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Evaluation of HYDROPLOT Position Filtering Procedure

Rockville, Md.
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Systems Planning and Applied Technology

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U.S. DEPARTMENT OF COMMERCE
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EVALUATION OF HYDROPLOT POSITION FILTERING PROCEDURE

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ABSTRACT. Performance of position editing, extrapolation, and smoothing procedures for the SMOOTHED mode of HYDROPLOT real-time software has been evaluated theoretically, for simulated ranges, and with field data. Results indicate that satisfactory operation can be obtained if the "speed"-test threshold is set to about 50 knots or greater. Two minor modifications are recommended.

INTRODUCTION

Background

The acceptance of super high frequency (SHF) positioning systems by the National Ocean Service (NOS), namely the Motorola MRS III Mini-Ranger and Del Norte Trisponder, as hydrographic sensors has resulted in a need to implement real-time range filtering algorithms in both the HYDROPLOT and Bathymetric Swath Survey (BS^3) hydrographic data acquisition systems. HYDROPLOT uses a procedure involving a double exponential smoother as described in Brown (1963), while BS^3 uses a so-called "fixed memory" technique recommended in Casey (1982). It was requested that the performance of these protocols be examined via computer simulation to determine whether they are suitable for meeting NOS requirements.

Procedure

The first step was analysis of the performance of the existing HYDROPLOT algorithm on simulation and field data. Results of this analysis are described in this report along with recommendations for improving performance. Follow-on goals will be to examine the performance of the BS^3 fixed memory filter, compare double exponential and fixed memory results, consider other potential alternatives, and recommend an optimum approach.

A Monte Carlo simulation of a single range channel has been created in BASIC on a Tektronix 4051 computer. Numerous runs have been conducted for cases with zero and with selected constant rates of change in the range. Performance was evaluated via computer generated plots of the resulting time series and statistical measures derived therefrom. Additionally, an existing BS[3] program has been modified to permit the application of HYDROPLOT algorithms to Mini-Ranger field data.

Terminology

For the purposes of this document, "smoothing" will be used to describe the application of an algorithm to a given set of ranges in order to reduce the effect of noise, i.e., the standard deviation about the mean trend. The process of excluding wild data points prior to smoothing will be called "editing". The process of replacing wild data points with forecast or predicted values will be termed "extrapolation". The net result of all these procedures will be called "filtering". This terminology is arbitrary and ad hoc and is not intended to conform to any literature standards.

THEORY

Exponential Smoothing

Assume, for the moment, that a set of ranges is derived from a stationary process, i.e., the mean range is a constant in time. The ranges can be represented as

$$R_i = R + e_i , \tag{1}$$

where: R_i is the observed range,
R is the actual range, and
e_i is the i^{th} measurement error from a zero-mean, random distribution with standard deviation σ_e.

As demonstrated in Brown (1963), the standard deviation of the observed ranges can be reduced by application of the following algorithm:

$$S_i = c\, R_i + (1-c)\, S_{i-1}, \tag{2}$$

where: S_i is the "smoothed" range,
S_{i-1} is the previous smoothed range, and
c is a constant over $0 < c < 1$.

It can be shown that for iteration of this recursion on a set of ranges, the effective weights applied to the earlier raw data values decay, in the continuous limit, exponentially: hence the term "exponential" smoothing. For the discrete case of interest, the weights are $c\,(1-c)^k$ for the $(i-k)$th range (the k^{th} range prior to the current (i^{th}) value), and are thus, more correctly, "geometric" in nature. In more modern digital filter terminology, this is known as a "first-order autoregressive" low-pass filter.

The standard deviation of the smoothed ranges, σ_s, is less than σ_e by a factor which depends on the value of c. For large values of c, the weights decay rapidly, the smoothed values are quantitatively similar to the raw values, and the reduction in standard deviation is slight. For small values of c, the weights decay slowly, the smoothed values owe more to the history of the time series, and a greater reduction in standard deviation is achieved. The actual average standard deviation reduction or "smoothing ratio" for random data is

$$\sigma_s/\sigma_e = [c\ /(2-c)]^{1/2}\ , \tag{3}$$

as seen in Fig. 1. The drawback with small values of c is that when the input process changes, the smoothed response is correspondingly slower to react due to its increased emphasis on historical data.

It is important to note here that for correlated (non-random) data, the smoothing ratio, for a given value of c, is significantly larger; i.e., the smoothing is much less effective (Brown 1963). Extrapolaion procedures which replace edited ranges with estimated values add, by their very nature, a degree of correlation. It will be shown in later sections that this can cause the smoothed output to meander.

If the underlying process is not stationary but rather varying at a constant rate, the "single" exponential smoother cannot adapt and will equilibrate to a constant bias with a magnitude proportional to the range rate of change. This situation can be remedied by applying the formal recursion to the smoothed data a second time, as will now be seen.

Double Exponential Smoothing

Let the range process vary at a constant rate: then

$$R_i = R_0 + Vt + e_i\ , \tag{4}$$

where: R_0 is the initial range, and
V is the range rate of change.

If the exponential smoothing recursion is applied to this set twice, one has a "double exponential" or "second-order autoregressive" low-pass filter:

$$S_{1,i} = c\ R_i + (1-c)S_{1,i-1}\ ,\ \text{and} \tag{5}$$

$$S_{2,i} = c\ S_{1,i} + (1-c)S_{2,i-1}\ . \tag{6}$$

Much as Eq.(5) yields a biased result, Eq.(6) yields a doubly biased result. It is easy to show, therefore, that the smoothed range

$$S_i \doteq 2S_{1,i} - S_{2,i} \tag{7}$$

is an unbiased smoothed range; i.e., $\langle S_i \rangle = \langle R_i \rangle$ after the initial transient damps out. It can also be shown that

$$v_i = c\ (S_{1,i} - S_{2,i})/(1-c) \tag{8}$$

is a smoothed range rate-of-change or speed. This speed is used for extrapolation in the wild point replacement procedure (to be described in the next section).

The two most important but competing performance factors are the smoothing ratio and the transient response time. These will now be described in detail.

For a random input distribution, the average smoothing ratio for the smoothed range estimate from a double exponential algorithm is

$$\sigma_s/\sigma_e = [c\ (1+4b+5b^2)/(1+b)^3]^{1/2}, \tag{9}$$

where $b = (1-c)$. This is plotted in Fig. 1 in comparison with the value for single exponential smoothing. For a given value of c, the maximum theoretical smoothing ratio of a double exponential algorithm is larger than that of a single exponential; i.e., the double exponential smoothing is not as effective, and the residual noise is greater. This can be understood on the basis that the second pass operates on partially correlated data produced by the first pass.

Note that if c=0.3, as in HYDROPLOT, the standard deviation of the smoothed output for a single exponential algorithm is 42% of the input, while it is 62% for a double exponential. Furthermore, it can be shown that this performance ratio between the two algorithms is nearly independent of c and thus holds in general. At c = 0.1, for example, the standard deviation reductions are 23% and 36%, respectively.

The response of the smoothing algorithm to changing range rates is characterized by the ramp response function. For an underlying range process as represented in Eq.(4), it can be shown that the ramp response function for the unbiased range estimate, S_i, is

$$r(t) = Vt(1 - b^{t+1}) \tag{10}$$

for the discrete case, where t+1 is the time of the $(i+1)^{st}$ range measurement. Several such functions are shown in Fig. 2 (plotted as continuous functions for clarity) for a range of c values. The magnitude of the deviation of the response from the input ramp during the startup transient is seen to increase as c decreases. Note that these functions are scaled to the range rate, V, and are valid for all V. The magnitude of the deviation from the input ramp is thus also proportional to V. For large c, the transient is seen to be short and of small relative magnitude; for small c, the reverse is true. The smaller the value of c, the greater the number of input ranges required to achieve bias-free equilibrium; i.e., the longer the startup transient. The larger the value of c, the shorter the transient, but the less the reduction in standard deviation.

The transient response of the smoothed speed to a speed step function of magnitude, V, (the same ramp function for the range as above) is

$$v(t) = V\ [1 - (1 + c\ t)\ b^t\ ]. \tag{11}$$

This expression is plotted for four selected values of c in Fig. 3. The smoothed speed converges on the true range rate in a time which depends on c. The response times are consistent with those for the equivalent smoothed ranges of Fig. 2.

It appears that, based on Figs. 2 and 3, a value of c less than 0.3, say 0.2, might not be inappropriate for HYDROPLOT, given that the response equilibrates after about 15 inputs. As seen in Fig. 1, the smoothing ratio at c = 0.2 is 50%.

EVALUATION PROCEDURES

Computer Simulation

A generalized, modular test program has been written which 1) generates a specified temporal range functionality for 100 time intervals; 2) adds Gaussian noise with specified standard deviation to the range values; 3) applies a selected filter procedure to the range data; 4) plots input values, edited values, and smoothed values as a function of time; and 5) reports statistics on results.

The first implementations were for single and double exponential smoothing (in a filter procedure operating according to HYDROPLOT protocol) applied to constant ranges and to ranges increasing (or decreasing) at a constant rate.

A flow chart of the filter algorithm used to simulate HYDROPLOT processing is presented in Fig.4a. The current version of the computer program is attached as Appendix 1 for those who might be interested in details. The program is concerned only with the "SMOOTHED" HYDROPLOT option for a single range.

The first step in the procedure is data editing: the examination of the time rate of change of consecutive ranges (the current versus the former). If this range "speed" is less than an operator-selectable value, that fact is noted, and the current range is considered to be valid. If not, the reverse is noted, and the current range is considered to be a wild point and is replaced by an extrapolation procedure (to be described shortly). As it stands, this procedure does not provide symmetric edits with respect to positive and negative noise amplitudes for non-zero range rates. It can, however, be modified to do so, as will be described in the next section.

The filter procedure has two modes: NAVUP and NAVDOWN. In the NAVDOWN mode, the ranging function is disabled, the output is set to a preset constant value as a NAVDOWN indicator, and the system attempts to achieve a NAVUP, or operational status. The program initializes in the NAVDOWN condition and requires five consecutive valid "speed" tests to move into the NAVUP mode. (Operationally, eleven consecutive successes have been required in the past, but this is now considered excessive, and the value is being reduced to five.) In the NAVUP mode, ranges are processed with a double exponential smoothing algorithm. When the NAVUP condition is achieved, the initial condition values needed by the smoothing algorithm are drawn from the NAVDOWN protocol. The previous actual data value (the fourth consecutive acceptable range) is used for that purpose. In the NAVUP mode, a counter keeps track of the number of consecutive wild points and consequent extrapolations. If eleven consecutive wild points are encountered, the extrapolation is considered excessive; the system returns to the NAVDOWN mode, outputs no further ranges, and resumes attempting to achieve NAVUP as before.

The smoothed speed term from the double exponential smoothing algorithm is used, when necessary, to extrapolate previous ranges for the replacement of wild points which have failed to pass the "speed" test. In this procedure the previous smoothed velocity is multiplied by the time difference between ranges (set equal to unity in the simulation), and this product is added to the previous range (regardless of whether it may also be an extrapolated value) to obtain an extrapolated replacement value for a wild point detected by the "speed" test. Note that the smoothed speed is <u>not</u> the same "speed" (raw range rate) used in the "speed" test.

In a separate test with slightly modified logic, the smoothed speed was also used to symmetrize the "speed" test over the basic noise distribution by removing the effect of the range rate.

Application to Mini-Ranger Data

The HYDROPLOT processing protocol with a double exponential smoothing algorithm has been applied to Mini-Ranger data acquired in the field with the Bathymetric Swath Survey System (BS^3). The BS^3 program "SMOOTH" (which performs off-line data editing based on a "fixed memory" algorithm) has been modified to include optional HYDROPLOT processing procedures. In this way, the algorithms have been evaluated for real-world anomalies. The added logic is equivalent to that implemented in the simulation (Figs. 4a,b), but it is applied to both ranges.

RESULTS

Data Editing and Extrapolation

The "speed" test implemented in the HYDROPLOT processing protocol deals with differences between successive ranges per unit time. The population of first differences from a Gaussian range distribution with standard deviation, σ_e, is known to exhibit a Gaussian distribution with standard deviation $\sqrt{2}\sigma_e$. The mean absolute value of a Gaussian distribution of standard deviation, σ, can be shown by integration to be $\sigma\sqrt{2/\pi}$. The mean apparent point-to-point "speed" for a constant range process ($V=0$) with Gaussian noise (per Eq. (1)) is thus $(2/\sqrt{\pi})\sigma_e = 1.13\sigma_e$ (for one second updates). For a range changing at a constant rate, V, as in Eq. (4), the "speed" distribution is shifted away from zero mean, thus resulting in a mean absolute "speed", $\langle|s|\rangle$, which, for $V > \sigma$, approaches the range rate, as seen in Fig. 5. For $V < \sigma$, the apparent mean "speed" is dominated by the σ_e dependence and is larger than V.

Data editing in HYDROPLOT is based on a comparison of these apparent "speeds" against a preset threshold. If a range results in an apparent "speed" greater than the threshold, the range is excised and replaced by a value extrapolated from the previous range using the smoothed speed from the double exponential smoother.

For a constant range process, the edit probability is equal in both directions (short ranges and long ranges), as desired. For ranges changing at a constant rate, V, however, the "speed" distribution is shifted away from zero mean. This leads to larger effective "speeds" in one direction and smaller in the other. The "speed" test will thus selectively edit primarily on the high "speed" side of the resulting distribution. With ranges increasing in time, for example, the larger range differences (high "speeds") and subsequent data edits will be primarily for points on the long range side of the distribution. The reverse is true for decreasing ranges.

It is easy to correct this problem by feeding back the smoothed speed, v, from the double exponential smoothing algorithm to the "speed"-test threshold logic, as described in Fig. 4b. This new procedure has been sucessfully demonstrated via the simulation and would be beneficial if added to existing HYDROPLOT code. Due to the use of the smoothed speed as an approximation of the true range rate, the technique is not effective during and immediately after a NAVDOWN condition.

Although the use of a generalized "speed" test for data editing is straightforward and seemingly sensible, it has a serious flaw for all but large thresholds, T, [$T \gtrsim (V +) 4\sigma_e$], as will now be seen. The parentheses indicate that the "V+" can be removed if the threshold logic is modified per Fig. 4b.

Because the editing procedure based on the "speed" test deals only with first differences, not with the ranges themselves, editing decisions are based not on the location of the range in question relative to the overall range population, but rather relative to the range preceeding it. A typical result of this protocol is seen in Fig. 6 for a constant range process. Points numbered 1 through 9 are from a typical time series based on a Gaussian distribution. The maximum permissible range difference for no data edit, ΔR_m, as set by the "speed"-test threshold ($=3\sigma_e$ for this example), is indicated with bars. Points 1 through 4 fall well within the body of the distribution. Point 5 is an outlier at the $-3.5\sigma_e$ level; but because it is not more than ΔR_m distant from the preceeding range, it is incorrectly retained. Point 6 is again a "good" range well within the main body of the distribution. It, however, differs by more than ΔR_m from point 5, and is hence considered to be an outlier and is edited out of the data set. Such behavior is clearly undesirable. It leads to even more severe problems upon replacement of the excised value by extrapolation.

The extrapolation process further exacerbates the improper editing procedure, as continued in Fig. 6. Upon arriving at point 5, the smoothed speed or, in the case of a constant range rate, the smoothed speed residual (compared to the constant rate) is generally in the direction <u>away</u> from the mean rate. The extrapolated value replacing point 6 (marked by an "x" denoted "6'") is thus an even worse outlier than point 5. Next, point 7, also in the main body of the distribution, is compared with point 6'. It fails the "speed" test (by an even larger amount) and is edited out of the data set and replaced by point 7' according to the previous smoothed speed. It is clear that this process can get quickly out of control as the good data is edited, and the extrapolated data "walks" away from the correct line (8' and 9'). Even if point 7 lies close enough to point 6' to be acceptable and hence terminates the walk, the procedure has magnified rather than eased the problem -- instead of no outlier at position #5, there are now two, #s 5 and 6', in correlation being output to the smoother.

With this "speed"-test approach to raw data editing, outliers can be ignored, and good data can be replaced with increasingly bad data, often until the NAVDOWN condition is achieved at eleven extrapolations. This frustrating situation is observed during HYDROPLOT operations unless the "speed"-test threshold is set to an arbitrary, large value.

A typical example of this type of behavior is demonstrated via simulation results for a 100-point time series, as seen in Fig. 7. Note that the ordinate in all such simulation outputs is the <u>residual</u>, i.e., the difference from the constant rate process. All illustrations are for constantly <u>increasing</u> ranges. Input data are represented by "o"s; edited inputs are overstruck with "#"s; extrapolated points are shown as "x"s; and the smoothed output is indicated as a solid line. The NAVDOWN condition is arbitrarily denoted by setting the smoothed output equal to -3S, where $S \equiv \sigma_e$. When x's exceed $\pm 4\sigma$, they are plotted at the $\pm 4\sigma$ level. Ancillary numerics on the figures may be ignored.

Because the data edits tend to be one-sided for non-zero range rates with the uncorrected "speed"-test logic, the wild excursions also tend to be one-sided, depending for direction on the sign of the range rate. For an increasing range process, for example, the extrapolations walk toward shorter ranges. Use of the smoothed speed in the threshold logic permits the desirable symmetrization of the walk direction probability.

The performance of the edit/extrapolation procedure depends strongly on the "speed" test threshold. If the threshold, T, is set to $T \lesssim (V +) 1.5\sigma_e$, the algorithm will continually fall into the NAVDOWN condition, as seen in Fig. 8. If the threshold is set to an intermediate value $[(V +) 1.5\sigma_e \lesssim T \lesssim (V +) 2.5\sigma_e]$, many "wild" points are incorrectly edited and extrapolated, and the NAVDOWN rate is roughly once per 100 points -- far too frequent for successful operations. In this regime, the "walk" is sometimes self-terminating, as seen in Fig. 9. This is the worst case because the system remains NAVUP, but significant biases (meanders) are introduced into the results by the incorrectly extrapolated values which are highly correlated to the previous outliers they were intended to replace.

For larger thresholds $[T \gtrsim (V +) 2.5\sigma_e]$, fewer edits occur, the system remains substantially NAVUP, and the raw data is fed mostly unaltered (except for gross outliers) to the smoothing algorithm. This has been the de facto mode of operation in the field when the SMOOTHED option is selected in order to maintain NAVUP. If T is set large enough, i.e., $T \gtrsim (V +) 4\sigma_e$, then the probability of ranges from the basic noise distribution exceeding the threshold is vanishingly small, and the "speed" test will perform the desired function of editing only <u>gross</u> outliers.

The smoothing coefficient, c, has a secondary effect on the propensity for "walking" due to its effects on the magnitude and transient response time of the smoothed speed. For a given change in c, either more or fewer dropouts may be incurred due to the opposing nature of these causal mechanisms.

Smoothing

For data without significant editing, the theoretical average smoothing ratios, σ_s/σ_e, (Eq. (9)) have been confirmed by simulation, as seen in Fig. 10 for c = 0.2. The sampled smoothing ratio is denoted SIGOUT/SIGIN in the lower right-hand corner.

With data editing, the smoothing ratio becomes <u>larger</u> (i.e., less effective) as more points are edited, as seen in Fig. 11 which presents the smoothing ratio as a function of the number of edits. It is tempting to blame this unexpected behavior on the improper edit/extrapolation procedure. This is not, however, the case. The same behavior has been noted for a proper edit/extrapolation procedure using a "fixed-memory" filter which is based on linear least-squares regressions of fixed length. The real problem is correlation in the extrapolated data, and the fact that extrapolated values tend to be generated in small groups. Extrapolation amplifies short-range correlation or -- in another way of looking at it -- generates low frequency behavior which falls outside the bandwidth capabilities of the smoothing algorithm.

Regardless of the explanation, the result is clear: in order to achieve the smoothest set of output ranges, one must not edit ranges from the fringes of the basic noise population, but only the gross outliers ($T \gtrsim (V + 4\sigma_e)$) which are generally judged to be from an entirely separate population. The smoothing algorithm will then perform at maximum efficiency.

If the basic noise process for Del Norte or Mini-Ranger is assumed to have a standard deviation of 5 meters at a 1/second update rate (say, 3 meters instrumental and several more for vessel motions, etc.), and given that typical range rates can be as large as 5 meters/second, then the threshold should be set at about 5+4x5=25 m/s = 50 knots(!) for the present code. Settings below this will result in degraded performance and frequent NAVDOWN conditions. The setting could be reduced to 40 knots if the "speed"-test logic were symmetrized.

Examples of transient response are seen in Figs. 12, 13, and 14 for c = 0.3, 0.2, and 0.1, respectively, at a range rate of +5 meters/second. Figure 15 repeats c = 0.2 for a higher, 10 m/s, range rate. The simulation results can be seen to be in good agreement with the predictions of Fig. 2 as far as the duration and magnitude of the transient are concerned. Smaller values of c exhibit transient deviations of larger magnitude and require longer to equilibrate; larger values of V also exhibit larger initial deviations. Note that the transient response is evoked anew after each NAVDOWN period.

An example of simulation results for the transient response of the smoothed speed is seen in Fig. 16 for c = 0.2. Note the good similarity to the theoretical functionality for the equivalent value of c as recalled from Fig. 3.

Field Data

Figure 17 presents ship tracks from a Chatham Strait (Alaska) survey with four examples of Mini-Ranger field data anomalies -- before and after application of a facsimile of the HYDROPLOT processing and smoothing protocol. Printed numbers are "record" numbers used (here) to indicate direction of motion. Symbols "○" and "▽" indicate NAVDOWN conditions for the two ranges; symbols "□" and "✱" indicate NAVUP. Short spikes perpendicular to the track indicate instances of zero ranges. During NAVDOWN, the raw data is simply passed through, unmodified, for viewing (unlike HYDROPLOT itself, where the data is replaced with all 9's). In Figs. 17a,b,c it can be seen that a variety of fliers of various magnitudes are successfully supressed. In Fig 17d, the lengthy excursion was corrected until NAVDOWN occurred. The erroneous data is then displayed until, at the end of the glitch, NAVUP is reestablished. In all cases, either complete or substantial improvement is achieved.

Two extreme cases are seen in Fig. 18. In Fig. 18a, the raw data begins to deviate from track prior to a string of zeros. The smoothed data extrapolates the deviation until NAVDOWN and then returns to NAVUP after the "flier". In Fig. 18b, the raw data contains both fliers and a large number of zeros. The output is nicely smoothed except during a brief NAVDOWN period -- during which the flier is plotted for viewing but would be excised from the formal output.

Overall, the performance is seen to be quite satisfactory.

CONCLUSIONS

1) When the present HYDROPLOT program is run in the SMOOTHED mode with the "speed"-test threshold set to a value only slightly greater than the vessel speed, the performance will be severely degraded. First, the system frequently tends to go into the NAVDOWN mode. If the threshold is raised only high enough to avoid the NAVDOWN condition, ranges will be improperly edited and improperly extrapolated, the output will wander and contain short-term biases, and the double exponential smoothing algorithm will become virtually ineffective.

Unnecessary extrapolation adds correlation to the range data and very rapidly causes the smoothing algorithm to be useless. It is imperative that edited data come only from the gross outlier or "flier" population, <u>not</u> from the fringes of the basic system noise distribution.

If the "speed"-test threshold is raised to about 50 knots, editing and extrapolation performance will be improved, short-term biases will not be generated, and the double exponential filter will achieve its maximum effectiveness. With this setting, the system should be able to run successfully in the SMOOTHED mode under nominal conditions. If long distances or poor propagation degrades positioning system performance, the threshold would need to be set even higher.

2) It appears that under most circumstances the value of "c", the double exponential smoothing constant, could be lowered from its present value of 0.3 to a value of 0.2. This would beneficially lower the theoretical smoothing ratio from 0.62 to 0.50, but would also require 15 seconds after turns for the transient response to damp out. This is expected to be acceptable except when turns are near-shore and perpendicular to the beach.

3) The present "speed"-test does not take the range rate into consideration and thus causes asymmetric editing and extrapolation. This can easily be remedied by replacing the present "speed"-test with threshold logic which includes the smoothed range rate, as described in Fig. 4b.

4) The HYDROPLOT protocol has been demonstrated to work quite well on actual BS^3/Mini-Ranger field data which includes several different types and levels of outliers. Detailed comparisons with "fixed-memory" filtering for the same data sets will be described in a future publication.

RECOMMENDATIONS

1) Under nominal conditions, the HYDROPLOT "speed"-test threshold should not be set below about 50 knots for acceptable operation in the SMOOTHED mode. Larger values will be required for degraded signals or high seas.

2) The dynamic response of the HYDROPLOT filter in the SMOOTHED mode should be evaluated in the field for a smoothing constant of 0.2 if the resulting reduction in smoothing ratio from 62% to 50% is considered desirable. It may be preferable to make the value of "c" operator selectable within fixed bounds.

3) The HYDROPLOT "speed"-test threshold logic could be modified to symmetrize the edits over the noise distribution by taking the range rate into consideration. The effect will be relatively small for recommended large thresholds, but the code change is correspondingly simple.

ACKNOWLEDGMENT

I wish to express thanks to Mr. Jack Wallace who provided the incentive for the study and to Ltjg. Steven Barnum who modified the BS3 programs and processed the field data.

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Casey, M. J., 1982: Improved Positioning Through Range Filtering. Technical Report, Canadian Hydrographic Service Central Region, Burlington, Ontario, Canada, 65 pp.

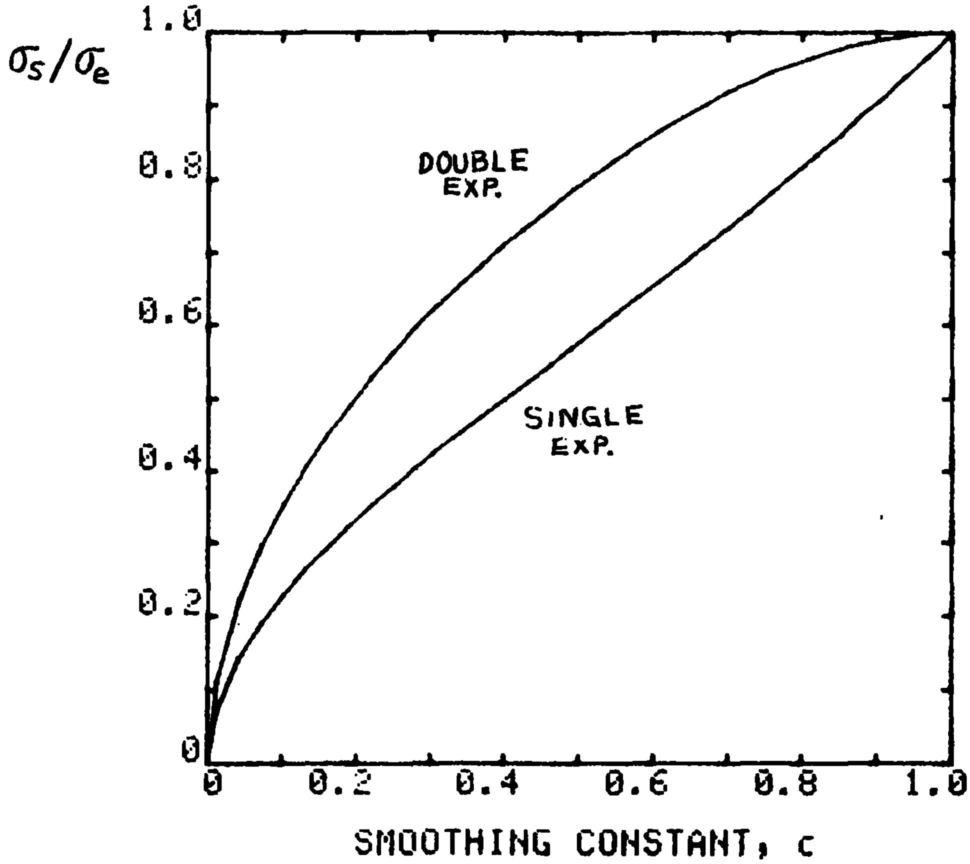

FIGURE 1. SMOOTHING RATIOS FOR SINGLE AND DOUBLE EXPONENTIAL SMOOTHING

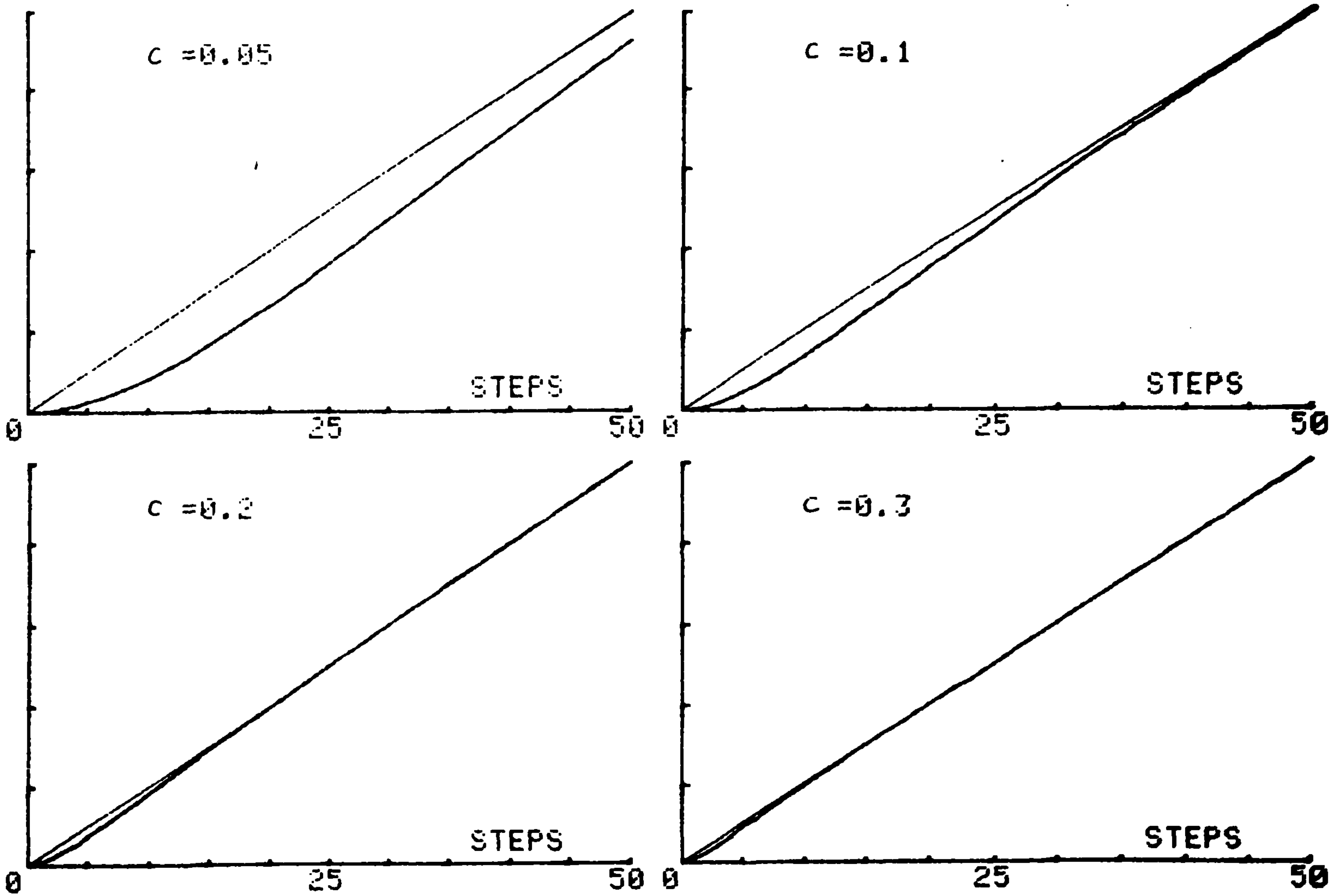

FIGURE 2. RAMP RESPONSE FUNCTIONS FOR DOUBLE EXPONENTIAL

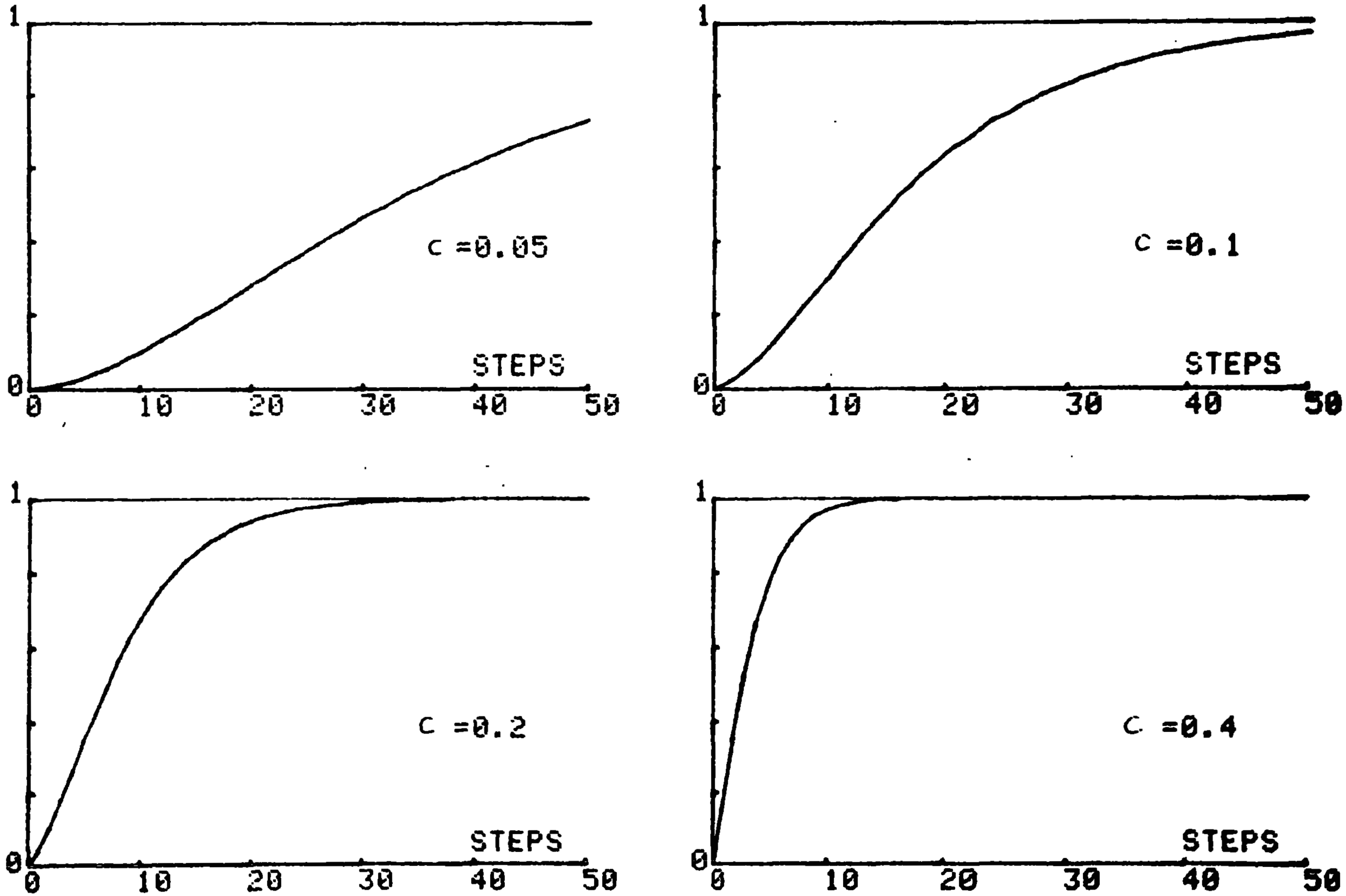

FIGURE 3. SMOOTHED-SPEED STEP RESPONSE FUNCTIONS

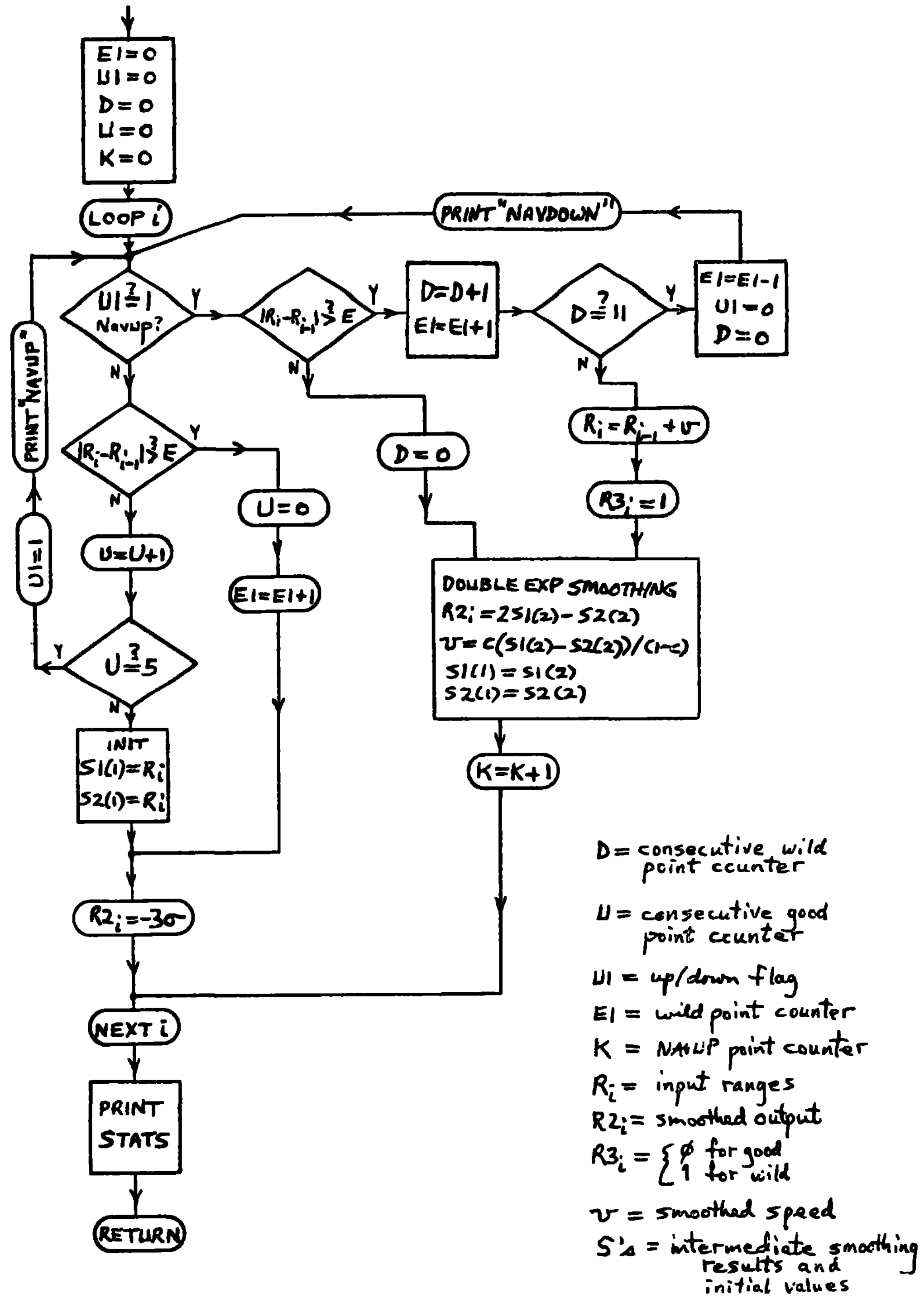

FIGURE 4a. FLOW CHART OF SIMULATED HYDROPLOT RANGE SMOOTHING PROTOCOL

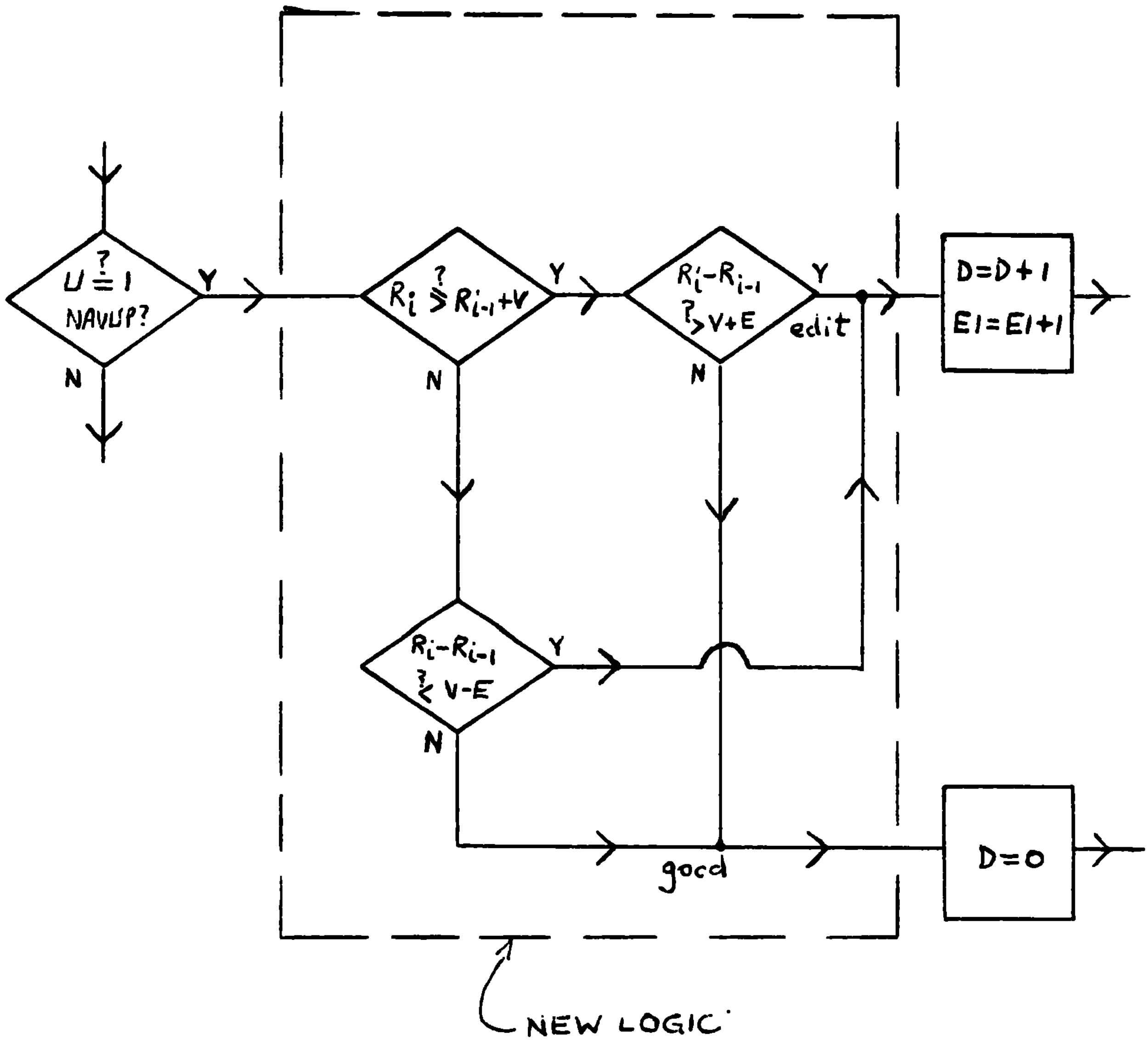

FIGURE 4b. PROGRAM MODIFICATION TO SYMMETRIZE "SPEED"-TEST LOGIC

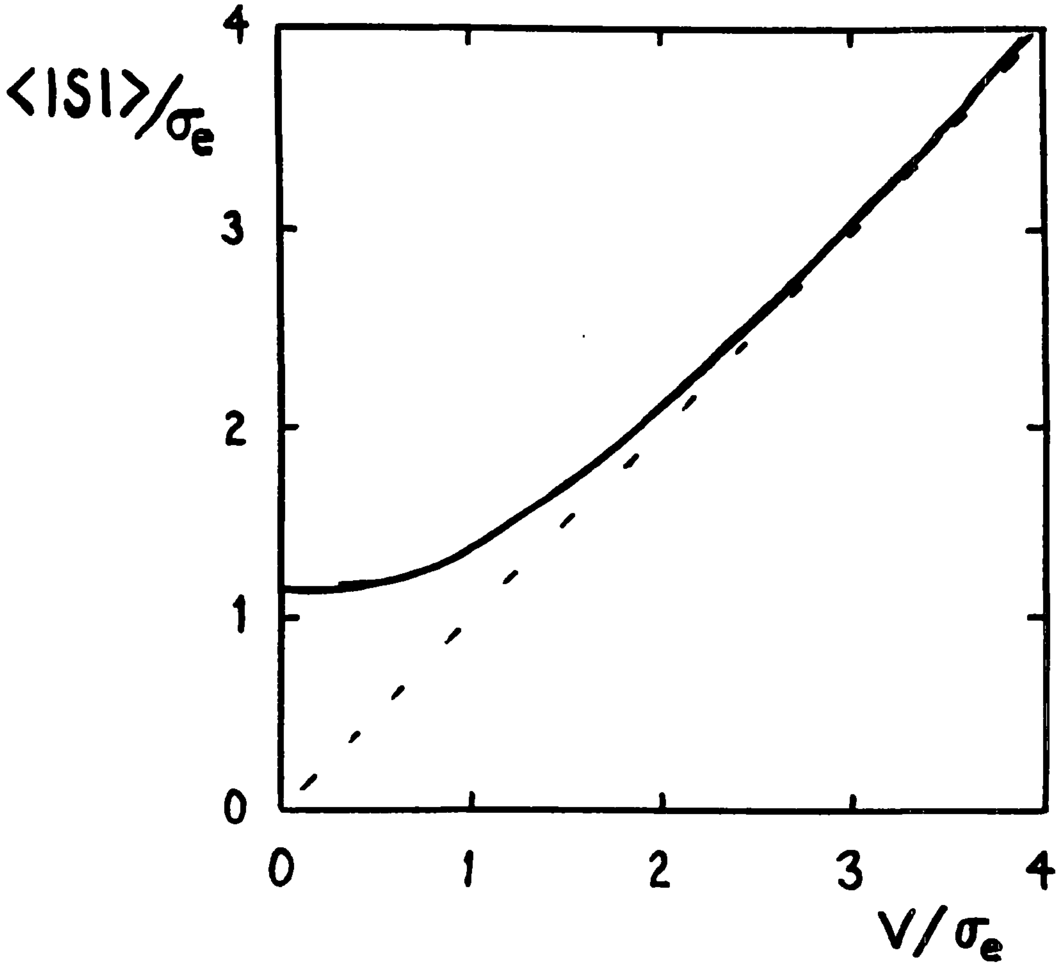

FIGURE 5. AVERAGE ABSOLUTE SPEED vs. RANGE RATE

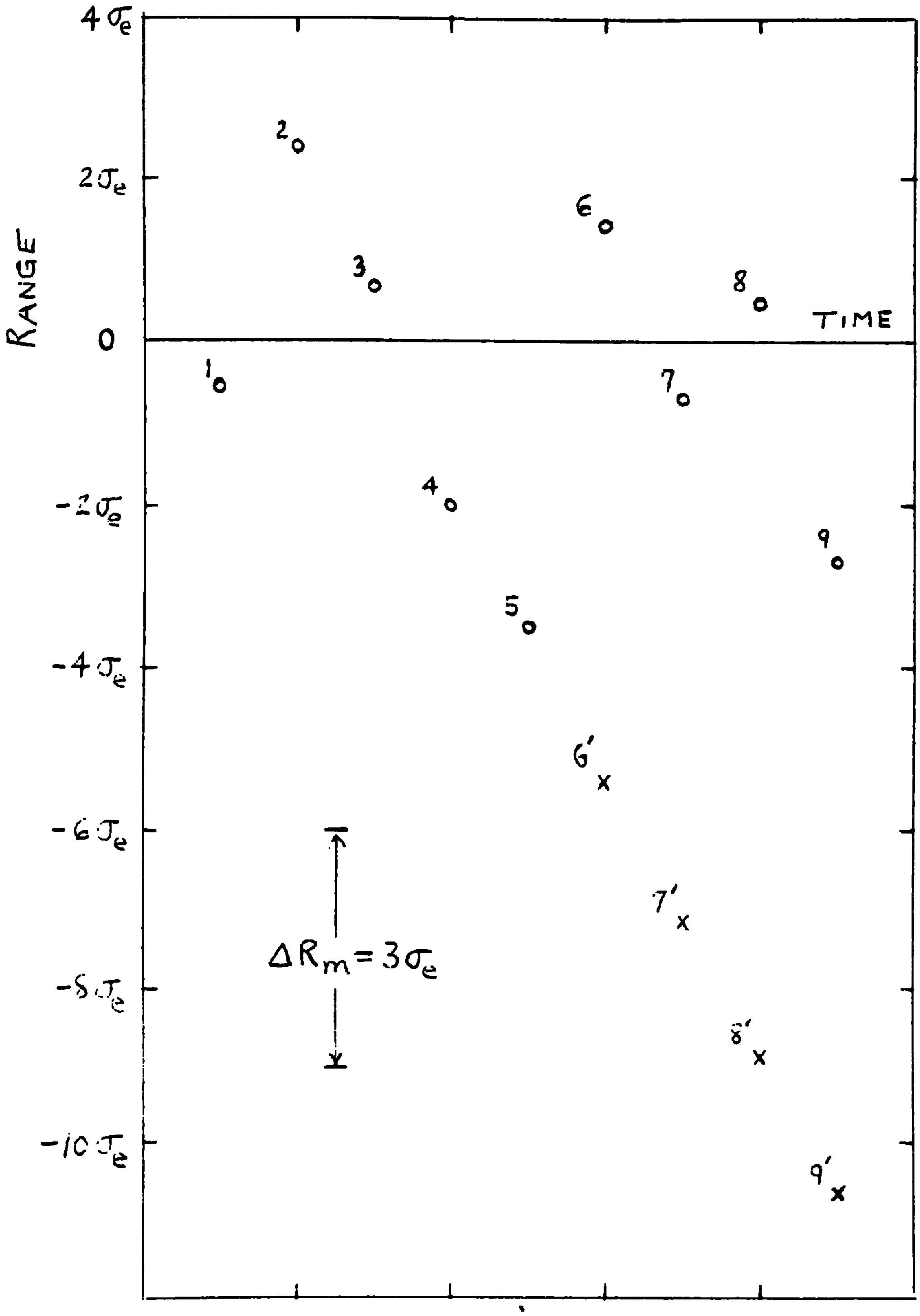

FIGURE 6. DEMONSTRATION OF IMPROPER EDIT PROCEDURE

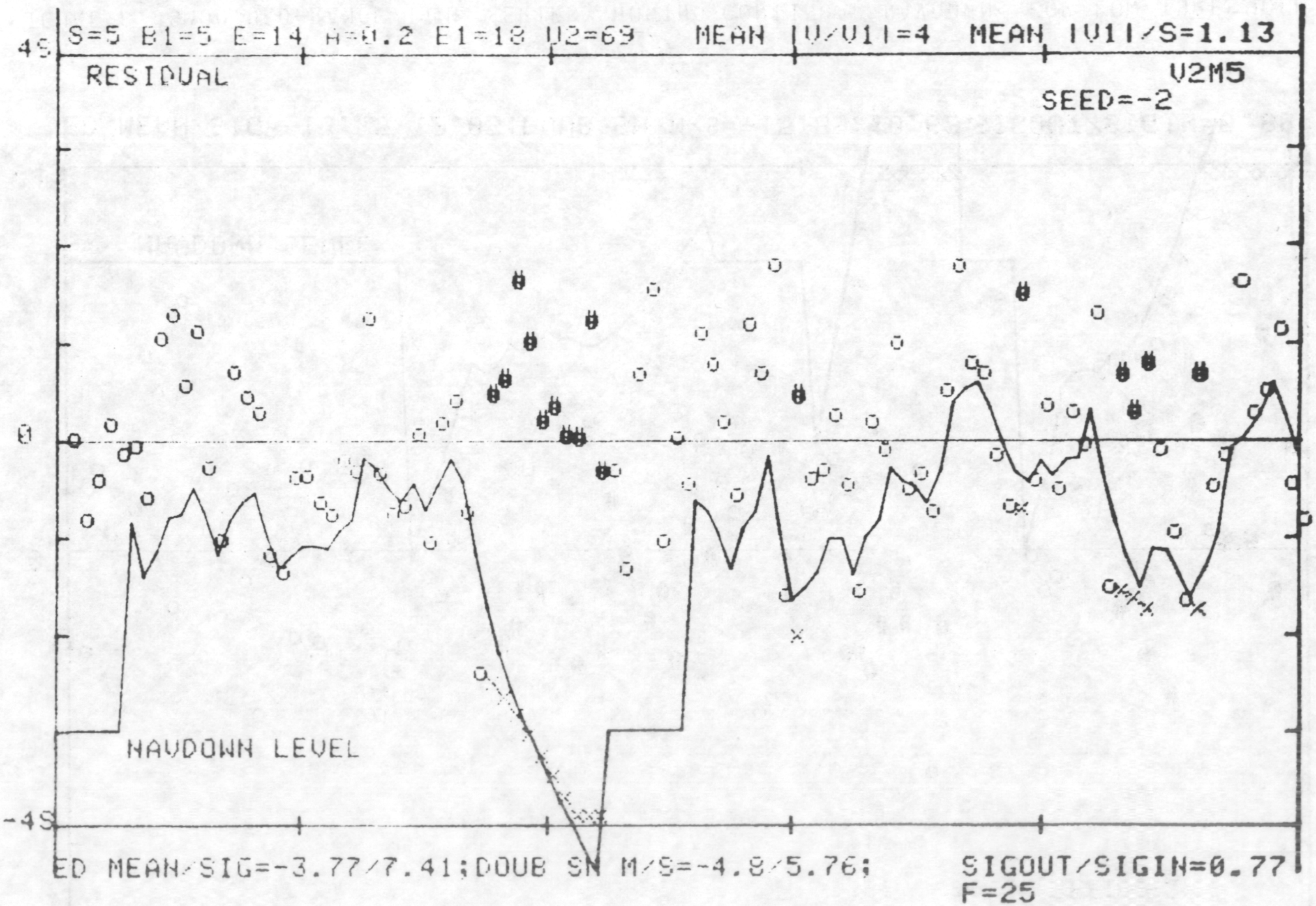

FIGURE 7. SMOOTHED-RANGE TIME SERIES SHOWING IMPROPER EDITS AND NAVDOWN

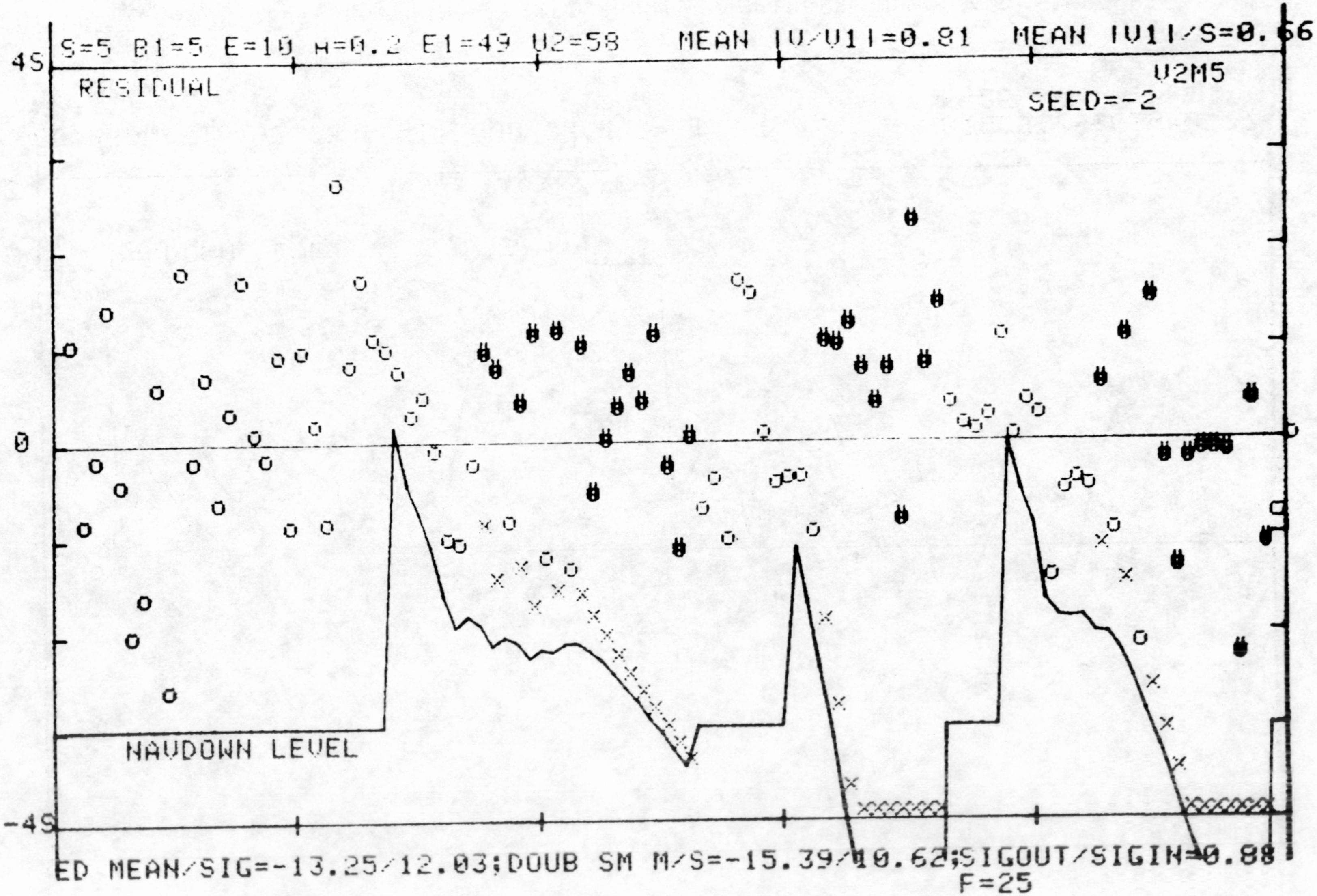

FIGURE 8. SMOOTHED-RANGE TIME SERIES SHOWING CONTINUAL NAVDOWNs FOR LOW THRESHOLD

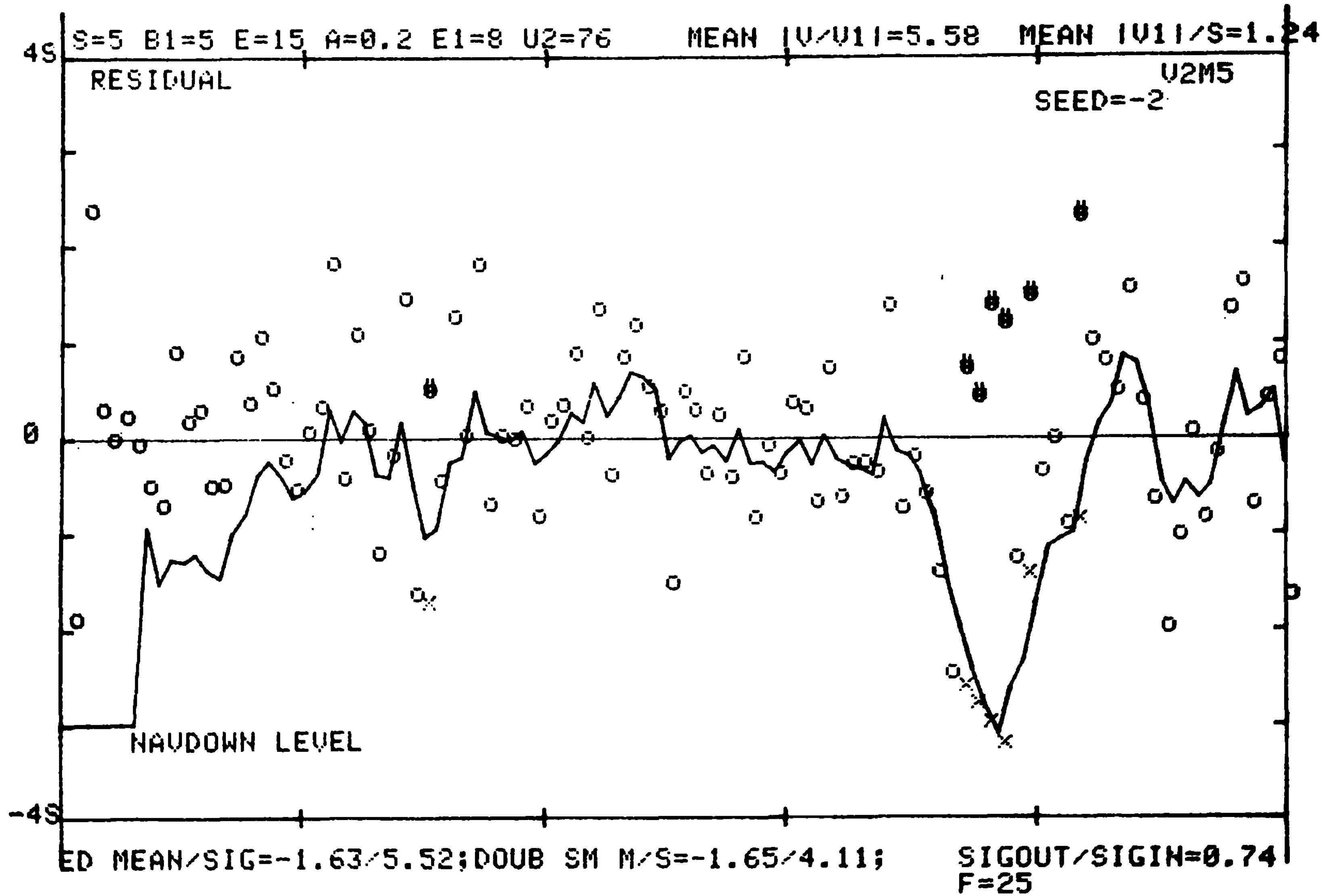

FIGURE 9. SMOOTHED-RANGE TIME SERIES SHOWING SHORT-TERM BIAS FROM IMPROPER EDITS

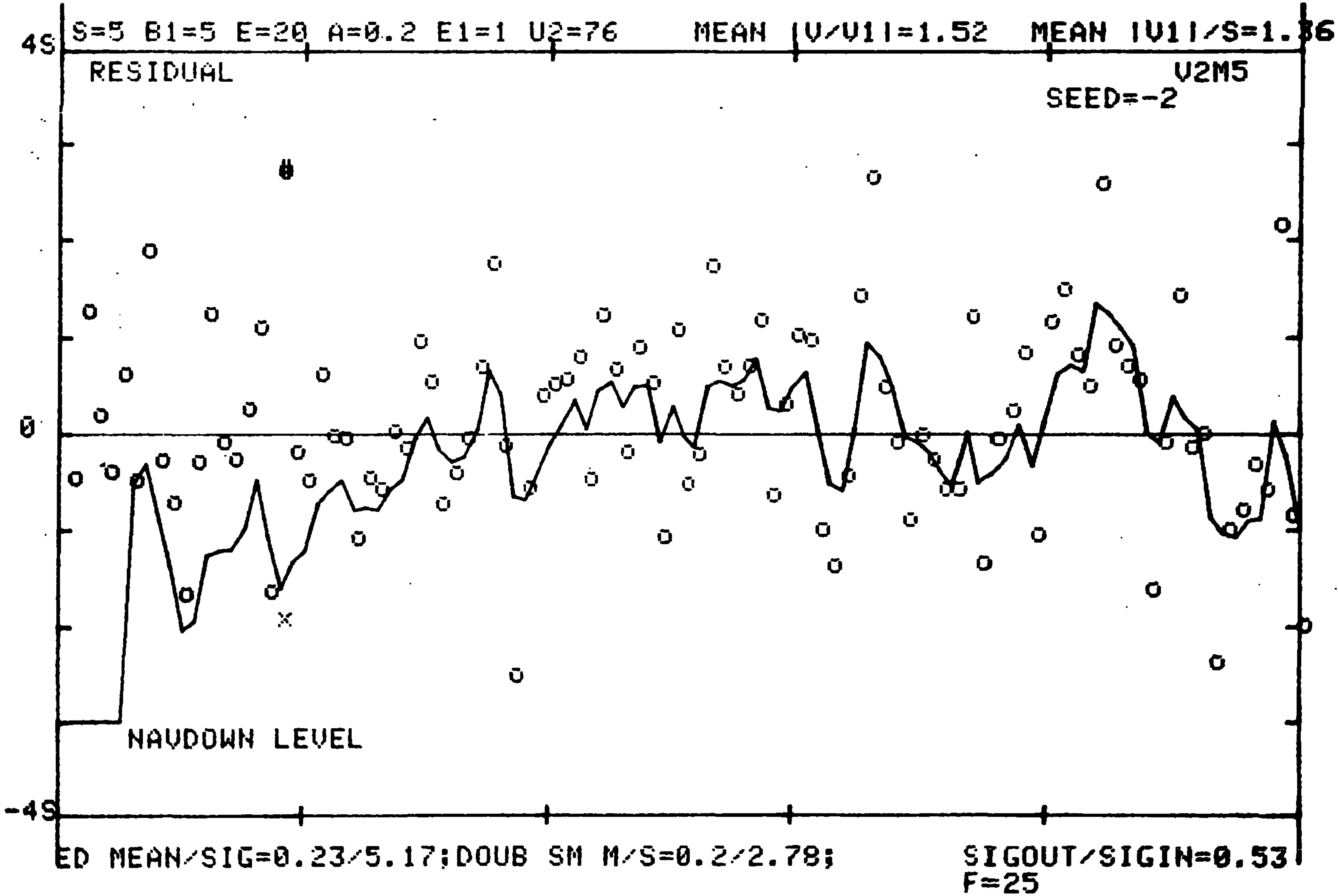

FIGURE 10. SMOOTHED-RANGE TIME SERIES SHOWING SMOOTHING RATIO VALUE

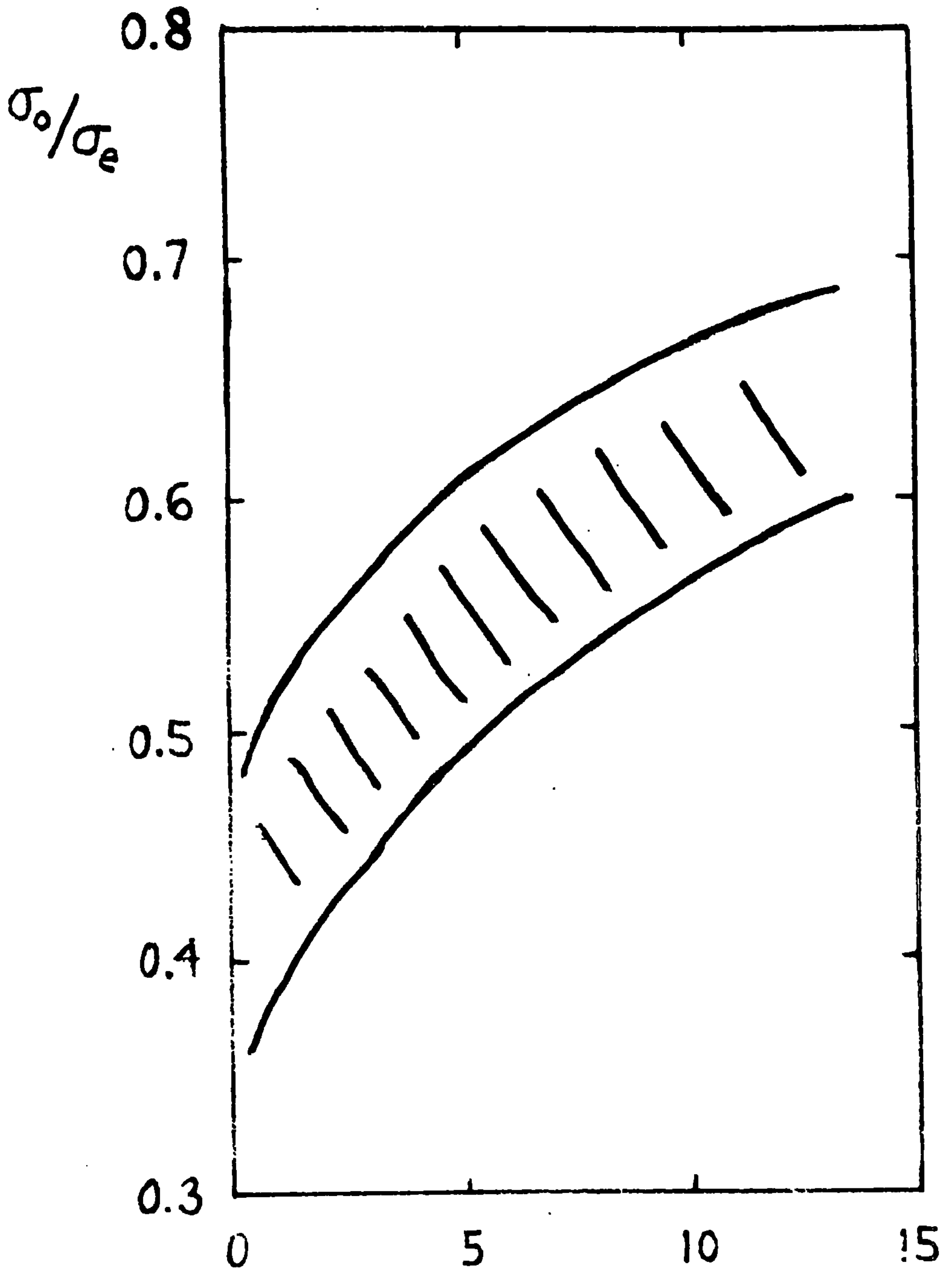

FIGURE 11. SMOOTHING RATIO vs. EDITS

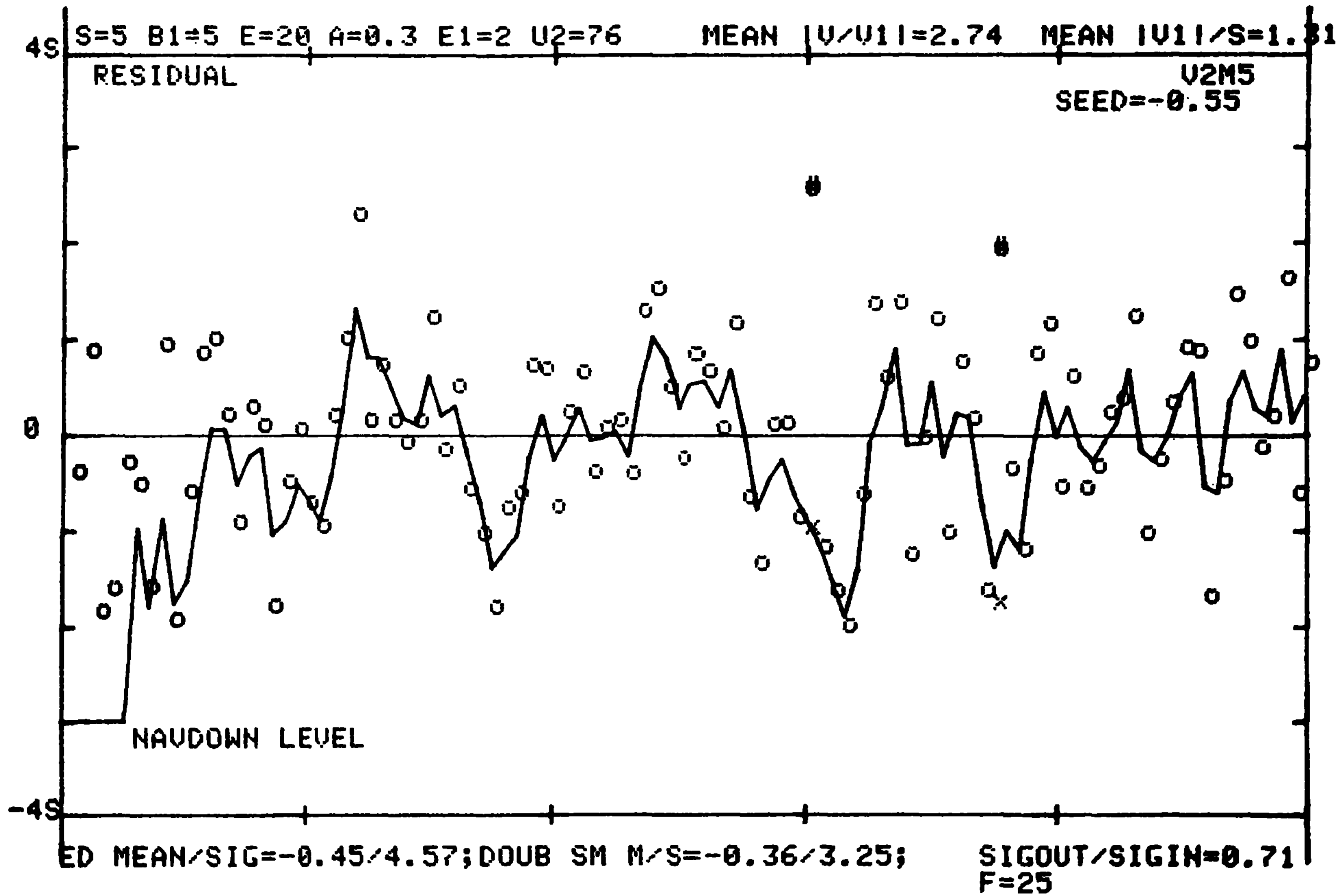

FIGURE 12. SMOOTHED-RANGE TIME SERIES: TRANSIENT RESPONSE FOR c=0.3, V=5 m/s

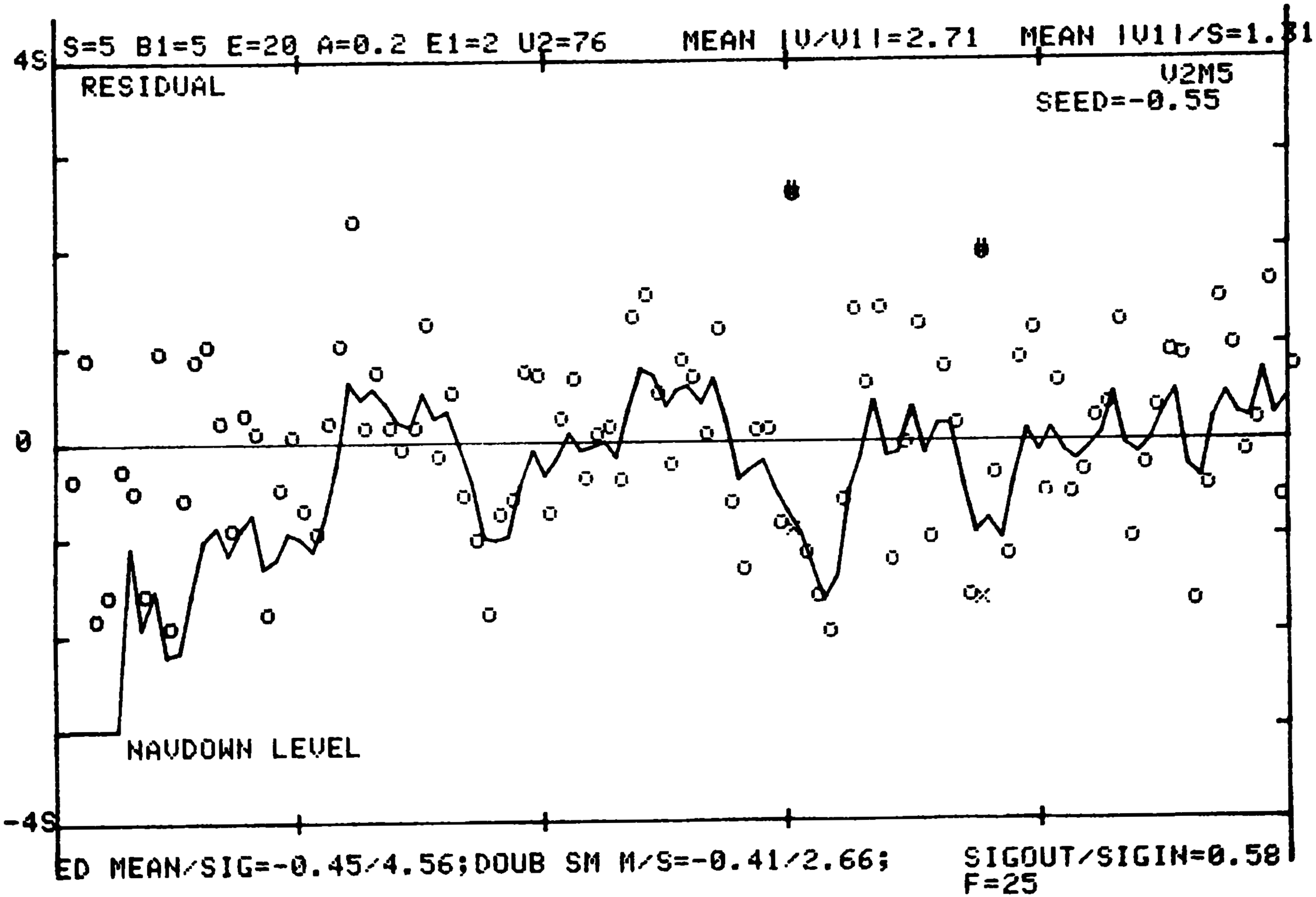

FIGURE 13. SMOOTHED-RANGE TIME SERIES: TRANSIENT RESPONSE FOR c=0.2, V=5 m/s

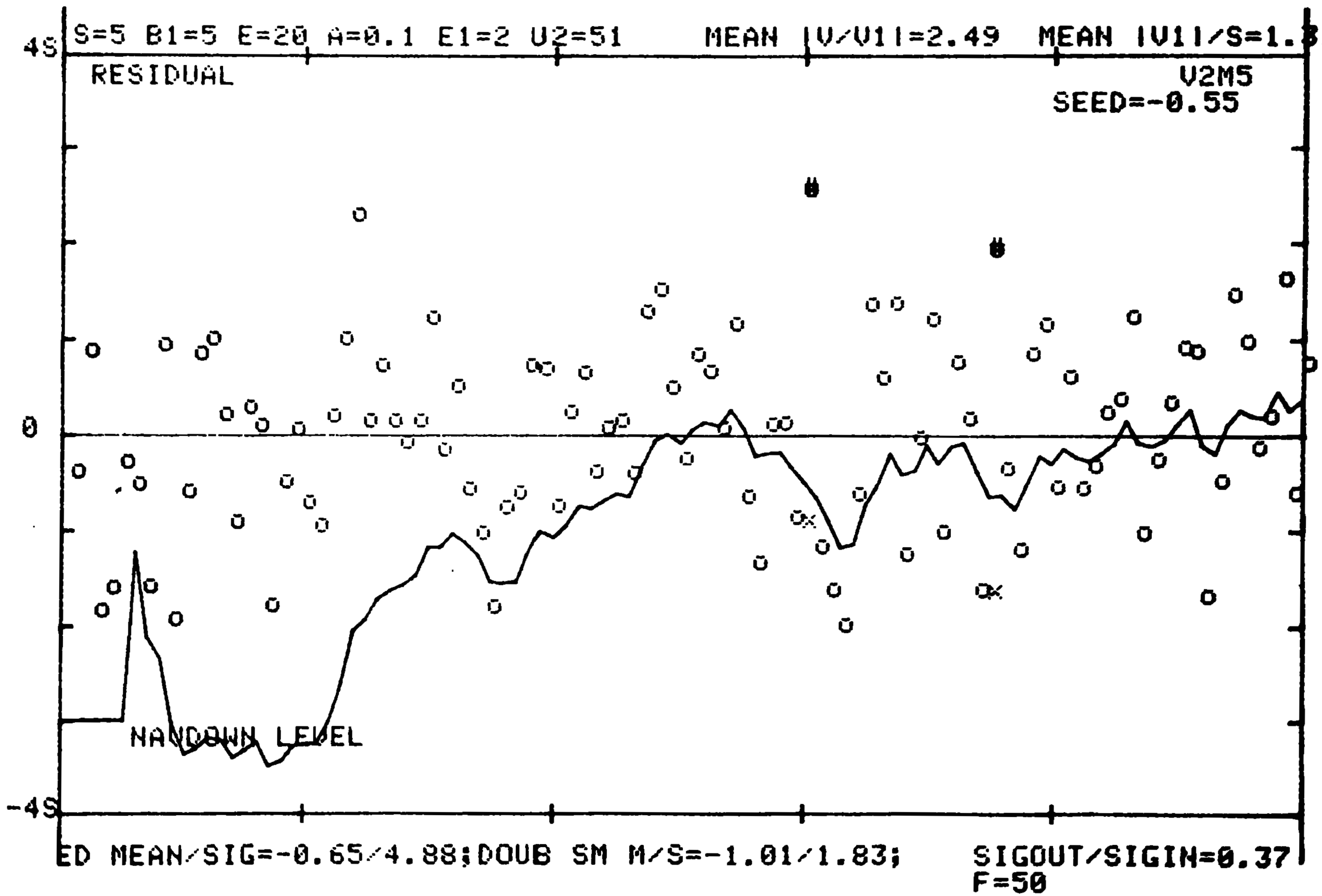

FIGURE 14. SMOOTHED-RANGE TIME SERIES: TRANSIENT RESPONSE FOR c=0.1, V=5 m/s

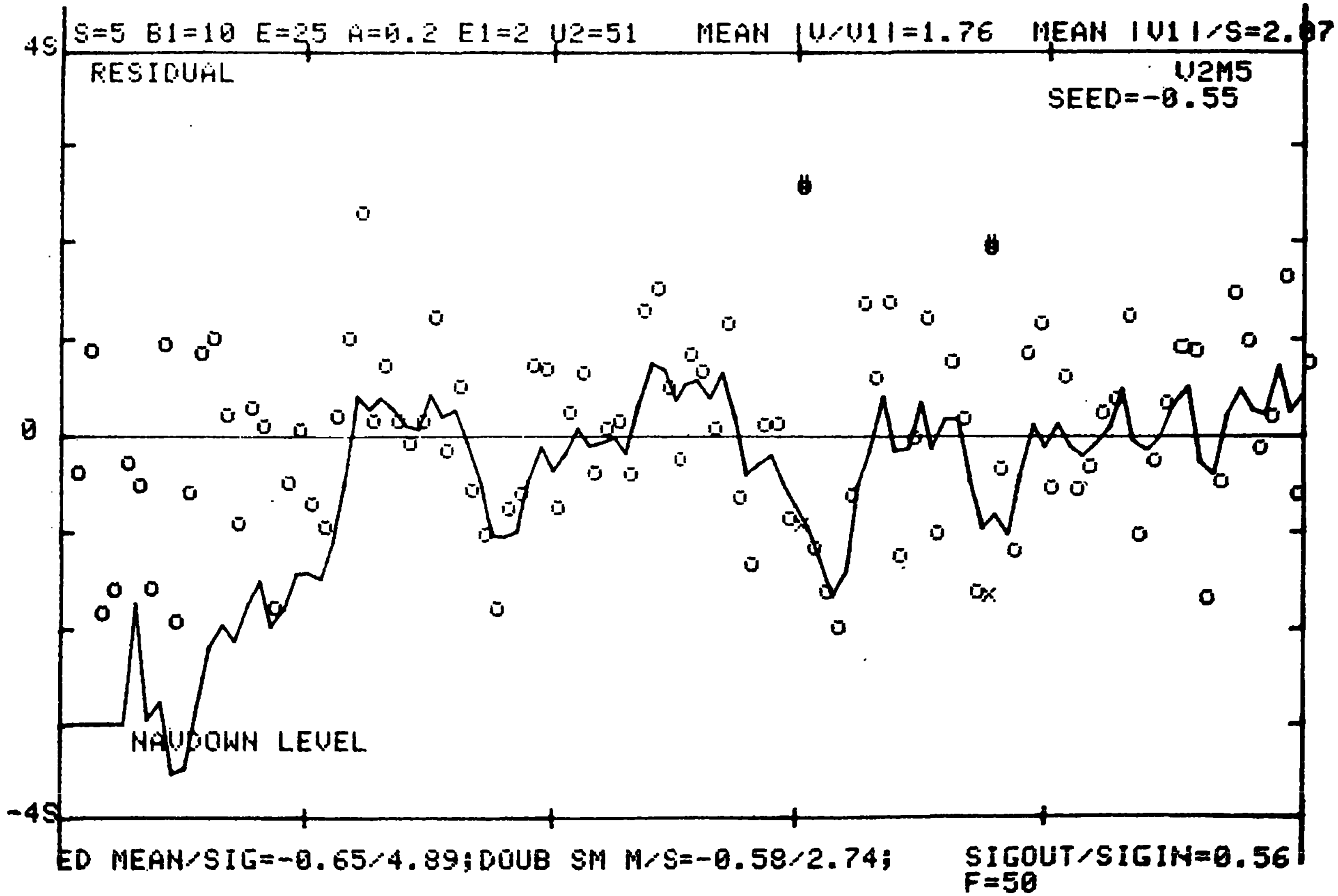

FIGURE 15. SMOOTHED-RANGE TIME SERIES: TRANSIENT RESPONSE FOR c=0.2, V=10 m/s

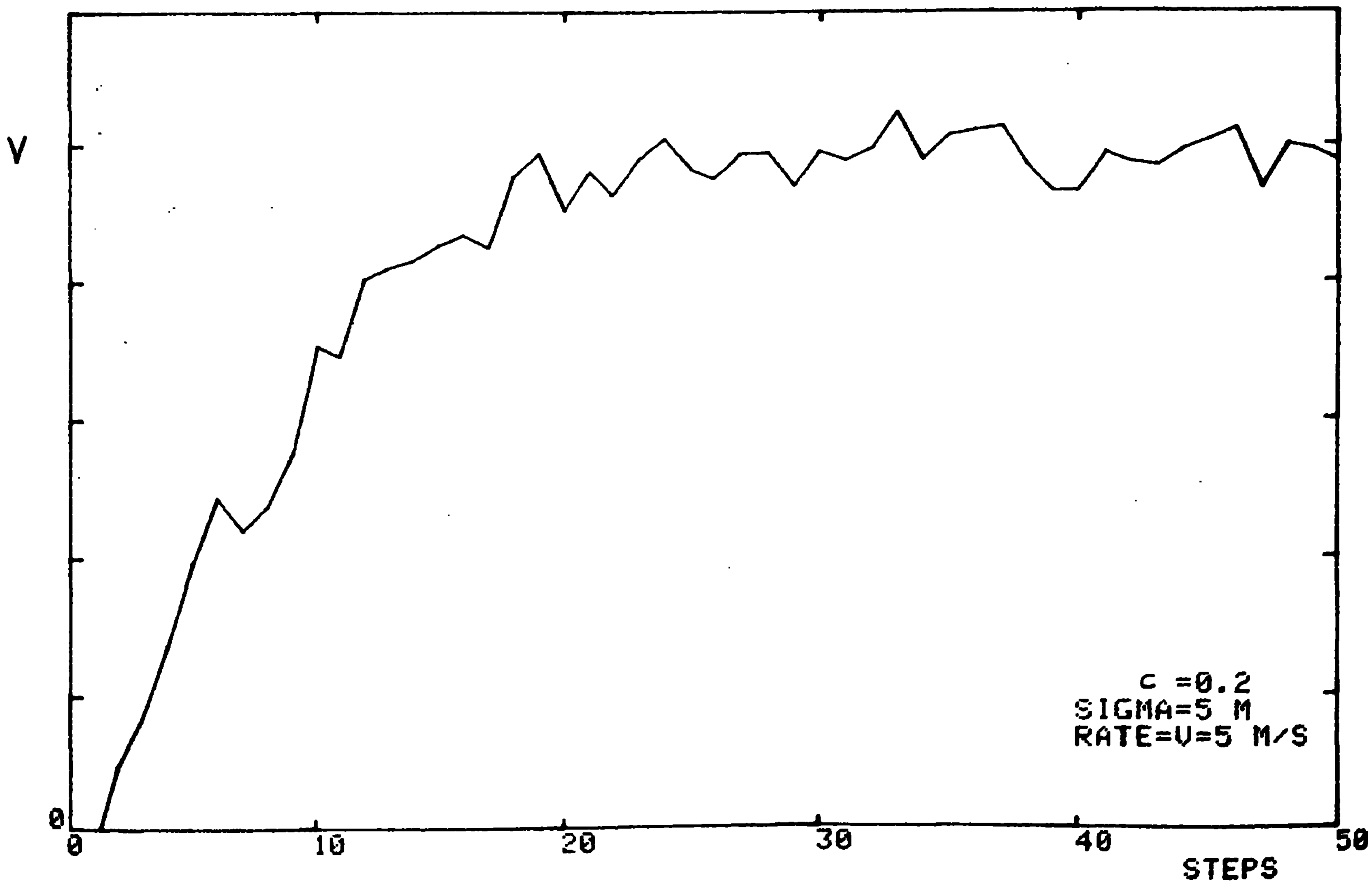

FIGURE 16. SMOOTHED SPEED vs. TIME FOR RANGE RAMP

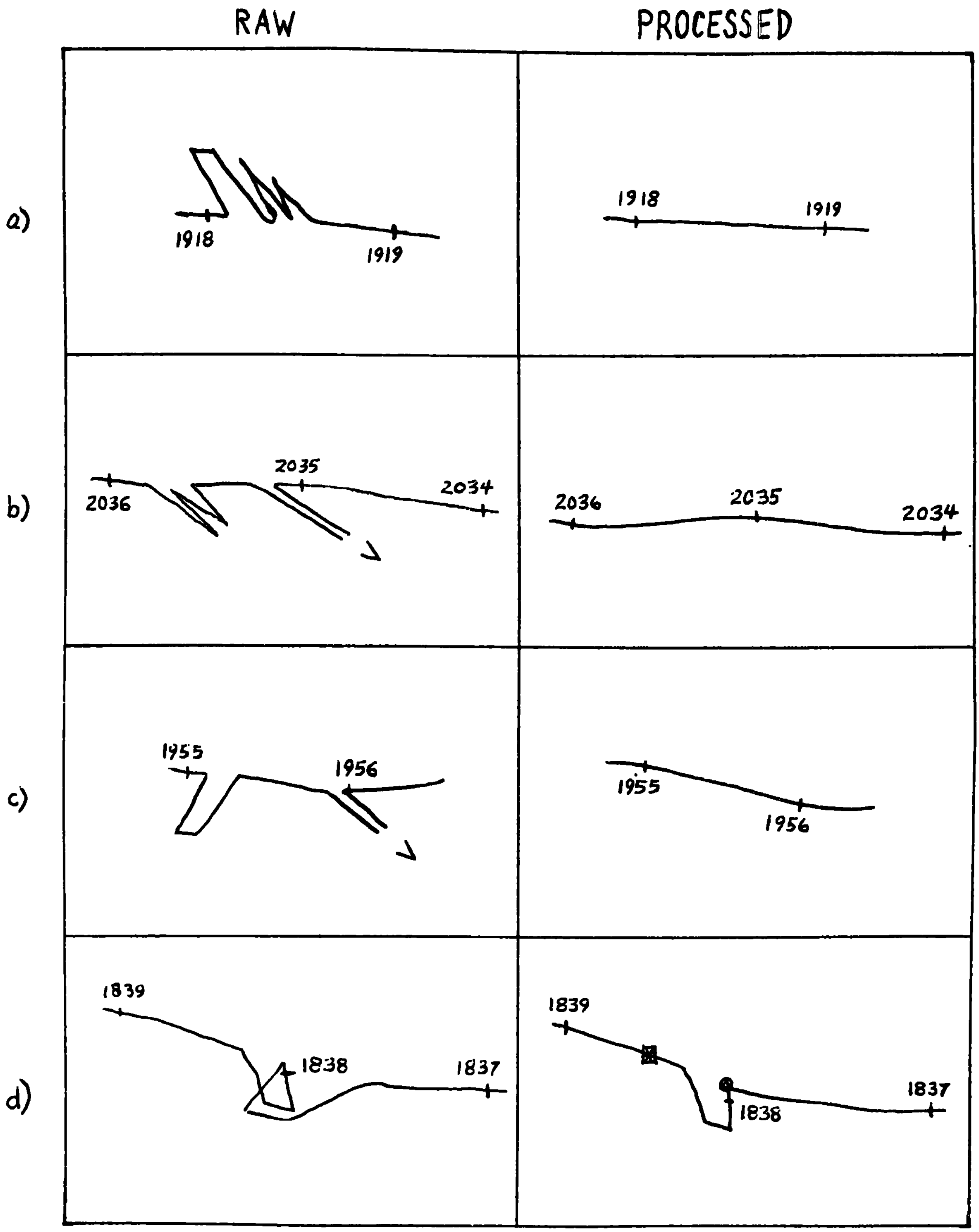

FIGURE 17. MINI-RANGER SHIP TRACKS BEFORE AND AFTER PROCESSING (1)

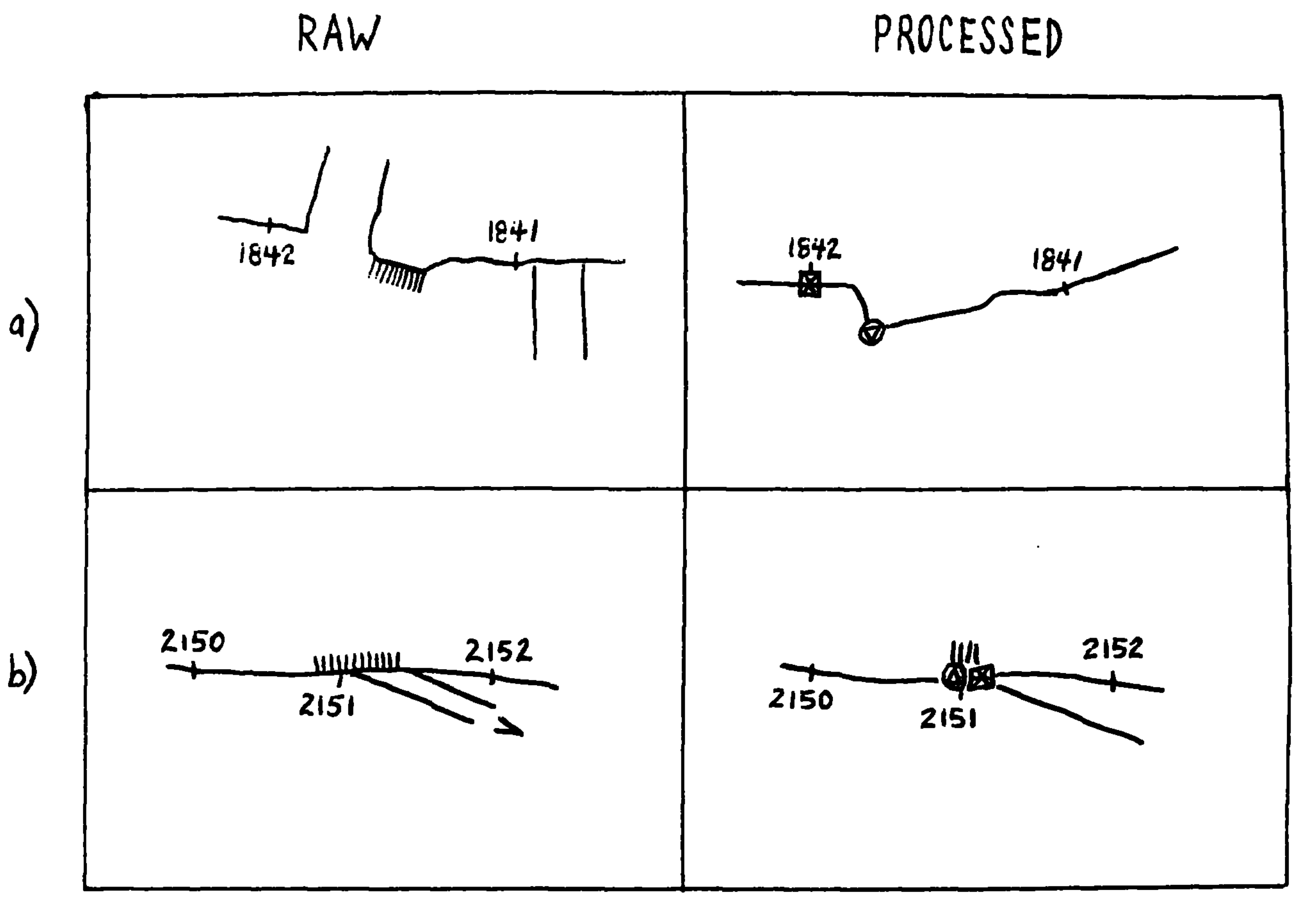

FIGURE 18. MINI-RANGER SHIP TRACKS BEFORE AND AFTER PROCESSING (2)

APPENDIX 1. SIMULATION PROGRAM LISTING

```
10 INIT
20 REM************* VER 2 MOD 6 ***************
21 REM*******************************************************************
22 PEM PROGRAM TO COMPARE SMOOTHING OF NOISY TIME SERIES BY
23 REM   DOUBLE EXPONENTIAL AND FIXED MEMORY FILTERS
24 REM*******************************************************************
25 REM
26 REM LOCATIONS OF DATA'ED VARIABLES AS FOLLOWS:
27 REM     1040: S, B1:     2050: A, E:       3222: F
28 REM RAND SEED IN 1063
29 REM
30 REM V1M2 ADD SINGLE EXPONENTIAL FILTER FOR COMPARISON W/ DOUBLE
35 REM V1M3: ADD "o" S FOR RAW INPUT DATA BEFORE SPEED EDIT/EXTRAP FIL
36 REM V1M3: ALTER PLOT PGM TO PRESERVE R(I) FOR LATER STATS
37 REM V1M3: CORRECT SELECTION OF PTS IN STAT CALCS
38 REM V1M3: ADD STATS FOR SING EXP SMOOTH
40 REM V2M1: CHANGE INPUT TO LINEAR RAMP ********************************
41 REM V2M2: FIX INITIAL CONDITIONS TO PREVIOUS R(I)
42 REM V2M3: REMOVE SINGLE EXPONENTIAL
43 REM V2M4: ADD VARIABLE SET RAND SEED
44 REM V2M4: ADD SELECTABLE STARTING PT FOR STATS
45 REM V2M5: CHANGE V1-V STATS TO JUST V STATS
46 REM V2M6: BALANCE SPEED TEST WITH V FEEDBACK
47 REM V2M6: ADD # CHR IN PLOT OVER EDITED POINTS
100 REM ROOT PGM
105 INIT
110 REM CALL TIME SERIES GEN
120 GOSUB 1000
150 REM CALL DOUBLE EXPONENTIAL FILTER
160 GOSUB 2000
170 REM CALL PLOT FOR DOUBLE EXPONENTIAL FILTER
180 GOSUB 3000
190 REM CALL STATS FOR DOUBLE EXP. FIL.
200 GOSUB 3500
210 REM CALL STATS PRINT
220 GOSUB 4000
230 END
1000 REM****************************************************************
1010 REM SUBROUTINE: TIME SERIES GENERATOR
1020 REM     GAUSIAN DISTRIB N(0,S)
1025 REM ADD TO CONSTANTLY INCREASING RANGE ASAT SPEED "B1" M/S
1030 REM****************************************************************
1040 DATA 5,5
1050 READ S,B1
1060 DIM R(100),R3(100),R5(100)
1063 X=-0.75
1064 REM THE FOLLOWING LINE PRESETS THE RANDOM SEQUENCE AND MUST
1065 REM     BE CHANGED FOR EACH DIFFERENT SEQUENCE (-1<X<0).
1066 I=RND(X)
1070 FOR I=1 TO 100
1080 R1=0
1085 R3(I)=0
1090 FOR J=1 TO 12
1100 R1=R1+RND(2)
1110 NEXT J
1120 R(I)=(R1-6)*S
1125 R5(I)=R(I)
1127 R(I)=R(I)+B1*I
1130 NEXT I
1140 RETURN
1150 REM****************************************************************
2000 REM****************************************************************
2010 REM SUBROUTINE: SMOOTH R(I) W/ DOUBLE EXPONENTIAL FILTER AND
2020 REM     OUTPUT R2(I)
2030 REM  FILTER PARAM "A" IS "ALPHA"
2040 REM****************************************************************
2045 PAGE
2050 DATA 0.2,13
2060 READ A,E
```

```
2070 DIM R2(100),S1(2),S2(2)
2080 B=1-A
2085 E1=0
2090 V8=0
2100 V9=0
2110 K=0
2120 V=0
2130 D=0
2140 V1=0
2170 FOR I=2 TO 100
2180 IF V1=1 THEN 2290
2185 REM GET NAV UP
2190 IF ABS(R(I)-R(I-1))>E THEN 2230
2200 U=U+1
2210 IF U=5 THEN 2260
2220 REM USE LAST ACCEPTABLE PREVIOUS DATA FOR INITIALIZATION
2224 S1(1)=R(I)
2225 S2(1)=R(I)
2226 GO TO 2240
2230 U=0
2235 E1=E1+1
2240 R2(I)=-3*S+I*B1
2250 GO TO 2470
2260 V1=1
2270 PRINT "NAVUP I=";I
2275 V=0
2280 GO TO 2180
2290 IF R(I)=>R(I-1)+V THEN 2293
2291 IF R(I)-R(I-1)<V-E THEN 2300
2292 GO TO 2357
2293 IF R(I)-R(I-1)>E+V THEN 2300
2294 GO TO 2357
2295 REM PROCESS AND TAKE NAV DOWN AS NEC
2300 D=D+1
2305 E1=E1+1
2310 IF D<11 THEN 2350
2320 V1=0
2325 D=0
2326 E1=E1-1
2330 PRINT "NAVDOWN I=";I
2340 GO TO 2180
2350 R(I)=R(I-1)+V
2352 R3(I)=1
2355 REM PERFORM SMOOTHING
2356 GO TO 2360
2357 D=0
2360 S1(2)=A*R(I)+B*S1(1)
2370 S2(2)=A*S1(2)+B*S2(1)
2380 R2(I)=2*S1(2)-S2(2)
2390 V=A*(S1(2)-S2(2))/B
2400 S1(1)=S1(2)
2410 S2(1)=S2(2)
2420 K=K+1
2425 REM COMPARE SPEEDS
2430 V1=R(I)-R(I-1)
2432 L1=ABS(V/V1)
2433 L2=ABS(V1)/S
2450 V8=V8+L1
2460 V9=V9+L2
2462 L1=INT(L1*100)/100
2463 L2=INT(L2*100)/100
2465 V7=INT(V*100)/100
2466 V1=INT(V1*100)/100
2467 REM PRINT "S=";S;"  V=";V7;"  V1=";V1;"  |V/V1|=";L1;" |V1|/S=";L2
2470 NEXT I
2475 IF K<>0 THEN 2480
2476 PRINT "NAV DID NOT COME UP"
2477 I=100
2478 GO TO 2530
2480 V8=V8/K
```

```
2490 V9=V9/K
2500 PRINT
2520 REM R2(I) CONTAINS DOUBLE EXP SMOOTHED RANGES
2530 RETURN
2540 REM************************************************************
3000 REM************************************************************
3010 REM SUBROUTINE: EXP FIL PLOT
3020 REM
3030 REM************************************************************
3036 PAGE
3040 WINDOW 0,100,-4.5*S,4.5*S
3050 VIEWPORT 5,125,5,95
3060 AXIS 20,S,0,-4*S
3070 AXIS 20,S,100,4*S
3073 MOVE -4,-4.05*S
3074 PRINT "-4S"
3075 MOVE -3,-0.05*S
3076 PRINT "0"
3077 MOVE -3,3.95*S
3078 PRINT "4S"
3080 MOVE 0,0
3090 DRAW 100,0
3092 FOR I=1 TO 100
3093 MOVE I,R5(I)
3094 PRINT "o"
3095 IF R3(I)<>1 THEN 3099
3096 MOVE I,R5(I)
3097 PRINT "#"
3099 NEXT I
3100 FOR I=1 TO 100
3110 IF ABS(R(I)-I*B1)<4*S THEN 3130
3115 MOVE I,SGN(R(I)-I*B1)*4*S
3120 GO TO 3135
3130 MOVE I,R(I)-I*B1
3135 IF R3(I)=1 THEN 3146
3140 PRINT "o"
3145 GO TO 3150
3146 PRINT "x"
3150 NEXT I
3160 MOVE 0,-3*S
3170 FOR I=2 TO 100
3180 DRAW I,R2(I)-I*B1
3190 NEXT I
3200 MOVE 6,-3.3*S
3210 PRINT "NAVDOWN LEVEL"
3222 DATA 25
3223 READ F
3265 MOVE 1,3.95*S
3266 PRINT "J RESIDUAL"
3267 MOVE 90,3.95*S
3268 PRINT "JV2M6"
3270 MOVE 80,3.95*S
3275 PRINT "JJSEED=";X
3276 RETURN
3280 REM************************************************************
3500 REM************************************************************
3510 REM SUBROUTINE: EXP FIL STATS
3520 REM************************************************************
3525 K1=0
3530 K2=0
3540 FOR I=F TO 100
3550 IF R2(I)-I*B1=-3*S THEN 3580
3560 K1=K1+1
3570 K2=K2+R(I)-I*B1
3580 NEXT I
3590 A1=K2/K1
3595 REM MEAN R(I) RESIDUAL
3600 K2=0
3610 FOR I=F TO 100
3620 IF R2(I)-I*B1=-3*S THEN 3640
```

```
3630 K2=K2+(R(I)-I*B1-A1)↑2
3640 NEXT I
3650 K2=K2/(K1-1)
3660 S3=SQR(K2)
3665 REM SIGMA R(I) RESIDUAL
3670 K1=0
3680 K2=0
3690 FOR I=F TO 100
3700 IF R2(I)-I*B1=-3*S THEN 3730
3710 K1=K1+1
3720 K2=K2+R2(I)-I*B1
3730 NEXT I
3740 A2=K2/K1
3745 REM MEAN R2(I) RESIDUAL
3750 K2=0
3760 FOR I=F TO 100
3770 IF R2(I)-I*B1=-3*S THEN 3790
3780 K2=K2+(R2(I)-I*B1-A2)↑2
3790 NEXT I
3800 K2=K2/(K1-1)
3810 S4=SQR(K2)
3815 REM SIGMA R2(I) RESIDUAL
3820 U2=K1
3830 RETURN
3840 REM*******************************************************************
4000 REM*******************************************************************
4010 REM SUBROUTINE: PRINT OUTPUTS
4020 REM
4030 REM*******************************************************************
4040 MOVE 1,4.1*S
4050 PRINT "S=";S;" B1=";B1;" E=";E;" A=";A;" E1=";E1;" U2=";U2
4052 V8=INT(V8*100)/100
4053 V9=INT(V9*100)/100
4055 MOVE 52,4.1*S
4056 PRINT "MEAN |V/V1|=";V8;"  MEAN |V1|/S=";V9
4060 MOVE 0,-4.3*S
4062 A1=INT(A1*100)/100
4063 A2=INT(A2*100)/100
4064 S3=INT(S3*100)/100
4065 S4=INT(S4*100)/100
4070 PRINT "J","ED MEAN/SIG=";A1;"/";S3;";DOUB SM M/S=";A2;"/";S4;";"
4071 MOVE 74,-4.3*S
4073 L3=S4/S3
4074 L3=INT(L3*100)/100
4075 PRINT "JSIGOUT/SIGIN=";L3
4076 MOVE 74,-4.3*S
4077 PRINT "JJF=";F
4080 RETURN
4090 REM*******************************************************************
```

(Continued from inside front cover)

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