plots of temperature (isotherm plots) are produced from TEMDAT tapes by program TMDCN. Closed contours cannot be seen directly, but temperature inversions can be identified by abrupt depth changes in individual isotherms. These plots contain up to 20 isotherms with the user selecting the start isotherm, the isotherm decrement, the start and stop time, and the first and last channels. Figure 3a displays 5 minutes of data for 30 channels in a region where significant temperature variations are occurring. Figure 3b shows another isotherm plot and will be further discussed later. Figure 3a was produced using a modified version of TMDCN which allows more isotherms for shorter time periods. In this case, almost 50 isotherms, beginning at 23.24°C with $\Delta T = 0.04$°C, are seen. Isotherm plots have proven useful in analyzing the TEMDAT data, both in conjunction with patch plots and separately. Program SPTRA uses the initial portion of the patch algorithm to produce sample averaged spectra (Figure 4) for specific channels. SPTRA was separated from PATCH to avoid having to overlay the computer software which would have increased software development time.

The Patch Algorithm

Program PATCH is used to produce data files where each record contains variance and temperature averages for 16 second bins for each channel within a user specified range of channels. In addition PATCH produces a shade of gray plot of variance vs. time. Due to memory size restrictions, the maximum amount of data which could be processed into a data file by one run of the program is 64 channels for 45 minutes (more memory has recently been added). However, since the programs which process the data files output by PATCH can do multiple file processing, the memory limitation does not affect the capability to examine larger sections of data at one time.

Once the user-selected start time is reached on the TEMDAT tape, data is read and stored (for up to 64 channels) in 16 second segments. For the usual tow speed, this corresponds to a 40 m length of ocean. Bad data channels are identified from a user input list (obtained during TEMDAT processing) and corrected by interpolating between the closest surrounding valid channels. For each channel the mean and linear trend are computed and removed and the variance is computed. The data are then windowed prior to computing a Fourier transform. The user can choose between a Hanning window or a cosine window with a 10% taper on each end. All processed data shown in this report used the cosine window.

The 64 point FFT is then computed and the spectral estimate for each bin obtained. The area under the spectrum is summed to obtain the post-FFT variance. The post-FFT variance will be less than the pre-FFT variance due to windowing. This effect is corrected by multiplying subsequent estimates by a correction factor, FACTR, where FACTR = (pre-FFT variance)/(post-FFT variance).

Next the variance, limited to a user-selected bandwidth, is calculated. Once all channels have been processed for each 16 second time interval, a record containing the variance for each channel (within the user selected interval) as well as the 16 second average temperature for each channel is written into the data file. This data file, containing variances and average temperatures, is used for all further processing.

Patch File Processing

The major patch file processing program is PTCHF. PTCHF processes patch files to produce shades of gray patch plots with additional processing options. The user can select the gray scale as well as certain other display parameters. In addition the user may choose to produce either unnormalized or normalized plots. The unnormalized plot is a display of the band limited temperature variance level represented as a shade of gray on a channel vs. time graph. In the normalized plot the variance is normalized by removing the vertical temperature gradient effect, i.e., the variance is divided by the square of the difference of the average temperature of the surrounding channels. The normalization helps remove energy variations caused by a changing vertical temperature gradient. Similarly, a bandwidth of 1 to 3 meters is typically used to remove longer wavelength effects. There are several nearly equivalent interpretations of the normalized values: (1) the variance has units of $(°C)^2$, so that by dividing by $(\Delta T)^2$ a non-dimensional number results which reflects real variability in the small-scale field; (2) ΔT is a vertical difference centered about the channel at which the variance has been calculated so that $\Delta T/\Delta z$, where $\Delta z \sim 1$ m, approximately represents the vertical derivative, $\partial T/\partial z$; thus, the normalized value can be thought as having units of $(°C)^2/(°C\ m^{-1})^2 = m^2$, units of squared displacement; (3) a third interpretation is as a "fine-structure Cox number", C_f. The microstructure Cox number is proportioned to $\langle(\partial T/\partial x)^2\rangle$, where <> denotes an average. In the present case, $\langle(\partial T/\partial x)^2\rangle$ in the finestructure range of 1-3 m would be roughly given by $\langle variance\rangle/\Delta x)^2$, where Δx represents the average wavelength in the band, say 2 m. Thus, $C_f = (\langle variance\rangle/(\Delta x)^2)/(\langle\Delta T\rangle/\Delta z)^2 \sim 0.25$ times the number plotted. In this report, interpretation (1) is used, thus, the presented values are dimensionless. The important point is that regardless of one's point of view, the modulation of the variance by the larger-scale stratification has been effectively removed.

Another output from the patch files consists of histograms, from program ANVAR, giving a variance histogram of each channel contained in the file for the time period comprising the file. Figure 5 shows some sample variance histograms for 40 minutes of data for each of channels 96 to 111. While the histograms have not been rigorously analyzed, the log-normal distribution of the data reported in [3] and [6] is indicated. Because of this log-normal distribution, the gray scales are assigned to the logarithm of the variance levels.

Although the software was written independently, the patch processing algorithm has historical roots in an algorithm developed several years ago [6] and discussed recently in [7]. For that algorithm, the temperature variance for each sensor was normalized by the mean value of the variance of that sensor in some long (usually 5 km) section of data. The resulting variable had no units, but, just as in the present case, the normalization was motivated by the need to depress the variance of the high gradient regions in order to study non-gradient caused variability. The previous algorithm was developed for an earlier variant of the NRL towed array. That system suffered DC offsets which made the mean temperatures relatively unreliable. Therefore, the local vertical gradients, as estimated by the difference of the nearby thermistor means, were prone to error. The normalization scheme really had no physical basis and, though it provided useful graphics, it fell into disuse. The most obvious deficiency of that type of algorithm was that a very strong patch at one location along the 5 km section of data would raise the mean value of the variance sufficiently that the normalized variable would be unrealistically depressed at other locations. Thus, the details of the contours were dependent upon the length of data being processed, and this was unsatisfactory.

The earlier algorithm also differed in the final graphic output. In that case, the array of normalized variances was contoured in two dimensions instead of being gray scaled. The additional limitation of that approach was that only a limited number of data points could be handled at one time by the contouring routine. The present technique is organized to treat the two dimensions in sequence. That is, sequences of 64 data points from every sensor in the array can be FFT'd, gray scaled, and plotted in sequence for very long data segments.

PROCESSED DATA

A five hour 20 minute data section from a 1981 towed thermistor chain experiment in the Atlantic Ocean has been examined using the patch processor. The experiment involved towing the thermistor chain through a front in the Sargasso Sea in the summer. The front likely is part of an E-W oriented front that is often indicated on sea-surface temperature maps in an area north of the subtropical convergence front. An overview of the temperature structure for this section was seen in Fig 3b. The high gradient region that deepens along the tow path corresponds to the sloping frontal surface. Note the change in mixed-layer depth across the front and the layers of temperature inversion above the high gradient region.

The full data set was processed using the normalized mode previously discussed (variance normalized by the vertical temperature difference) with a bandwidth of 1-3 meters. Figures 6a-13a each represent 40 minute segments of data in chronological order (40 minute sections have been

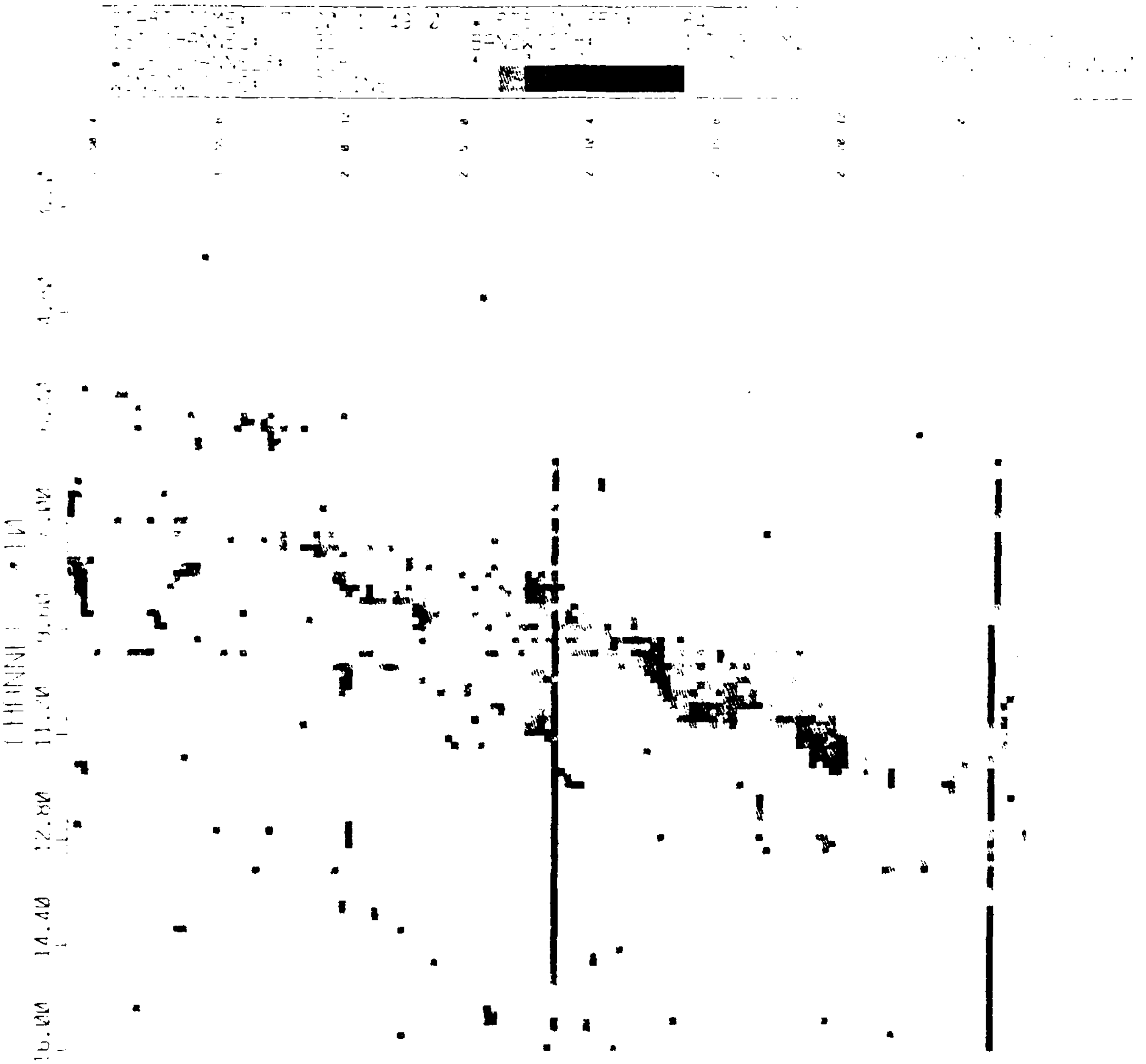

Fig. 8a — 3rd 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

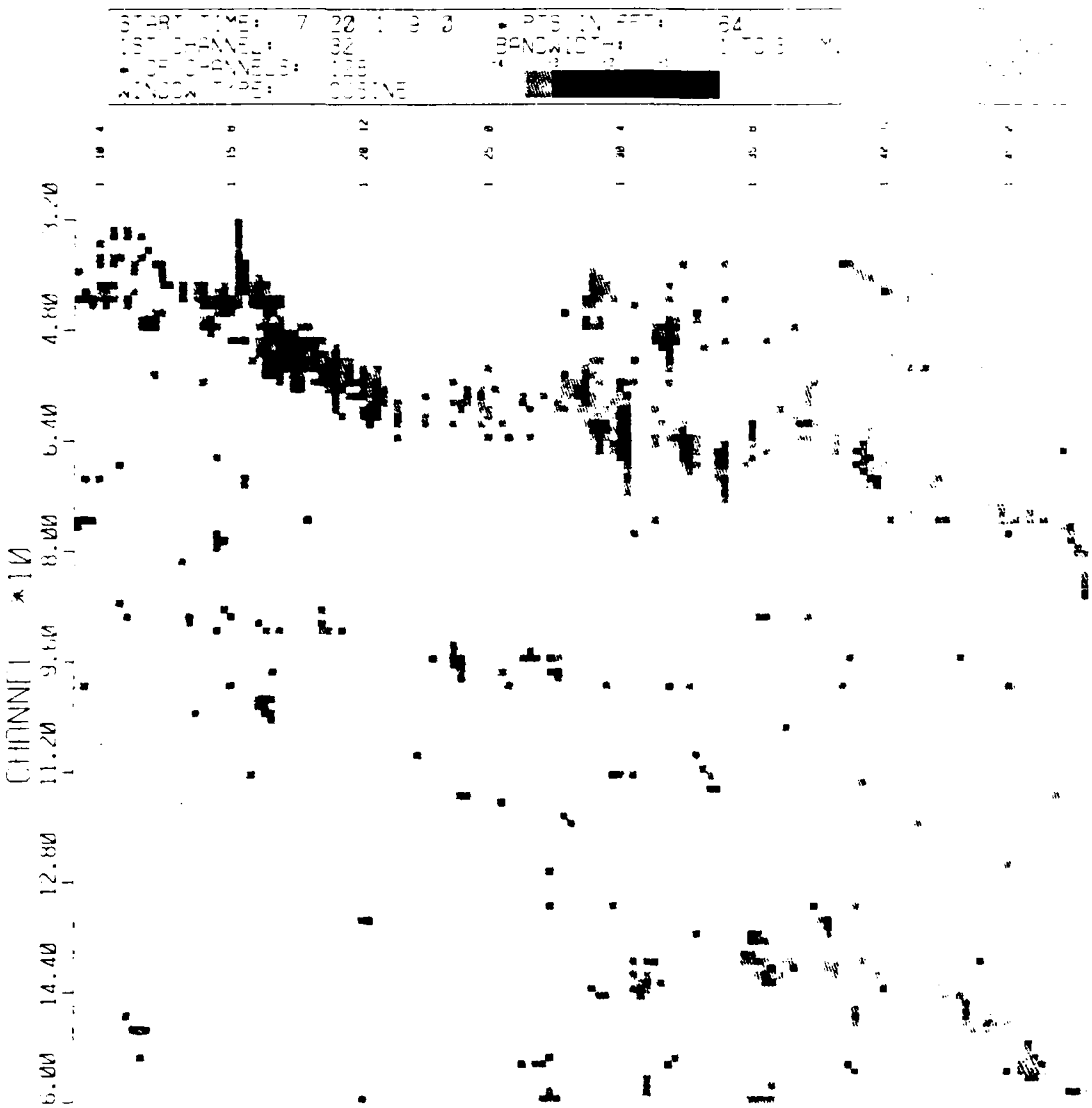

Fig. 7a — 2nd 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

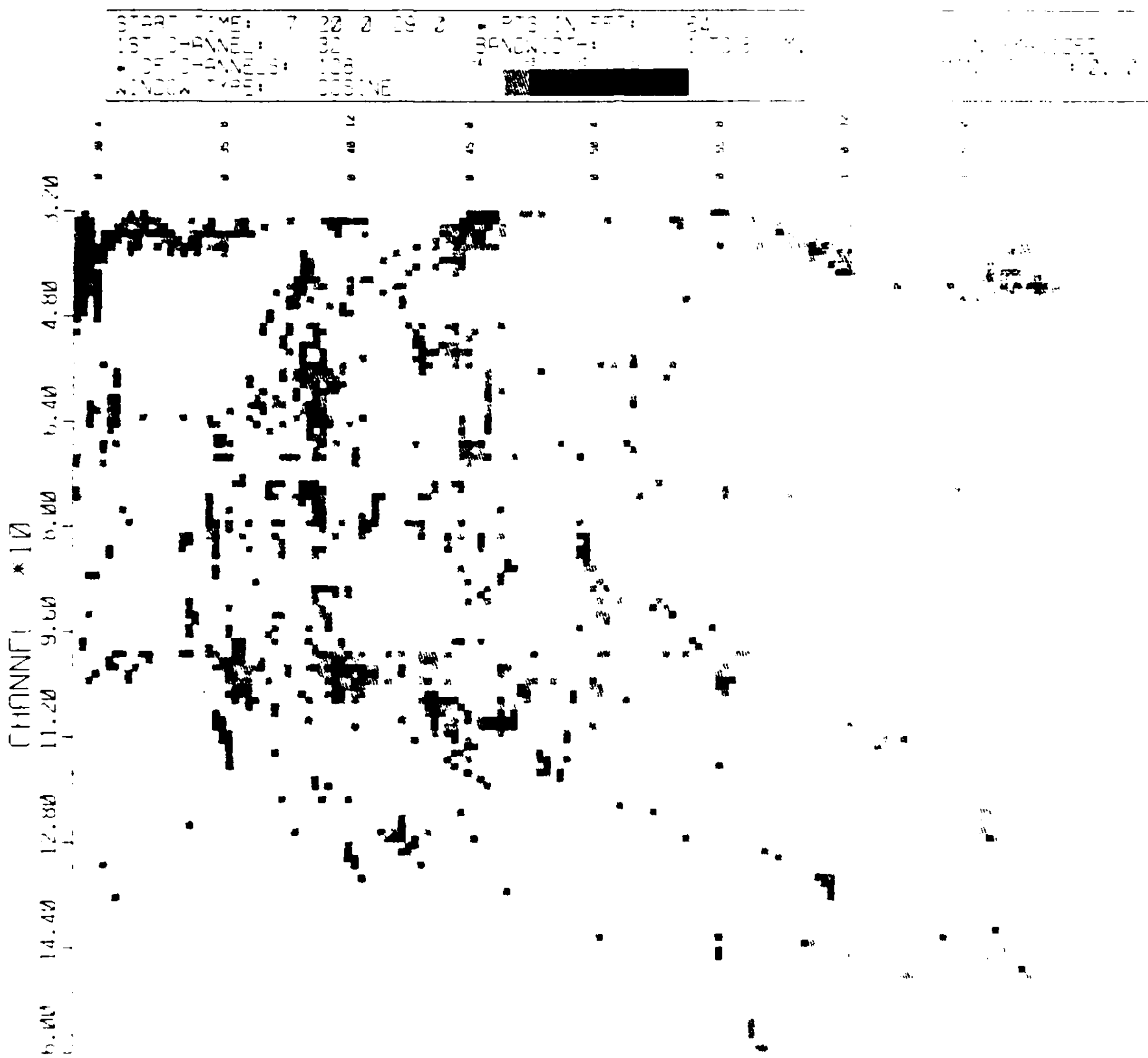

Fig. 6a — 1st 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

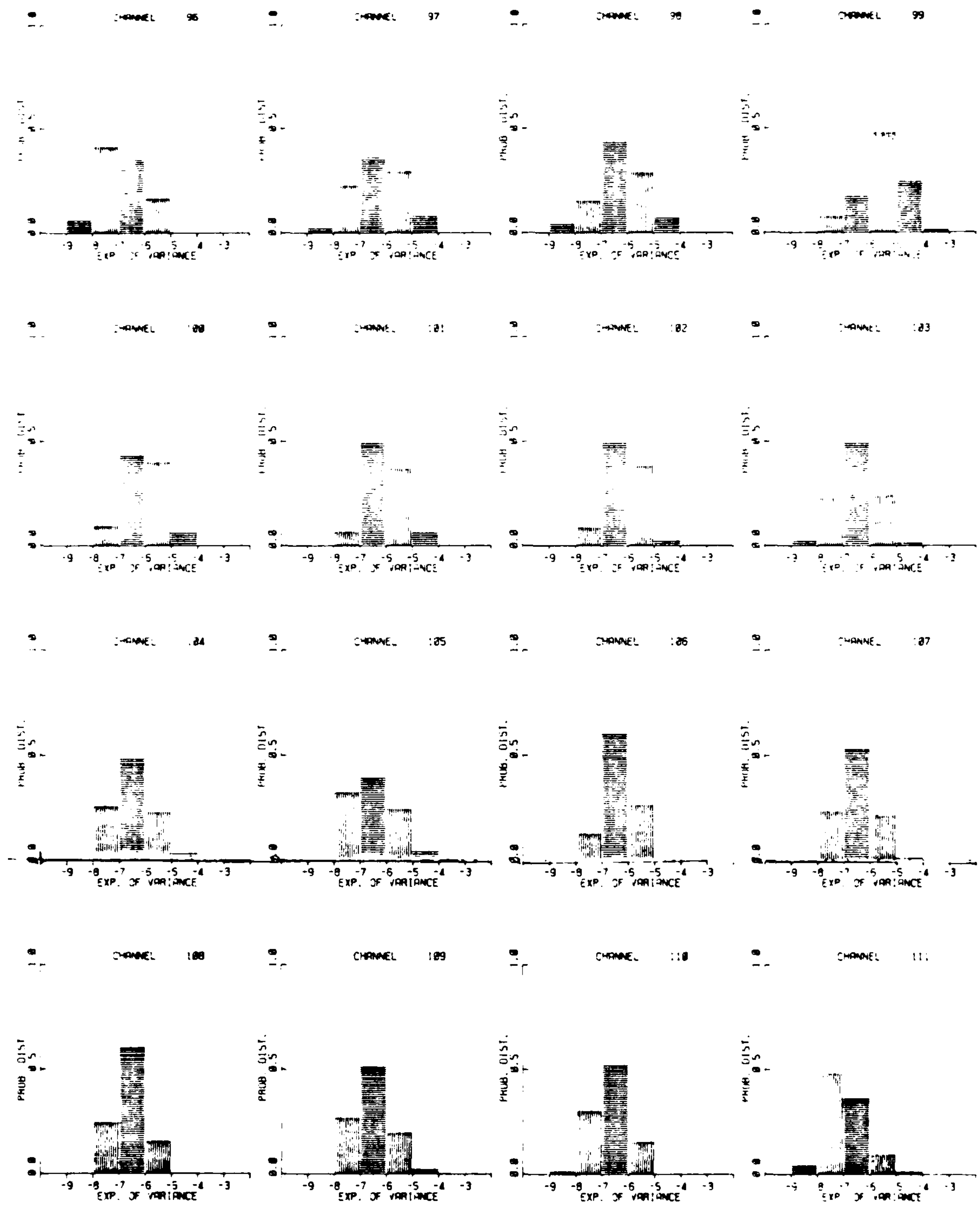

Fig. 5 — Sample histograms of unnormalized variance distributions

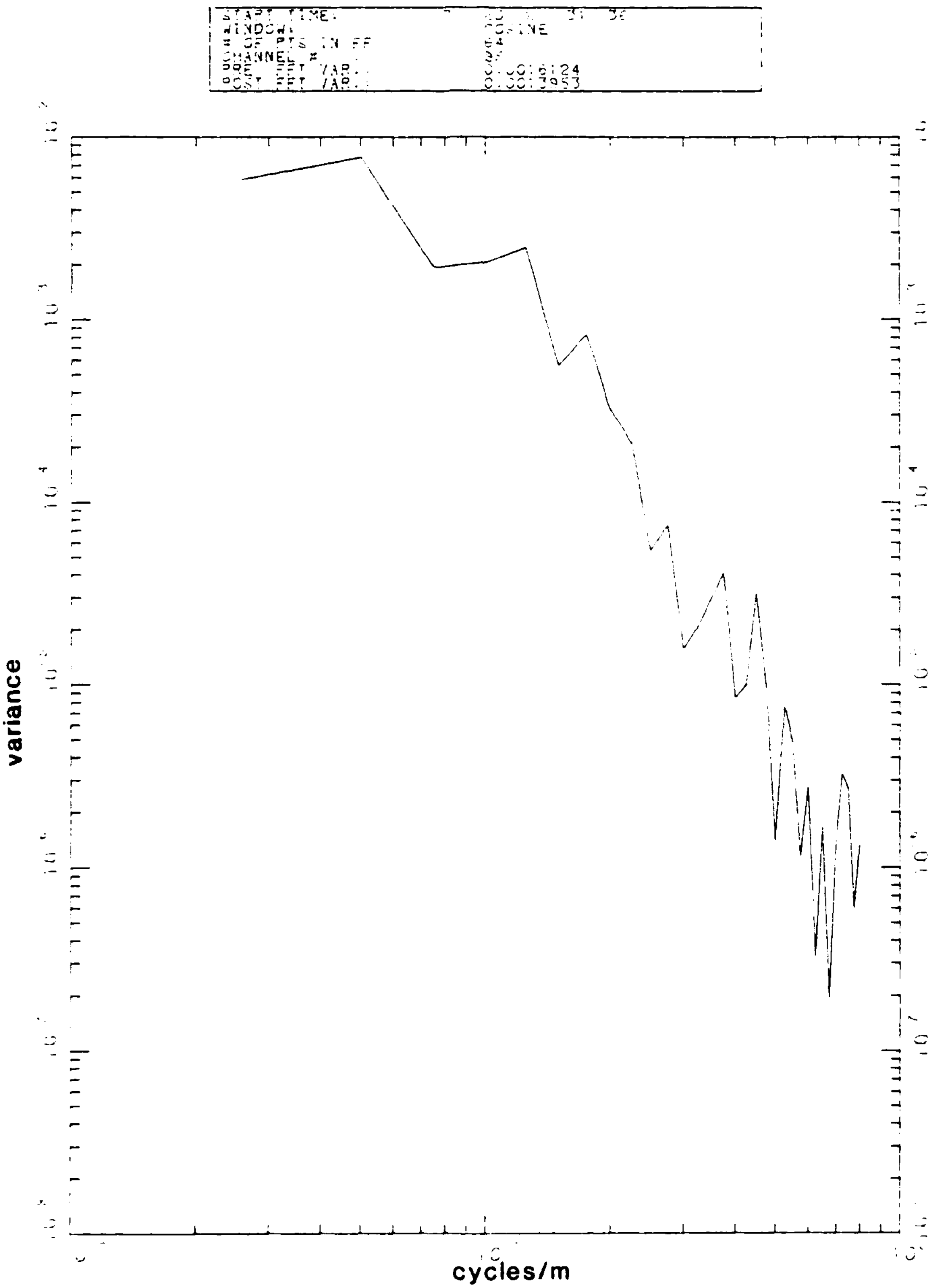

Fig. 4 — Typical spectra for 16 sec of data

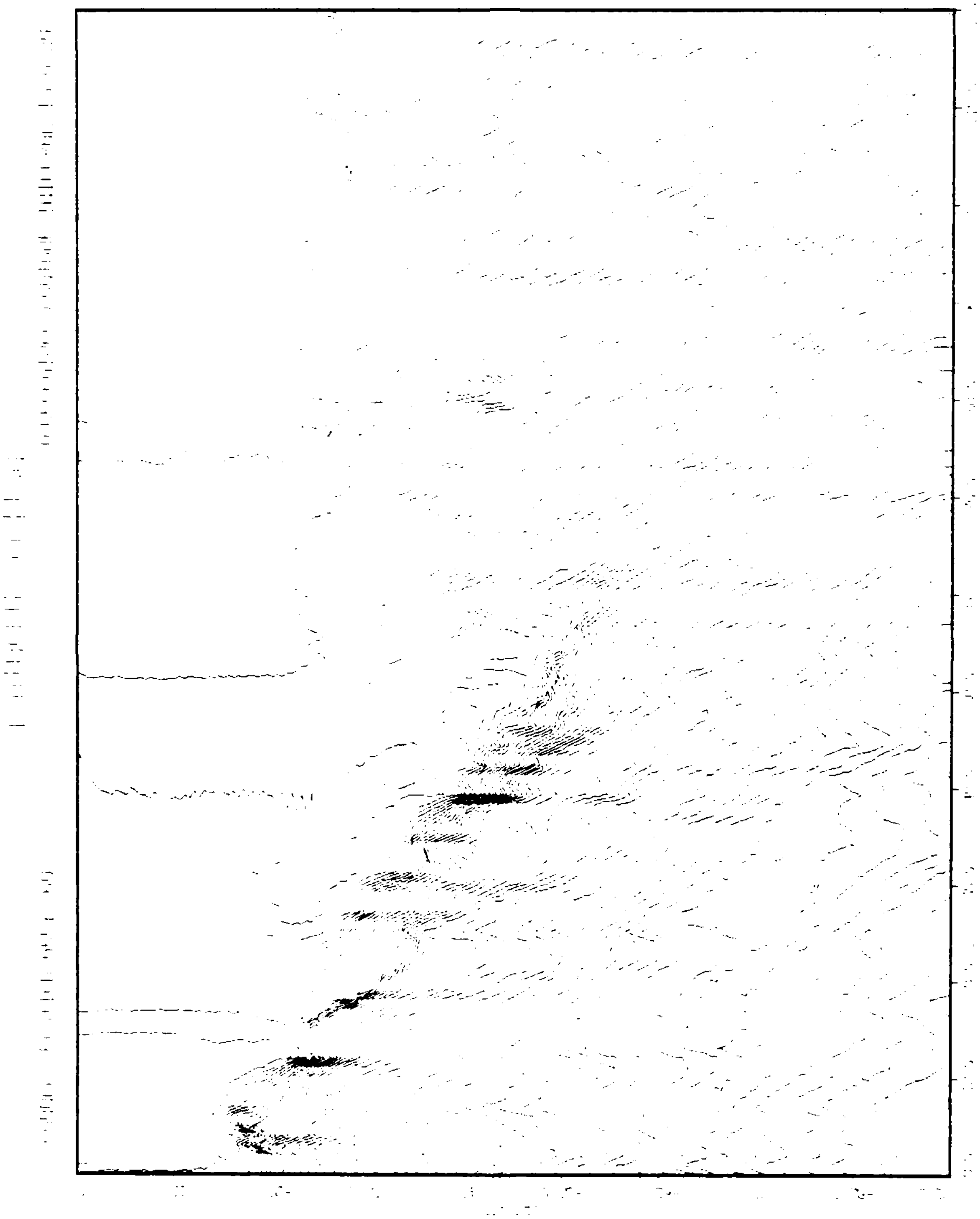

Fig. 3b — 50 km section of TT6

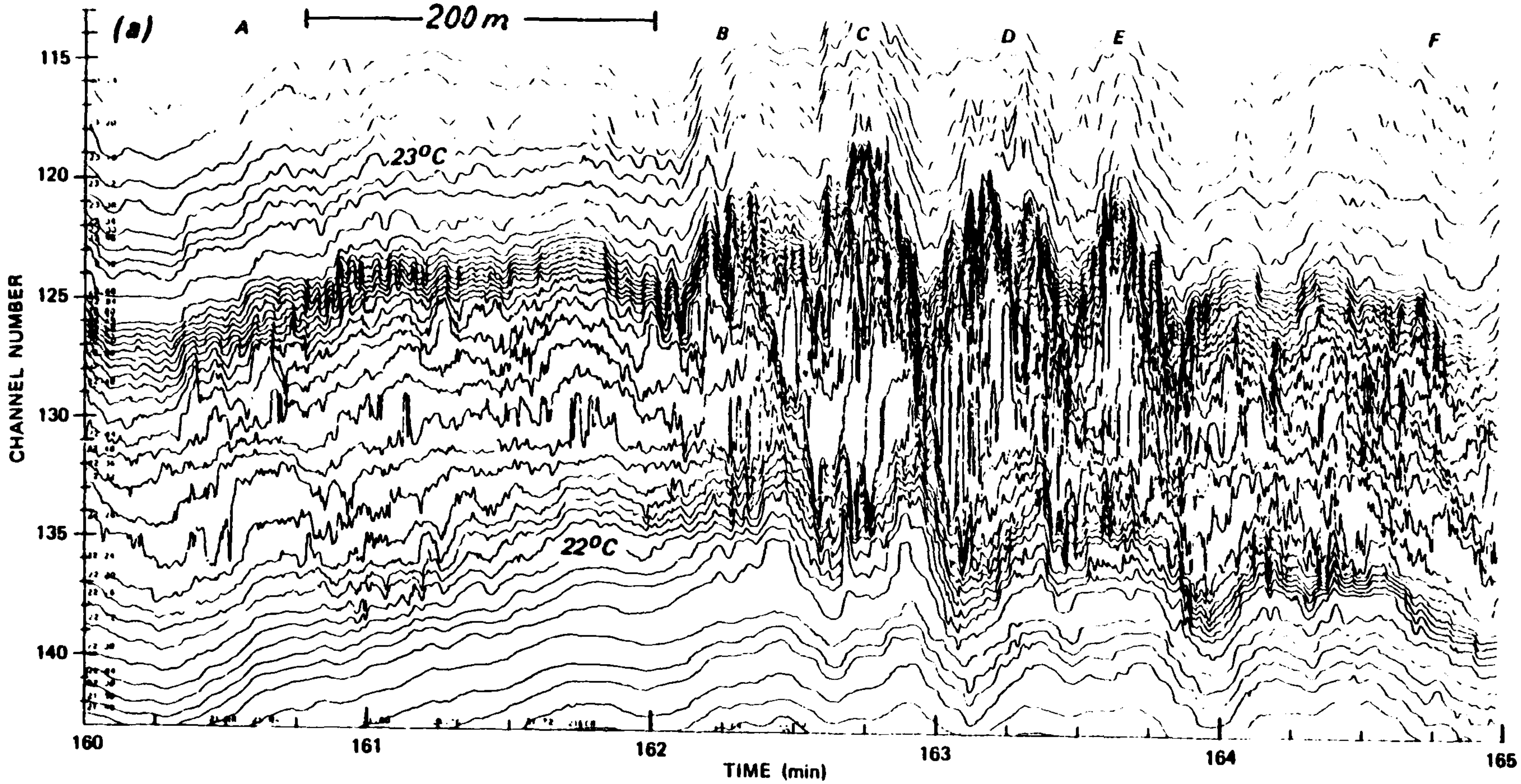

Fig. 3a — 5 min isotherm plot in "patchy" region

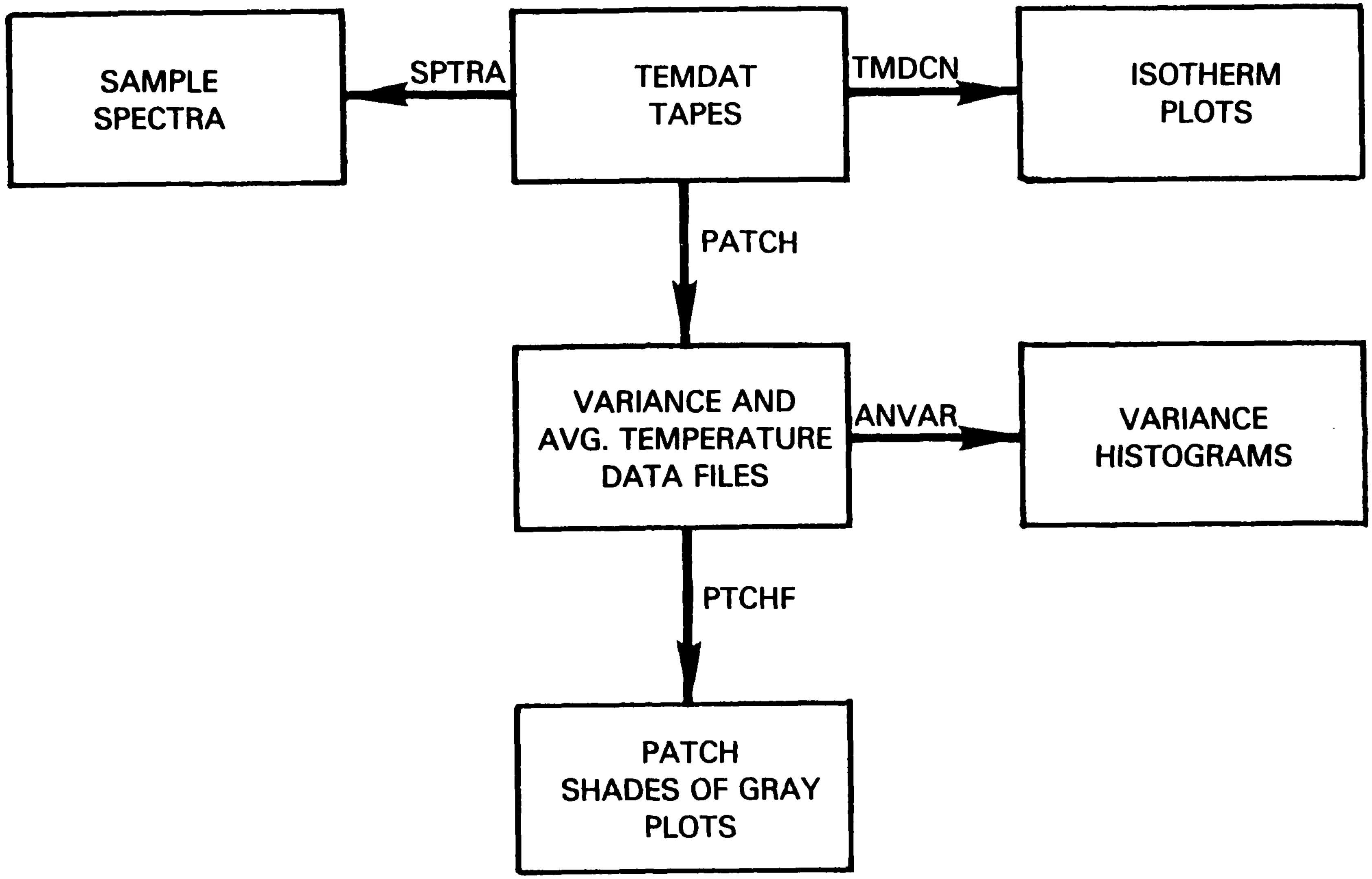

Fig. 2 — Patch detection processing flow chart

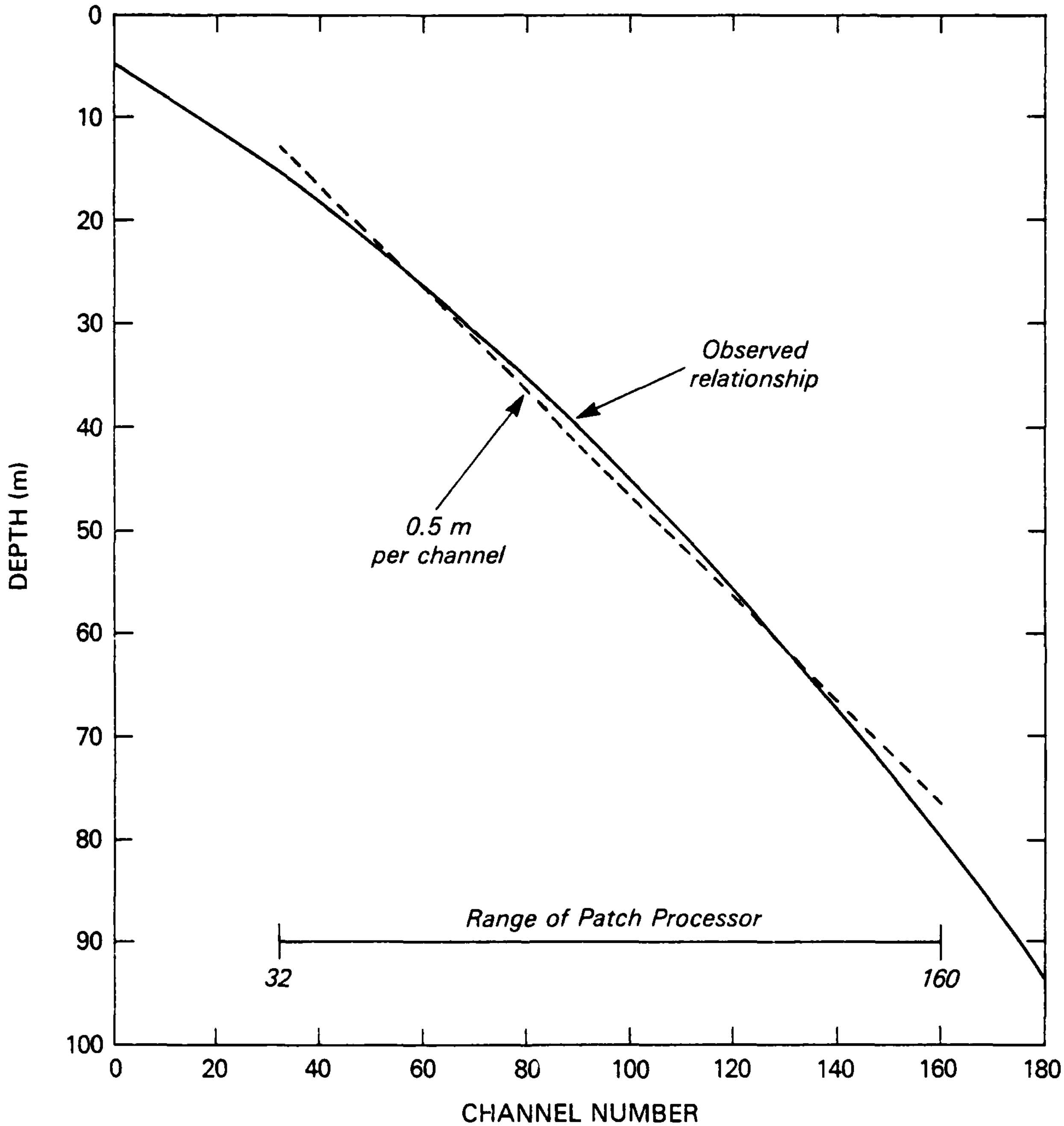

Fig. 1b — Channel number vs depth for chain during TT6

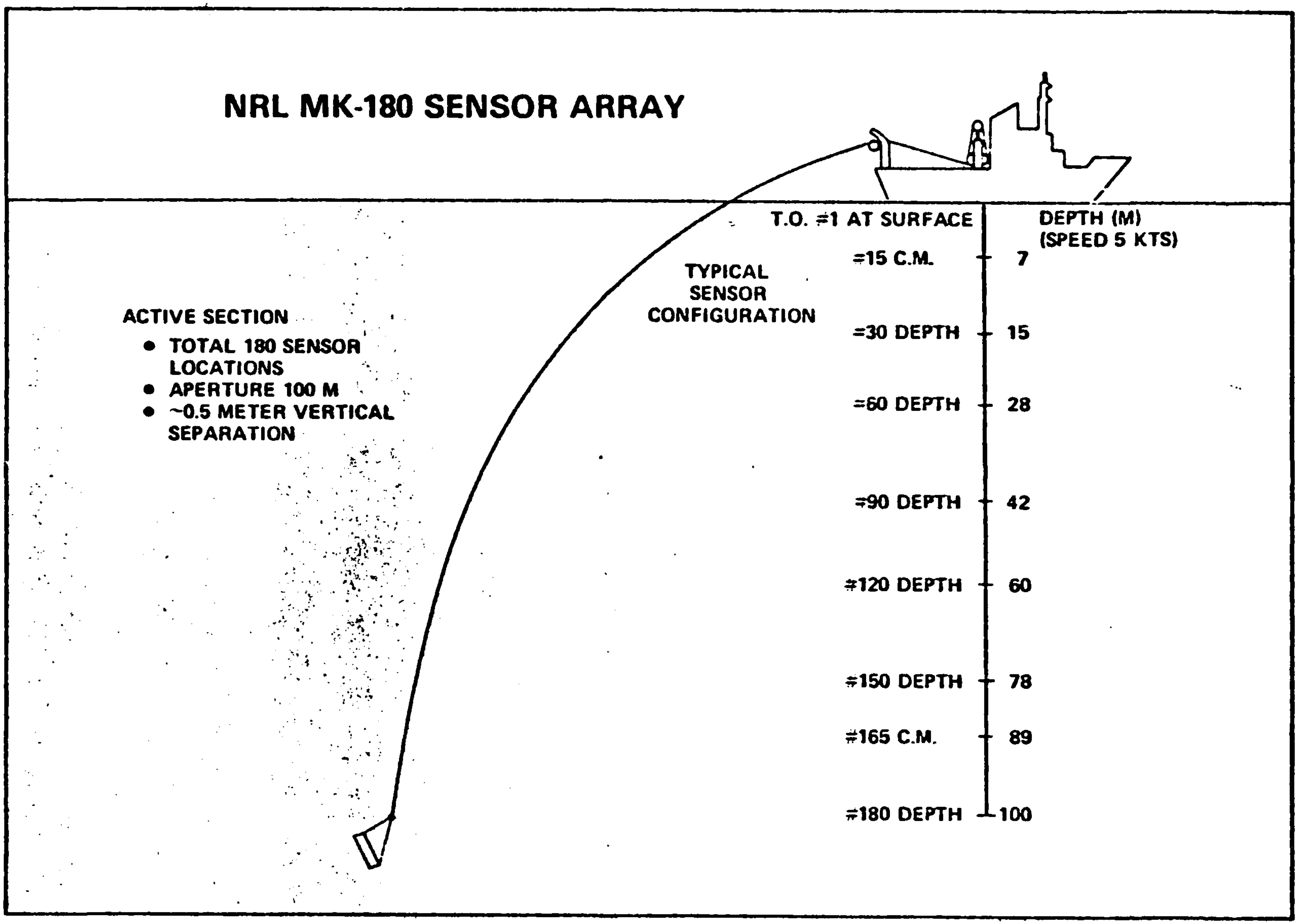

Fig. 1a — NRL thermistor chain schematic an effort to increase the information content of the patch display, the authors have begun experimenting with imaging techniques to represent and manipulate variance level using false color on a raster color device. Preliminary indications are that color offers significantly improved detail for studying the dynamics of finescale structure.

The patch processor algorithm described in this report, with either shades of gray or color graphical output, provides an effective medium for the portrayal of high energy patches of ocean fine structure. Future tasks include the application of the algorithm to additional data, quantification of patch statistics, and, perhaps, production of a model or estimation technique for patch evaluation.

ACKNOWLEDGMENTS

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Finally, Figure 21 is an example of the output of the earlier patch processor [6] discussed previousl . The contour lines enclose regions in which the normalized variance is greater than the threshold values. The level of the first contour level was set at 30% greater than the mean level, and the next level was 130% greater than the mean. This particular section of data corresponds to the middle portion of Figure 10a. Although the fine details are not identical in these two presentations of the data, similarity in the gross structure can be seen.

CONCLUSIONS

As has been seen, the patch processor takes thermistor chain data and provides a two dimensional snapshot of the ocean energy structure. The patch processor provides an attractive and effective means of identifying and enhancing the analysis of patches and allows plotting of essentially unlimited amounts of data in a continuous picture. This is a clear improvement over either tedious and limited hand contouring or array size limited machine contouring. More complicated normalization schemes are possible, but there seems little reason to expect any significant improvement in the final output.

However, shades-of-gray plots, while good for identifying and portraying patches, are still limited. Although 16 shades of gray are available on the plotter, only 8 were used due to difficulty in distinguishing between adjacent shades. Experimentation has shown that the background must be primarily white to obtain good contrast, thus, only 4 to 6 shades end up being used to cover the full data range. Hence, the dynamic range is very limited. Application of current graphics techniques to oceanography often realizes significant display and analysis improvements [10]; accordingly, in calibration errors between sensors. Figure 14 is a typical plot of the temperature difference. Figure 9a used a lower bound of 0.1° C for the local temperature gradient. Figures 15 and 16 reveal what occurs as the permissible lower bound is made smaller. In Figure 15 a lower bound of 0.05° C was used. More energy is accordingly indicated, especially for the upper channels where the temperature gradient is consistently small. In Figure 16 a lower bound of 0.01°C is used for the gradient. Here a great deal of "energy" has been added to the patch output display for those regions with small gradient. In general, values of the lower bound in the range 0.05 to 0.1° C/m are reasonable choices to assure both that gradient effects are removed in regions with large temperature gradients and that extraneous effects are not introduced in regions of very small gradients.

Figure 17 shows data segment T9B displayed for a 1-3 m bandwidth without normalization. This figure shows how the "fingers" of high energy extend out from the patch which occurs at 2:31. A comparison of Figures 17 with 9a reveal the value of the normalization in removing temperature gradient effects and isolating patches. Figure 18 shows T9B patch processor output for a 1-10 m band with normalization starting at 10^{-4}. Compared with Figure 9a, Figure 18 provides a subjective indication of how much more energy is present for a 1-10 m bandwidth. Figures 19 and 20 both represent patch output for a 1-10 m band without normalization. Figure 19 uses four decades of variance starting at 10^{-6} while Figure 20 starts at 10^{-7}. The comparison provides a good indication of the importance of choosing the display range to suit the data. Comparison of Figure 17 with Figure 18 also provides another measure of the energy difference between the 1-10 m band and the 1-3 m band.

used for publication convenience). Hence, these figures placed consecutively give a five hour picture of the patch structure during the tow. Figures 6b-13b show the isotherm plots for the same 40 minute sections of these data sets. The two vertical lines seen in Figure 8a at about 2:08 and 2:27 are caused by short time gaps in the data. Figure 3 is approximately the last five minutes of Figure 9b expanded as previously discussed for channels 113-143. The reader should compare this with the patch arising in the same depth and time in Figure 9a. The high variance structure seen in the first twenty minutes of Figure 6a is also interesting, as it differs considerably from the sort of patch structure seen elsewhere in the data set. The interpretation of the physical processes indicated by the combined patch and isotherm plots and their relationship to conductivity sensor data from the chain is expected to be the subject of a forthcoming journal article and will not be discussed in detail here.

In the course of developing the patch algorithm, other patch outputs have been produced and some will be shown. These patch displays will all use a 40 minute segment of data seen in Figure 9a (denoted T9B: TEMDAT tape 9, second half) starting at 02:29 EST on July 22. This data set is of special interest due to a large patch which arises between channels 125-140 during the last 5 minutes and continues for another 12 minutes on the next tape [8]. The normalization divides the variance by the square of the local vertical temperature difference. Since differences may be very small, a lower bound must be placed on the local difference value, else a low energy area will appear large simply because the measured vertical ΔT happens to be very small. This issue arises because the thermistor array is not perfect. Small vertical differences are more likely to be measured inaccurately because of

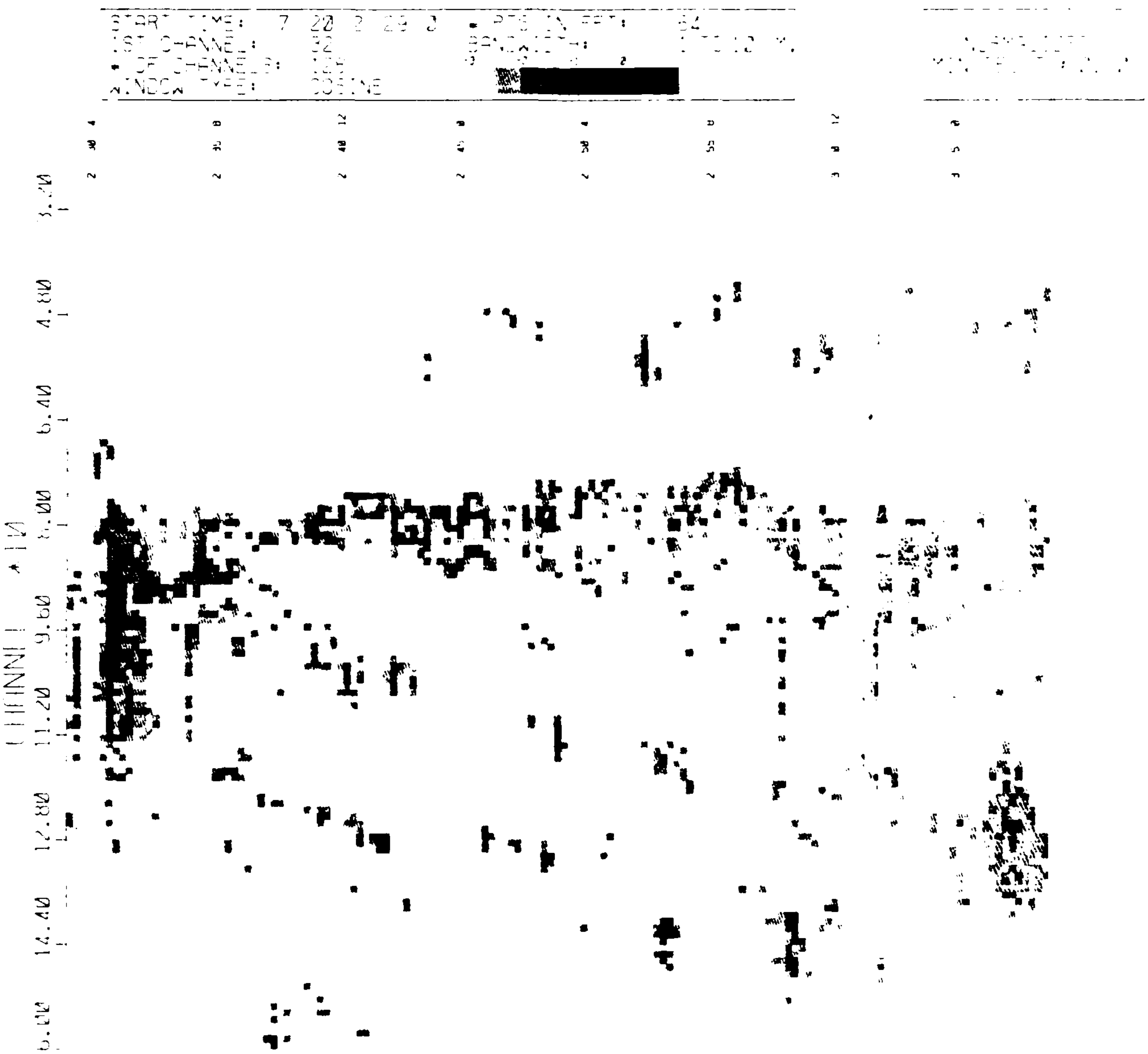

Fig. 9a — 4th 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

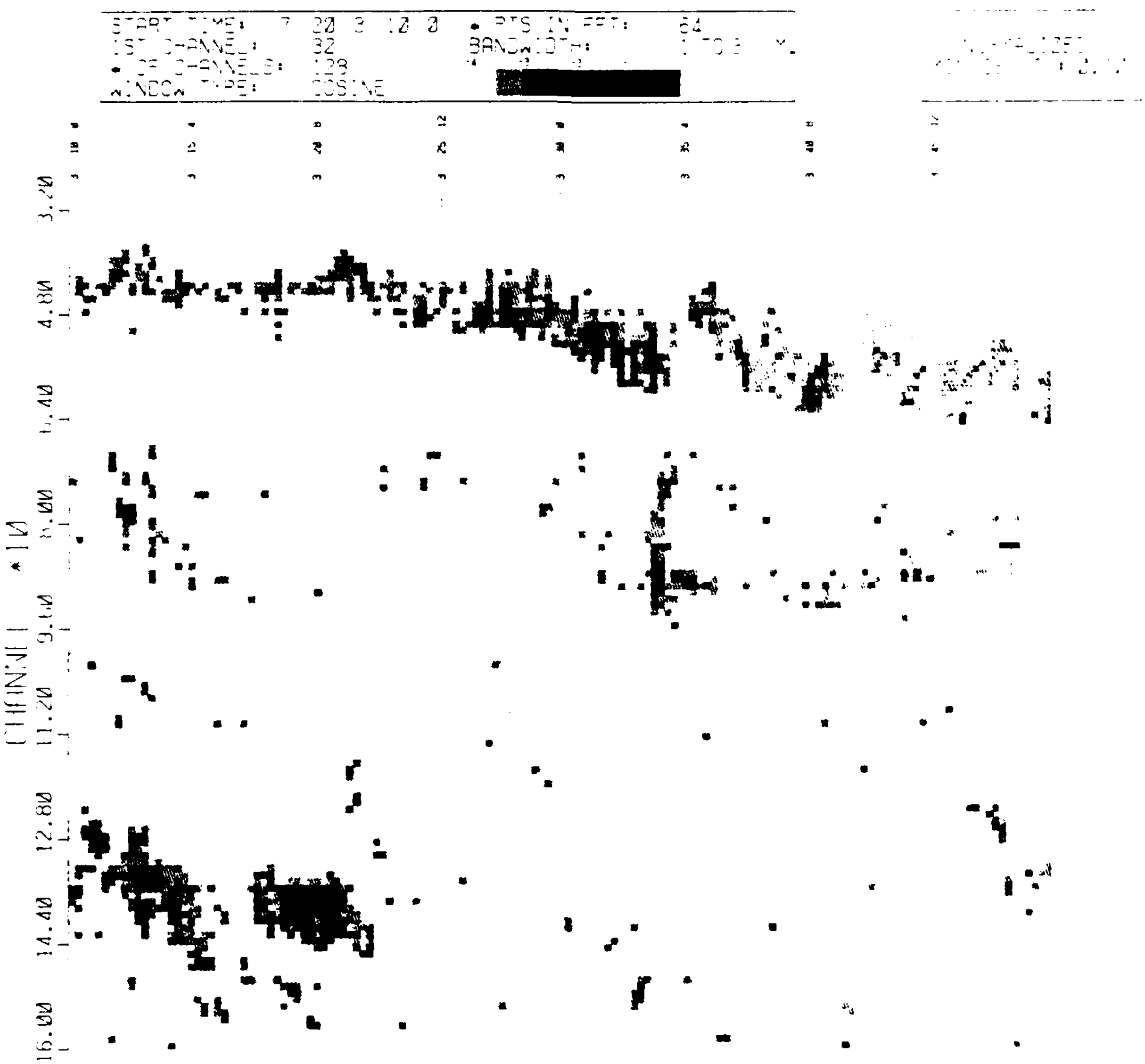

Fig. 10a — 5th 40 min (6 km) of TT6. 1-3 m band, normalized min dT 0.1°C.

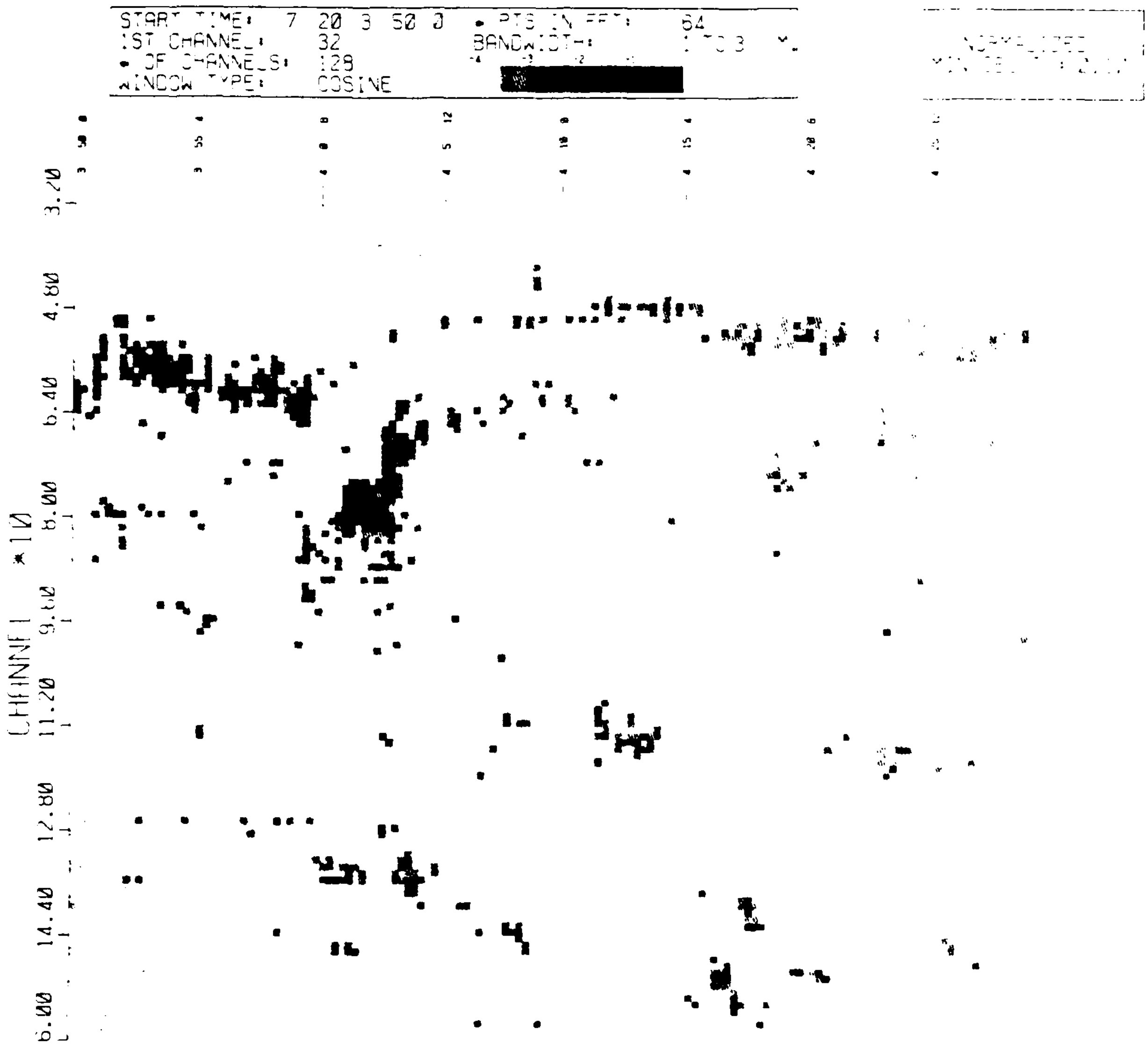

Fig. 11a — 6th 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

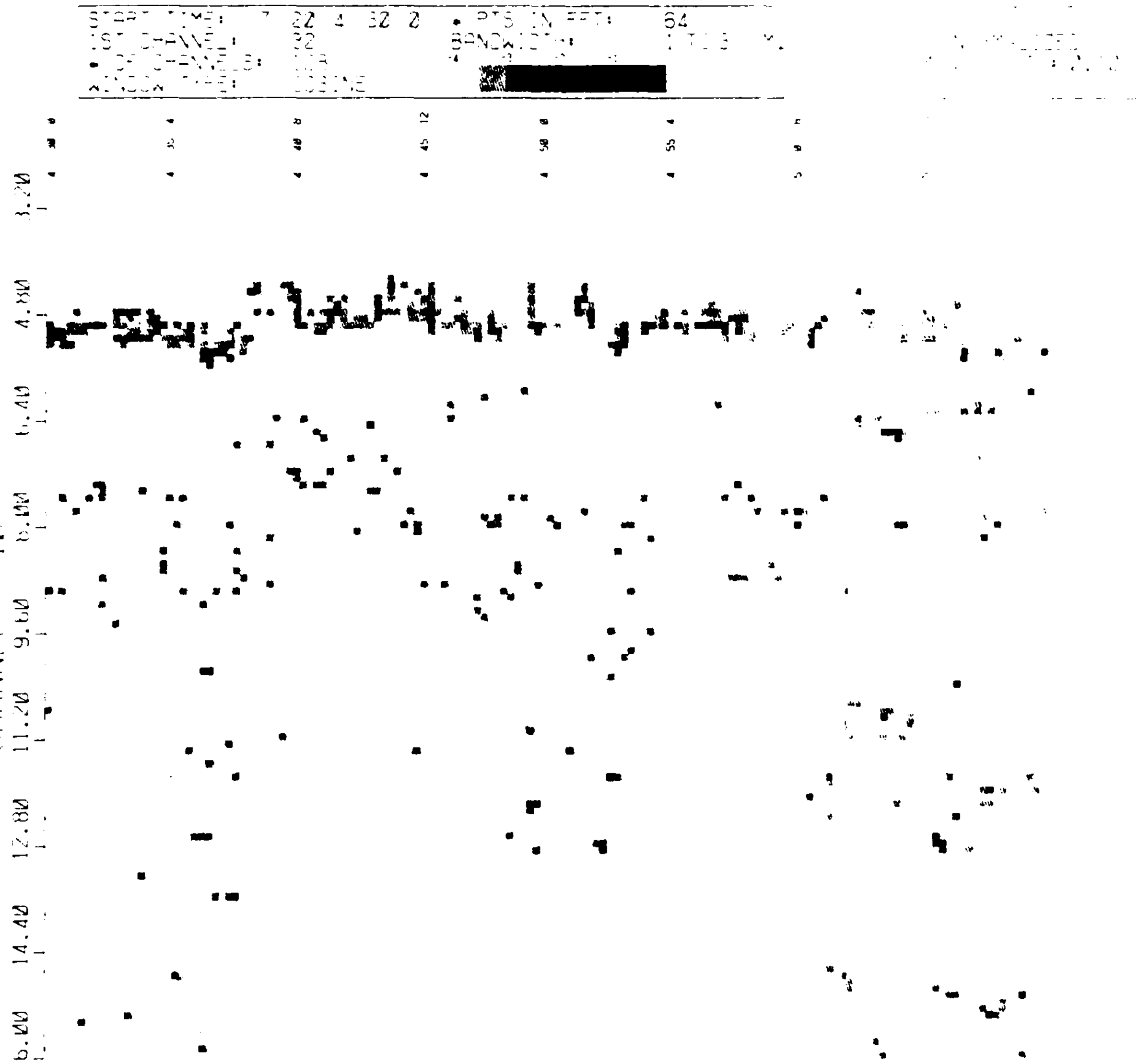

Fig. 12a — 7th 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

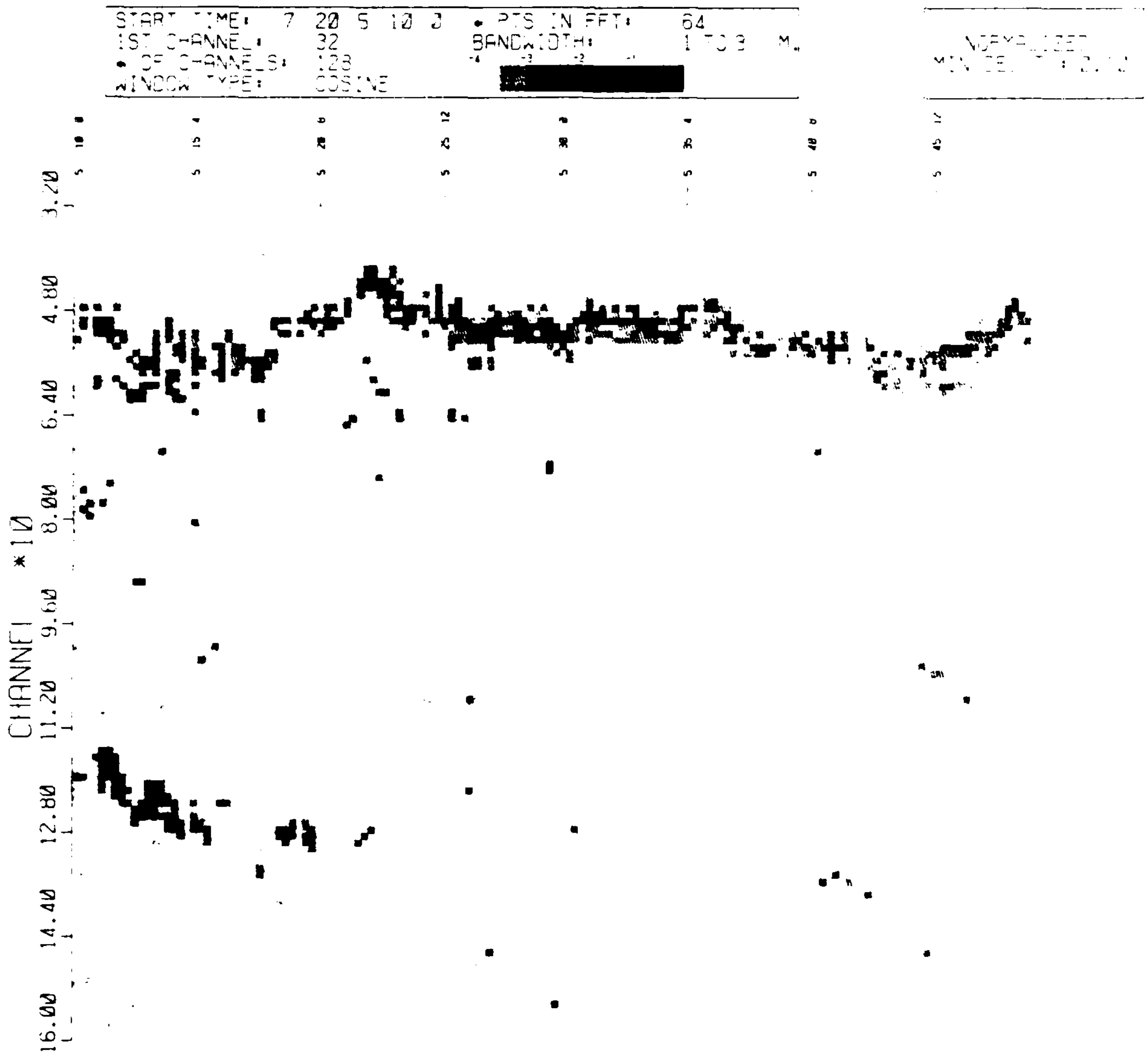

Fig. 13a — 8th 40 min (6 km) of TT6. 1-3 m band, normalized, min dT 0.1°C.

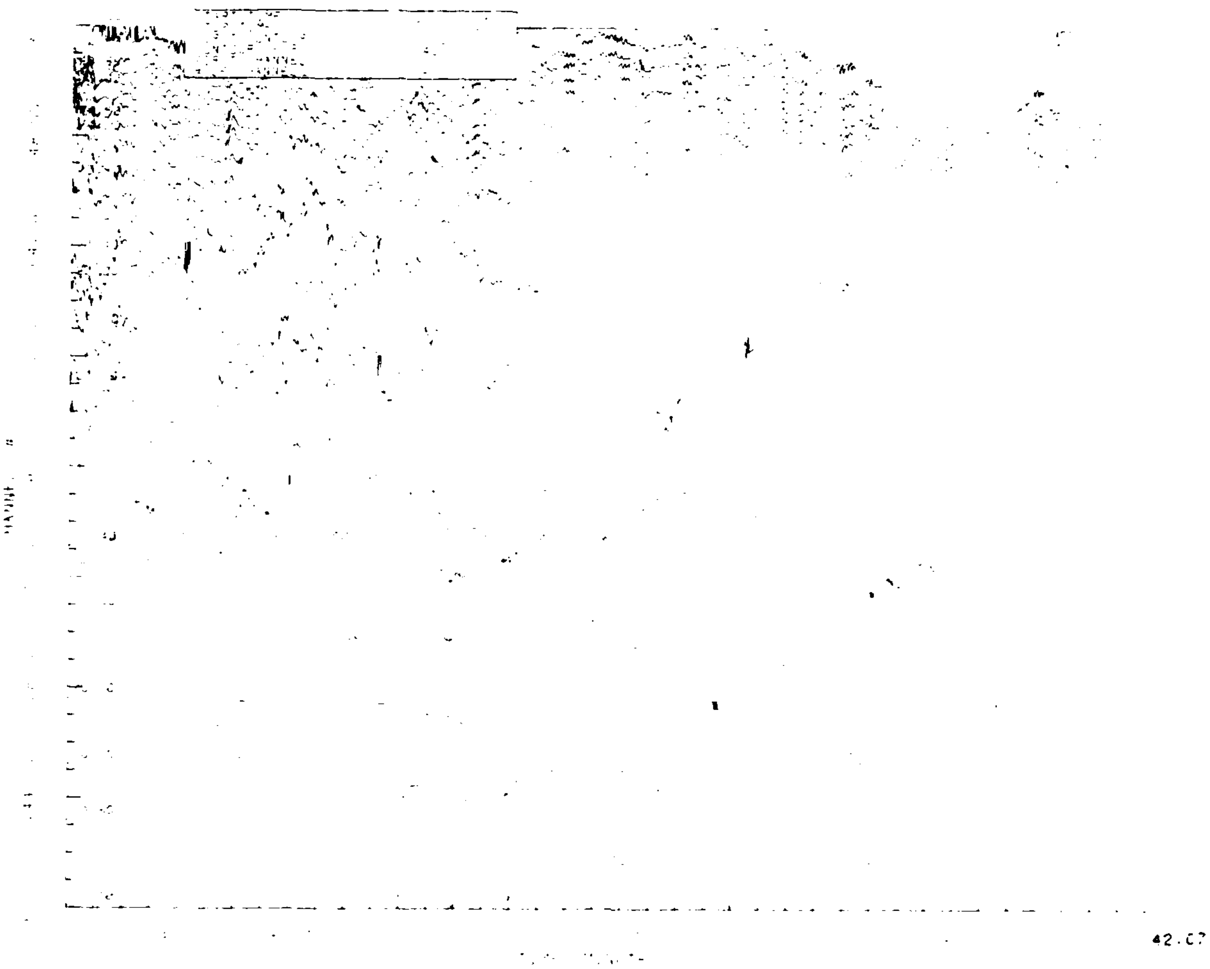

Fig. 6b — Isotherm plot for 1st 40 min

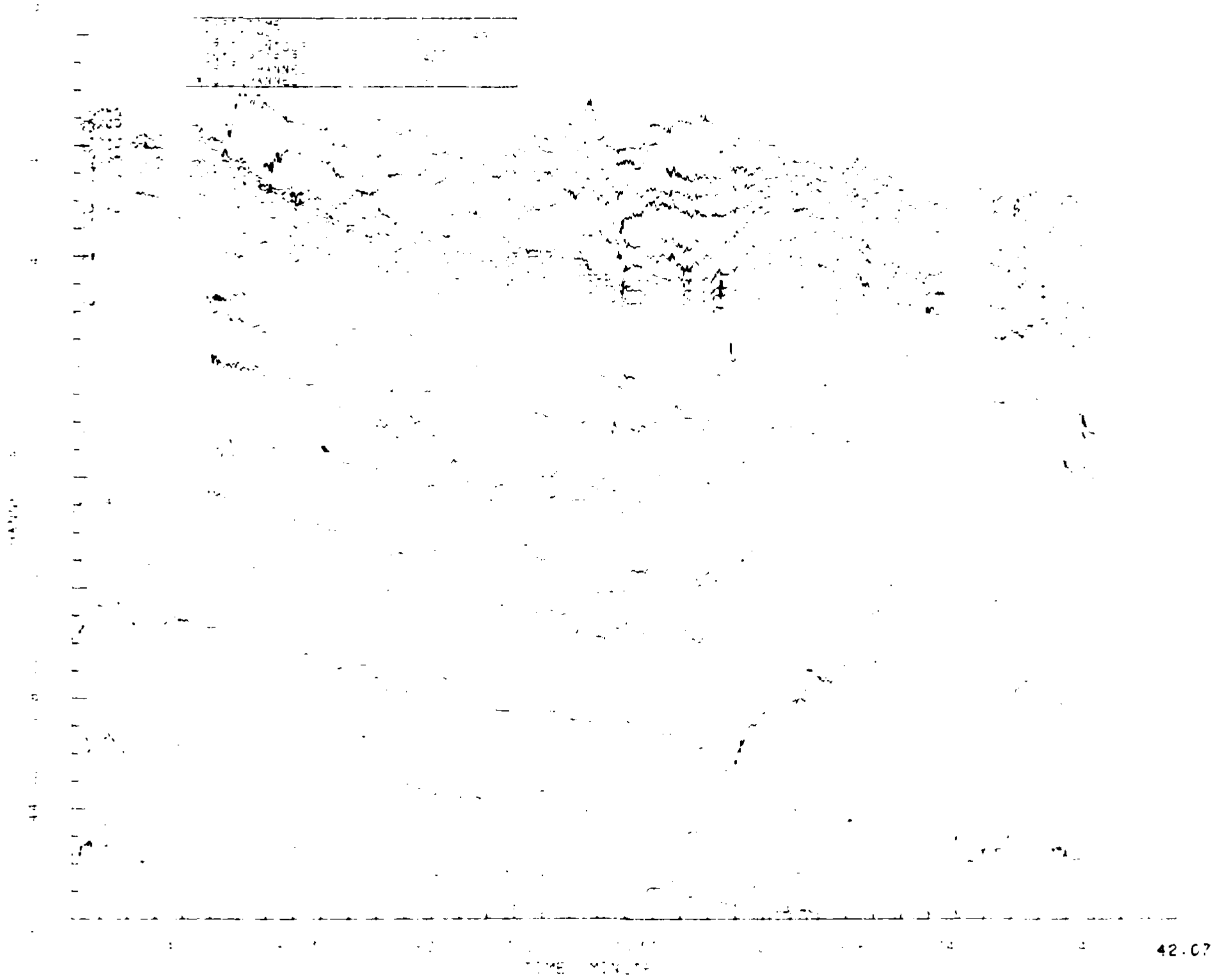

Fig. 7b — Isotherm plot for 2nd 40 min

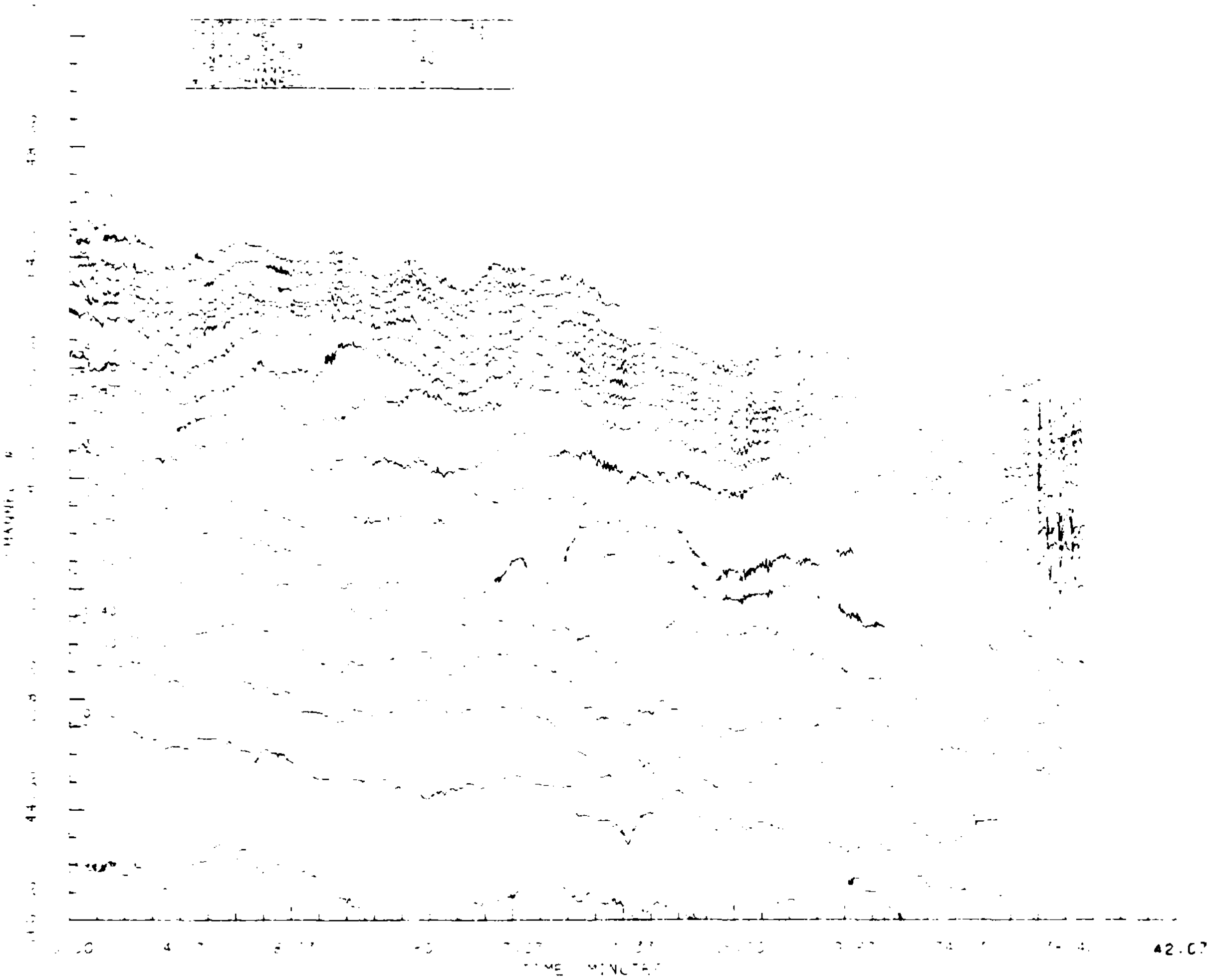

Fig. 8b — Isotherm plot for 3rd 40 min

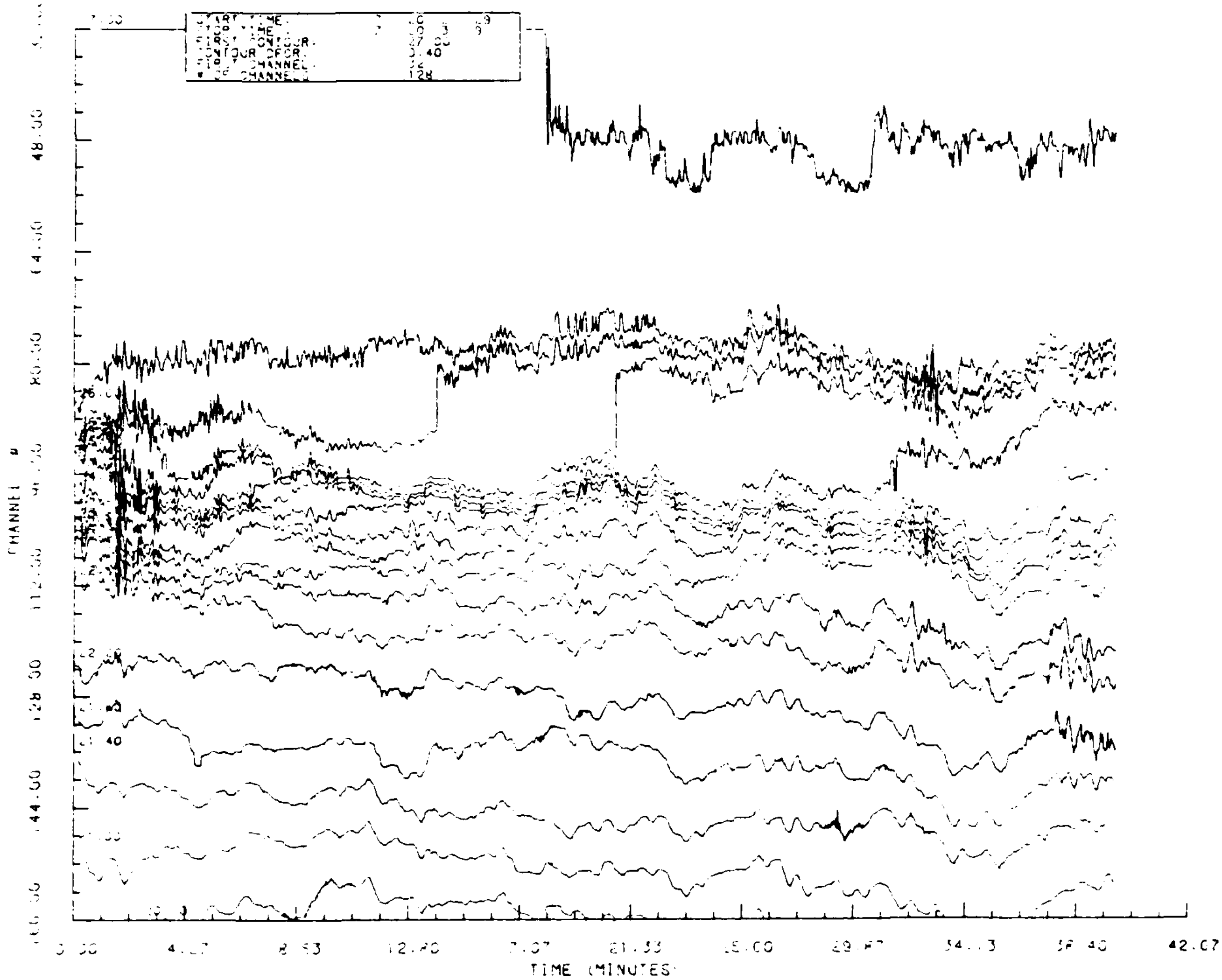

Fig. 9b — Isotherm plot for 4th 40 min

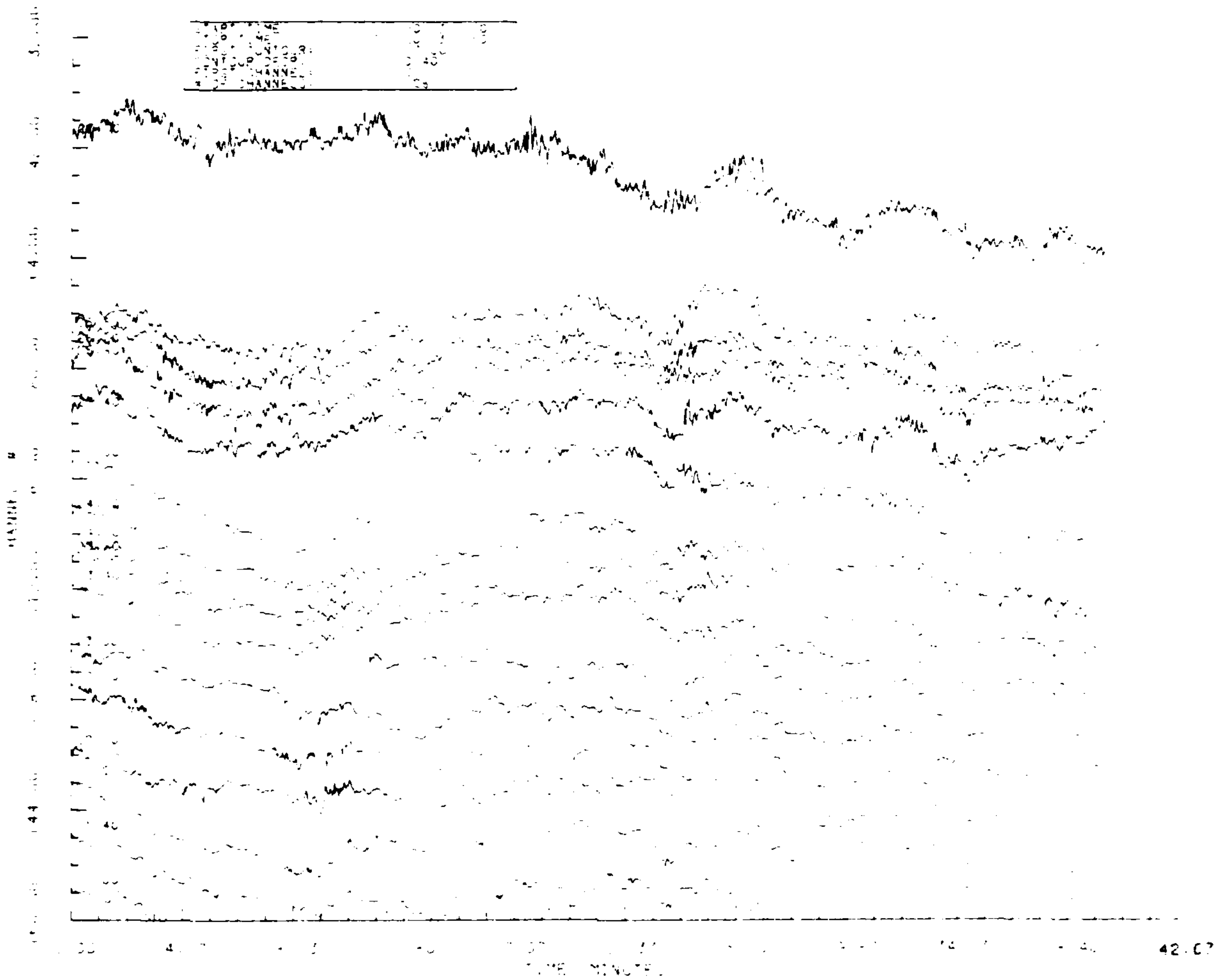

Fig. 10b — Isotherm plot for 5th 40 min

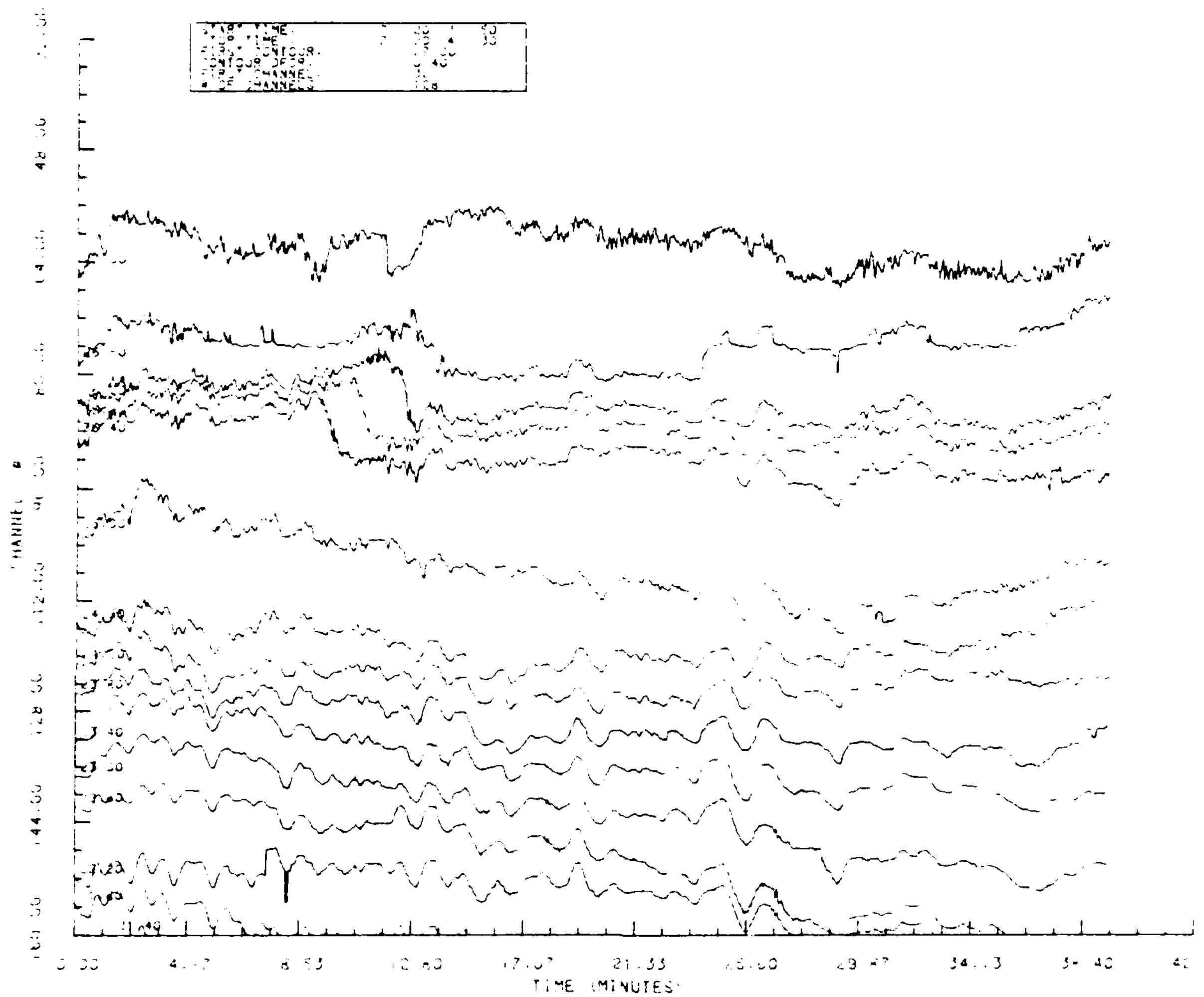

Fig. 11b — Isotherm plot for 6th 40 min

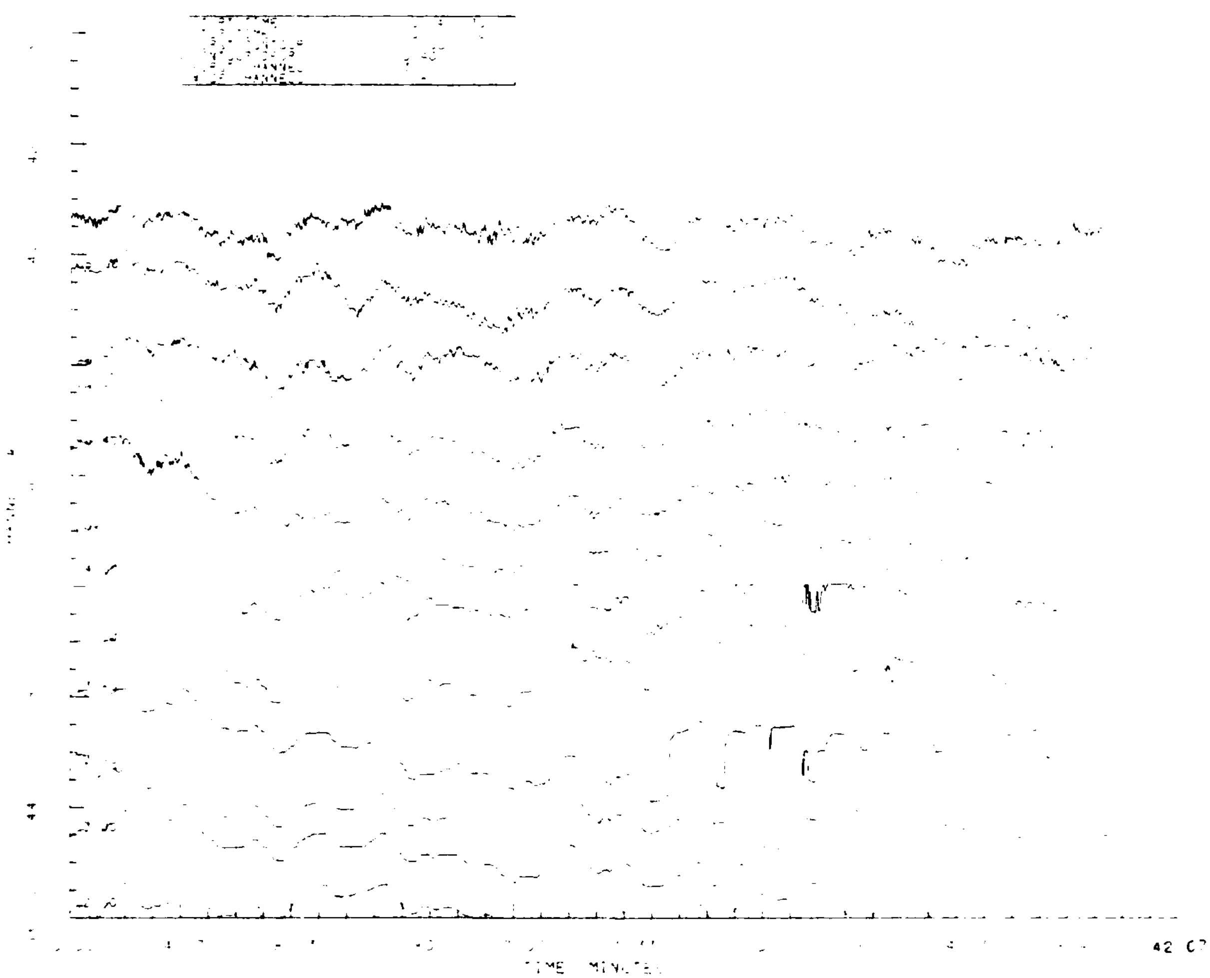

Fig. 12b — Isotherm plot for 7th 40 min

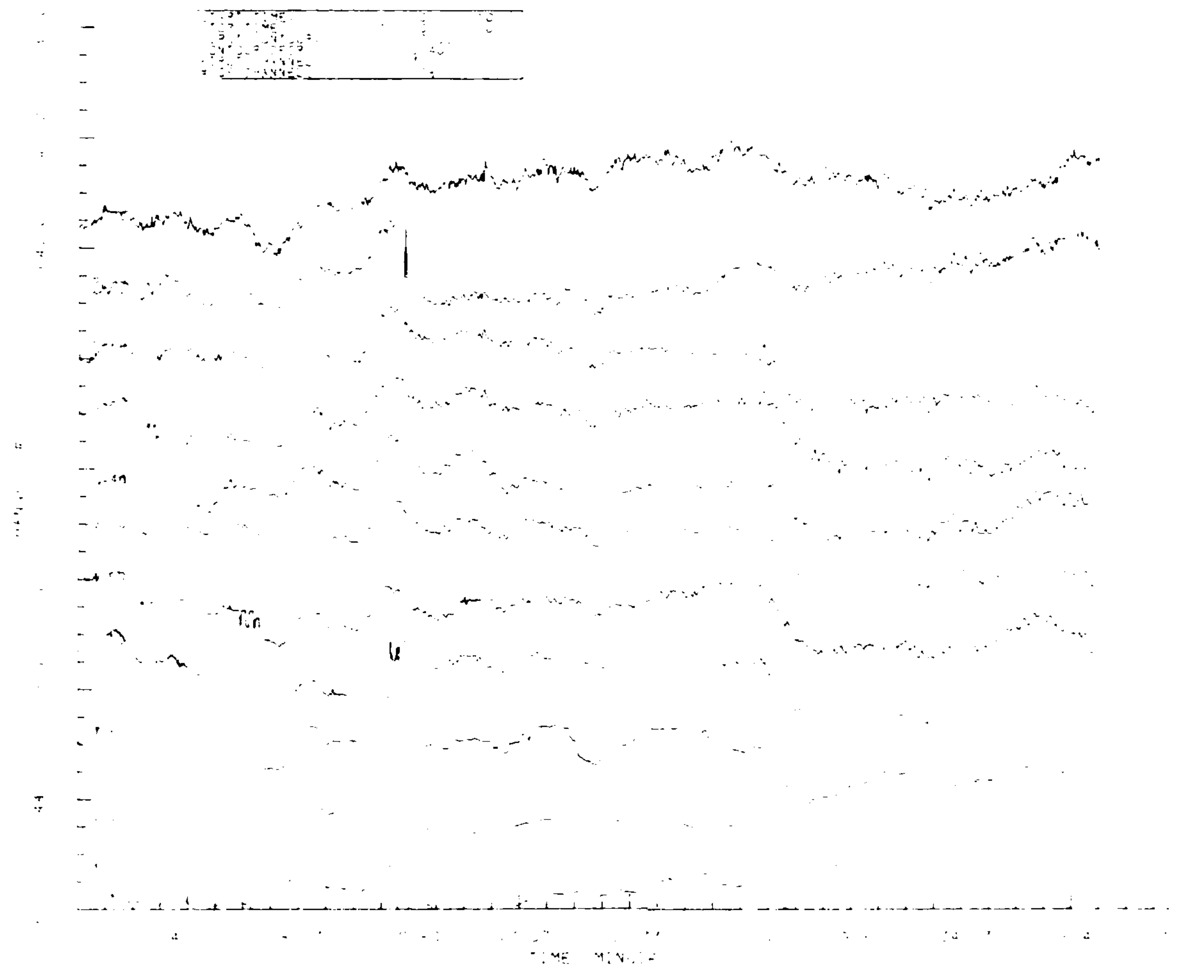

Fig. 13b — Isotherm plot for 8th 40 min

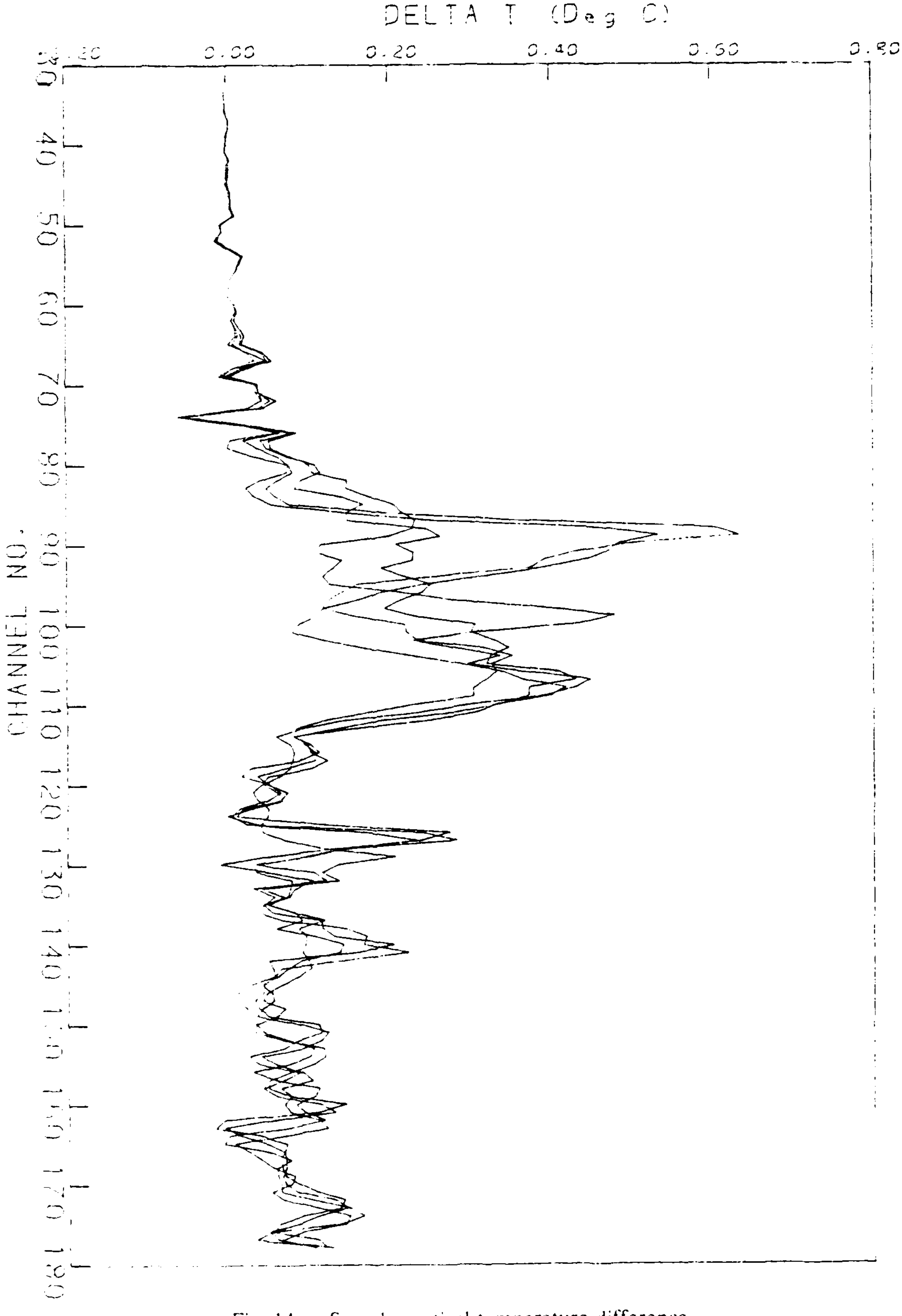

Fig. 14 — Sample vertical temperature difference

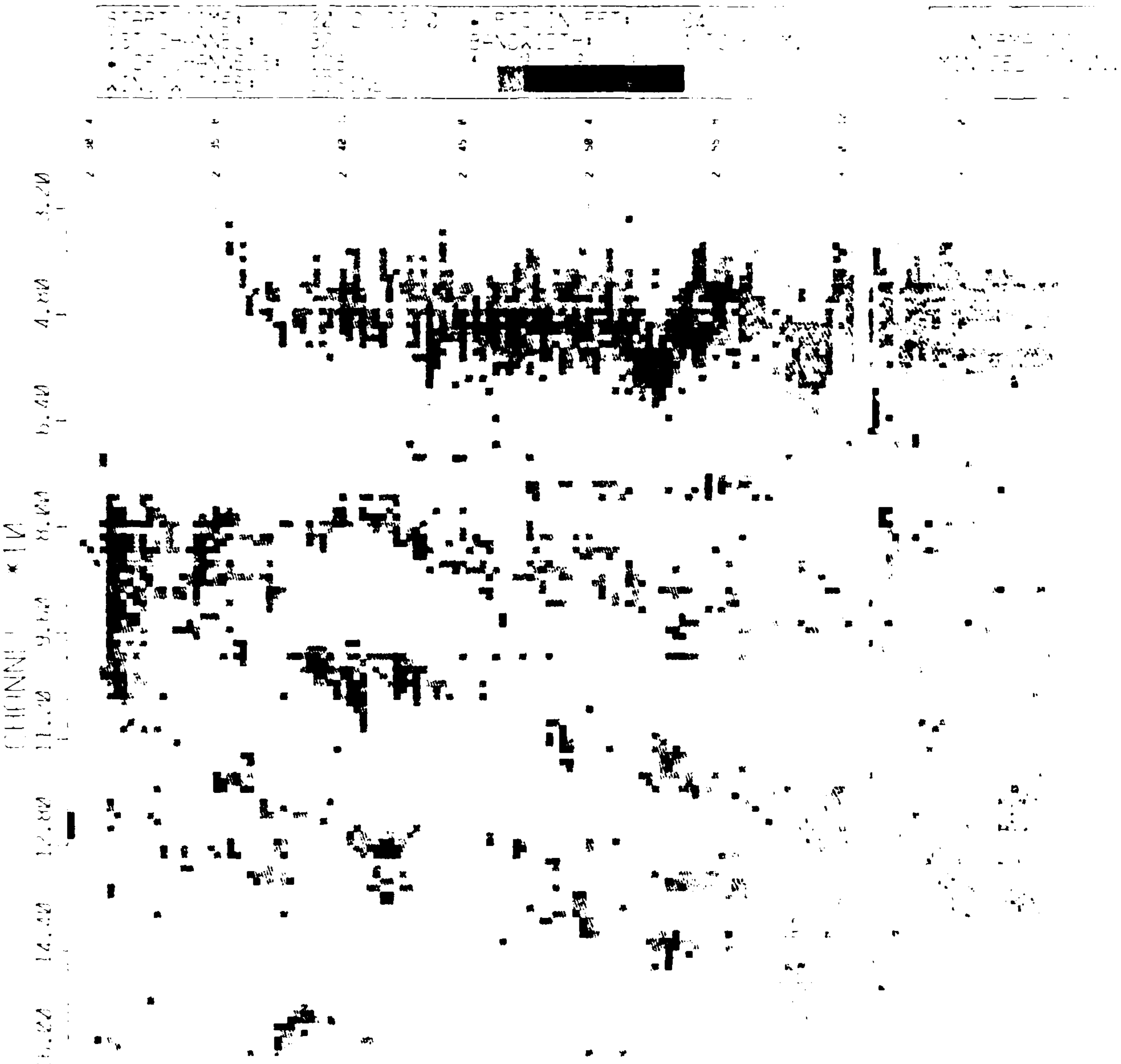

Fig. 15 — Fig. 9a with min dT 0.05

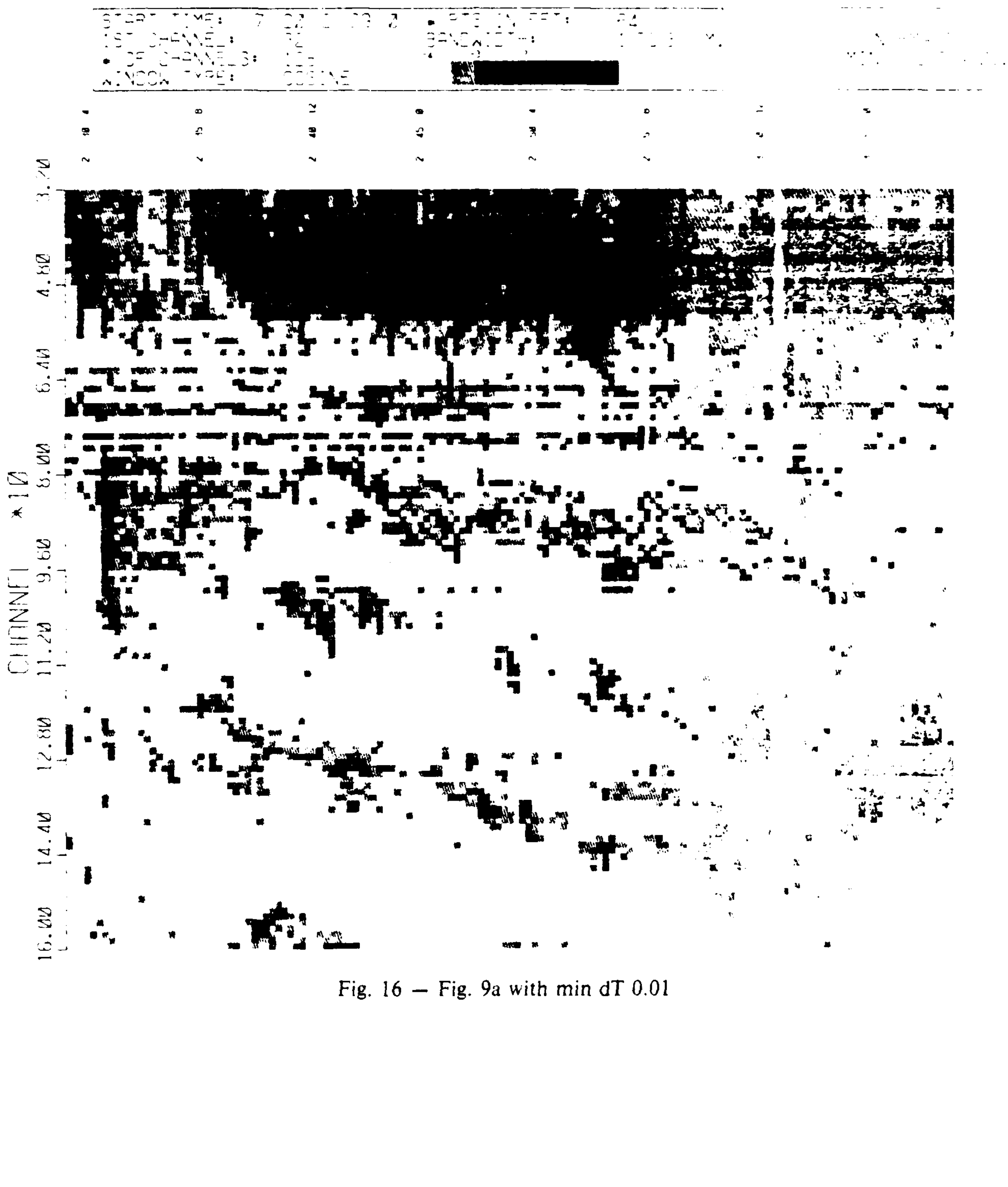

Fig. 16 — Fig. 9a with min dT 0.01

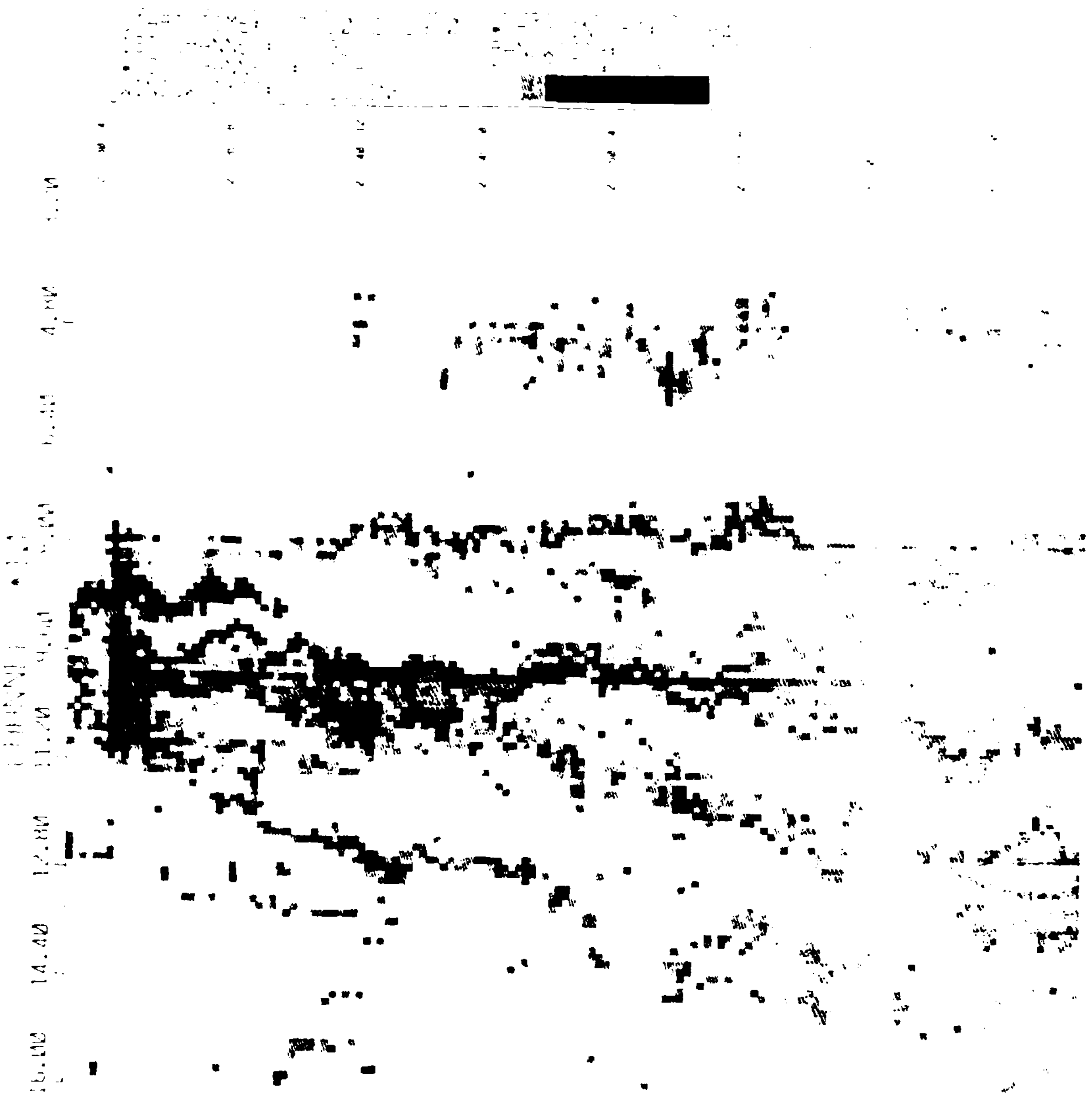

Fig. 17 — Fig. 9a with 1-3 m band, unnormalized, white level 10^{-6}

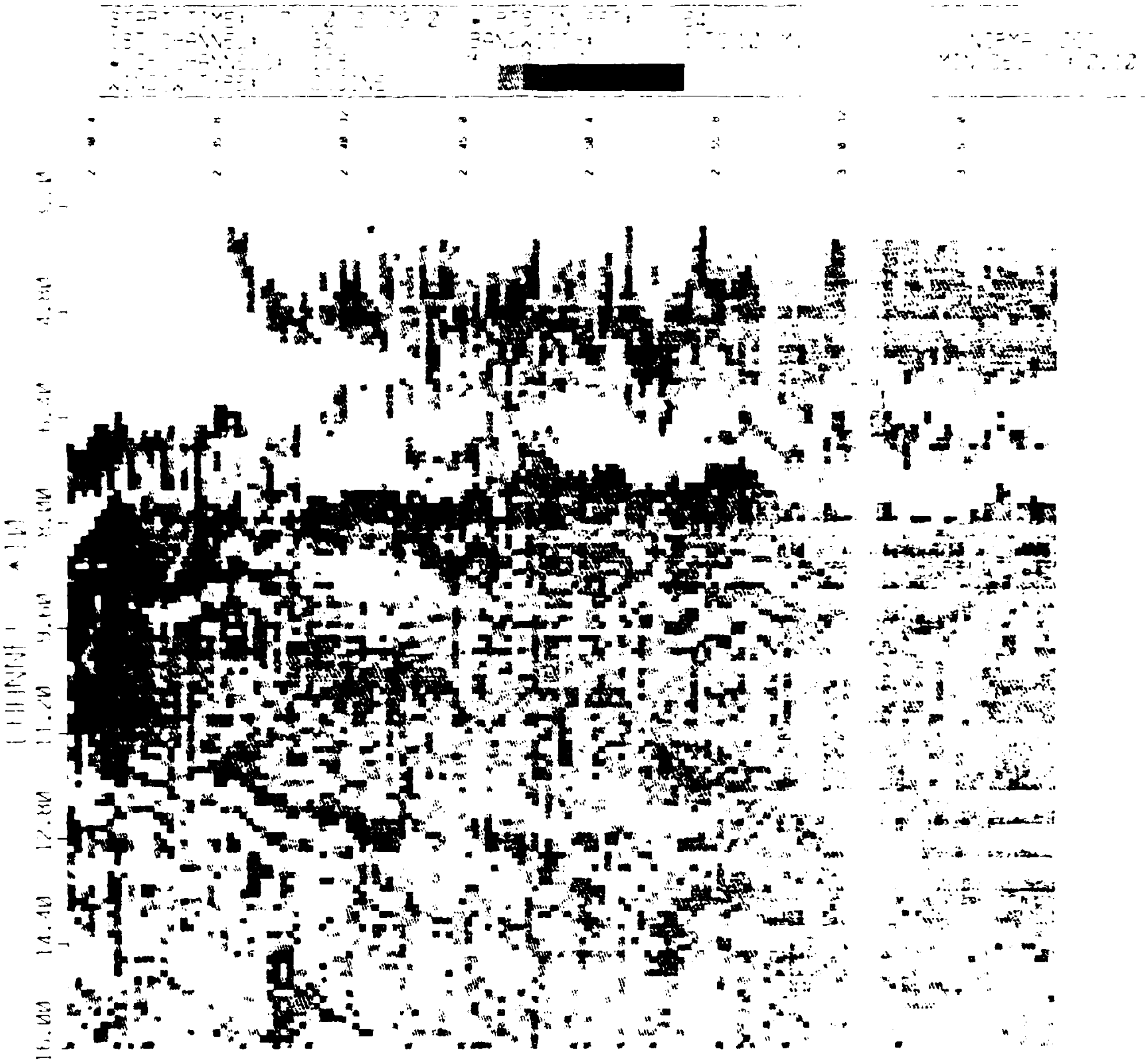

Fig. 18 — Fig. 9a with 1-10 m band, normalized, white level 10^{-4}

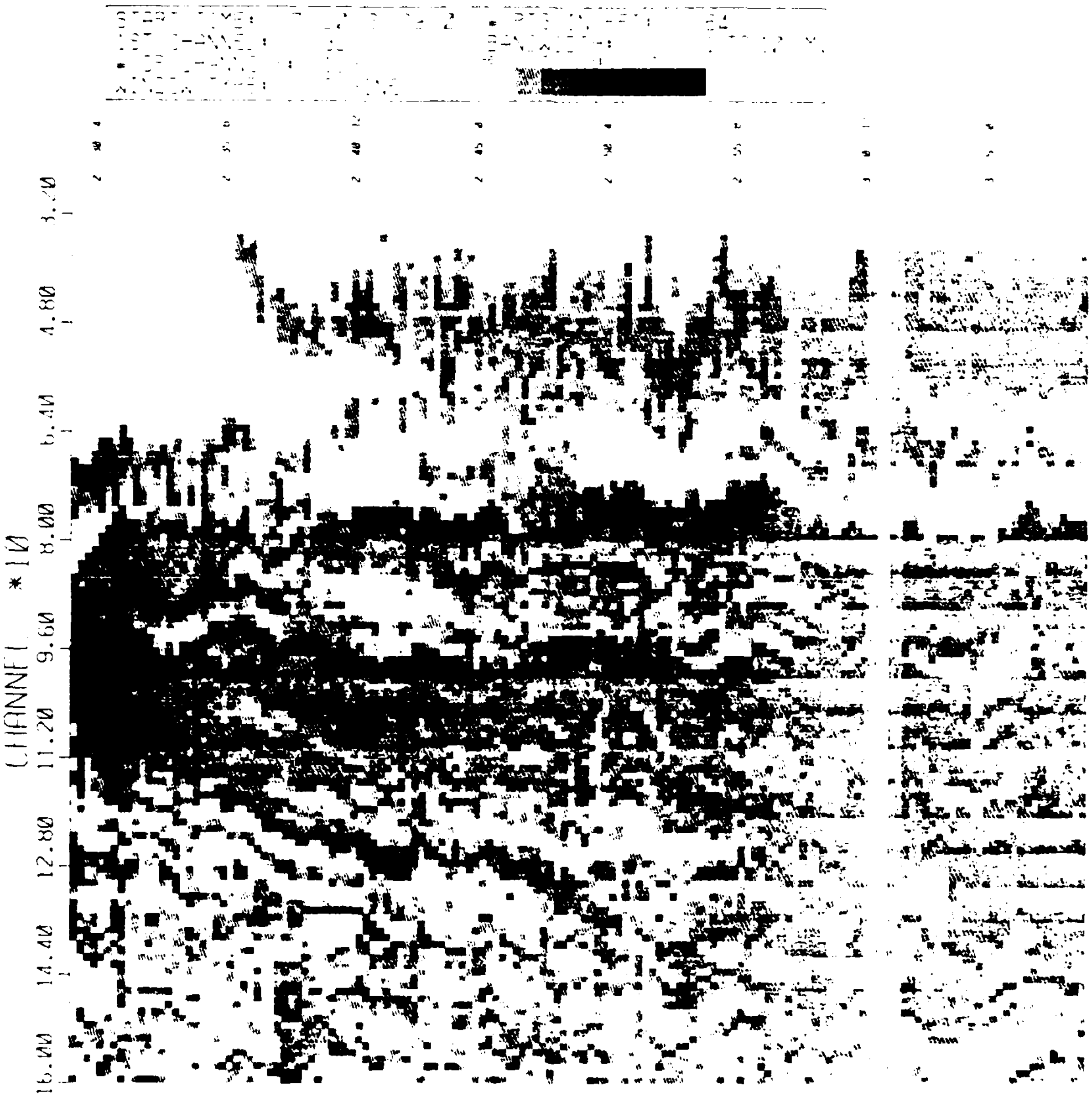

Fig. 19 — Fig. 9a with 1-10 m band, unnormalized, white level 10^{-6}

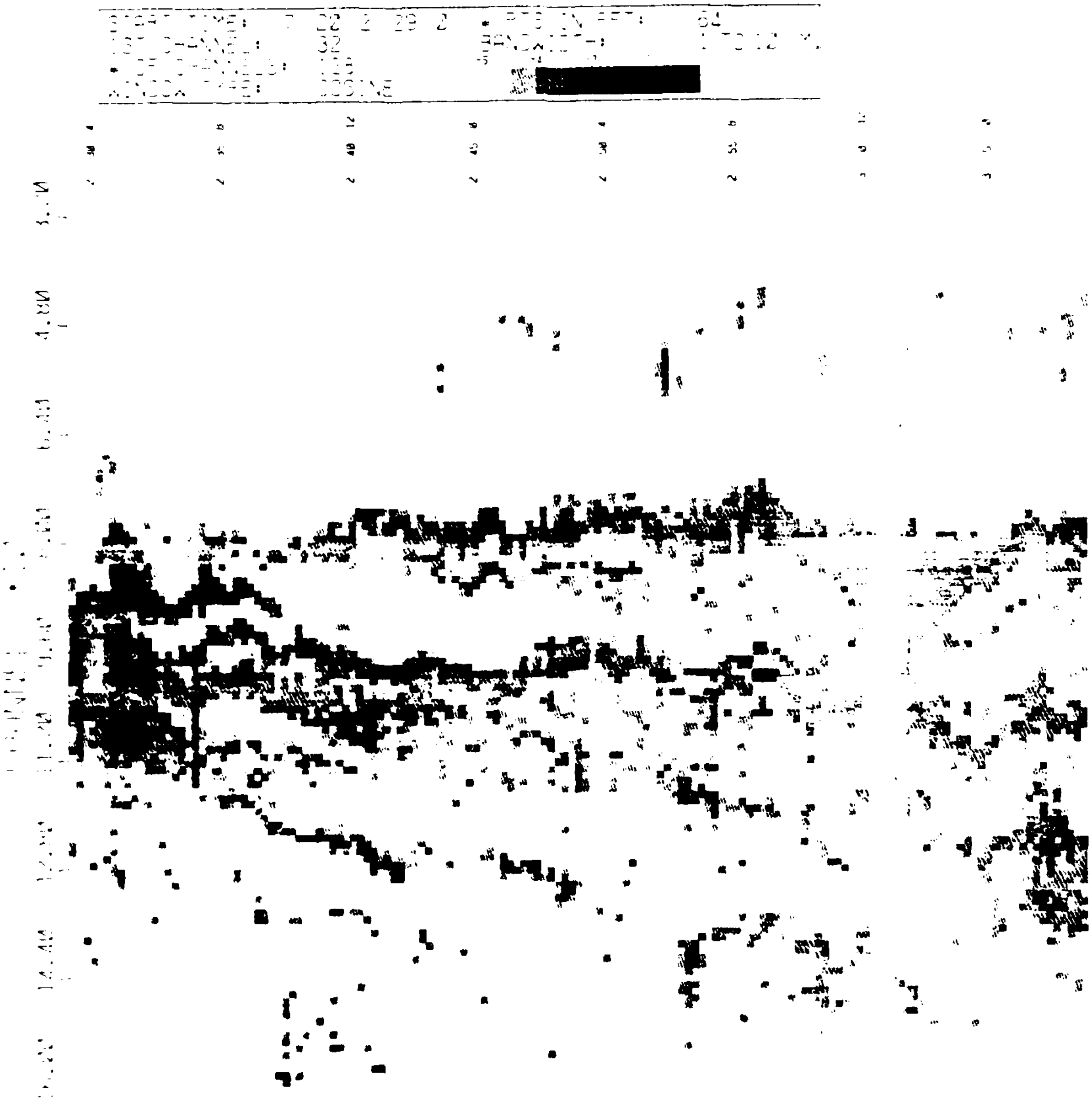

Fig. 20 — Fig. 9a with 1-10 m band, unnormalized, white level 10^{-5}

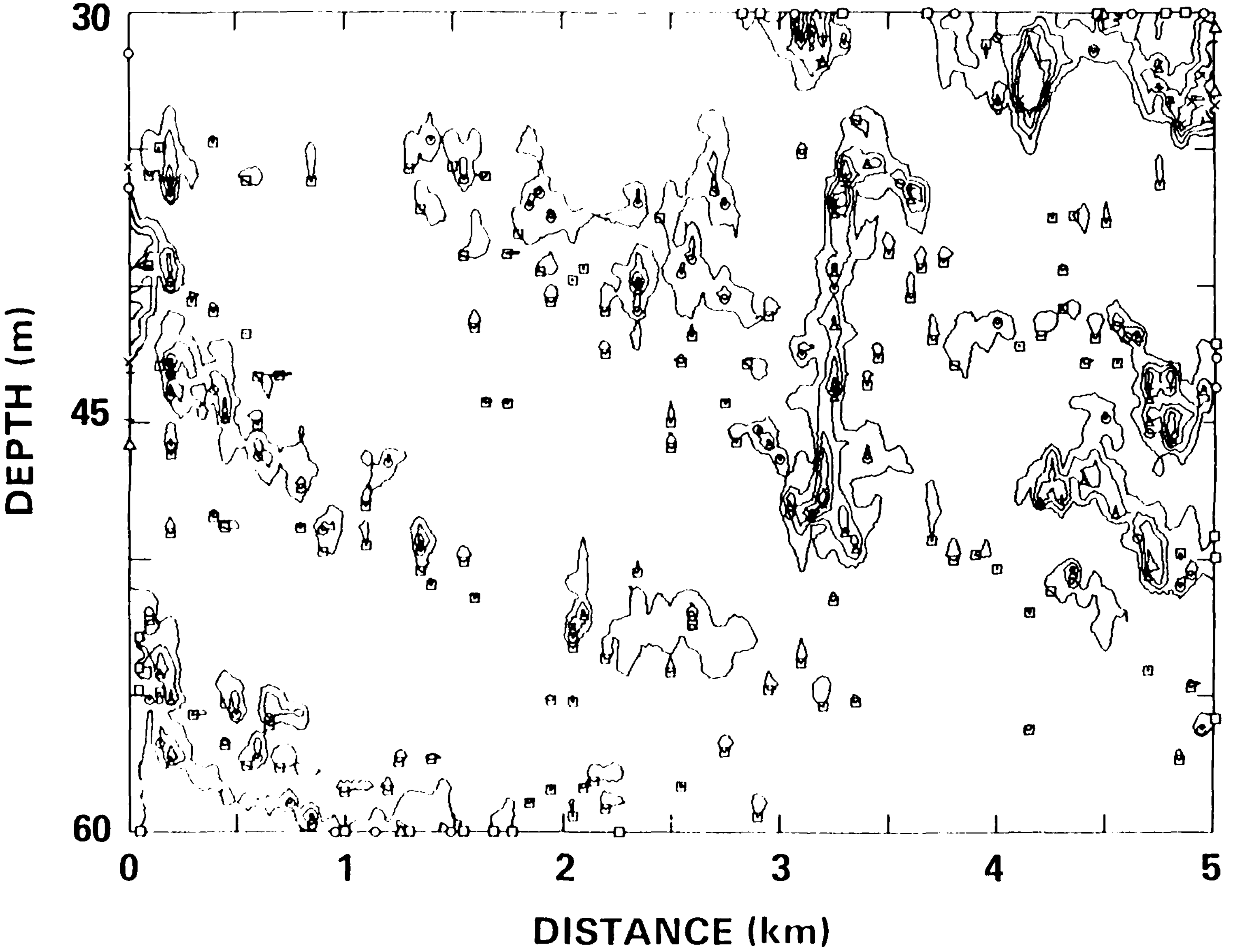

Fig. 21 — Contour plot from DUGAN-OKAWA patch processor

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