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Boundary - Layer Pressure Fluctuations at High Reynolds Numbers on a Second Free - Flight Test Vehicle

by

D. R. Roberts

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BOUNDARY-LAYER PRESSURE FLUCTUATIONS AT HIGH REYNOLDS NUMBERS ON A SECOND FREE-FLIGHT TEST VEHICLE

by

D. R. Roberts

SUMMARY

Measurements have been made of the boundary-layer pressure fluctuations at two positions on the body of a free-flight aerodynamic test vehicle powered by a solid-fuel rocket motor. The vehicle reached a maximum Mach number of 2.2 with a maximum Reynolds number of about 118 millions at the front measuring station and 207 millions at the rear.

Pressure spectra have been deduced, and have been found to compare reasonably with a theoretical spectrum. The scale of the boundary-layer turbulence fluctuates appreciably but is for the most part between 30% and 80% of the turbulence boundary-layer thickness for all Mach numbers up to 2.2. The root mean square boundary-layer pressure reduced with Mach number from about 0.01 times the free stream dynamic pressure at M = 1 to about 0.003 at M = 2.2, the front station tending to be slightly the higher at each Mach number.

* Replaces RAE Technical Report 74029 - ARC 35404

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PREFACE

At the time of his death D.R. Roberts had prepared an advanced draft of this Report. It included all the figures up to 10, the tables up to 4 and a draft manuscript of the text, including the Appendix, with indications of how he intended completing the Report: the general pattern was the same as that used by him in Ref.1. Several of his colleagues and I have completed the Report in the form he appeared to intend and made no attempt to include any opinions of our own.

J. Taylor

1 INTRODUCTION

This paper presents the results of boundary-layer pressure fluctuations made on a free-flight aerodynamic test vehicle, the third and last of the 'Shark' series, which was designed and constructed by Aerodynamics Department, RAE, and launched by them at RAE Aberporth firing range.

On Shark 1, measurements were made of skin friction drag by means of surface pitot tubes, and boundary-layer pressure fluctuations using a piezo-electric pressure transducer, and the results of the latter measurements were presented in Ref.1. The Shark 2 vehicle was abandoned because of technical instrumentation difficulties. On Shark 3, measurements of boundary-layer pressure fluctuations were made employing two piezo-electric pressure transducers, one at a rear station similar to that used on Shark 1, and the other at a station positioned to give a Reynolds number about half that at the rear station.

2 DESCRIPTION OF TEST EXPERIMENT

2.1 Description of test vehicle

2.1.1 General

The vehicle was made as nearly as possible similar to Shark 1, having a 4 calibre tangent circular ogival nose fitted to a cylindrical body 8 calibre long followed by a 2 calibre tail section; to the tail section were fitted three stabilising fins, radially equally distributed. The body and tail tubes were constructed of resin bonded paper tube, and the nose was a glass fibre moulding. The vehicle was propelled by a non-separating solid fuel rocket motor mounted inside the body. The overall length was about 230 inches (5.85 metres) and the launch weight was about 1370 pounds (621.4 kg). A general arrangement drawing is given in Fig.1.

2.1.2 Instrumentation

Transducers were installed to measure:-

(a) Boundary-layer pressure fluctuations at two stations as indicated in Fig.1 (Kistler Type 410B Sp piezo-electric quartz pressure transducers, ± 0.4 lbf/in^2 (± 2758 N/m^2).

(b) Accelerations normal and perpendicular to a given vehicle-body radius (variable inductance accelerometers, ± 3 g).

(c) Acceleration parallel to vehicle body longitudinal axis (variable inductance accelerometer, 0-3 g, positive acceleration sternwards).

The output signal of each of the two pressure transducers was translated by a suitable modulator unit to frequency-modulate the transmission of a 465MHz (nominal) oscillator. The output signals of the three accelerometers were similarly modulated *via* a motor-driven sequence switch and modulator unit, to control a third 465MHz oscillator. The oscillator output signals were transmitted through separate aerial systems, and hence received and translated at the ground receiving station, to be recorded on magnetic tape and oscilloscope record films.

2.2 Aerodynamic environment

The maximum Mach number achieved was about 2.2 [$q_{max} \simeq 6474$ lbf/ft^2 (310 kN/m^2)]. The maximum Reynolds number at the forward measuring station was about 118 millions, and at the rear measuring station was about 207 millions.

The maximum altitude was about 3771 feet (1150 metres).

2.3 Range facilities

The firing range afforded facilities for obtaining velocity, altitude and timing data, and high-speed ciné camera records of the flight. Measurements were recorded during the useful flight, the duration of which was about 32 seconds.

3 METHOD OF DATA ANALYSIS

The transmitted signal representing the output from the forward station pressure transducer was frequency-translated after reception, and recorded on magnetic tape at a tape speed of 60 inches per second. It was later replayed at a speed of 7.5 inches per second, and re-recorded at 60 inches per second. The resulting magnetic tape was then replayed at 7.5 inches per second, and the recorded pressure level sampled at a rate equivalent to 50000 samples per second of real flight time. The sample levels were recorded on tape as digital values on a scale of approximately 540 units per 1 lbf/in^2 (78.318 units per 1 kN/m^2).

A similar process was employed on the signal from the rear station pressure transducer, but because of a slightly different instrument sensitivity, the digital scale was approximately 513 units per 1 lbf/in^2 (74.402 units per 1 kN/m^2).

This work was executed at RAE Aberporth Data Centre, using the BRAMBLE[2] equipment. The remaining main analysis of the experimental data was done at RAE Farnborough, using the Mathematics Department ICL 1907 computer.

To facilitate comparison of the derived data with that from the Shark 1 [1] experiment, it was expedient to express the pressure readings in the same units as were used in that analysis, i.e.

$$1 \text{ pressure unit} = 0.0031163 \text{ lbf/in}^2 = 0.02149 \text{ kN/m}^2 .$$

The quantity of data resulting from a sampling rate of 50000 per second over a useful flight time of 32 seconds for each of two measuring stations was considerable, and it was therefore decided to restrict the analysis to 27 portions of flight time, referred to hereafter as runs, each of 0.5 second duration. These were identified by run numbers, which designated the time after launching of the commencement of the run. The portions of the flight selected for analysis were as shown below:-

Run No.	0	5	10	15	20	25	30	35	40	45	50	55	70	85
Time after launching(s)	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	7.0	8.5

Run No.	100	115	130	145	160	175	190	205	220	235	260	285	310
Time after launching(s)	10.0	11.5	13.0	14.5	16.0	17.5	19.0	20.5	22.0	23.5	26.0	28.5	31.0

The selected portions of digitised data were extracted from the tapes prepared by RAE Aberporth, converted to the required scale, and recorded on two master tapes, one for the forward station and one for the rear, by means of a suitable computer program.

The remainder of the analysis was performed in a similar manner to that employed with Shark 1, and is described in detail in the Appendix to this paper.

4 PRESENTATION OF RESULTS

Tabulated values of the unsmoothed spectral density estimate (USSD) for values of $1 \leqslant k \leqslant 100$ for each of the 27 runs at each measuring station are presented in Table 1. The value of the frequency corresponding to each value of k is given in Table 2. Table 3 presents values of vehicle velocity, height and Mach number, of local and turbulence Reynolds numbers (R_x and $R_{\$t}$), turbulence thickness ($\$t$), maximum unsmoothed spectral density estimate (SD_{max}), the corresponding value of frequency factor (k_m), the turbulence scale (ℓ_u), the ratio $\ell_u/\$_t$ and the rms pressure for each run at the forward station. Table 4 gives the corresponding values of these parameters at the rear station.

The vehicles trajectory data are given in Figs.2-5 and are compared with those previously obtained[1] for Shark 1: Fig.2 shows the vehicle velocity against time, Figs.3 and 4 the height above sea level against time and range respectively, Fig.5 shows the Mach number against time. Fig.6.1 to 6.54 shows the auto-correlation functions against τ and smoothed and unsmoothed spectral density estimates against k for front and rear stations for each of the 27 runs presented in Table 1.

The scales of the turbulence for the two stations are plotted in Figs.7.1 and 7.2 against time and Mach number, and the corresponding turbulence thicknesses are shown in Fig.8. The variation with time of the rms pressure and position of the maximum spectral density are shown in Fig.9; the values for Shark 1 are also given for comparison. A comparison of the spectral density distribution near the maximum Mach number for Shark 1 and 3 is made in Fig.10; the runs taken are run 40 for Shark 3 (i.e. time 4.0 to 4.5 seconds after firing) and the collective run for Shark 1 (i.e. time 4.1 to 4.6 seconds after firing).

4.1 Comparison of experimentally determined spectra with a theoretical spectrum

Taylor[4] has tabulated a theoretical $(\text{pressure})^2$ spectrum for a range of Reynolds number in a non-dimensional form. The one for very high Reynolds numbers ($A = 0$) has been used for comparison with the experimental spectra. Figs.11.1 to 11.7 compare the unsmoothed spectral densities, as shown in Fig.6, for each of the runs for both measuring stations. In each case two spectra have been calculated and shown as full lines and broken lines. The full line is the spectrum that has the same mean square pressure as the experimental value and has its maximum spectral density at the same frequency as that of the maximum experimental value. The broken line is the spectrum that has the same mean square pressure as the experimental value and in addition has the same mean square pressure as the experimental data for frequencies greater than 10000 Hz, i.e. gives a good fit with the experimental points over the high frequency range.

4.2 The scale of turbulence, ℓ_u

The values of ℓ_u given in Tables 3 and 4 are based on the values of f_m indicated by the coincident peaks of the experimental points and the full-line theoretical spectra. The peaks of the broken-line theoretical spectra are at different frequencies from those of the full-line spectra and correspond to different scales of turbulence. The values of ℓ_u for the full-line and broken-line spectra are compared in Table 5 for both measuring stations.

A comparison is made of the scale of the turbulence as a fraction of the turbulence thickness at different Mach numbers in Fig.12. It can be seen that there is much less scatter on the broken-line than on the full-line; to appreciate this fully it is necessary to note the number of values that are off the scale. For the most part the scale lies between 30% and 80% on the turbulence boundary-layer thickness and does not seem to depend on Mach number.

4.3 Rms pressure

The rms pressure is also given in Table 5 for each run as a fraction of the dynamic pressure q. These values are compared for different Mach numbers in Fig.13. The comparison is made for the whole of the flight but it is considered that less reliance can be placed on the recording below Mach number 1.0 especially in the accelerating phase as there is appreciable change in Mach number and dynamic pressure between the beginning and end of the 0.5 second duration of each record. It is apparent that the fraction of dynamic pressure decreases with increasing Mach number and also is smaller for the high Reynolds number, for the same Mach number; it is of the order of 0.01 times the dynamic pressure at M = 1 reducing to about 0.003 at M = 2.2. There is an indication that values are higher when the vehicle is decelerating than when it is accelerating.

5 CONCLUSIONS

Measurements of boundary-layer pressure fluctuations have been made for a short flight-time on a free-flight aerodynamic test vehicle at Mach numbers up to 2.2 and local Reynolds numbers up to 2.07×10^8 at the front measuring station and 1.18×10^8 at the rear. Autocorrelation functions and (pressure)^2 spectral densities have been determined and are presented in tabular and graphical form. Representative experimental spectra are compared with a theoretical spectrum, and are found to be in reasonable agreement.

Values have been obtained of the scale of the turbulence, and the ratio of scale of the turbulence to turbulence boundary-layer thickness, and these are similarly presented. There is considerable variation in the scale; apart from a number of records with a high value the scale lies between about 30% and 80% of the turbulence boundary-layer thickness at all Mach numbers up to 2.2, there being no apparent tendency to vary with Mach number. The root mean square of the boundary-layer pressure has rather less scatter and reduces with Mach number being about 0.01 times the free stream dynamic pressure at M = 1 and 0.003 at M = 2.2 and the front station being rather the higher at each Mach number.

Appendix

METHOD OF DATA ANALYSIS

The following operations were carried out for each of the 27 runs of one half-second duration, for each of the two measuring stations. Thus 54 batches of 25000 digital pressure values were operated on. Where necessary, the suffix (1) was used to designate results for the forward measuring station, and the suffix (2) for the rear measuring station. 1900 Fortran language was used for all but the early computation stages, in which EMA language was used.

A.1 The arithmetic mean of all the samples in the run, was subtracted from each value in turn:-

$$y_t = \text{(recorded value)} - \text{(arithmetic mean)} \quad .$$

A.2 The root mean square of the pressure fluctuations was evaluated using the expression

$$\sigma_p = \left[\frac{1}{(N+1)} \sum_{t=1}^{N+1} y_t^2\right]^{\frac{1}{2}}$$

where $(N + 1)$ is the number of discreet values contained in the run.

A.3 The auto correlation function is defined as

$$R_\tau = \frac{1}{(N+2-\tau)} \sum_{t=1}^{N+2-\tau} y_t y_{(t+\tau-1)}$$

where $\tau = 1, 2, 3, \ldots\ldots (M + 1)$

where M is the number of correlated intervals used in the spectral density analysis.

The expression was evaluated for $\tau = 1, 2, 3, \ldots\ldots (100)$.

A.4 The unsmoothed spectral density estimates were calculated from[3]:-

$$V_k = \Delta t \left\{ R_1 + R_{(M+1)} \cos\left[(k-1)\pi\right] + 2 \sum_{\tau=2}^{M} R_\tau \cos\left[\frac{[(k-1)(\tau-1)\pi]}{M}\right] \right\}$$

where $k = 1, 2, 3, \ldots\ldots (M + 1)$

and Δt is the time interval between each two consecutive discreet values = 0.00002 second.

Tabulated values of unsmoothed spectral density estimates for $k = 1, 2, \ldots\ldots 100$ are presented in Table 1.

A.5 The frequencies to which these estimates refer were calculated from the expression

$$f_k = \frac{(k-1)}{2\Delta t M} \quad .$$

Values of k with the corresponding values of frequency are presented in Table 2.

A.6 The estimates of hanning-smoothed and hamming-smoothed spectral densities were calculated from the expressions:-

hanning smoothing

$$W_k = 0.5V_1 + 0.5V_2 \qquad k = 1$$

$$= 0.25(V_{k-1} + V_{k+1}) + 0.5V_k \qquad 1 < k < M$$

$$= 0.5V_M + 0.5V_{M+1} \qquad k = M + 1$$

hamming smoothing

$$Z_k = 0.54V_1 + 0.46V_2 \qquad k = 1$$

$$= 0.23(V_{k-1} + V_{k+1}) + 0.54V_k \qquad 1 < k < M$$

$$= 0.46V_M + 0.54V_{M+1} \qquad k = M + 1 \quad .$$

A.7 For very high Reynolds numbers (non-dimensional viscosity function $A = 0$) it was shown[4] that the maximum $(\text{pressure})^2$ spectral density occurred at

$$X = 2.111$$

where X, the non-dimensional frequency was defined as

$$X = a\omega = \frac{2\pi f a}{U}$$

where ω was the wave-number, f the measured frequency, U the velocity of the stream relative to the measuring station, and a was a length to make wave-numbers non-dimensional.

The frequency at which the spectral density was found to be a maximum was determined for the run, and defined as f_m, so that

$$2.111 = \frac{2\pi f_m a}{U}$$

or

$$a = \frac{2.111 U}{2\pi f_m} .$$

The scale of the turbulence was defined[4] as

$$\ell_u = LUa$$

and

$$LU = 0.74677 \quad \text{when} \quad A = 0 .$$

If the frequency of the maximum value of the experimental spectrum is made to coincide with that of the theoretical spectrum, the scale of the turbulence is given by

$$\ell_u = \frac{2.111(0.74677U)}{2\pi f_m}$$

$$= \frac{0.25088U}{f_m} \quad .$$

This expression was used to calculate the value of ℓ_u for the run.

A.8 The local Reynolds number R_x was calculated, using the expression

$$R_x = \frac{XU}{\nu h}$$

assuming that the effective start of the turbulence was at a distance X upstream from the measuring station, equal to the axial distance of the station from the nose of the test vehicle, and where U was the stream velocity, and ν_h was the coefficient of kinematic viscosity at height h above sea level. The Reynolds number at the forward station was designated $R_{x(1)}$ and at the rear station $R_{x(2)}$.

A.9 Taylor[5] has concluded that a reasonable estimate of the turbulence thickness $\$_T$ is equal to about 80% of the total boundary-layer thickness \$ predicted by Spalding[6], so that

$$R_{\$_T} = 0.8R_{\$} \quad .$$

The relationship between $R_{\$}$ and R_x has also been defined by Spalding, and using this relationship together with the expression

$$\$_T = \left(\frac{0.8R_{\$}}{R_x}\right) X$$

the values of $\$_{T(1)}$ and $\$_{T(2)}$ were calculated.

A.10 The ratios $\ell_{u(1)}/\$_{T(1)}$ and $\ell_{u(2)}/\$_{T(2)}$ were then calculated.

Table 1

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run 0 Front	Run 0 Rear	Run 5 Front	Run 5 Rear	Run 10 Front	Run 10 Rear	Run 15 Front	Run 15 Rear
1	2253	3655	1877	9503	1378	2311	3512	5252
2	2033	2171	1411	2363	42	276	152	104
3	2267	1348	1370	1962	63	328	209	299
4	2013	1670	1262	1823	51	238	170	186
5	1460	1597	1791	1427	40	245	94	110
6	1300	1334	1426	1051	43	278	112	89
7	1061	992	1510	744	55	449	100	74
8	671	846	1376	627	84	604	131	107
9	834	832	1157	552	245	712	123	106
10	674	578	807	575	780	800	115	153
11	550	665	225	450	828	584	108	140
12	434	470	167	281	1330	538	130	84
13	335	483	50	274	1462	499	141	104
14	319	345	54	215	1129	538	166	117
15	230	339	21	192	1076	368	167	134
16	279	244	30	174	1378	288	176	145
17	195	280	7	160	743	268	190	198
18	161	226	21	134	809	303	348	219
19	123	212	6	131	1363	209	311	266
20	92	198	14	107	769	156	565	265
21	76	151	4	95	544	132	501	290
22	82	158	10	119	322	88	773	292
23	73	149	0	83	160	92	903	325
24	58	120	8	85	140	75	927	295
25	49	105	0	90	56	91	1002	305
26	34	99	6	100	65	62	850	312
27	30	110	0	81	33	62	949	227
28	36	106	5	67	43	69	527	278
29	29	91	0	73	20	54	412	223
30	23	88	4	65	36	50	449	256
31	20	71	0	81	24	47	355	217
32	22	71	4	63	21	54	282	269
33	19	71	0	68	13	54	322	194
34	12	59	3	66	19	46	308	177
35	9	77	0	64	11	45	339	152
36	15	58	3	60	18	40	209	123
37	12	55	0	68	8	34	178	119
38	10	59	3	71	15	44	203	78
39	13	67	0	67	8	40	156	85
40	10	57	3	59	11	44	172	64
41	6	63	1	49	9	44	151	62
42	7	47	3	60	12	40	112	55
43	6	48	1	55	6	42	113	58
44	6	45	2	69	11	48	110	49
45	8	46	1	67	7	44	99	58
46	8	47	3	62	10	56	124	38
47	6	53	1	73	8	40	118	49
48	5	44	3	69	10	36	135	27
49	5	53	2	95	7	39	117	53
50	6	48	3	77	12	49	94	39

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run 0 Front	Run 0 Rear	Run 5 Front	Run 5 Rear	Run 10 Front	Run 10 Rear	Run 15 Front	Run 15 Rear
51	5	48	2	87	7	45	118	22
52	5	68	5	185	19	110	260	23
53	5	49	4	67	7	31	132	21
54	5	37	6	70	12	40	92	23
55	6	43	6	86	6	45	104	20
56	5	45	7	75	8	47	70	19
57	5	40	6	75	5	37	92	15
58	5	37	7	71	9	42	78	15
59	5	44	6	73	5	35	76	14
60	5	50	7	96	8	46	88	14
61	5	53	7	91	6	43	125	11
62	6	40	9	87	9	40	113	10
63	5	44	10	78	5	38	108	10
64	5	48	12	107	7	45	83	10
65	4	41	9	102	4	32	135	10
66	5	40	9	94	7	41	102	9
67	6	40	8	95	5	31	84	8
68	5	35	9	82	9	38	84	9
69	4	43	7	89	8	48	96	7
70	4	41	7	99	12	29	80	7
71	4	35	5	68	10	43	110	7
72	5	32	6	85	13	39	80	7
73	6	43	5	78	12	32	110	8
74	5	42	5	89	15	30	94	6
75	4	35	4	79	12	38	76	8
76	5	34	5	86	14	34	109	7
77	4	37	4	83	14	37	97	7
78	5	32	4	92	14	39	95	7
79	5	38	4	87	13	34	111	7
80	5	33	6	83	14	31	113	6
81	4	45	5	89	11	30	124	6
82	5	37	6	90	12	31	78	7
83	5	38	6	88	9	24	94	5
84	5	40	7	83	9	32	78	7
85	4	38	7	93	6	28	53	7
86	5	34	9	73	6	28	84	7
87	4	32	6	77	6	25	66	7
88	4	45	8	87	6	25	60	7
89	4	38	6	79	5	31	62	7
90	5	37	7	83	6	29	59	7
91	5	44	5	85	4	27	54	6
92	5	36	6	93	6	28	67	7
93	5	33	4	84	6	24	64	6
94	4	33	5	74	5	30	54	6
95	4	30	3	78	5	26	54	6
96	4	38	4	70	7	24	56	7
97	4	38	3	94	5	24	56	6
98	4	42	3	85	6	27	50	7
99	4	42	2	61	5	25	52	7
100	0	29	0	74	8	36	53	7

Table 1 (continued)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "K".
(100 pressure units = 0.3116 Lbf/in^2 = 2.1485 kN/m^2)

K	Run 20 Front	Run 20 Rear	Run 25 Front	Run 25 Rear	Run 30 Front	Run 30 Rear	Run 35 Front	Run 35 Rear
1	1070	1226	684	1830	307	1234	4414	3119
2	360	265	124	326	193	491	435	497
3	392	533	218	623	243	599	366	578
4	391	443	196	515	191	428	412	442
5	248	265	132	377	128	514	341	547
6	253	219	129	324	155	416	457	441
7	234	215	146	444	124	480	362	500
8	197	364	159	598	157	460	333	406
9	187	381	224	554	216	592	402	513
10	200	527	213	870	250	707	331	514
11	205	404	188	601	195	638	387	671
12	199	159	212	313	259	553	293	620
13	195	210	181	399	241	860	416	707
14	169	167	171	315	189	782	343	694
15	152	160	121	343	234	842	344	741
16	152	139	132	276	221	662	361	684
17	159	128	123	277	260	846	342	685
18	165	136	137	325	236	871	391	879
19	175	156	147	289	295	754	388	708
20	176	164	111	312	220	674	351	749
21	173	190	124	297	229	520	433	653
22	157	165	115	226	146	701	326	782
23	189	173	116	223	151	537	287	801
24	162	163	108	226	118	443	326	534
25	191	174	108	232	135	532	325	574
26	205	215	91	183	130	434	297	692
27	234	214	99	167	128	388	347	631
28	190	233	104	157	108	284	333	595
29	256	239	89	135	120	221	311	357
30	232	273	98	125	104	218	311	393
31	271	264	94	121	114	171	267	346
32	296	290	101	125	95	145	272	344
33	401	318	91	133	96	149	254	302
34	456	220	111	175	74	143	219	317
35	457	261	103	160	103	139	195	291
36	472	222	119	124	98	132	252	282
37	484	224	119	156	109	156	254	263
38	475	258	147	184	105	154	213	304
39	539	236	158	181	138	129	301	298
40	590	216	181	159	135	158	249	307
41	421	160	170	195	137	140	252	226
42	653	175	207	204	128	172	203	275
43	528	177	169	208	172	139	229	270
44	505	133	214	153	149	165	220	235
45	610	123	256	215	175	150	206	225
46	486	111	340	204	176	162	232	298
47	464	100	362	177	177	164	270	246
48	466	98	332	187	163	178	193	227
49	412	99	392	153	190	165	190	257
50	321	70	410	177	220	148	252	208

Density of (pressure squared x 10000) spectrum with respect to frequency factor "K".
(100 pressure units = 0.3116 Lbf/in^2 = 2.1485 kN/m^2)

K	Run 20 Front	Run 20 Rear	Run 25 Front	Run 25 Rear	Run 30 Front	Run 30 Rear	Run 35 Front	Run 35 Rear
51	420	58	384	164	256	147	199	204
52	459	48	438	140	268	140	265	207
53	286	48	527	145	301	150	176	156
54	256	42	483	138	278	123	187	232
55	218	38	421	98	331	118	158	188
56	199	33	493	109	363	154	140	170
57	168	33	441	94	431	116	155	181
58	180	28	447	93	479	129	135	167
59	174	30	416	84	437	107	127	157
60	152	22	386	74	462	116	147	160
61	151	22	347	62	492	111	129	175
62	128	17	381	73	519	108	151	144
63	125	18	337	61	461	110	113	135
64	113	16	299	68	428	96	138	145
65	113	15	254	58	429	85	156	140
66	102	16	196	58	368	75	119	145
67	106	15	250	48	316	72	149	126
68	116	12	190	35	333	75	116	115
69	128	14	181	37	277	69	117	127
70	93	10	157	33	256	66	128	145
71	116	11	165	38	295	60	120	121
72	91	9	137	33	271	64	123	121
73	110	10	131	22	222	61	132	116
74	94	10	97	30	233	57	95	92
75	86	9	129	23	187	49	99	119
76	88	6	111	21	188	55	129	116
77	121	6	95	20	173	50	120	101
78	113	5	99	22	145	53	136	78
79	74	8	86	17	165	41	104	97
80	95	6	94	18	140	37	121	87
81	91	6	93	17	119	39	103	97
82	92	5	79	15	122	34	98	96
83	73	5	76	15	124	34	112	86
84	95	6	69	11	130	32	92	77
85	100	5	74	12	110	30	79	104
86	85	4	72	12	98	29	88	80
87	84	6	67	11	111	26	98	80
88	81	5	62	12	106	27	100	80
89	96	5	62	12	92	30	91	93
90	105	5	49	12	85	26	98	86
91	94	7	66	10	77	23	118	98
92	84	6	61	12	78	24	102	85
93	84	5	60	9	89	19	96	73
94	86	4	66	11	98	23	95	85
95	85	5	67	10	96	19	94	74
96	83	5	57	11	90	20	114	79
97	74	5	64	10	83	19	97	75
98	85	4	62	11	74	20	110	96
99	87	5	63	10	88	19	98	93
100	83	3	58	8	102	24	84	64

Table 1 (continued)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run 40 Front	Run 40 Rear	Run 45 Front	Run 45 Rear	Run 50 Front	Run 50 Rear	Run 55 Front	Run 55 Rear
1	806	283	241	193	342	288	195	198
2	352	285	180	187	169	238	218	149
3	379	302	188	219	168	241	166	165
4	363	266	201	225	140	229	150	155
5	297	344	156	213	167	198	158	179
6	360	276	178	211	135	202	139	152
7	344	285	181	215	140	230	157	182
8	349	278	166	208	130	167	125	182
9	377	285	191	232	167	256	132	164
10	431	342	191	209	138	240	160	217
11	431	320	200	233	153	231	126	199
12	399	310	200	237	142	221	146	182
13	488	329	199	243	207	217	211	226
14	392	341	232	219	134	219	160	200
15	530	341	218	253	186	242	203	248
16	517	419	254	301	191	250	232	257
17	589	348	238	290	202	268	229	222
18	621	361	280	233	244	296	198	292
19	686	394	234	314	219	308	205	290
20	668	394	245	319	173	344	219	338
21	754	438	286	307	244	336	201	319
22	826	434	300	342	182	317	191	340
23	681	380	269	374	220	352	186	390
24	799	435	329	390	232	362	244	345
25	727	374	310	413	276	401	218	357
26	772	472	439	434	228	397	230	492
27	846	433	353	374	262	393	248	432
28	741	523	503	455	278	392	273	539
29	1099	469	515	432	355	462	282	510
30	929	380	569	434	254	533	369	473
31	924	550	610	469	403	365	313	493
32	943	574	575	559	347	559	385	633
33	1056	559	567	649	471	563	408	580
34	940	569	675	577	437	545	410	629
35	1001	525	854	620	561	667	447	739
36	992	641	711	539	477	675	499	720
37	1149	561	739	711	535	771	466	781
38	1144	633	871	618	553	742	580	949
39	1031	633	1185	592	717	678	605	845
40	1058	587	948	791	692	686	599	849
41	1102	630	1046	911	767	772	764	971
42	1399	657	1190	877	663	786	867	907
43	970	587	1338	765	948	926	873	1008
44	1081	572	1399	744	925	965	951	969
45	1028	589	1557	728	1030	816	989	1120
46	1276	582	1680	746	1264	899	1286	945
47	1093	626	1724	814	1239	1052	1492	913
48	1002	477	1695	982	1502	916	1236	933
49	762	697	1615	684	1371	965	1428	739
50	816	582	2004	914	1680	963	1288	902

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run 40 Front	Run 40 Rear	Run 45 Front	Run 45 Rear	Run 50 Front	Run 50 Rear	Run 55 Front	Run 55 Rear
51	979	654	1804	765	1343	859	1741	981
52	778	634	1781	918	1573	804	1489	1031
53	726	578	1885	753	1684	859	1724	904
54	644	603	1560	896	1975	848	1705	674
55	637	537	1729	835	1450	728	2004	753
56	533	612	1576	718	2105	840	2159	808
57	576	610	1450	702	1950	845	2049	702
58	476	554	1370	703	1630	756	2159	744
59	494	399	1394	731	1818	695	1865	676
60	469	490	1234	603	1991	580	1961	637
61	370	471	916	690	1614	527	1915	637
62	392	481	1200	606	1447	659	1547	410
63	311	476	1025	546	1217	563	1146	484
64	295	385	880	585	1270	570	1022	411
65	295	367	711	563	1164	464	904	416
66	273	338	708	507	923	516	824	398
67	244	333	595	463	796	397	636	380
68	212	325	597	376	726	324	631	318
69	209	267	410	368	454	355	485	235
70	214	265	452	359	529	336	512	294
71	227	293	389	331	448	353	409	232
72	152	241	368	275	435	266	398	259
73	143	249	333	241	378	221	354	234
74	181	243	276	223	332	224	270	220
75	138	204	275	278	328	203	229	194
76	124	206	222	250	241	203	239	157
77	147	161	180	215	227	185	218	163
78	128	197	186	178	208	177	177	166
79	103	183	154	175	181	181	172	136
80	104	139	129	161	196	189	123	151
81	98	171	130	163	126	149	114	132
82	105	130	141	149	135	161	108	123
83	108	155	103	151	107	153	85	134
84	103	125	102	153	112	129	86	135
85	104	134	94	150	91	160	88	126
86	97	122	79	150	100	118	72	156
87	92	146	92	157	89	143	72	124
88	98	133	87	118	91	136	69	114
89	96	139	87	130	76	87	69	123
90	77	117	75	125	88	123	67	136
91	84	130	70	129	63	138	70	119
92	91	105	70	121	65	116	63	116
93	93	134	66	130	57	117	63	116
94	89	119	71	130	76	148	60	109
95	101	121	68	120	62	109	55	107
96	104	106	69	136	71	109	64	120
97	90	130	63	127	56	125	60	103
98	78	117	71	119	73	119	58	106
99	84	137	73	132	60	98	63	120
100	95	132	70	130	67	148	69	107

Table 1 (continued)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 70 Front	70 Rear	85 Front	85 Rear	100 Front	100 Rear	115 Front	115 Rear
1	196	321	729	854	1951	1017	2934	832
2	182	250	331	619	1207	864	2109	969
3	170	294	357	488	1066	755	1848	811
4	203	206	287	565	1292	750	1492	763
5	157	229	327	446	1089	773	1126	685
6	197	228	337	601	1190	885	987	709
7	143	234	389	564	1193	791	755	522
8	164	228	384	521	1161	857	554	576
9	164	[illegible]	349	452	1037	945	430	601
10	167	210	457	554	841	990	408	545
11	147	261	475	538	658	887	305	507
12	168	292	422	650	636	773	333	419
13	185	291	576	639	452	829	275	362
14	212	272	503	751	348	830	228	380
15	194	351	702	737	322	820	186	462
16	231	359	739	815	218	730	155	440
17	262	440	818	938	224	700	153	313
18	300	419	954	1048	184	633	138	309
19	269	427	1341	976	173	513	105	430
20	377	425	1298	942	105	430	117	317
21	367	421	1294	1023	164	484	92	342
22	411	589	1532	1040	129	503	93	302
23	503	610	1559	1063	140	370	86	318
24	620	656	1353	1094	114	488	80	334
25	638	738	1142	1221	101	416	66	298
26	674	706	1120	962	87	372	74	288
27	716	708	851	949	84	504	73	289
28	852	733	871	934	64	401	78	232
29	1035	977	637	774	79	247	57	216
30	1189	971	571	910	82	310	63	213
31	1315	982	497	797	61	337	44	205
32	1489	1307	483	787	54	254	45	212
33	1488	1201	483	785	56	297	37	172
34	1580	1157	367	574	49	257	42	187
35	1964	1411	378	587	47	304	41	171
36	2013	1521	409	563	40	263	44	184
37	2166	1279	383	586	46	261	37	163
38	1843	1312	353	611	43	203	50	169
39	2399	1023	395	548	44	228	36	165
40	2773	1063	352	479	47	208	35	134
41	2161	1157	295	470	38	230	32	152
42	2161	1266	297	502	42	205	32	123
43	2034	945	305	420	48	196	34	152
44	1795	901	282	400	37	201	37	134
45	1458	774	223	367	35	179	32	130
46	1508	781	191	394	34	192	40	117
47	1706	707	209	284	32	158	33	125
48	1115	664	186	309	38	177	28	151
49	803	543	189	275	36	177	33	124
50	814	524	177	274	31	169	31	146

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 70 Front	70 Rear	85 Front	85 Rear	100 Front	100 Rear	115 Front	115 Rear
51	609	468	140	293	36	172	34	124
52	590	421	168	281	38	152	40	125
53	455	429	140	261	31	162	29	122
54	422	387	132	246	31	145	31	120
55	359	335	118	186	36	150	31	101
56	324	280	123	214	25	128	27	101
57	308	271	124	197	34	151	26	96
58	279	263	121	182	32	120	25	97
59	286	253	119	181	29	116	27	87
60	239	238	121	161	25	125	26	102
61	218	178	111	156	27	119	27	87
62	194	184	98	153	27	127	27	95
63	174	175	91	165	24	115	26	93
64	123	158	87	144	26	107	26	84
65	165	143	95	124	29	107	29	70
66	150	135	87	123	26	115	26	97
67	117	130	85	125	24	102	29	92
68	120	113	96	147	26	104	31	77
69	134	125	88	120	23	104	23	91
70	116	129	81	114	24	104	29	74
71	87	101	74	112	24	97	24	72
72	94	107	65	112	24	99	22	80
73	95	115	89	108	25	104	22	82
74	91	125	70	105	22	84	24	71
75	81	110	69	117	28	92	28	69
76	78	104	78	101	20	83	22	79
77	76	95	71	99	25	83	22	75
78	85	113	65	100	20	92	23	68
79	69	90	71	108	17	85	23	85
80	72	105	70	99	21	94	20	82
81	68	96	64	99	21	89	21	79
82	77	107	67	84	19	94	24	79
83	78	112	78	93	18	103	21	76
84	76	97	64	78	22	94	24	64
85	69	89	70	90	21	101	22	72
86	73	89	64	99	17	85	18	64
87	72	84	76	95	21	84	23	68
88	59	93	59	95	17	75	17	74
89	77	99	63	90	19	94	25	63
90	76	91	69	86	16	75	22	63
91	81	84	62	80	17	75	21	75
92	71	89	61	75	13	88	20	76
93	64	74	72	99	22	81	20	63
94	79	92	59	77	26	80	20	63
95	64	95	72	84	21	70	21	74
96	68	92	62	84	21	82	22	79
97	82	107	50	76	24	83	25	68
98	69	89	50	90	24	77	22	69
99	59	83	65	83	25	83	20	68
100	81	97	65	94	30	75	23	59

Table 1 (continued)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 130		145		160		175	
	Front	Rear	Front	Rear	Front	Rear	Front	Rear
1	493	643	537	641	319	717	508	1062
2	410	565	251	501	314	443	626	583
3	666	666	431	516	443	518	646	552
4	865	662	539	571	604	456	918	572
5	1556	564	904	556	891	606	1700	621
6	1777	585	1398	486	1947	588	2962	582
7	1774	471	2474	534	2946	565	2907	685
8	1398	425	2039	486	2366	461	1513	616
9	1030	430	1486	480	1151	493	825	491
10	722	350	999	385	883	556	596	442
11	635	357	532	338	575	428	445	412
12	456	288	539	332	388	362	255	398
13	327	331	287	363	284	422	244	306
14	274	338	292	223	202	333	204	305
15	202	333	219	276	220	353	184	310
16	193	278	213	244	152	292	130	259
17	182	273	135	221	140	257	134	237
18	137	243	167	275	121	239	94	230
19	129	279	117	229	102	231	92	203
20	116	227	117	213	111	281	80	225
21	104	206	98	208	81	167	75	197
22	104	241	86	229	74	218	64	215
23	88	233	79	146	67	220	63	220
24	99	217	92	164	65	182	50	201
25	77	222	63	204	61	215	55	191
26	71	223	76	180	64	167	55	179
27	67	228	59	201	61	210	58	149
28	70	188	60	184	49	200	45	154
29	57	216	53	139	56	148	45	138
30	58	193	58	141	53	148	42	138
31	57	197	46	103	37	139	40	135
32	53	165	42	139	41	131	39	126
33	48	159	47	155	37	139	41	136
34	45	134	54	134	36	114	39	117
35	53	176	39	117	34	126	39	145
36	51	132	39	136	34	139	28	101
37	47	131	42	132	32	109	29	96
38	43	118	44	124	34	121	31	101
39	52	133	37	114	25	112	34	89
40	50	109	45	108	28	110	30	114
41	48	105	37	105	30	98	32	101
42	39	113	42	104	27	91	32	97
43	40	125	29	93	26	96	31	83
44	39	106	39	98	27	94	33	84
45	41	95	33	89	24	103	29	82
46	36	96	33	94	20	101	30	76
47	43	106	33	82	24	94	33	89
48	36	95	27	81	25	94	31	86
49	36	93	36	86	26	89	30	80
50	42	99	32	82	20	98	27	75

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 130		145		160		175	
	Front	Rear	Front	Rear	Front	Rear	Front	Rear
51	43	90	28	75	21	93	30	83
52	40	108	40	79	21	127	27	92
53	38	80	30	76	22	66	23	64
54	32	85	27	78	20	91	24	73
55	38	92	33	72	20	78	26	76
56	40	96	26	68	20	86	19	66
57	38	74	28	73	21	72	20	64
58	36	95	28	75	18	74	18	66
59	33	86	34	68	18	65	20	66
60	30	100	31	75	16	73	18	62
61	33	79	28	72	17	65	18	54
62	32	86	30	69	19	70	15	52
63	33	72	29	65	14	90	17	56
64	32	85	30	68	17	83	14	67
65	29	66	28	59	21	67	14	60
66	32	84	30	54	19	58	15	61
67	28	71	25	55	16	55	15	56
68	30	66	31	70	17	65	12	56
69	27	72	25	57	17	67	13	54
70	31	73	24	58	14	70	17	52
71	28	62	21	58	14	68	14	55
72	28	71	24	52	17	64	10	54
73	29	57	22	60	16	57	14	47
74	27	66	25	55	13	65	12	58
75	30	67	19	66	14	64	13	48
76	25	66	28	49	14	70	11	45
77	26	60	25	57	11	55	14	47
78	27	51	27	56	11	57	12	51
79	29	59	21	54	13	62	11	56
80	27	56	23	59	14	63	11	54
81	24	55	23	54	16	55	10	58
82	21	62	22	59	15	57	11	53
83	27	58	19	48	12	53	12	49
84	26	51	23	55	12	57	8	53
85	27	47	22	51	13	63	11	57
86	24	54	28	43	14	56	10	49
87	26	63	23	43	12	59	11	50
88	28	58	28	48	15	61	9	51
89	26	57	26	51	14	51	12	43
90	30	49	23	45	14	54	12	55
91	26	67	22	44	13	45	13	55
92	22	54	21	44	15	58	11	48
93	26	68	22	47	15	48	11	48
94	31	52	30	47	14	55	11	58
95	31	53	22	51	13	53	11	52
96	31	48	24	48	13	44	11	45
97	26	60	25	49	13	57	12	57
98	26	68	27	48	13	61	9	50
99	27	55	17	45	13	43	12	43
100	34	61	25	42	15	44	11	46

Table 1 (continued)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 190 Front	190 Rear	205 Front	205 Rear	220 Front	220 Rear	235 Front	235 Rear
1	744	2232	693	1146	936	3679	1182	2016
2	941	653	2153	816	1399	979	1700	1164
3	1464	1126	1504	1300	1048	1170	1409	1992
4	1772	870	1151	958	941	1112	1697	1480
5	2732	823	1421	800	826	965	1907	970
6	2619	795	614	683	988	1001	1432	907
7	1543	777	586	758	699	989	624	679
8	1027	719	340	788	392	829	274	639
9	570	634	364	715	271	752	385	700
10	535	705	524	673	445	810	261	671
11	367	492	648	474	365	666	356	460
12	252	439	587	509	307	612	300	511
13	241	384	520	412	423	460	374	449
14	149	350	373	347	426	356	389	370
15	145	335	510	383	381	370	231	339
16	99	318	463	355	389	351	291	342
17	92	256	393	291	452	282	295	279
18	82	286	373	280	496	230	230	277
19	75	257	221	263	392	204	314	218
20	71	206	226	256	341	203	194	271
21	63	238	180	224	317	187	201	222
22	57	212	195	210	301	175	184	177
23	47	201	168	209	317	167	147	190
24	46	174	121	176	273	167	246	168
25	48	188	163	188	247	158	218	205
26	50	171	162	185	241	177	233	205
27	37	181	123	141	186	134	261	152
28	42	168	100	185	151	131	171	157
29	42	164	79	153	126	124	212	146
30	34	149	113	134	146	116	208	151
31	36	139	96	133	129	105	239	133
32	28	135	79	148	112	109	283	127
33	26	135	99	130	131	106	269	119
34	25	145	91	116	118	97	257	110
35	21	126	81	110	92	96	236	137
36	19	120	83	103	89	108	167	115
37	15	111	75	111	77	97	220	114
38	19	104	77	126	81	96	170	105
39	17	86	59	101	81	75	168	101
40	17	93	58	101	70	79	145	107
41	16	107	67	101	86	69	92	79
42	18	89	69	97	77	78	121	96
43	13	88	78	100	65	77	105	84
44	14	86	71	91	63	81	81	95
45	16	94	67	82	65	82	91	85
46	13	88	79	89	73	77	80	89
47	15	95	73	84	77	63	87	94
48	13	82	91	91	67	68	85	81
49	14	98	74	97	80	65	84	74
50	13	75	73	94	67	66	82	89

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	Run number 190 Front	190 Rear	205 Front	205 Rear	220 Front	220 Rear	235 Front	235 Rear
51	11	89	69	97	60	67	72	91
52	12	133	79	84	56	74	62	91
53	12	76	84	85	68	65	87	70
54	9	84	132	77	110	62	113	75
55	10	66	171	69	182	56	199	65
56	10	83	245	78	268	65	277	91
57	11	55	301	68	351	63	353	67
58	12	63	403	70	412	56	466	71
59	10	72	434	66	523	51	587	69
60	9	62	407	68	563	56	482	68
61	9	68	446	71	542	62	517	72
62	10	65	452	58	478	53	500	74
63	9	60	356	68	494	54	506	63
64	8	62	289	66	412	50	356	64
65	9	62	276	63	271	51	316	67
66	8	63	182	67	209	56	221	61
67	8	52	162	59	171	55	186	64
68	7	59	91	56	111	53	113	70
69	6	58	109	56	58	46	97	58
70	6	57	62	65	64	56	83	69
71	6	55	81	54	58	46	71	72
72	6	59	93	57	69	56	71	61
73	7	50	92	61	71	50	83	66
74	7	59	97	61	97	48	93	59
75	6	61	91	63	97	42	100	60
76	6	56	74	62	80	56	93	66
77	6	50	94	62	91	54	102	67
78	7	58	84	53	81	46	99	71
79	7	55	105	59	79	49	107	68
80	6	47	92	50	89	47	91	54
81	6	47	120	55	90	43	108	65
82	7	51	96	53	87	47	100	64
83	6	65	96	60	73	39	108	55
84	7	56	90	58	78	44	91	65
85	7	55	92	56	66	40	89	55
86	7	55	73	51	69	48	67	56
87	7	51	65	60	57	48	60	54
88	8	51	68	55	67	39	72	60
89	7	49	58	43	63	41	76	65
90	8	53	64	52	48	36	51	59
91	7	40	70	58	72	49	75	68
92	6	57	68	52	63	45	66	54
93	6	54	67	57	54	40	67	54
94	6	50	68	56	66	41	68	55
95	6	52	64	56	55	43	76	52
96	6	43	78	55	81	44	88	56
97	6	55	67	51	60	42	68	51
98	4	54	83	48	58	38	59	58
99	5	50	76	52	80	49	101	49
100	5	59	63	63	54	44	61	67

Table 1 (concluded)

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	260 Front	260 Rear	285 Front	285 Rear	310 Front	310 Rear
1	484	3718	545	3629	229	3556
2	3043	1715	2883	1936	3812	2125
3	1560	2758	1481	2780	2174	2630
4	1217	1629	1074	1980	1698	1683
5	2093	998	1736	1167	2142	1089
6	1050	925	1242	1078	1929	1019
7	723	675	693	814	844	737
8	261	691	261	659	267	503
9	380	543	321	642	324	761
10	328	581	307	402	336	554
11	373	359	323	372	299	431
12	362	384	369	398	382	368
13	524	344	433	401	601	457
14	477	326	407	308	564	365
15	348	238	327	311	405	285
16	196	307	233	229	238	272
17	246	278	244	222	271	306
18	263	280	259	232	275	254
19	302	238	292	261	286	256
20	209	220	190	187	193	247
21	261	233	217	224	212	222
22	224	268	197	217	223	200
23	156	186	146	215	155	175
24	164	189	164	200	118	212
25	173	160	131	256	113	233
26	196	183	165	219	148	177
27	215	173	210	136	176	212
28	130	160	109	177	118	125
29	140	145	120	149	124	186
30	126	145	122	164	118	154
31	119	138	104	148	95	123
32	150	154	101	140	93	142
33	139	119	112	118	111	118
34	169	119	170	135	162	135
35	175	124	160	125	148	114
36	116	135	118	133	85	106
37	142	114	104	108	106	105
38	183	112	150	102	126	97
39	211	102	183	102	153	99
40	198	106	176	95	174	93
41	194	114	221	100	167	101
42	164	94	199	111	215	108
43	169	94	198	83	184	83
44	151	92	185	74	161	74
45	178	91	203	88	210	95
46	172	99	212	83	205	79
47	149	100	194	84	142	82
48	116	82	177	73	142	99
49	142	105	139	91	128	94
50	114	80	170	83	110	76

Density of (pressure squared x 10000) spectrum with respect to frequency factor "k".
(100 pressure units = 0.3116 lbf/in^2 = 2.1485 kN/m^2)

k	260 Front	260 Rear	285 Front	285 Rear	310 Front	310 Rear
51	136	93	115	84	102	84
52	115	132	121	112	71	112
53	134	66	93	65	123	87
54	200	85	191	72	126	89
55	251	67	195	66	204	73
56	323	68	335	81	295	77
57	399	71	365	66	369	76
58	463	70	535	64	385	86
59	532	66	506	77	535	80
60	558	85	522	70	569	88
61	540	73	504	75	526	79
62	513	63	573	66	504	85
63	493	72	533	68	466	77
64	391	64	391	72	421	86
65	347	65	350	58	286	75
66	286	77	269	59	269	80
67	196	68	210	66	163	73
68	143	59	148	59	139	75
69	135	59	124	68	92	74
70	113	76	102	66	104	77
71	114	59	134	64	85	69
72	137	70	110	73	127	72
73	120	66	128	61	97	71
74	135	72	147	53	114	76
75	133	60	133	68	96	80
76	117	62	130	62	118	70
77	123	68	134	63	94	79
78	137	66	136	69	122	80
79	145	67	121	68	110	77
80	116	64	142	74	155	89
81	124	66	150	73	151	98
82	124	63	111	62	113	85
83	141	60	129	60	118	77
84	129	61	119	72	97	71
85	120	63	126	70	91	84
86	90	68	98	62	101	80
87	100	57	99	70	71	71
88	98	67	107	61	114	81
89	117	63	103	76	80	80
90	74	65	69	72	63	81
91	106	51	98	58	91	71
92	97	65	98	67	81	68
93	98	58	112	65	83	70
94	92	59	82	70	77	81
95	80	56	82	73	72	73
96	102	52	115	69	115	69
97	92	57	101	69	79	79
98	84	49	71	74	83	77
99	110	46	111	55	101	74
100	91	51	94	59	84	70

Table 2

Frequency and corresponding frequency factor "k"

k	Frequency (Hz)	k	Frequency (Hz)	k	Frequency (Hz)	k	Frequency (Hz)
1	0.00	26	6313.13	51	12626.26	76	18939.39
2	252.53	27	6565.66	52	12878.79	77	19191.92
3	505.05	28	6818.18	53	13131.31	78	19444.44
4	757.58	29	7070.71	54	13383.84	79	19696.97
5	1010.10	30	7323.23	55	13636.36	80	19949.49
6	1262.63	31	7575.76	56	13888.89	81	20202.02
7	1515.15	32	7828.28	57	14141.41	82	20454.55
8	1767.68	33	8080.81	58	14393.94	83	20707.07
9	2020.20	34	8333.33	59	14646.46	84	20959.60
10	2272.73	35	8585.86	60	14898.99	85	21212.12
11	2525.25	36	8838.38	61	15151.52	86	21464.65
12	2777.78	37	9090.91	62	15404.04	87	21717.17
13	3030.30	38	9343.43	63	15656.57	88	21969.70
14	3282.83	39	9595.96	64	15909.09	89	22222.22
15	3535.35	40	9848.48	65	16161.62	90	22474.75
16	3787.88	41	10101.01	66	16414.14	91	22727.27
17	4040.40	42	10353.54	67	16666.67	92	22979.80
18	4292.93	43	10606.06	68	16919.19	93	23232.32
19	4545.45	44	10858.59	69	17171.72	94	23484.85
20	4797.98	45	11111.11	70	17424.24	95	23737.37
21	5050.51	46	11363.64	71	17676.77	96	23989.90
22	5303.03	47	11616.16	72	17929.29	97	24242.42
23	5555.56	48	11868.69	73	18181.82	98	24494.95
24	5808.08	49	12121.21	74	18434.34	99	24747.47
25	6060.61	50	12373.74	75	18686.87	100	25000.00

Table 3

DERIVED QUANTITIES FOR FORWARD STATION

Run No.	Velocity (ft/s)	Height (ft)	Mach No.	R_{x1} ($\times 10^6$)	$R_{\delta_{T1}}$ ($\times 10^6$)	δ_{T1} (ft)	k_m	S.D. max	Scale (Lu) (ft)	Lu/δ_{T1}	r.m.s. pressure (lbf/in^2)	Run No.
0	164.0	450.0	0.1502	8.350	0.140	0.133	3	0.2267	0.081	0.611	0.092	0
5	492.0	501.6	0.4490	25.000	0.380	0.121	5	0.1791	0.122	1.011	0.083	5
10	810.0	586.6	0.7384	41.080	0.590	0.116	13	0.1462	0.067	0.580	0.086	10
15	1132.0	706.8	1.0351	57.240	0.800	0.112	25	0.1002	0.047	0.418	0.101	15
20	1457.0	858.1	1.3342	73.390	1.000	0.110	42	0.0653	0.035	0.322	0.105	20
25	1788.0	1039.1	1.6391	89.660	1.200	0.108	53	0.0527	0.034	0.317	0.094	25
30	2137.0	1148.3	1.9617	106.610	1.400	0.106	62	0.0519	0.035	0.328	0.098	30
35	2365.0	1481.1	2.1740	117.310	1.530	0.105	6	0.0457	0.470	4.469	0.107	35
40	2393.0	1717.0	2.2026	118.020	1.540	0.105	42	0.1399	0.058	0.552	0.157	40
45	2344.0	1936.3	2.1599	114.990	1.500	0.105	50	0.2004	0.048	0.451	0.169	45
50	2289.0	2136.5	2.1108	111.750	1.470	0.106	56	0.2105	0.041	0.391	0.164	50
55	2232.0	2320.4	2.0598	108.480	1.430	0.106	56	0.2159	0.040	0.381	0.163	55
70	2063.0	2779.1	1.9058	99.180	1.320	0.107	40	0.2773	0.053	0.492	0.161	70
85	1913.0	3134.4	1.7725	91.200	1.220	0.108	23	0.1559	0.086	0.803	0.127	85
100	1773.0	3402.0	1.6446	83.990	1.130	0.108	4	0.1292	0.587	5.418	0.093	100
115	1654.0	3594.5	1.5353	78.010	1.060	0.109	2	0.2109	1.643	15.062	0.088	115
130	1548.0	3708.5	1.4377	72.810	0.990	0.110	6	0.1777	0.308	2.802	0.089	130
145	1449.0	3768.0	1.3465	68.060	0.930	0.110	7	0.2474	0.240	2.172	0.089	145
160	1358.0	3771.2	1.2620	63.780	0.880	0.111	7	0.2946	0.225	2.024	0.089	160
175	1275.0	3708.0	1.1844	59.970	0.830	0.112	6	0.2962	0.253	2.268	0.091	175
190	1201.0	3576.1	1.1150	56.670	0.790	0.112	5	0.2732	0.298	2.657	0.090	190
205	1134.0	3396.7	1.0519	53.730	0.750	0.113	2	0.2153	1.127	9.986	0.107	205
220	1075.0	3170.6	0.9968	51.200	0.720	0.113	2	0.1399	1.068	9.425	0.106	220
235	1032.0	2887.5	0.9551	49.490	0.700	0.114	5	0.1907	0.256	2.255	0.114	235
260	987.0	2290.7	0.9106	48.010	0.680	0.114	2	0.3043	0.981	8.604	0.119	260
285	964.0	1553.1	0.8863	47.730	0.680	0.114	2	0.2883	0.958	8.399	0.117	285
310	950.0	680.9	0.8657	48.070	0.680	0.114	2	0.3812	0.944	8.282	0.121	310

Table 4

DERIVED QUANTITIES FOR REAR STATION

Run No.	Velocity (ft/s)	Height (ft)	Mach No.	R_{X2} ($\times 10^6$)	$R_{\$T2}$ ($\times 10^6$)	$T2 (ft)	k_m	S.D. max	Scale (Lu) (ft)	Lu/$T2	r.m.s. pressure (lbf/in^2)	Run No.
0	164.0	450.0	0.1502	14.652	0.230	0.223	2	0.2171	0.163	0.732	0.101	0
5	492.0	501.6	0.4490	43.902	0.630	0.202	2	0.2363	0.489	2.423	0.109	5
10	810.0	586.6	0.7384	72.120	0.980	0.193	10	0.0800	0.069	0.464	0.077	10
15	1132.0	706.8	1.0351	100.500	1.330	0.187	23	0.0325	0.051	0.272	0.073	15
20	1457.0	858.1	1.3342	128.850	1.670	0.183	3	0.0535	0.724	3.953	0.077	20
25	1788.0	1039.1	1.6391	157.420	2.000	0.180	10	0.0870	0.197	1.097	0.090	25
30	2137.0	1148.3	1.9617	187.170	2.340	0.177	18	0.0871	0.125	0.705	0.107	30
35	2365.0	1481.1	2.1740	205.960	2.560	0.176	18	0.0879	0.138	0.788	0.122	35
40	2393.0	1717.0	2.2026	207.200	2.570	0.175	49	0.0697	0.050	0.282	0.134	40
45	2344.0	1936.3	2.1599	201.880	2.510	0.176	48	0.0982	0.050	0.282	0.141	45
50	2289.0	2136.5	2.1108	196.200	2.450	0.176	47	0.1052	0.049	0.280	0.142	50
55	2232.0	2320.4	2.0598	190.470	2.380	0.177	45	0.1120	0.050	0.285	0.142	55
70	2063.0	2779.1	1.9058	174.130	2.200	0.178	36	0.1521	0.059	0.329	0.142	70
85	1913.0	3134.4	1.7725	160.120	2.030	0.180	25	0.1221	0.079	0.441	0.139	85
100	1773.0	3402.0	1.6446	147.470	1.890	0.181	10	0.0990	0.196	1.082	0.119	100
115	1654.0	3594.5	1.5353	136.950	1.760	0.182	2	0.0969	1.643	9.025	0.100	115
130	1548.0	3708.5	1.4377	127.840	1.660	0.183	3	0.0666	0.769	4.197	0.089	130
145	1449.0	3768.0	1.3465	119.500	1.560	0.184	4	0.0571	0.480	2.603	0.084	145
160	1358.0	3771.2	1.2620	111.980	1.470	0.185	5	0.0606	0.337	1.819	0.087	160
175	1275.0	3708.0	1.1844	105.290	1.390	0.186	7	0.0685	0.211	1.132	0.086	175
190	1201.0	3576.1	1.1150	99.490	1.320	0.187	3	0.1126	0.597	3.184	0.095	190
205	1134.0	3396.7	1.0519	94.330	1.260	0.188	3	0.1300	0.563	2.992	0.095	205
220	1075.0	3170.6	0.9968	89.900	1.200	0.189	3	0.1170	0.534	2.824	0.099	220
235	1032.0	2887.5	0.9551	86.880	1.170	0.190	3	0.1992	0.513	2.703	0.102	235
260	987.0	2290.7	0.9106	84.280	1.130	0.190	3	0.2758	0.490	2.578	0.105	260
285	964.0	1553.1	0.8863	83.810	1.130	0.190	3	0.2780	0.479	2.516	0.108	285
310	950.0	680.9	0.8657	84.390	1.140	0.190	3	0.2630	0.472	2.481	0.108	310

Table 5

SCALE AND RMS PRESSURE AT THEORETICAL SPECTRA

Run No.	Station	(full-line) $\ell_{u(f)}$ (ft)	(broken-line) $\ell_{u(b)}$ (ft)	$\ell_{u(b)}/\ell_{u(f)}$	σ_p/q
0	FRONT	0.08146	0.10604	1.30	0.41756
5	FRONT	0.12220	0.27899	2.28	0.04208
10	FRONT	0.06706	0.36649	5.47	0.01613
15	FRONT	0.04686	0.10961	2.34	0.00971
20	FRONT	0.03531	0.07594	2.15	0.00614
25	FRONT	0.03416	0.06127	1.79	0.00367
30	FRONT	0.03480	0.07656	2.20	0.00270
35	FRONT	0.46993	0.17630	0.38	0.00242
40	FRONT	0.05799	0.13912	2.40	0.00349
45	FRONT	0.04753	0.07189	1.51	0.00395
50	FRONT	0.04135	0.05890	1.42	0.00403
55	FRONT	0.03890	0.05625	1.45	0.00425
70	FRONT	0.05255	0.12581	2.39	0.00499
85	FRONT	0.08639	0.24302	2.81	0.00462
100	FRONT	0.58713	0.43176	0.74	0.00394
115	FRONT	1.64339	0.37666	0.23	0.00435
130	FRONT	0.30759	0.30849	1.00	0.00504
145	FRONT	0.23992	0.32329	1.35	0.00575
160	FRONT	0.22485	0.42920	1.91	0.00650
175	FRONT	0.25334	0.41362	1.63	0.00753
190	FRONT	0.29829	0.55980	1.88	0.00836
205	FRONT	1.12672	0.08927	0.08	0.01116
220	FRONT	1.06810	0.07958	0.07	0.01222
235	FRONT	0.25632	0.08091	0.32	0.01409
260	FRONT	0.98067	0.06780	0.07	0.01578
285	FRONT	0.95781	0.06224	0.06	0.01591
310	FRONT	0.94390	0.07321	0.08	0.01661
0	REAR	0.16295	0.03204	0.20	0.46245
5	REAR	0.48884	0.06175	0.13	0.05557
10	REAR	0.08941	0.11233	1.26	0.01455
15	REAR	0.05112	0.27809	5.44	0.00701
20	REAR	0.72368	0.22056	0.30	0.00452
25	REAR	0.19737	0.19083	0.97	0.00351
30	REAR	0.12489	0.26433	2.12	0.00294
35	REAR	0.13821	0.22533	1.63	0.00277
40	REAR	0.04953	0.11227	2.27	0.00298
45	REAR	0.04955	0.09011	1.82	0.00329
50	REAR	0.04944	0.08768	1.77	0.00350
55	REAR	0.05040	0.08865	1.76	0.00370
70	REAR	0.05856	0.14259	2.44	0.00439
85	REAR	0.07919	0.19660	2.48	0.00506
100	REAR	0.19572	0.19049	0.97	0.00508
115	REAR	1.64339	0.16388	0.10	0.00494
130	REAR	0.76888	0.14714	0.19	0.00500
145	REAR	0.47984	0.14375	0.30	0.00542
160	REAR	0.33729	0.13256	0.39	0.00640
175	REAR	0.21111	0.13689	0.65	0.00717
190	REAR	0.59653	0.14607	0.24	0.00888
205	REAR	0.56325	0.13551	0.24	0.00994
220	REAR	0.53395	0.16256	0.30	0.01137
235	REAR	0.51259	0.13400	0.26	0.01257
260	REAR	0.49024	0.13204	0.27	0.01402
285	REAR	0.47881	0.13323	0.28	0.01467
310	REAR	0.47186	0.11997	0.25	0.01483

SYMBOLS

A	non-dimensional viscosity function
LU	ℓ_u/a
Ma	Mach number
M	number of correlated intervals used
N	number of intervals in one run
$R_{\$}$	boundary-layer Reynolds number
$R_{\$_T}$	turbulence Reynolds number
R_x	local Reynolds number at distance x from the effective start of turbulence
R_τ	autocorrelation function for interval τ
U	stream velocity relative to measuring station
V_k, SD_k	unsmoothed spectral density estimate at frequency f_k
SD_{max}	maximum value of unsmoothed spectral density estimate for one run
W_k	hanning-smoothed spectral density estimate at frequency f_k
X	ωa
Z_k	hamming-smoothed spectral density estimate at frequency f_k
a	a length to make wave numbers non-dimensional
f_k	frequency corresponding to frequency factor k (see Table 2)
f_m	frequency at which the maximum spectral density occurs
k	integer included between 1 and $(M + 1)$; the frequency factor corresponding to frequency f_k
k_m	frequency factor corresponding to f_m
ℓ_u	the scale of the turbulence
Δ_t	time interval separating each discrete value y_t from the next
y_t	recorded discrete pressure value at time t, referred to the mean value for that run
$\$$	total boundary-layer thickness
$\$_T$	turbulence thickness
τ	integer included between 1 and $(M + 1)$

SYMBOLS (concluded)

ω	wave number = 2π/wavelength
σ_p	root mean square pressure
q	free stream dynamic pressure

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4	J. Taylor	The energy and pressure spectra of homogeneous isotropic turbulence. RAE Technical Report 66346 (ARC 29097) (1966)
5	J. Taylor	Kinetic heating of aircraft structures. 15 Mitchell Memorial Lecture of the RAeS February 1968
6	D.B. Spalding	A new analytical expression for the drag of a flat plate valid for both the turbulent and laminar regimes. Int. J. of heat and mass transfer, Vol.5 (1962)

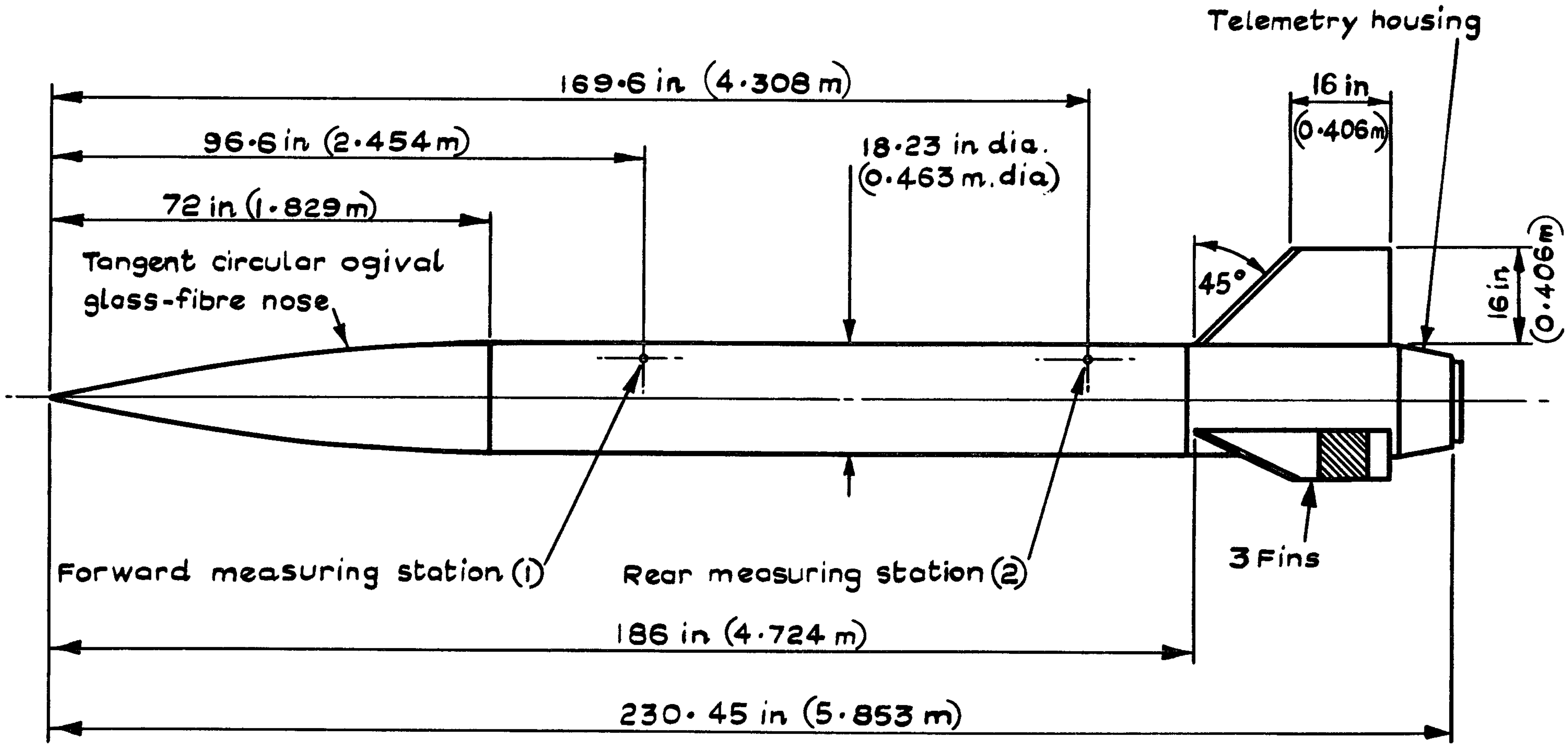


Fig. 1 General arrangement drawing of 'Shark 3'

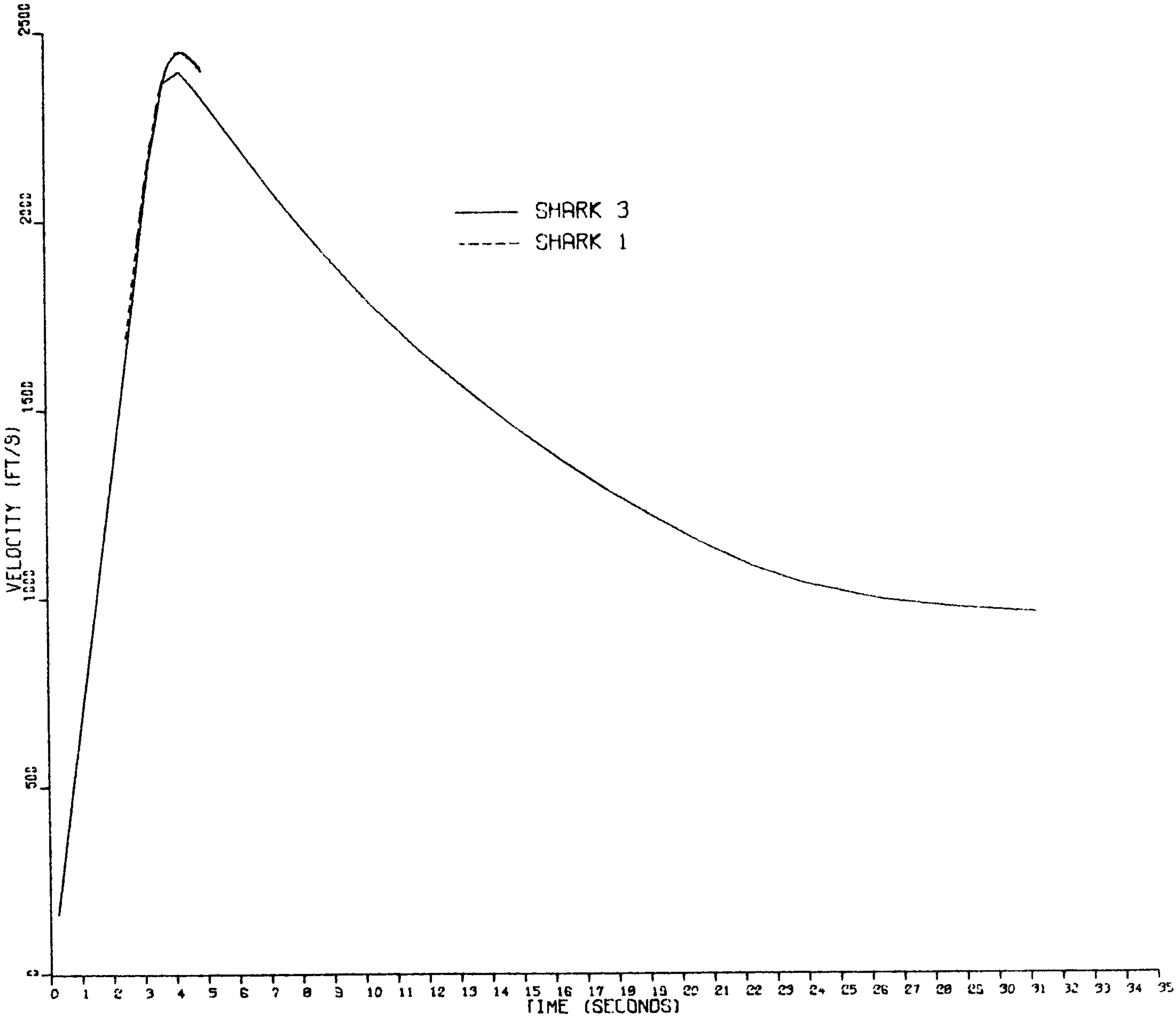


Fig.2 Plot of vehicle velocity / time

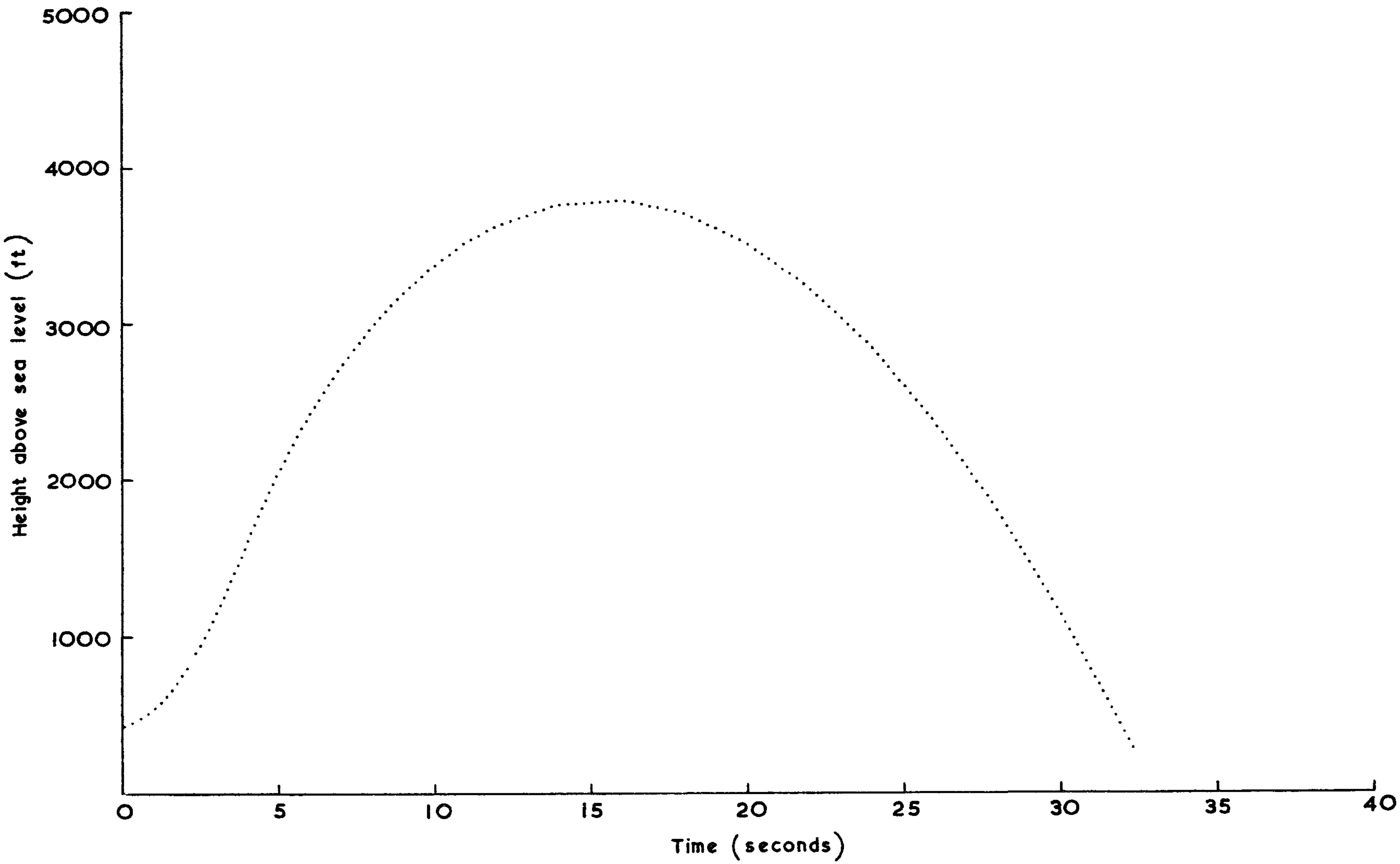


Fig. 3 Plot of vehicle height above sea level / time

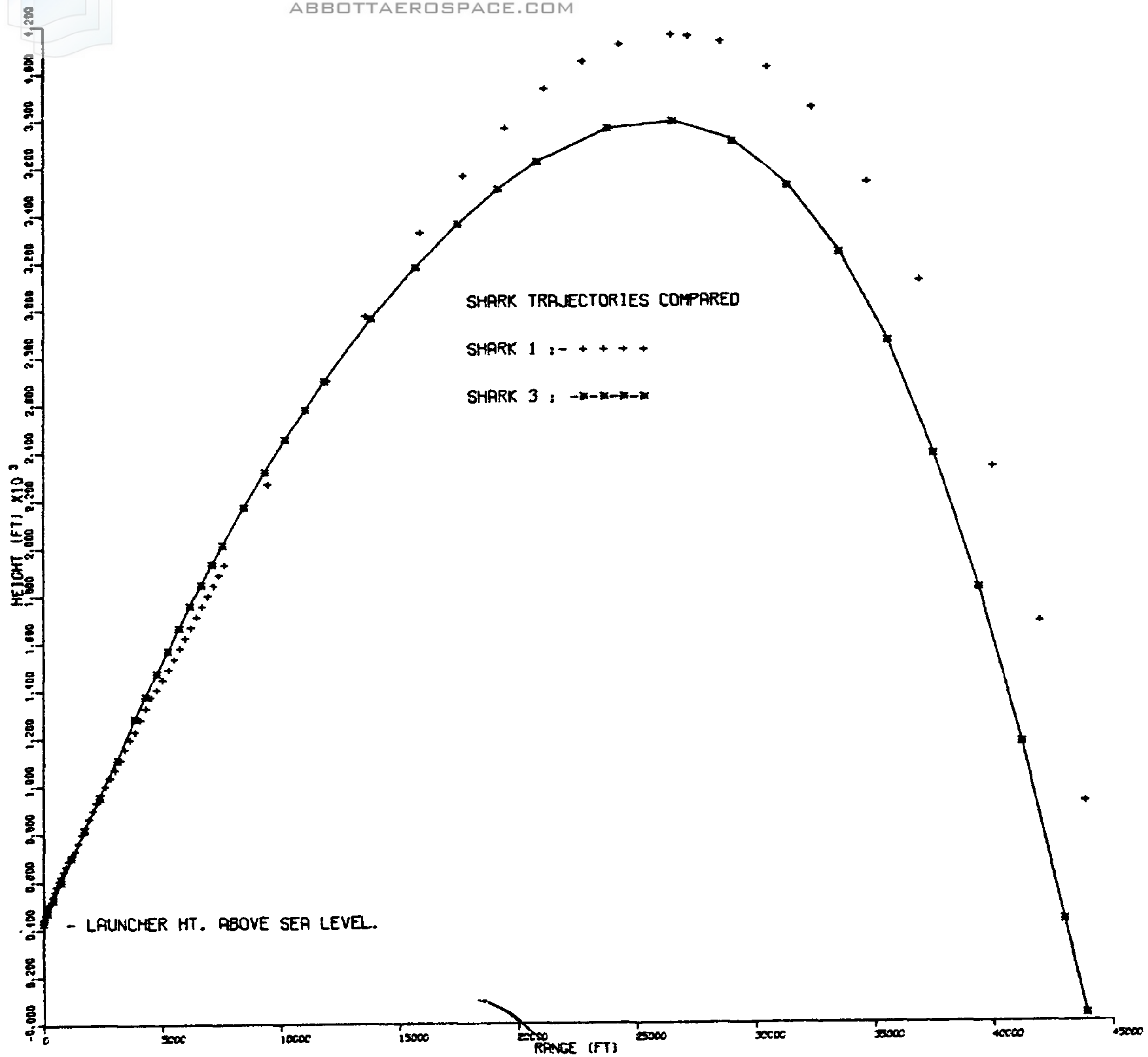


Fig. 4 Plot of vehicle height above sea level / range

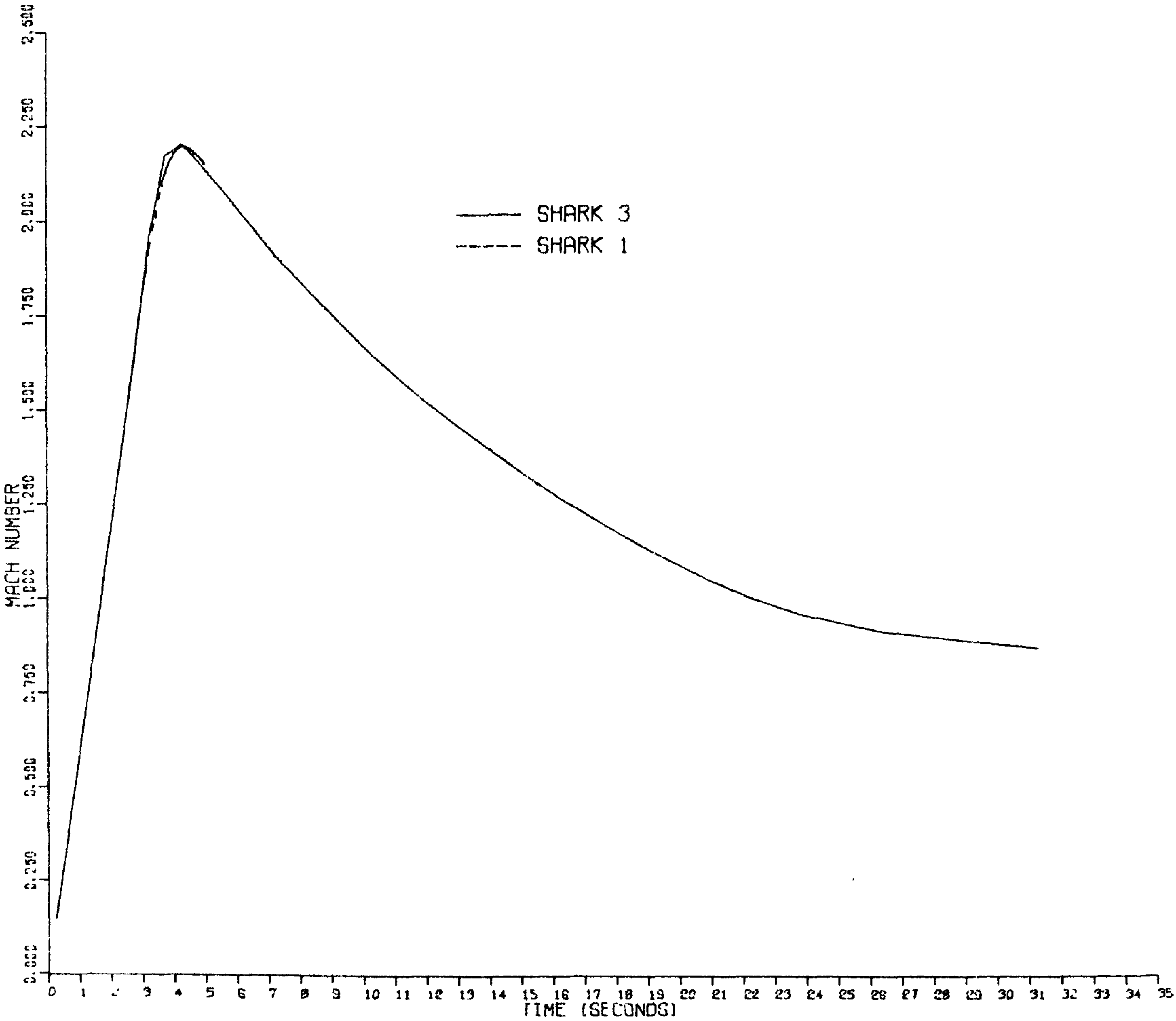


Fig. 5 Plot of Mach No / time

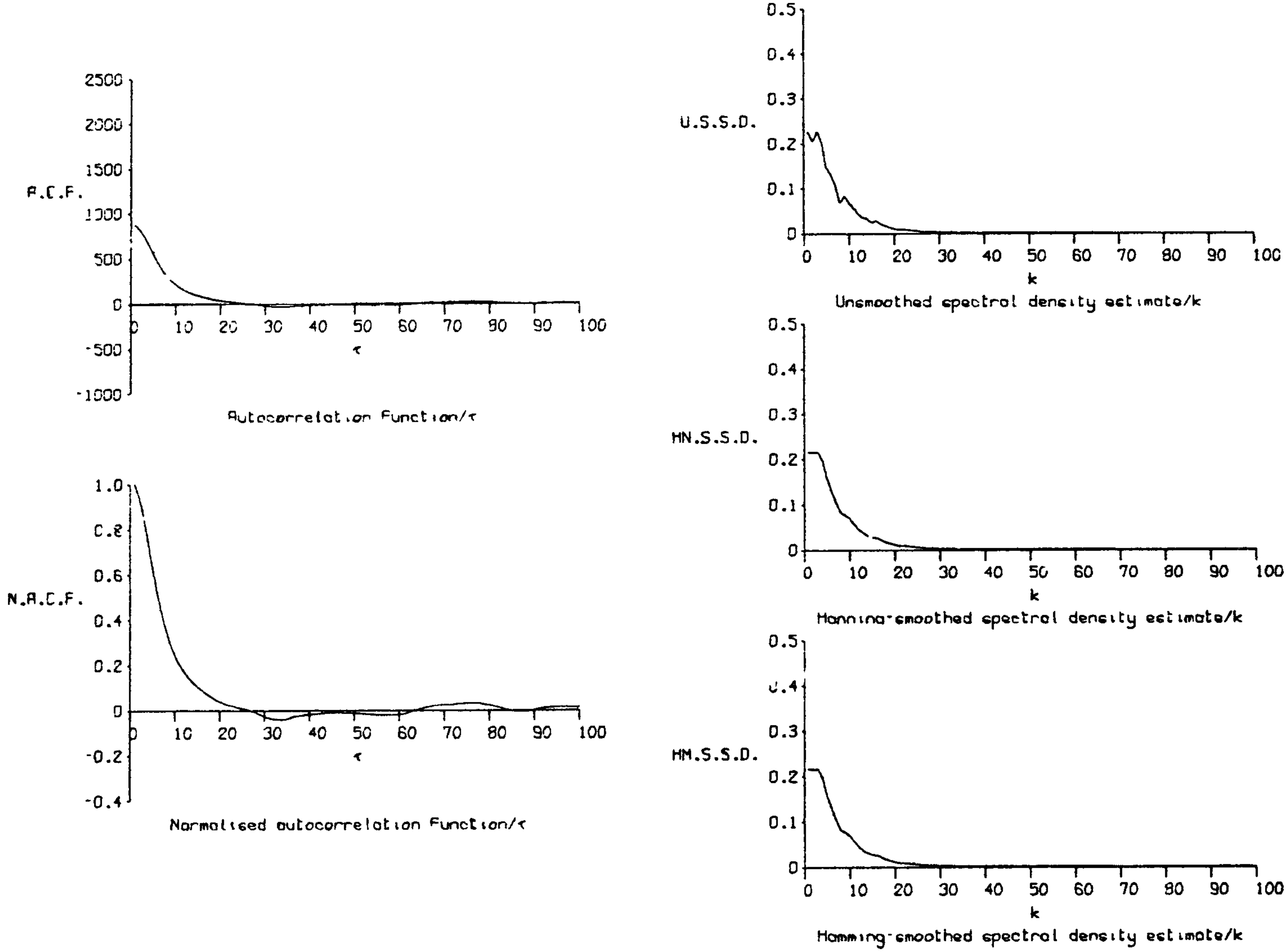


Fig. 6.1 Shark 3. Run O. Forward station

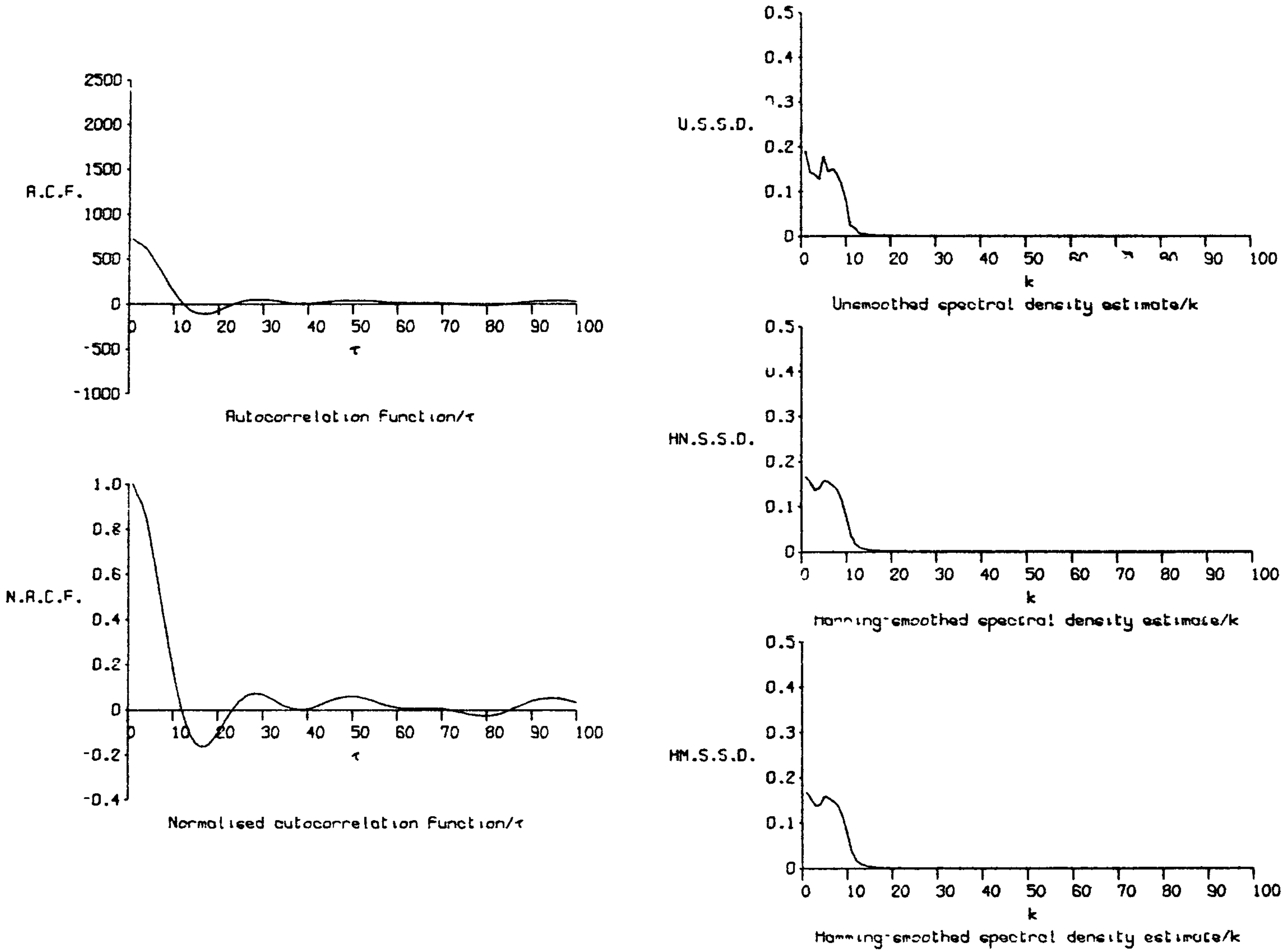


Fig.6.2 Shark 3. Run 5. Forward station

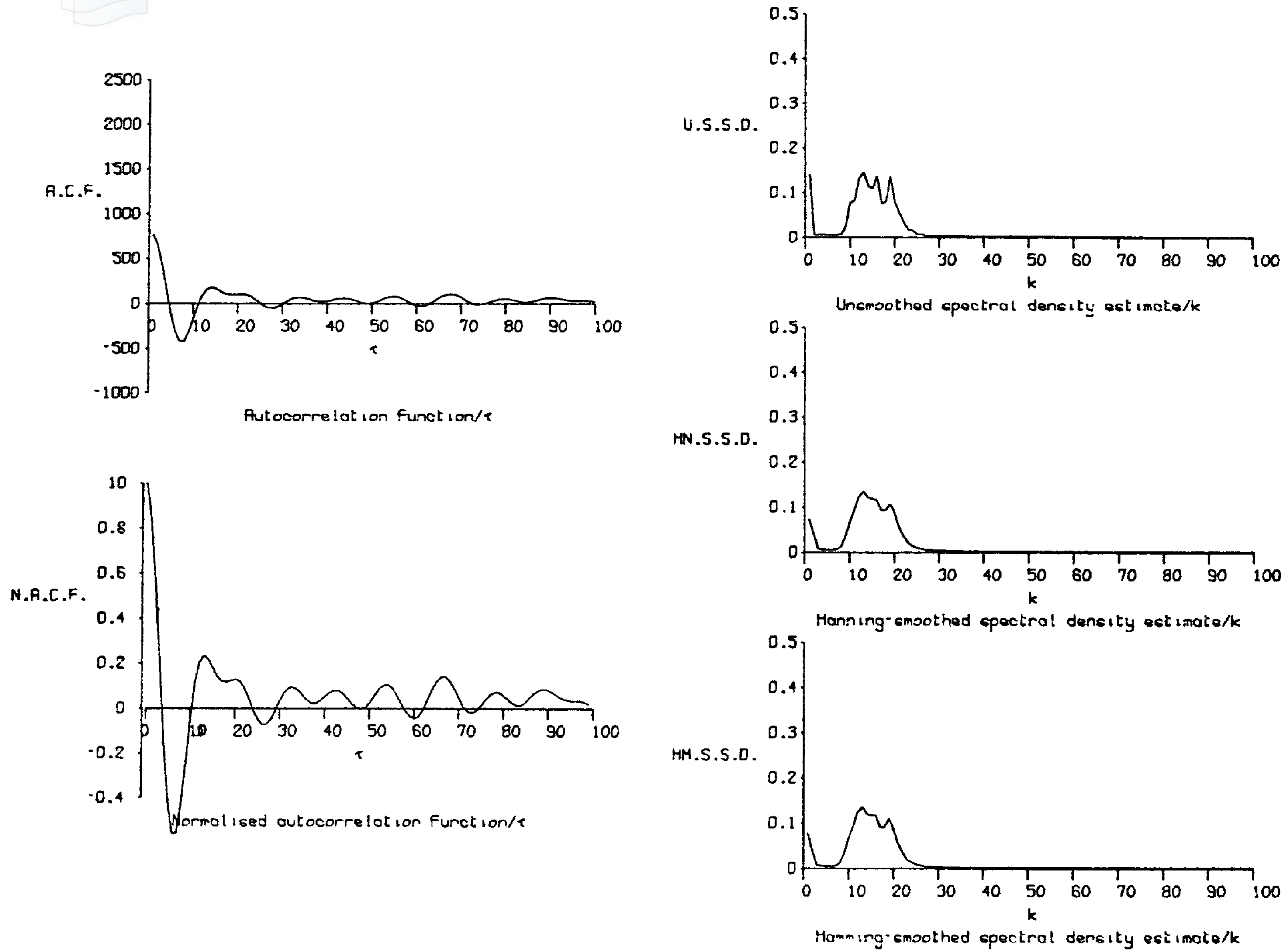


Fig. 6.3 Shark 3. Run 10. Forward station

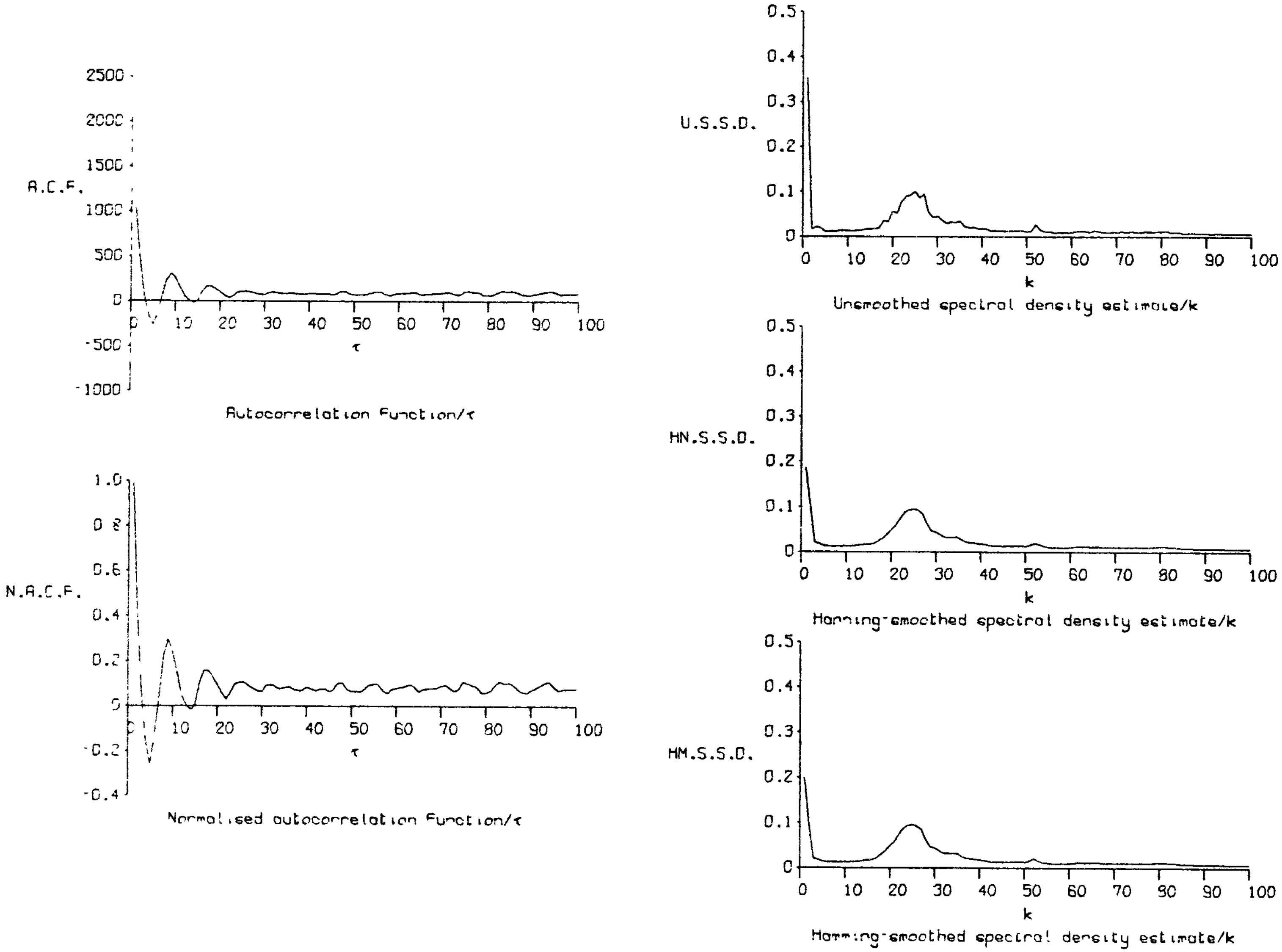


Fig. 6. 4 Shark 3. Run 15. Forward station

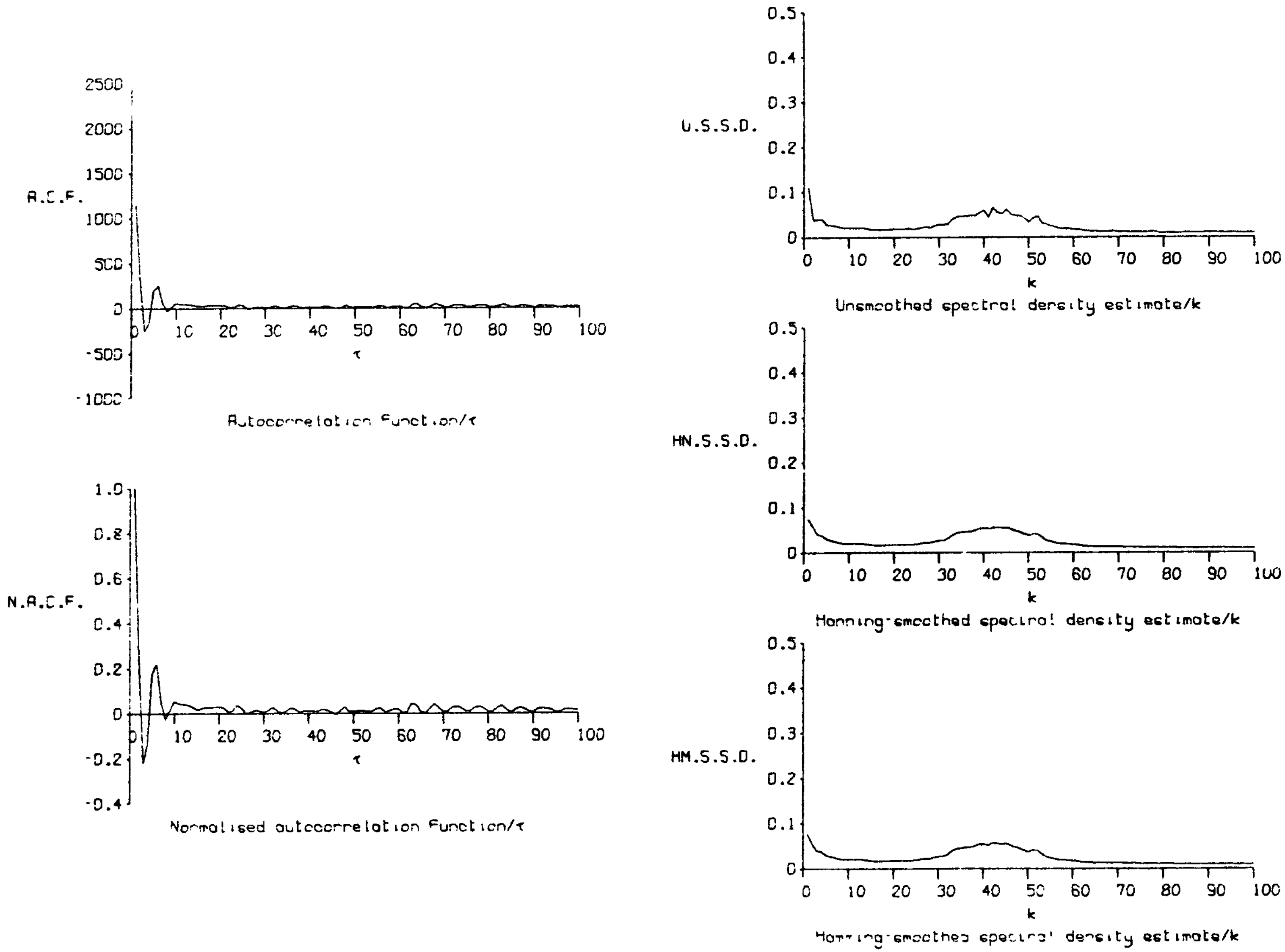


Fig.6.5 Shark 3. Run 20. Forward station

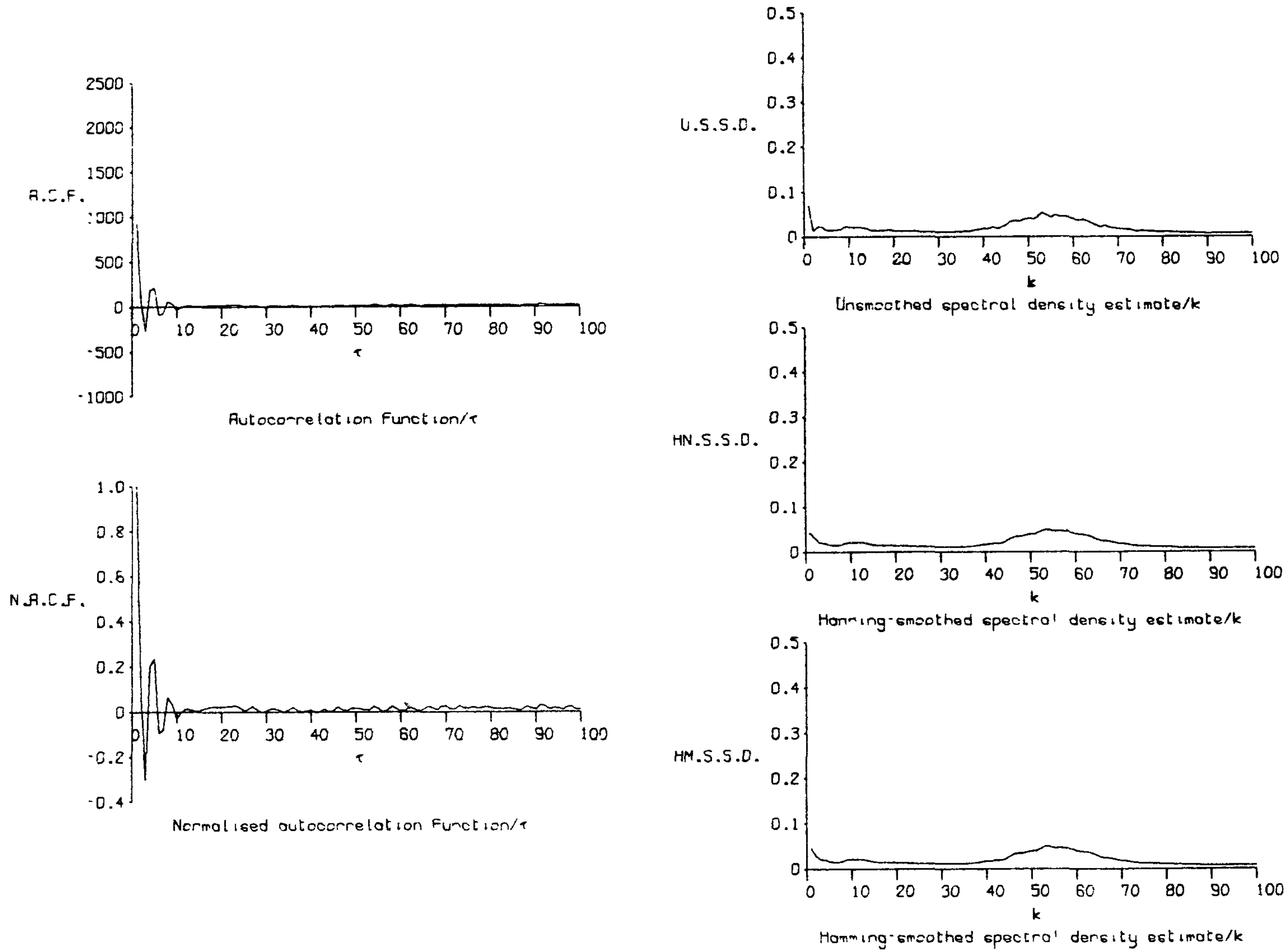


Fig. 6.6 Shark 3. Run 25. Forward station

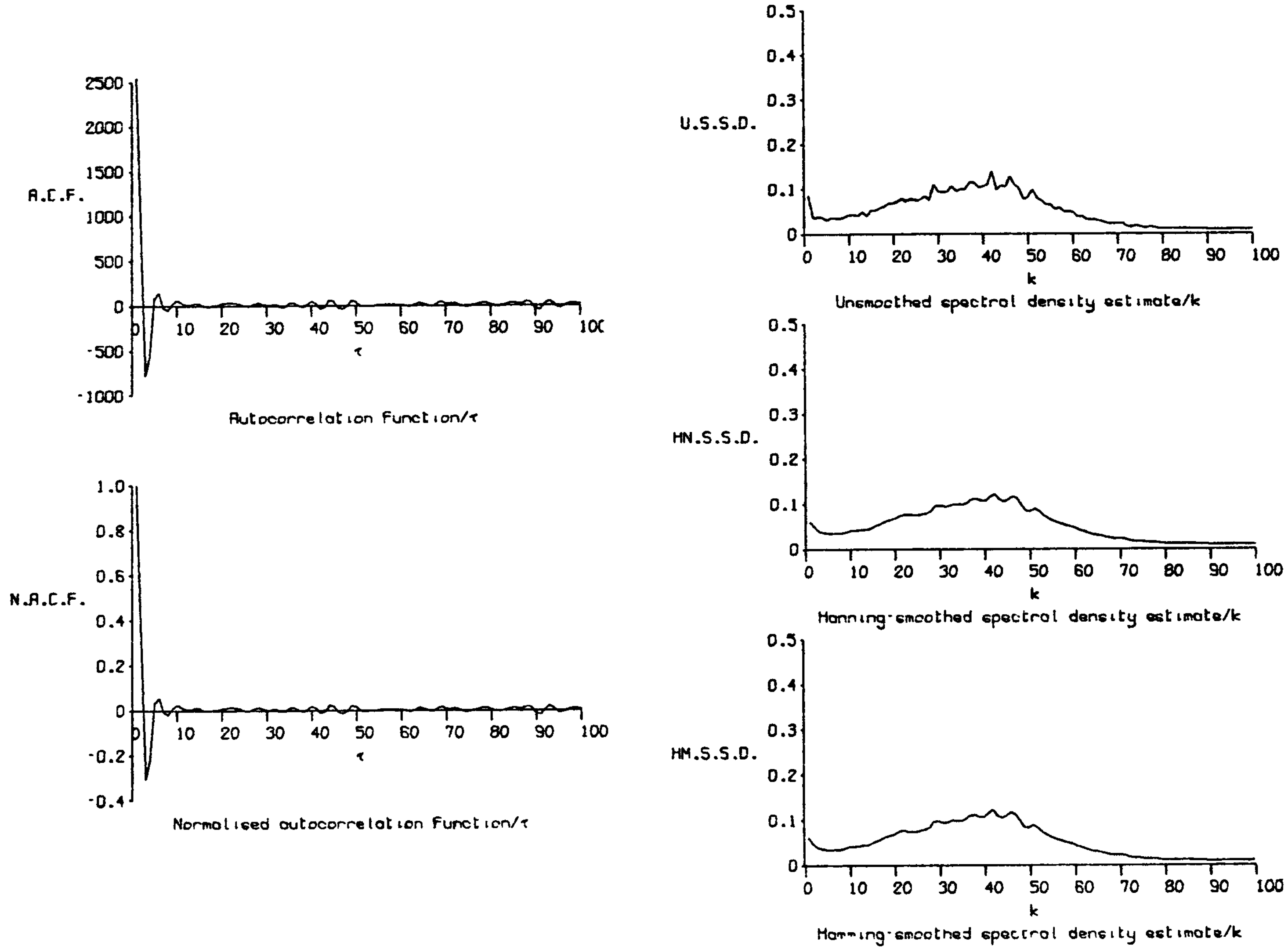


Fig. 6.9 Shark 3. Run 40 Forward station

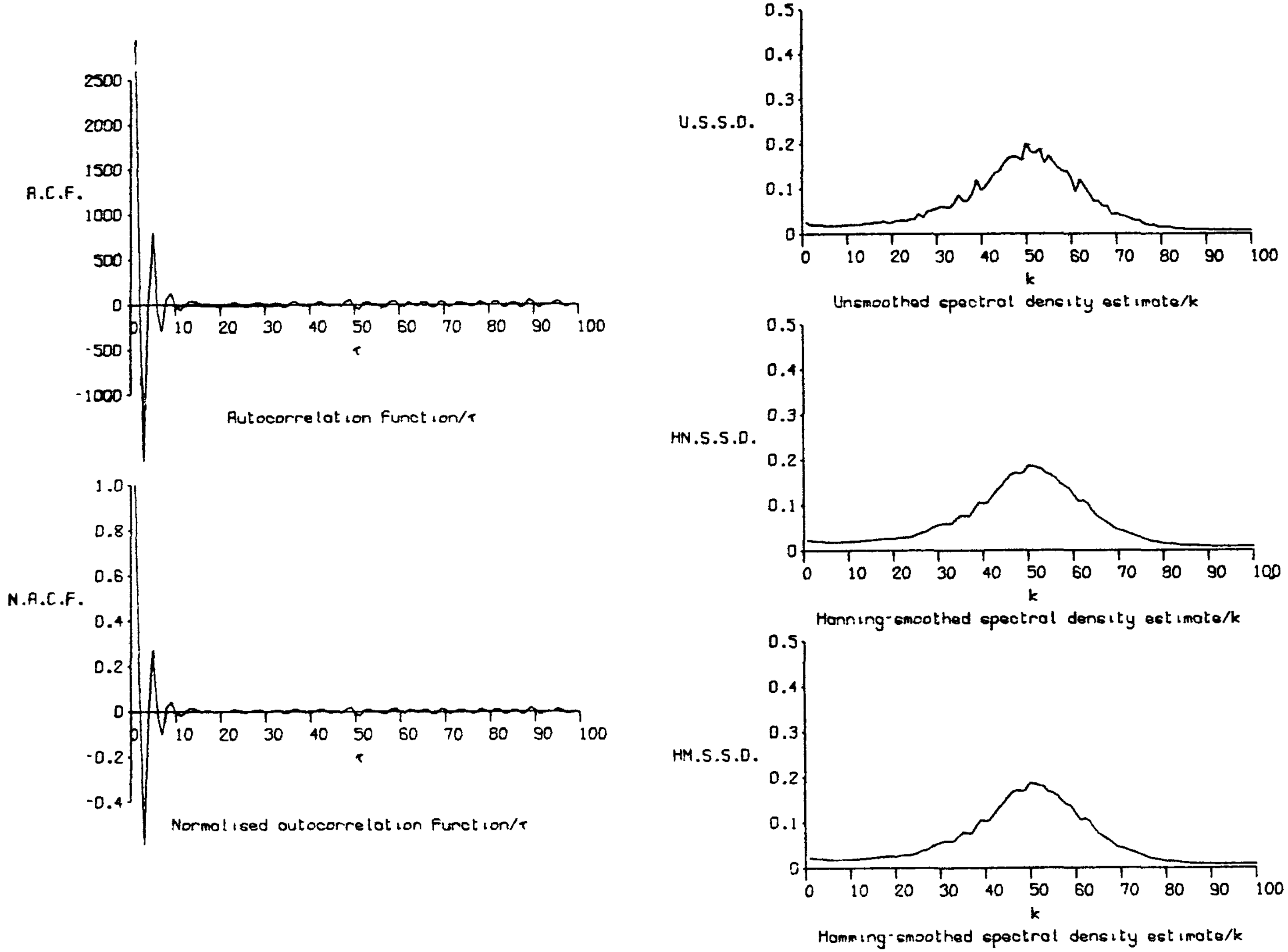


Fig. 6.10 Shark 3. Run 45. Forward station

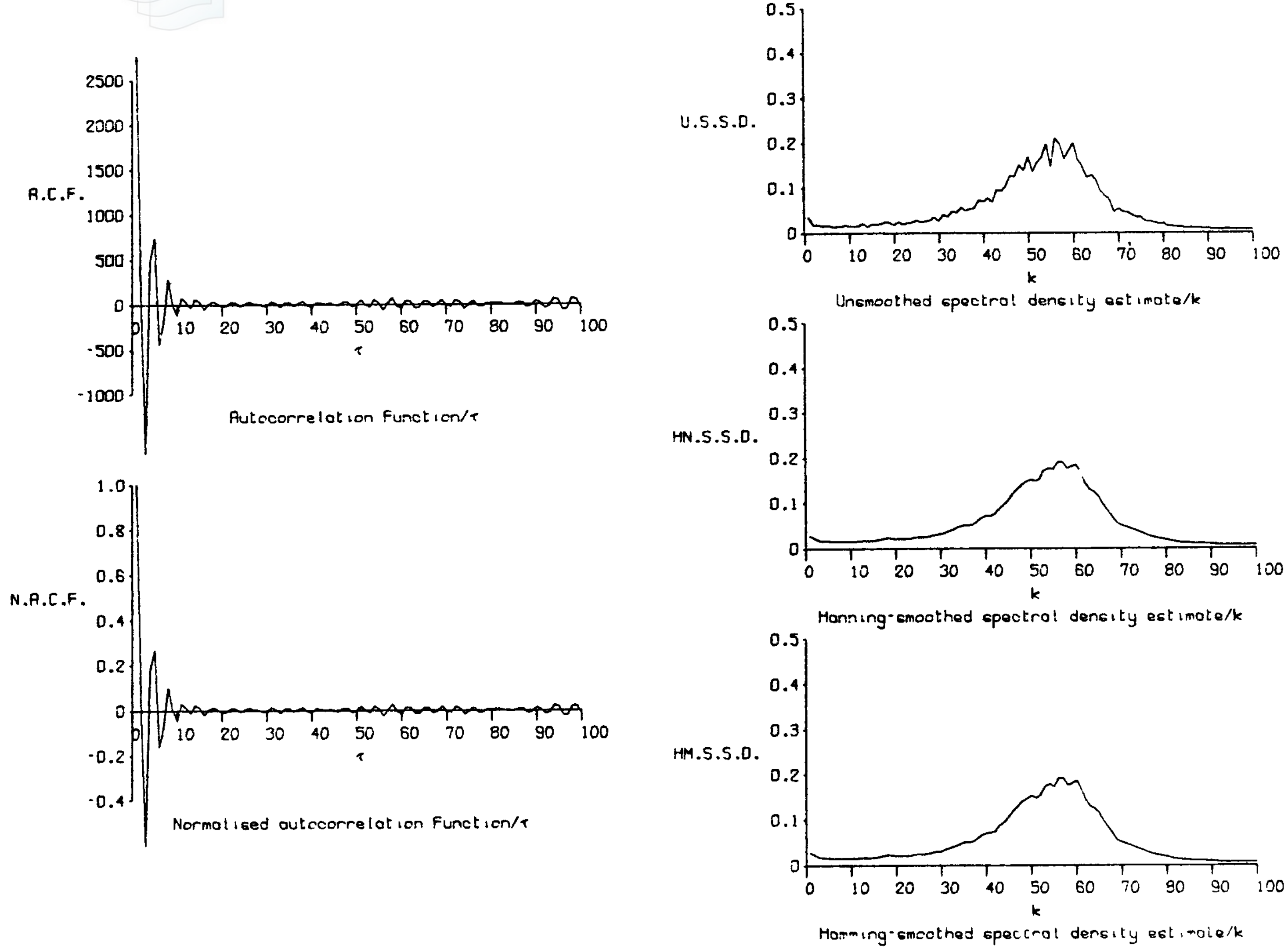


Fig. 6.11 Shark 3. Run 50. Forward station

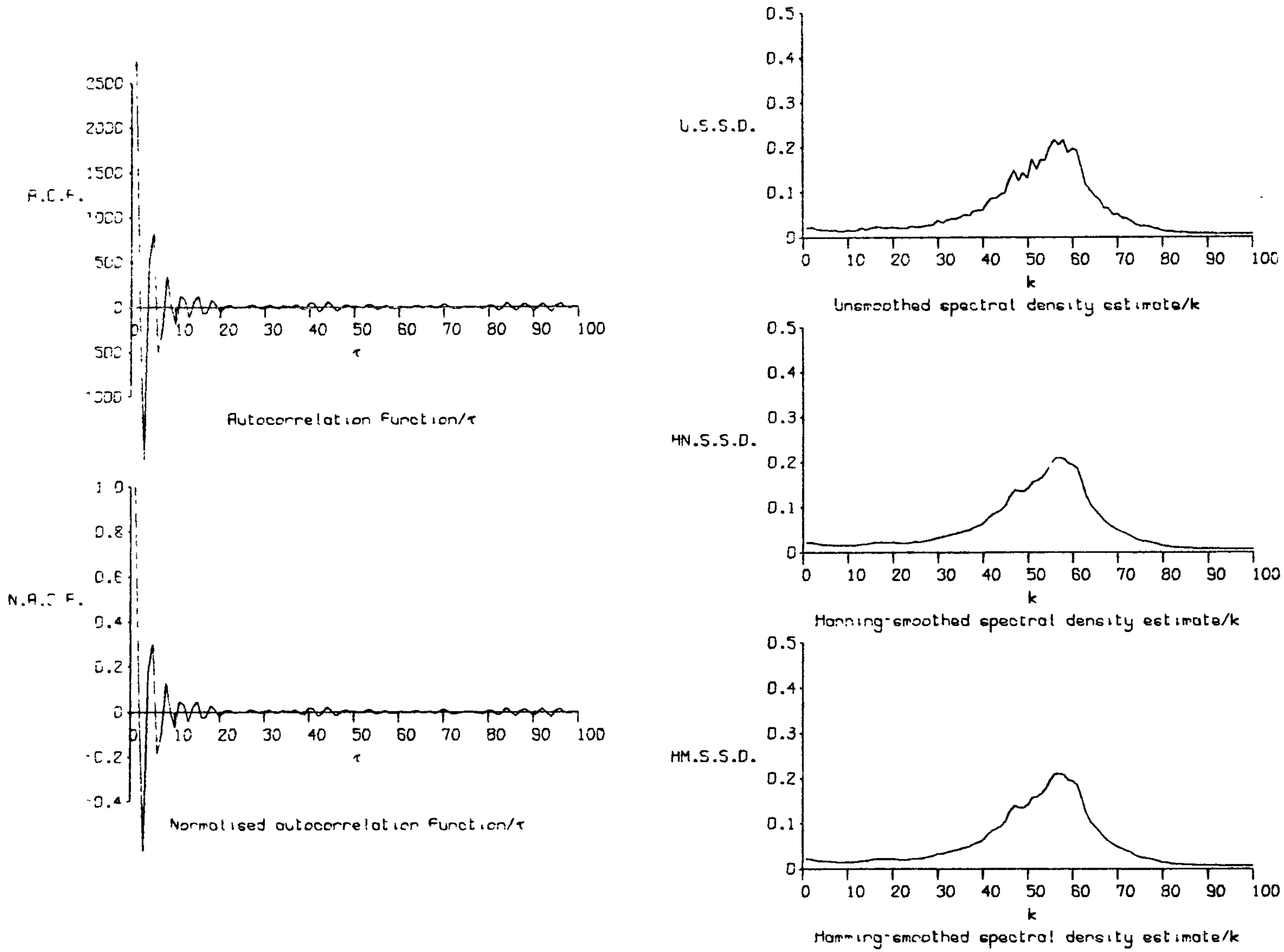


Fig. 6.12 Shark 3. Run 55. Forward station

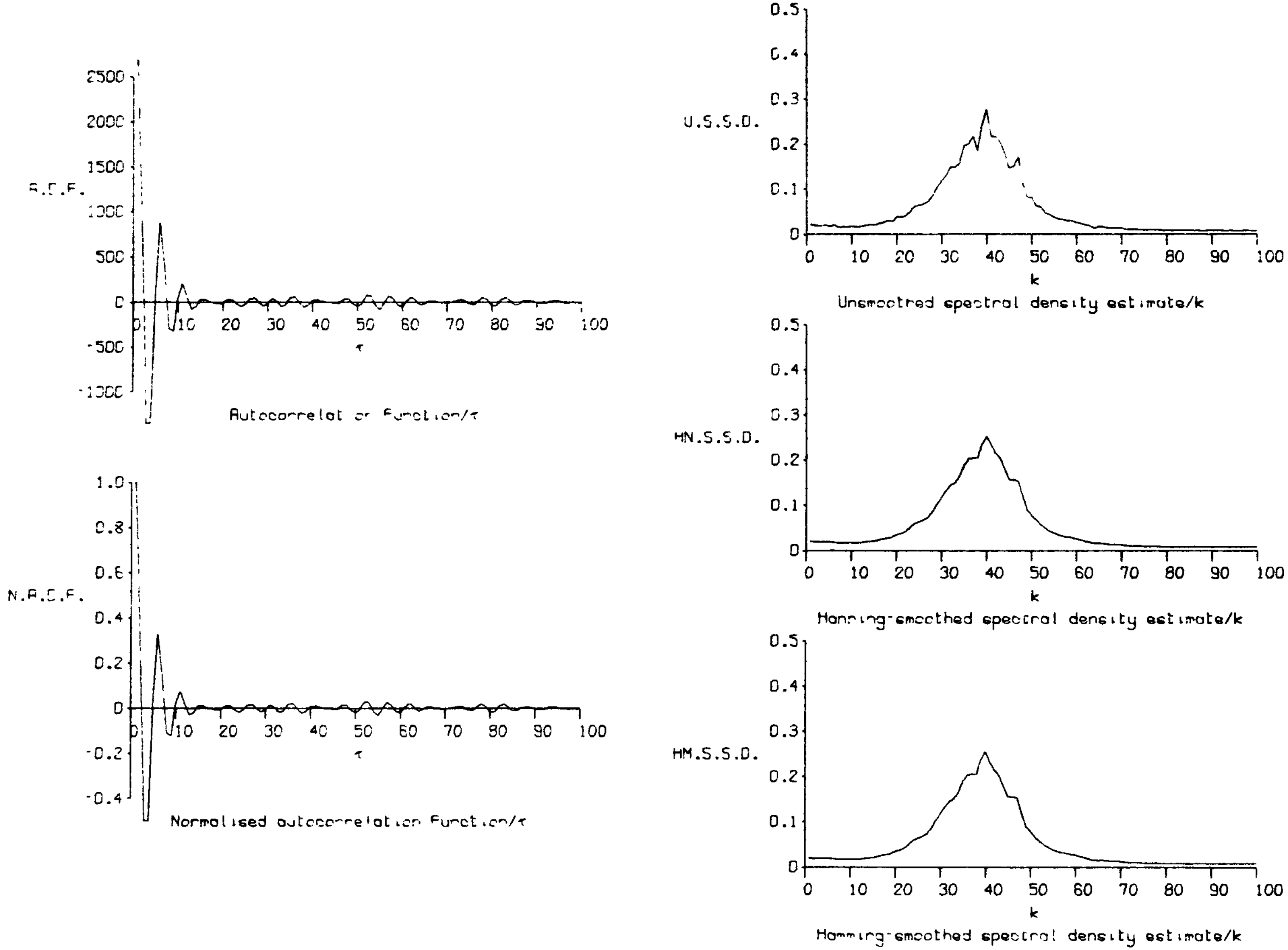


Fig. 6. 13 Shark 3. Run 70. Forward station

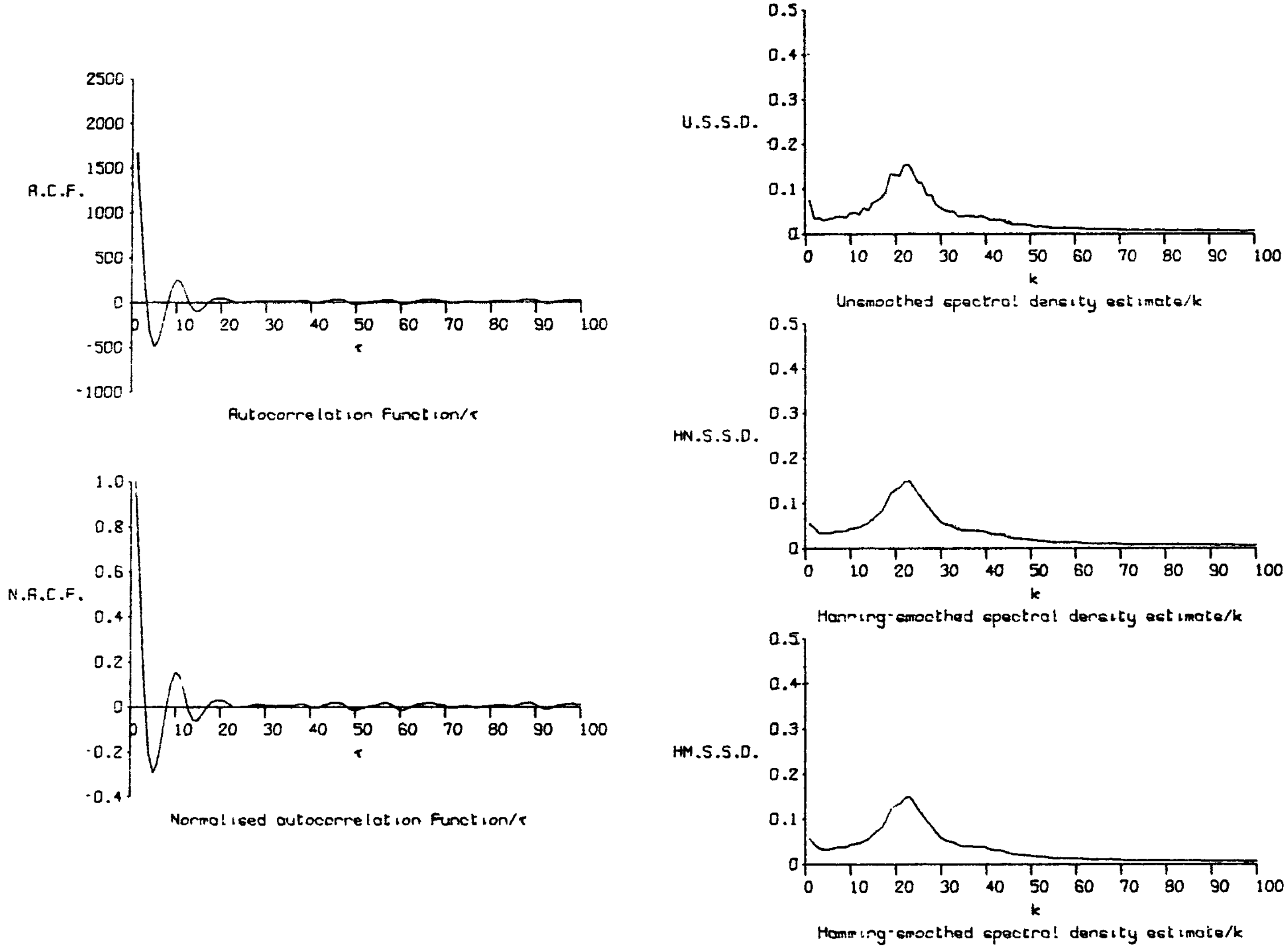


Fig. 6.14 Shark 3. Run 85. Forward station

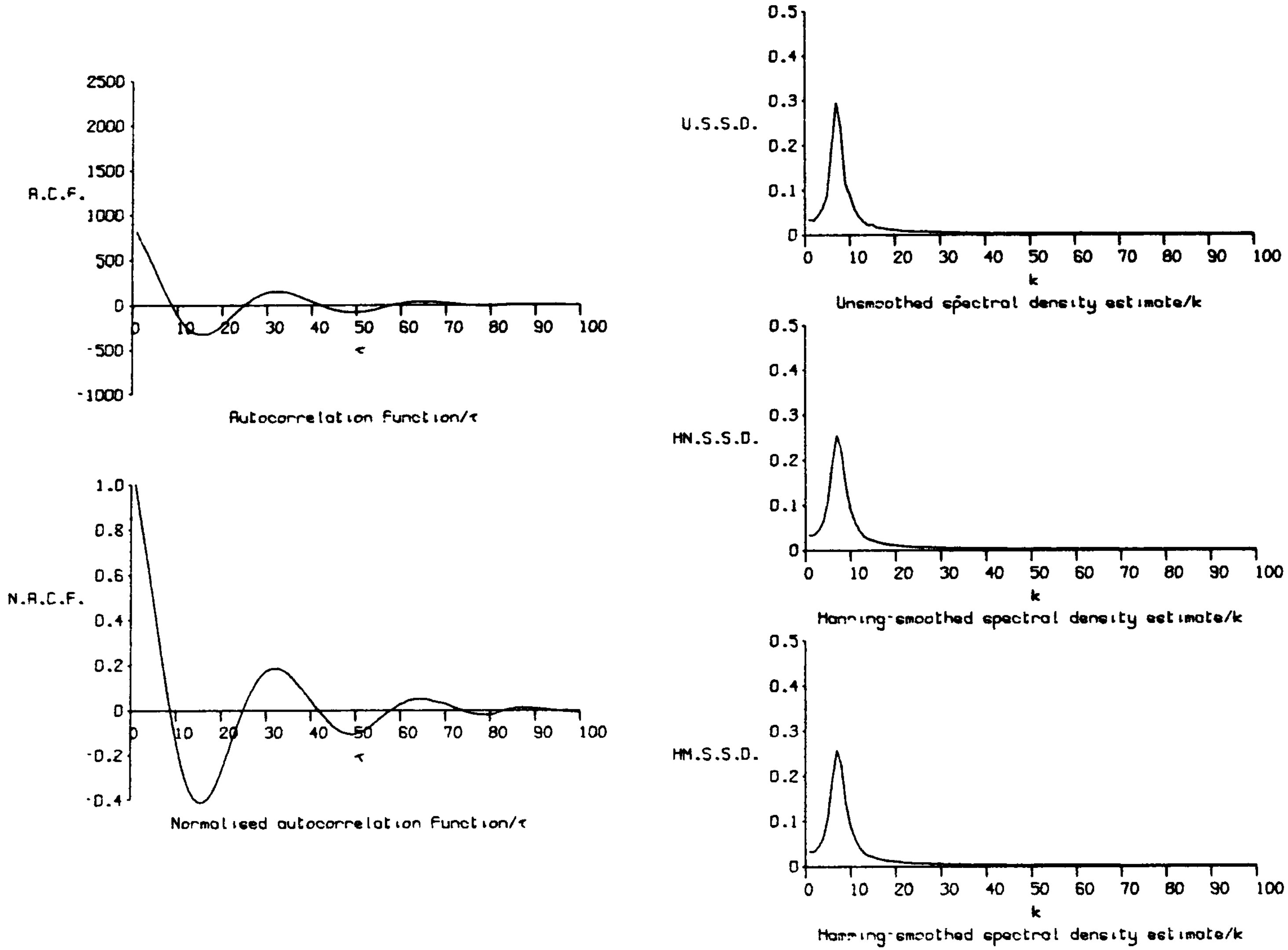


Fig.6.19 Shark 3. Run 160. Forward station

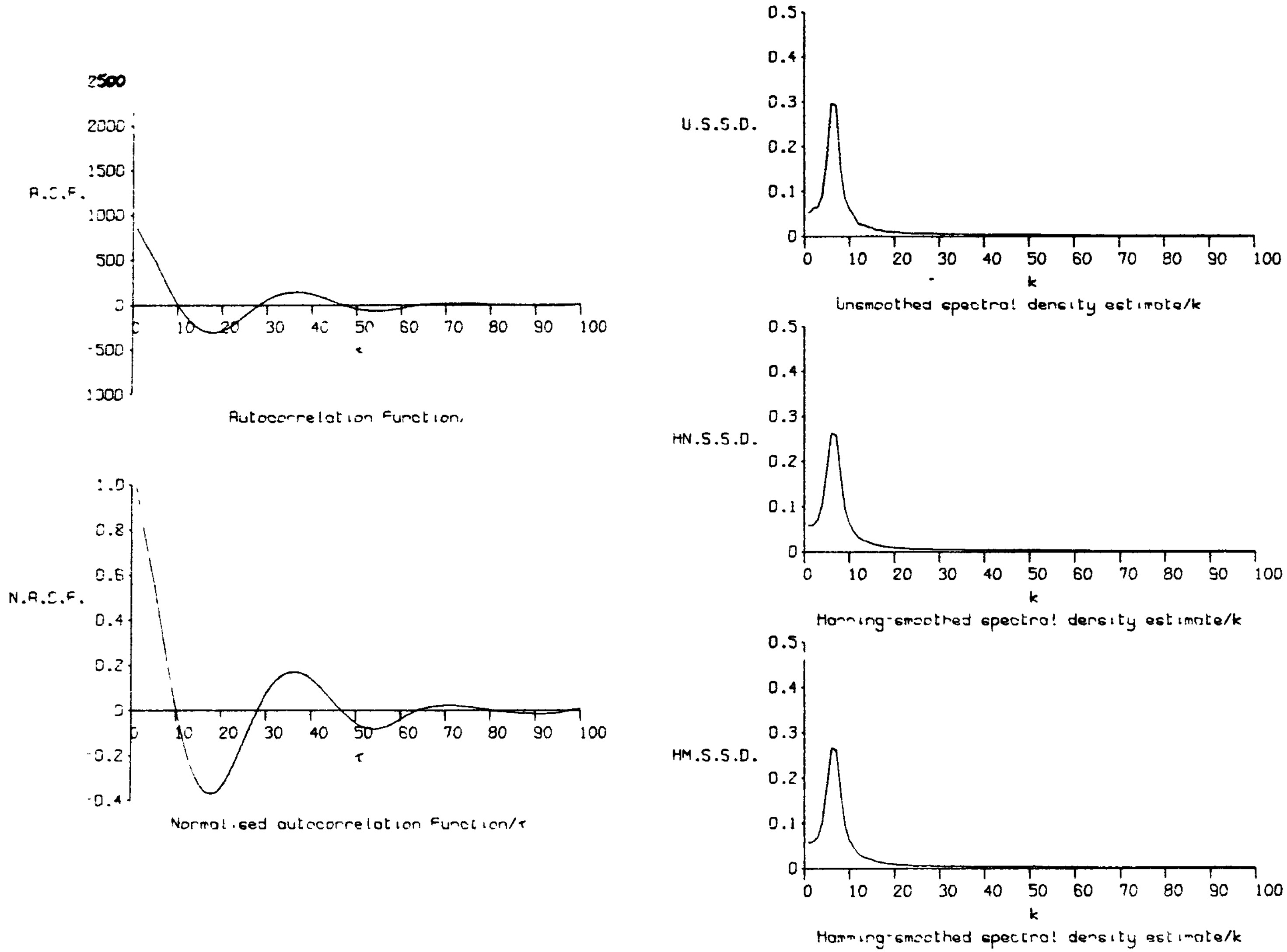


Fig. 6. 20 Shark 3. Run 175. Forward station

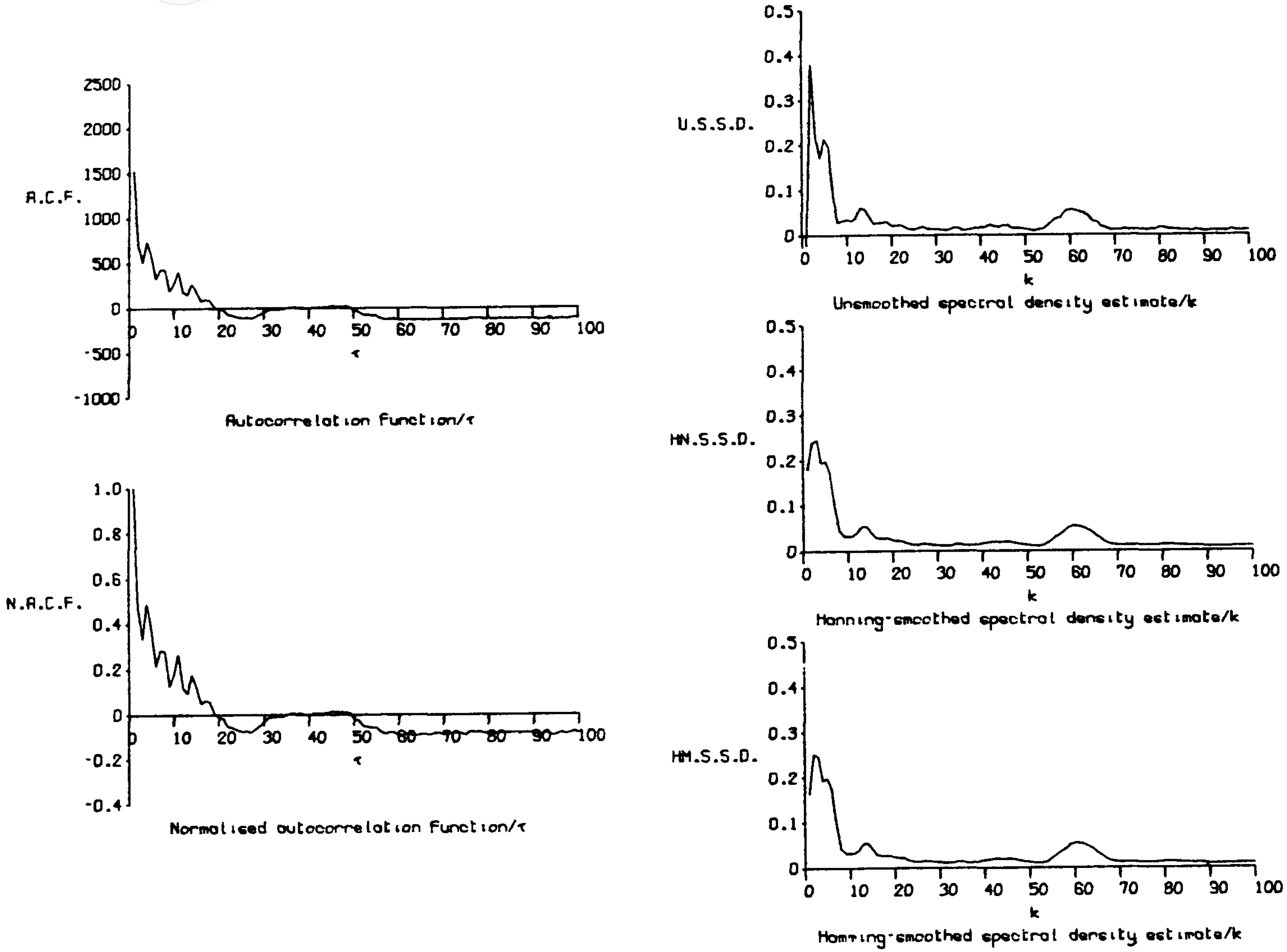


Fig. 6.27 Shark 3. Run 310. Forward station

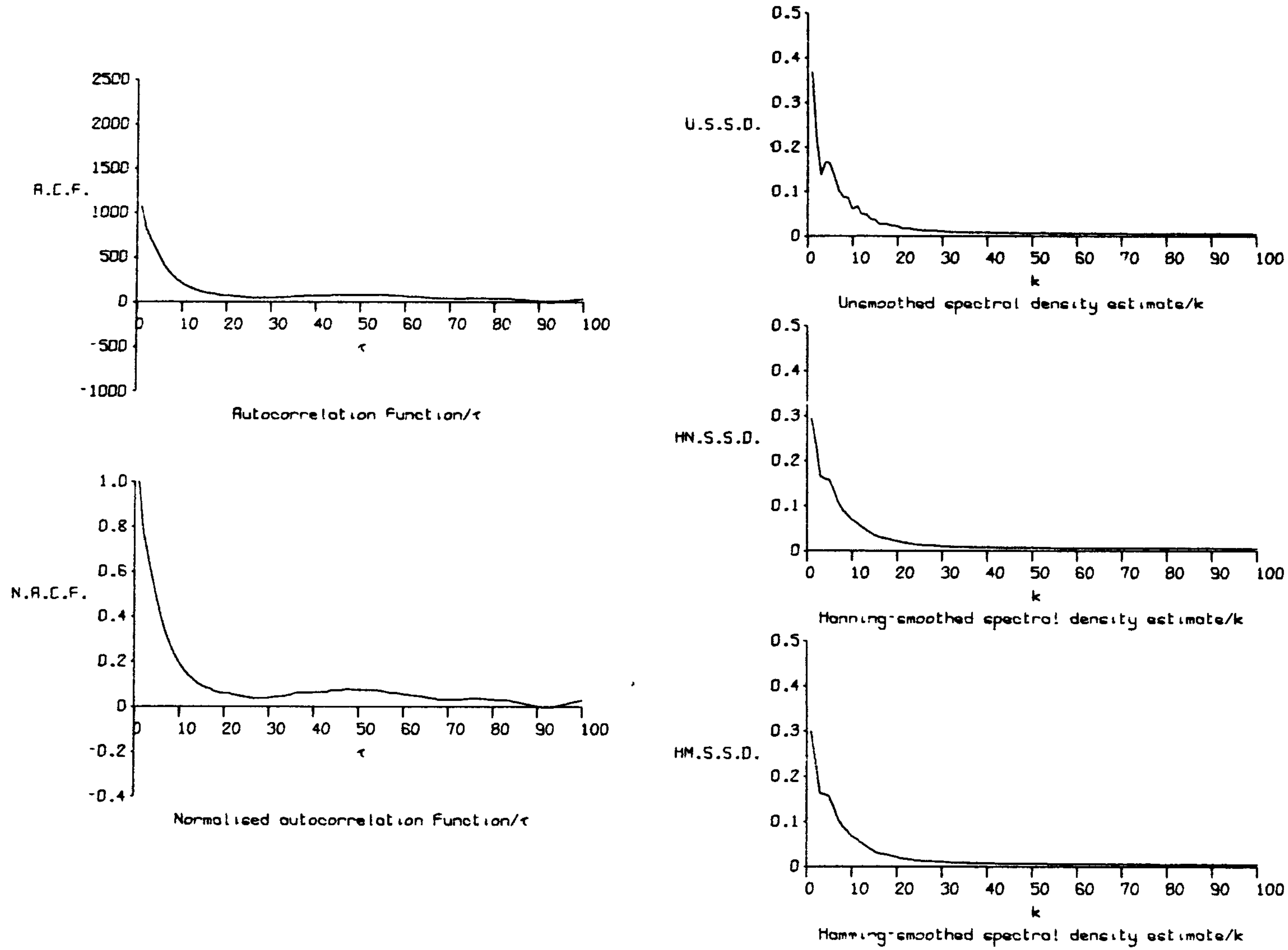


Fig. 6.28 Shark 3. Run O. Rear station

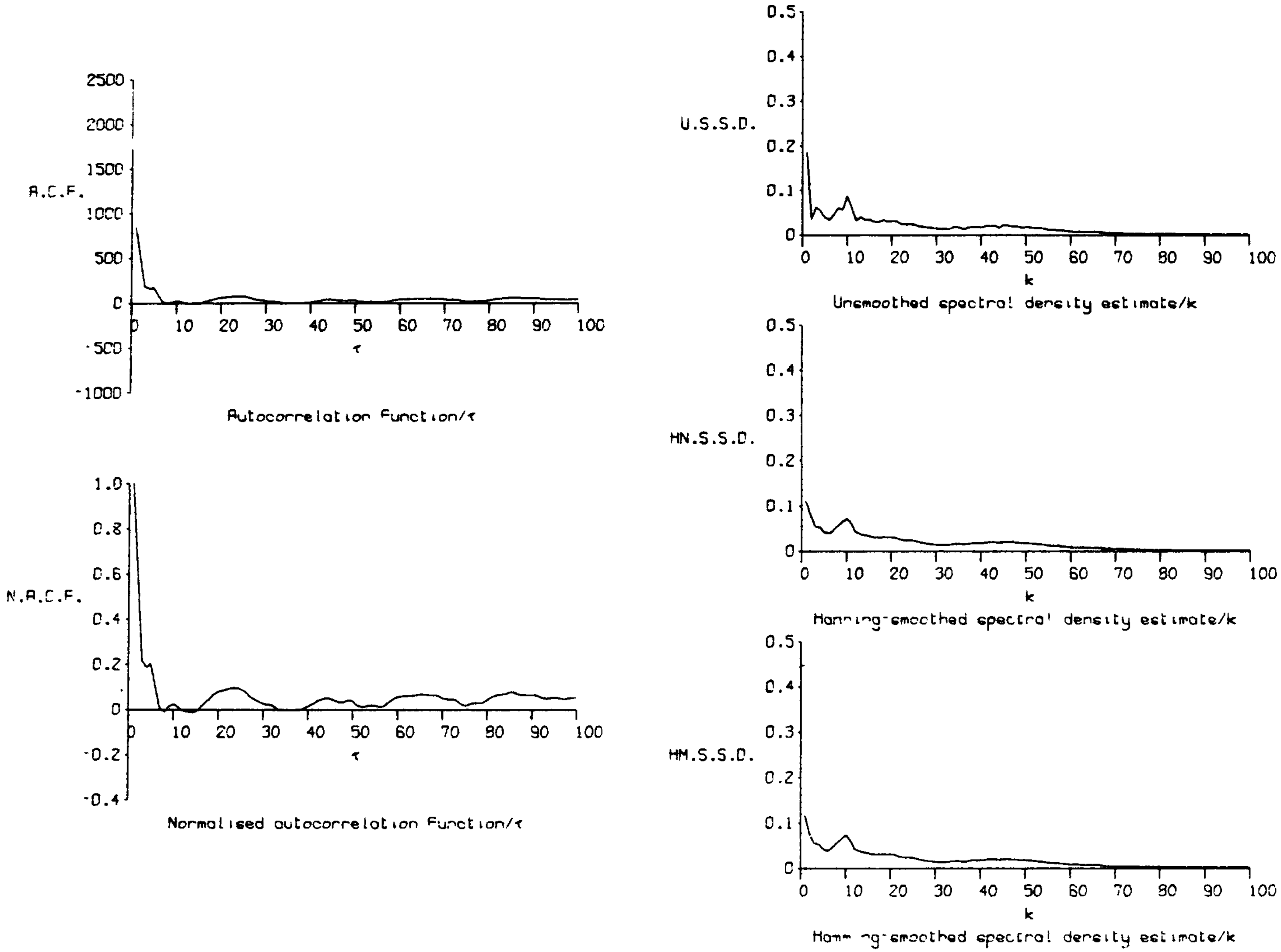


Fig. 6. 33 Shark 3. Run 25. Rear station

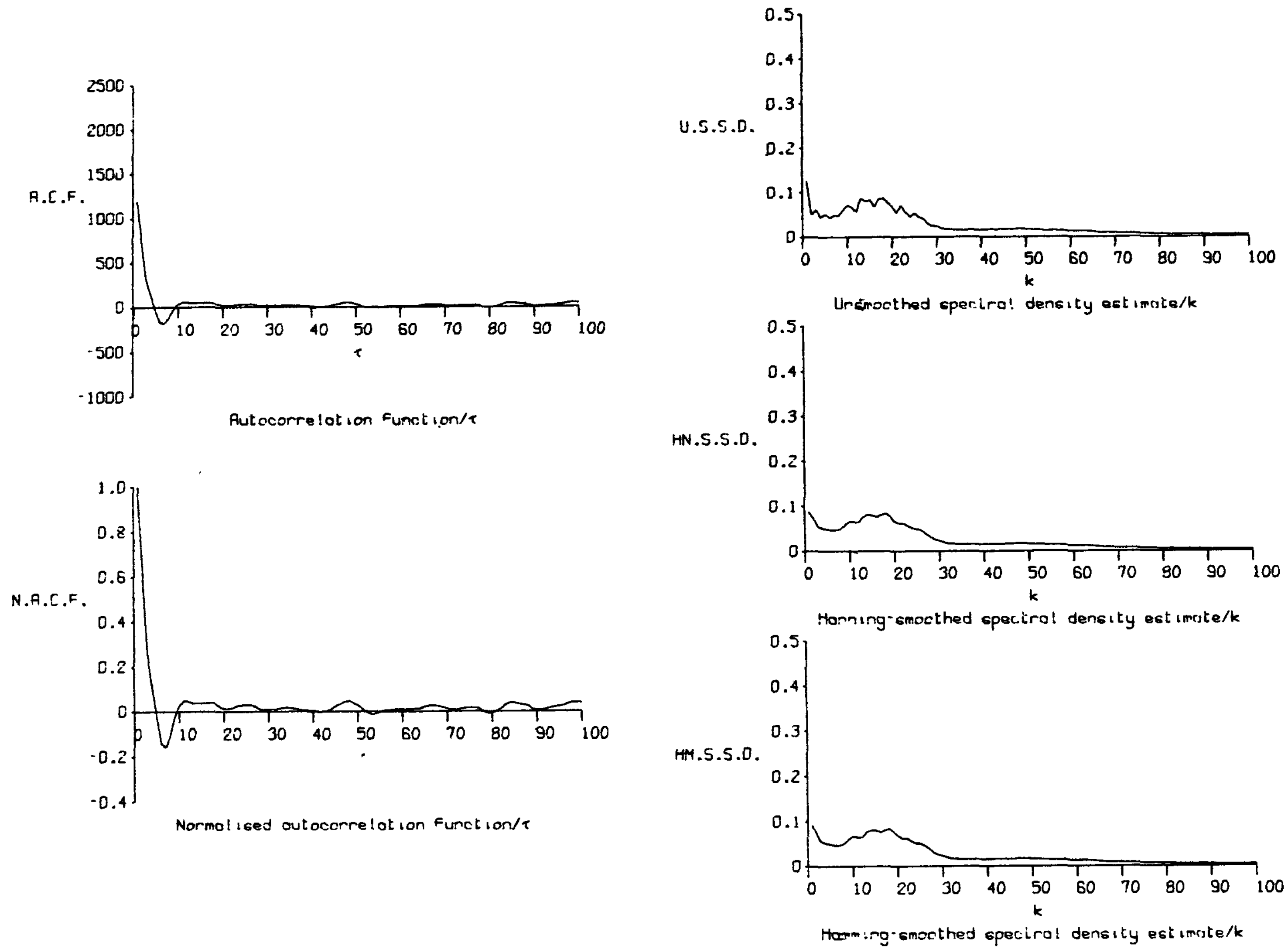


Fig. 6. 34 Shark 3. Run 30. Rear station

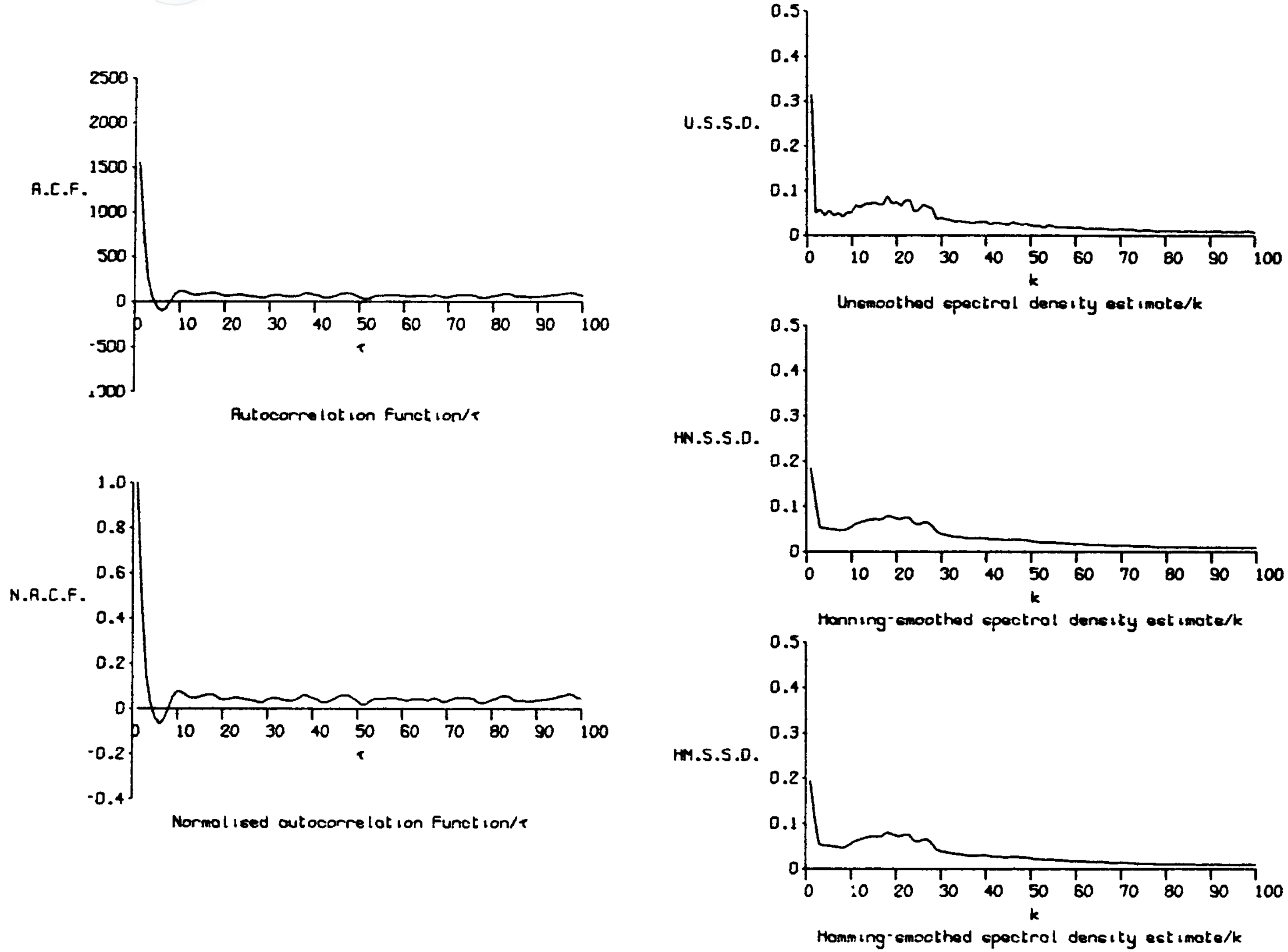


Fig. 6. 35 Shark 3. Run 35. Rear station

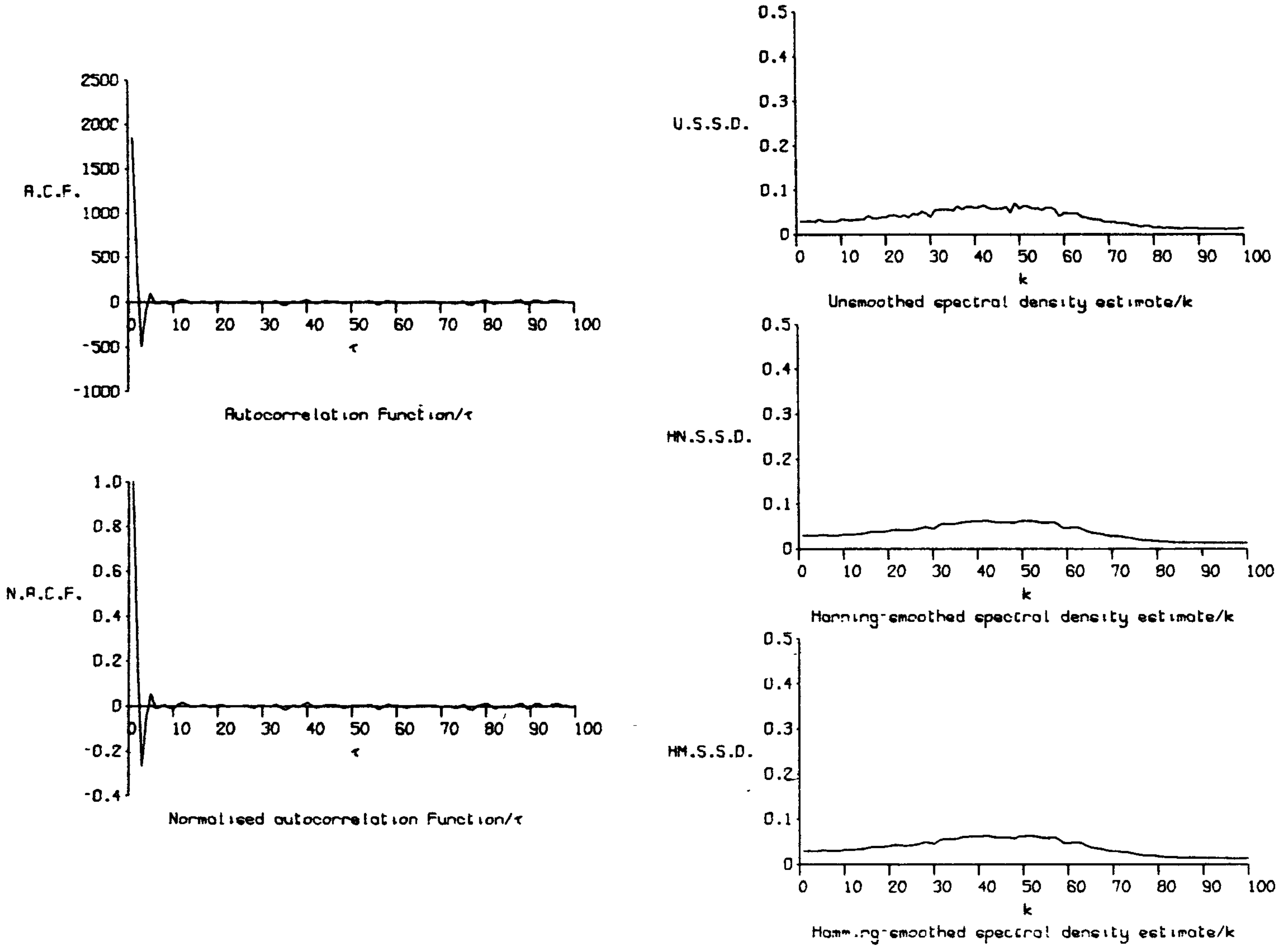


Fig. 6. 36 Shark 3. Run 40. Rear station

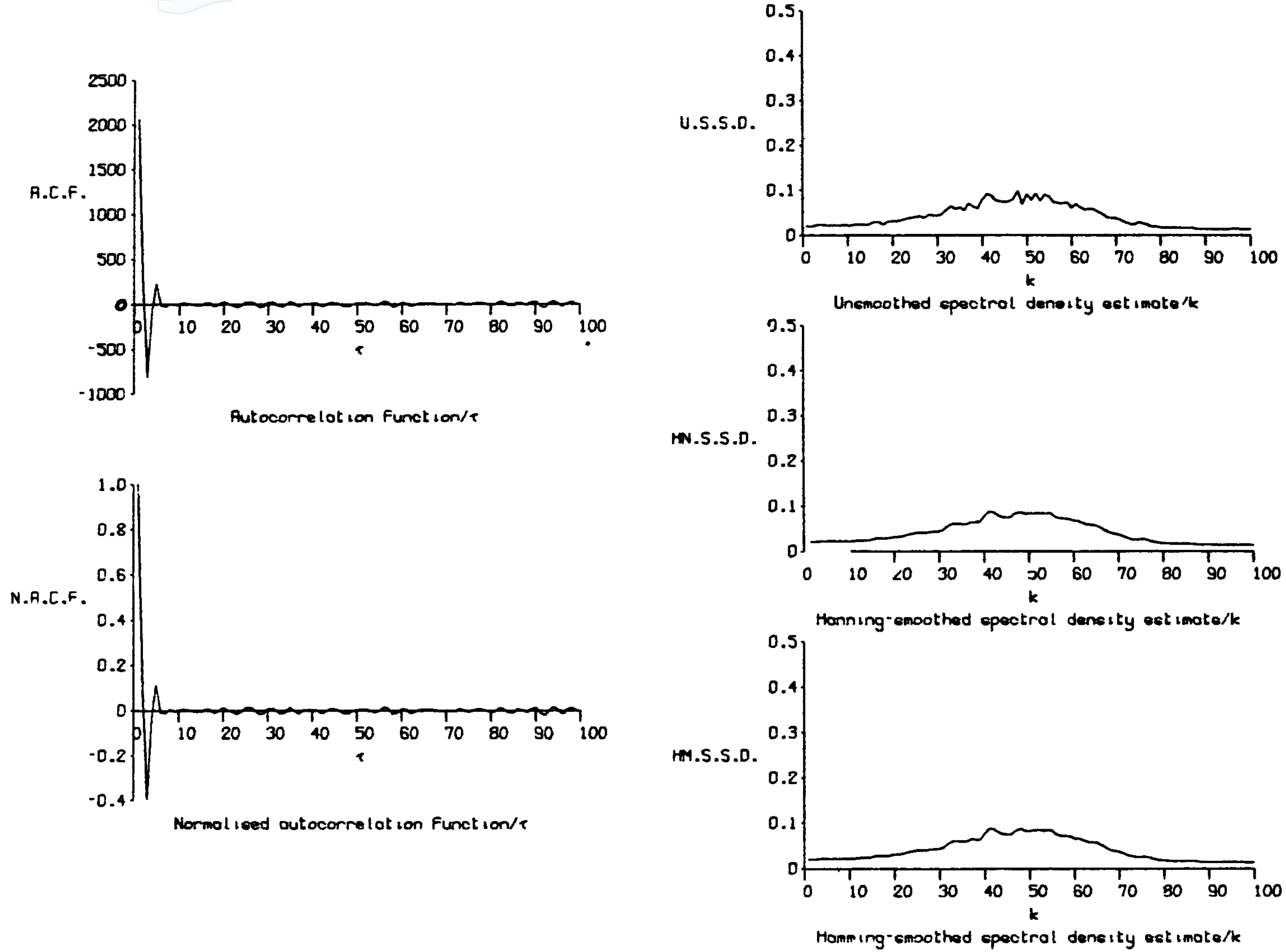


Fig. 6.37 Shark 3. Run 45. Rear station

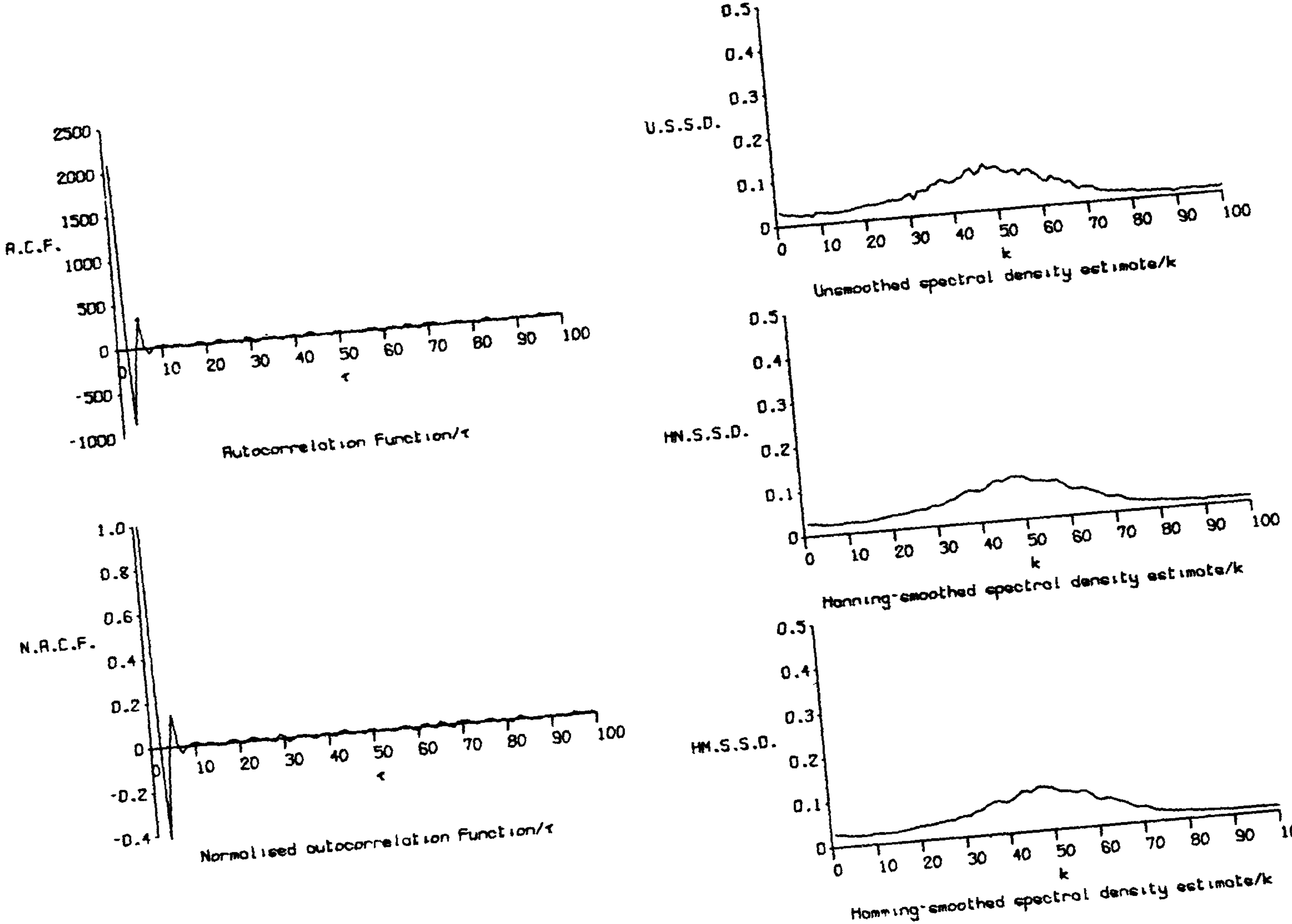


Fig. 6.38 Shark 3. Run 50. Rear station

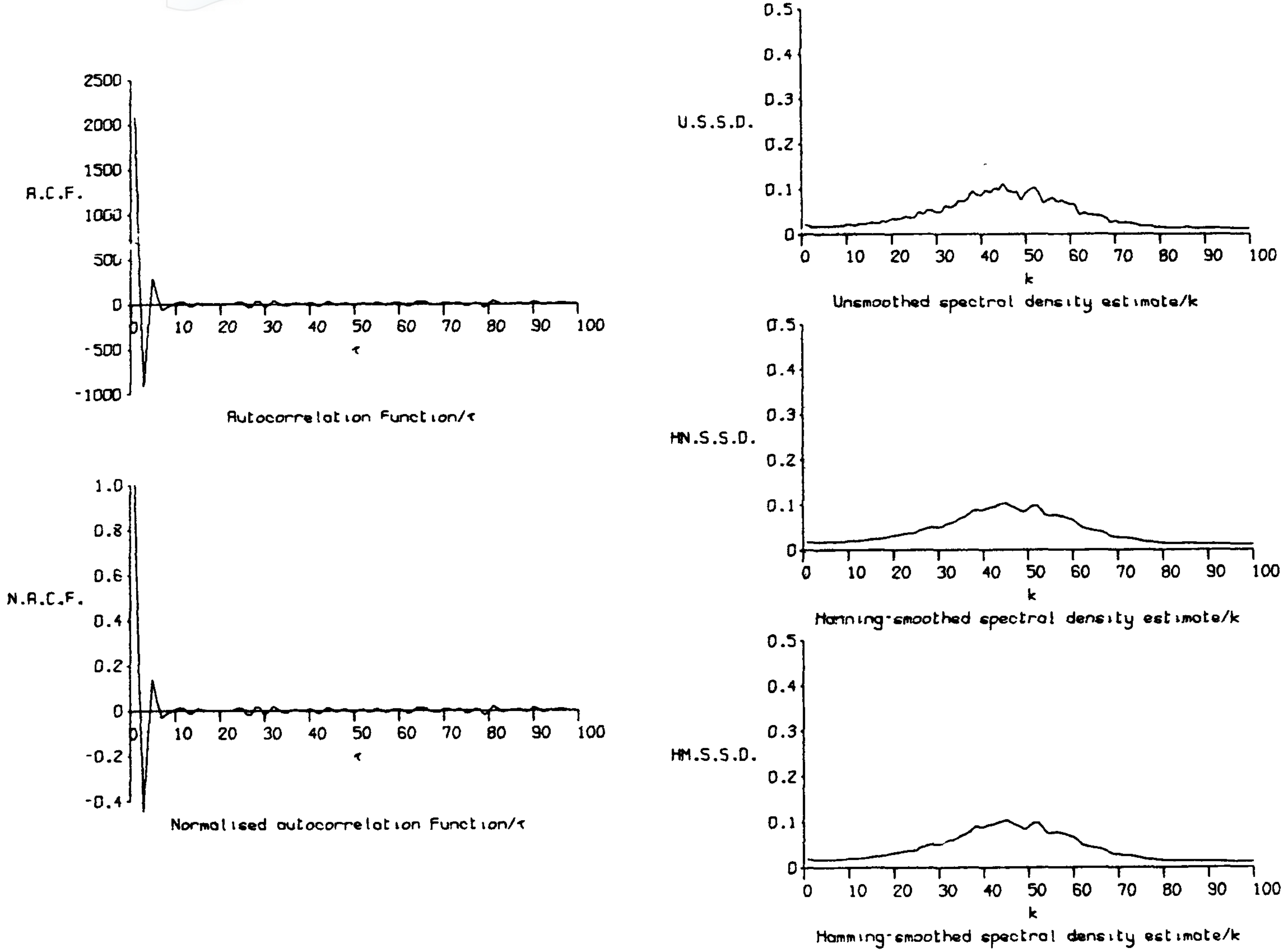


Fig. 6.39 Shark 3. Run 55. Rear station

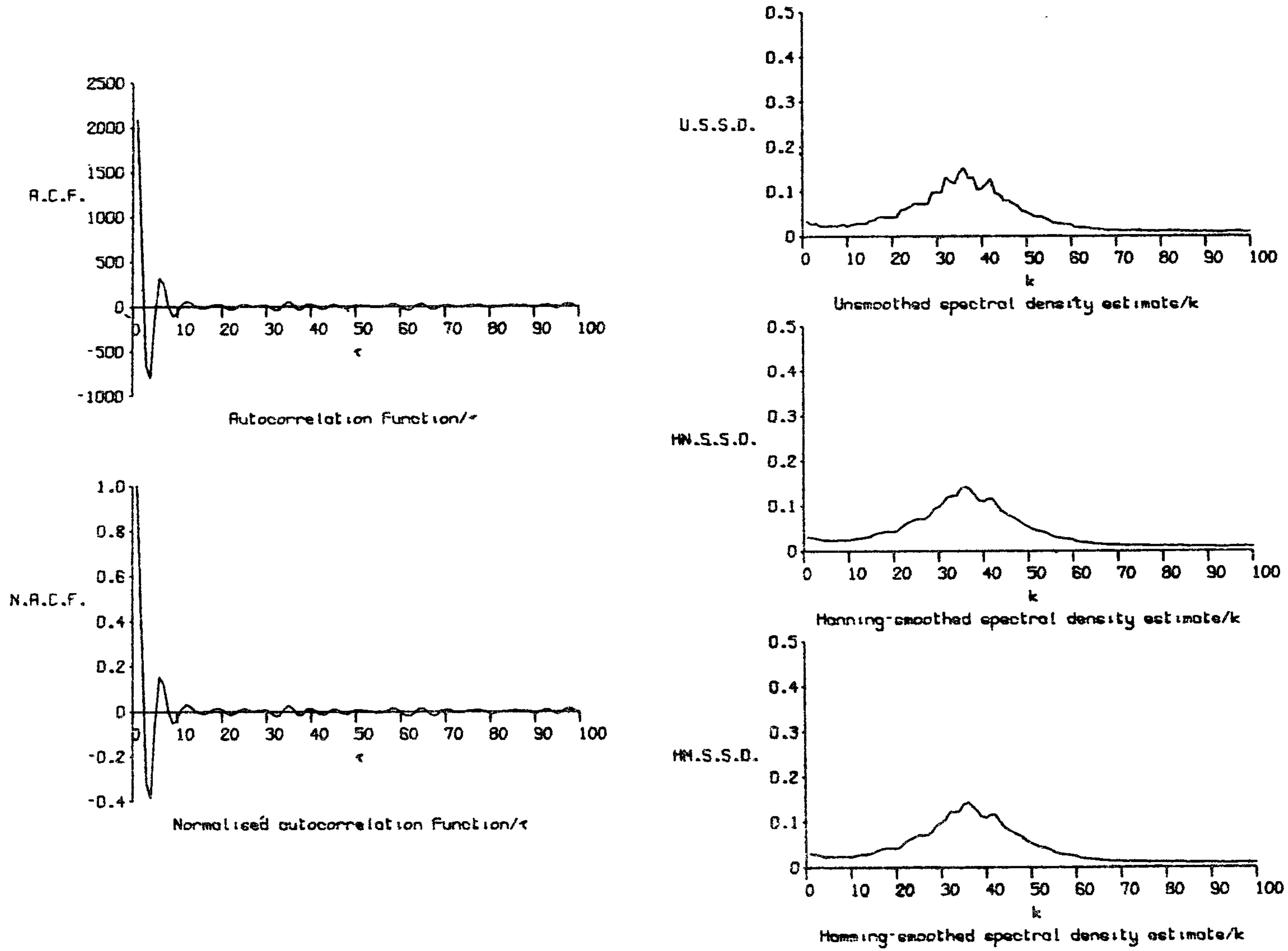


Fig. 6.40 Shark 3. Run 70. Rear station

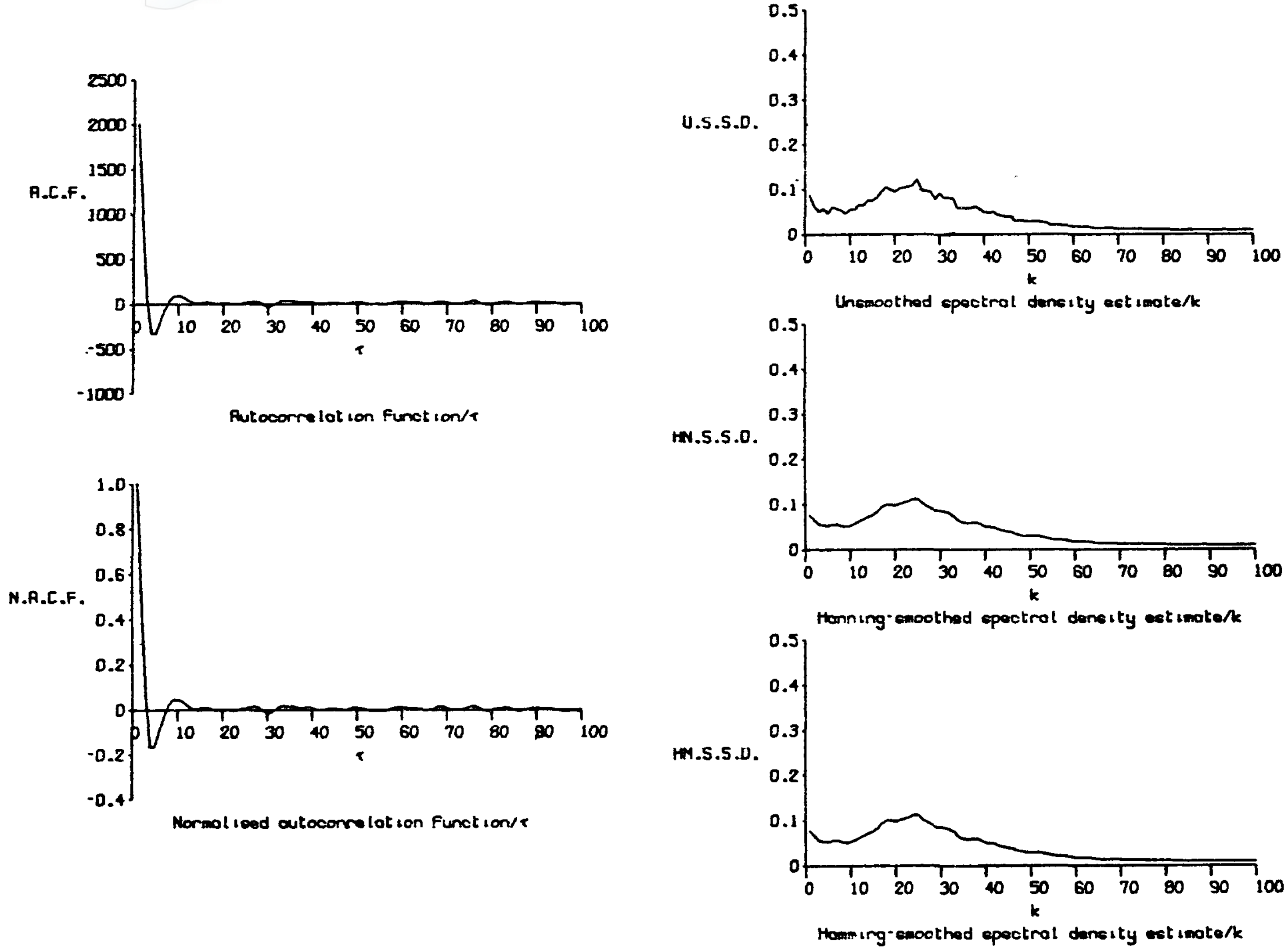


Fig. 6. 41 Shark 3. Run 85. Rear station

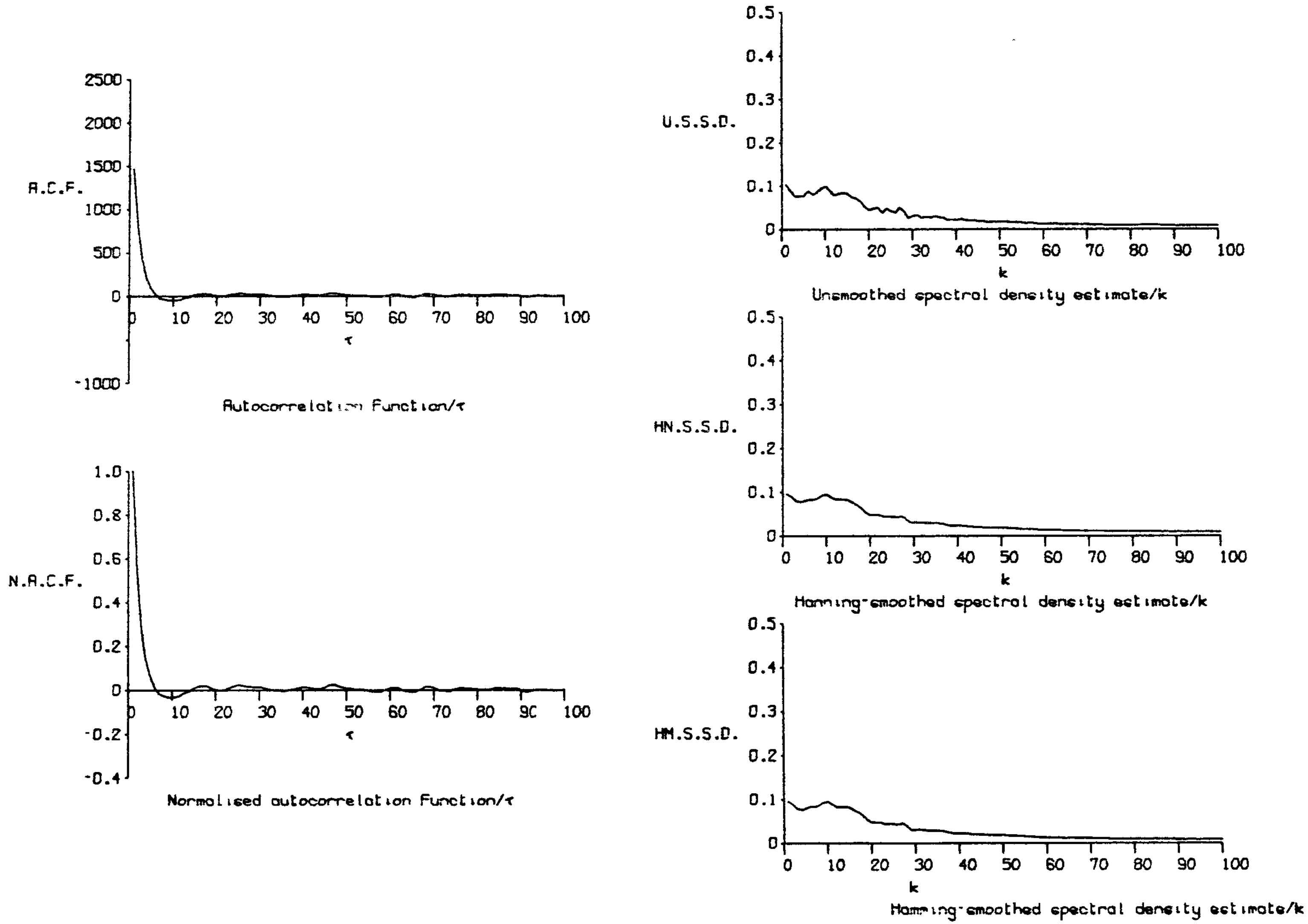


Fig. 6.42 Shark 3. Run 100. Rear station

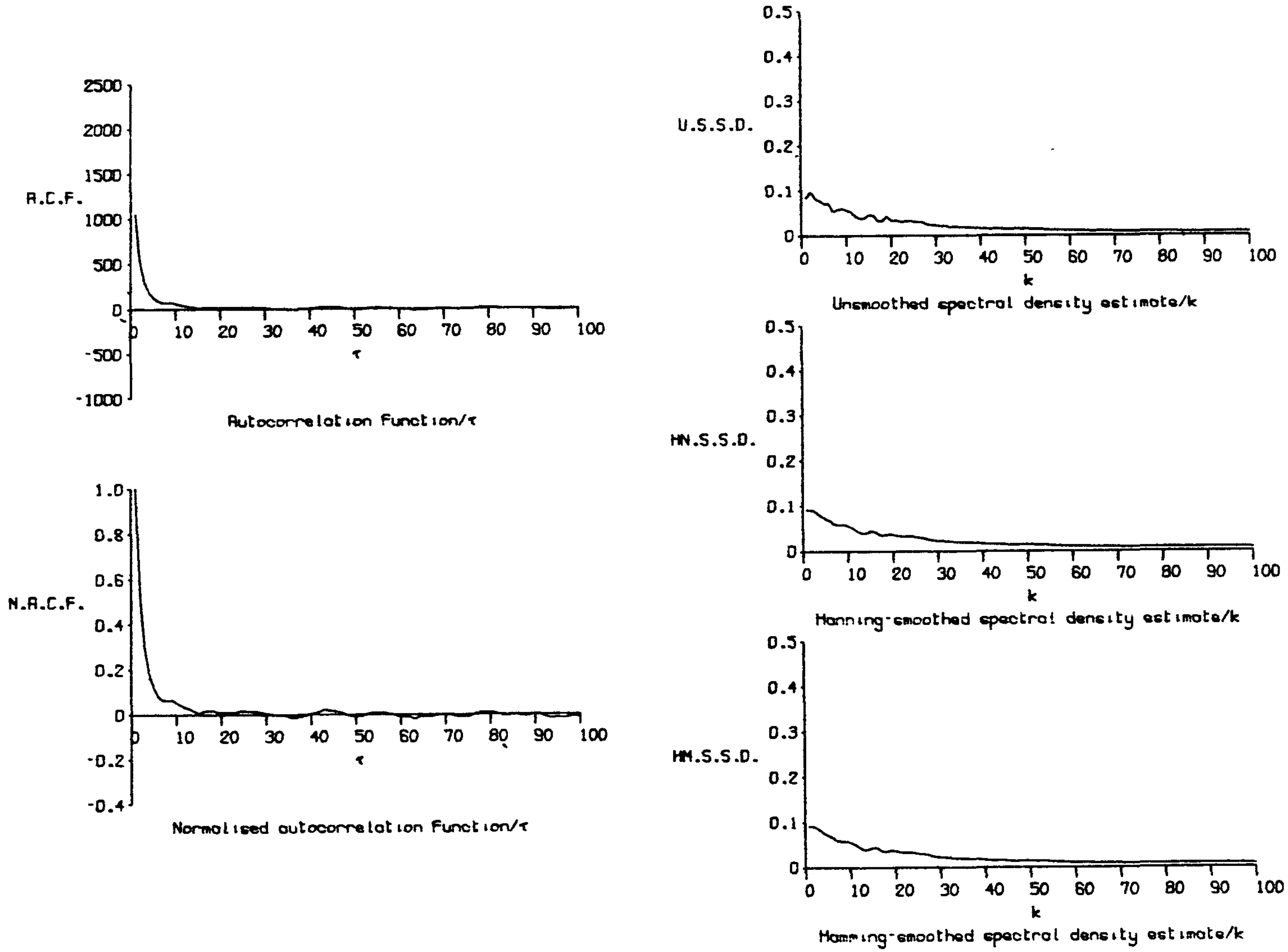


Fig. 6.43 Shark 3. Run 115. Rear station

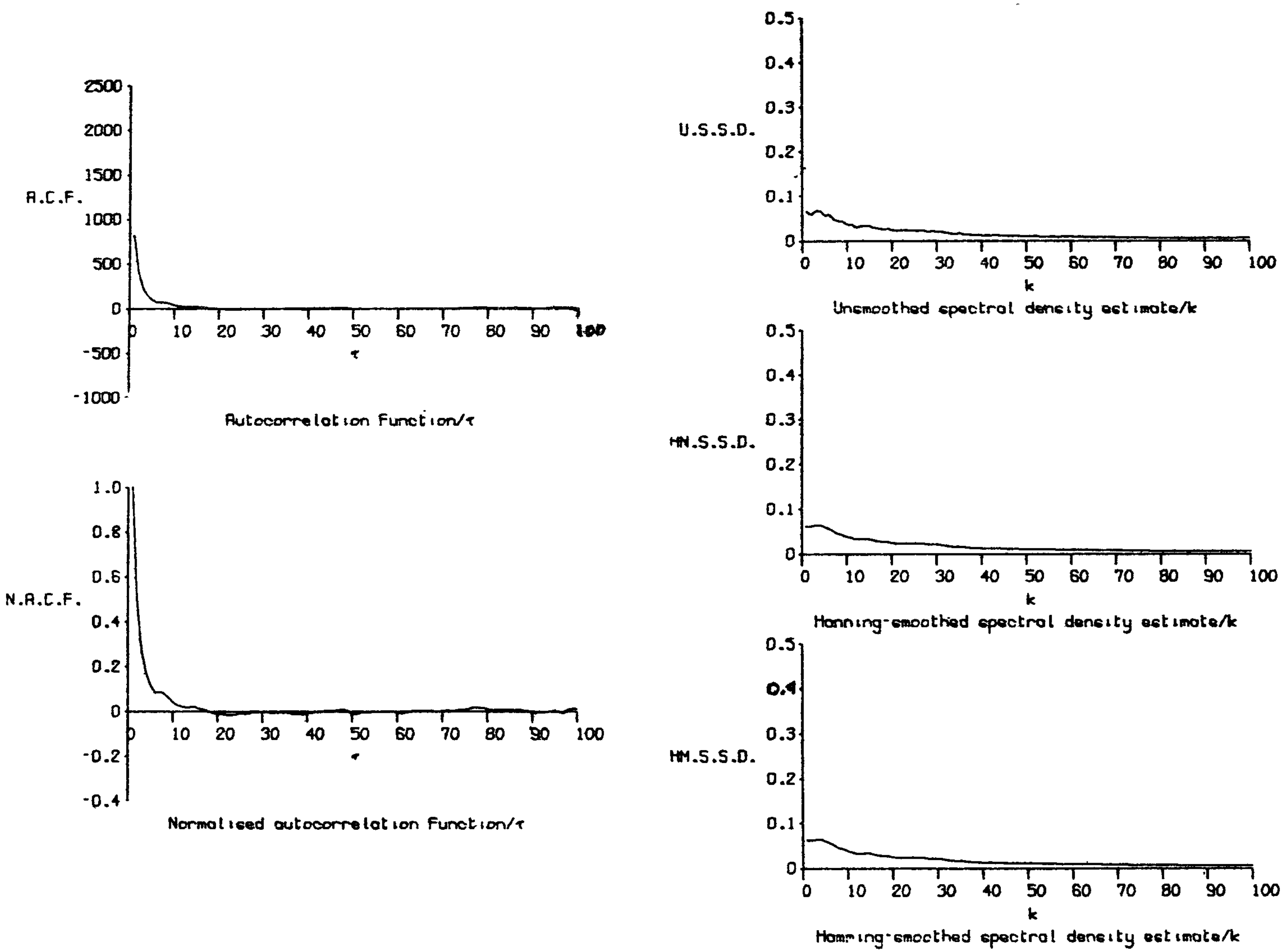


Fig. 6.44 Shark 3. Run 130. Rear station

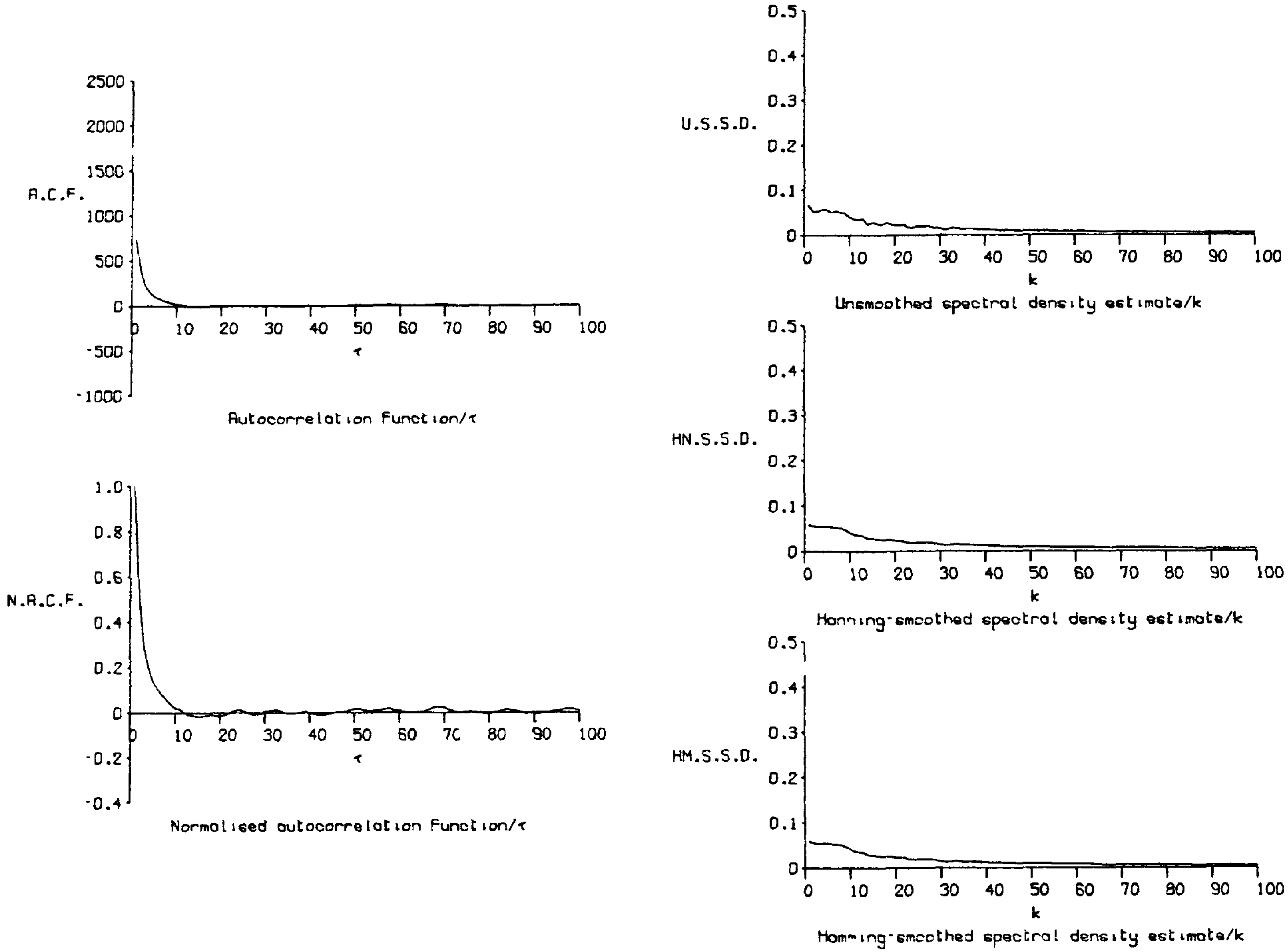


Fig. 6. 45 Shark 3. Run 145. Rear station

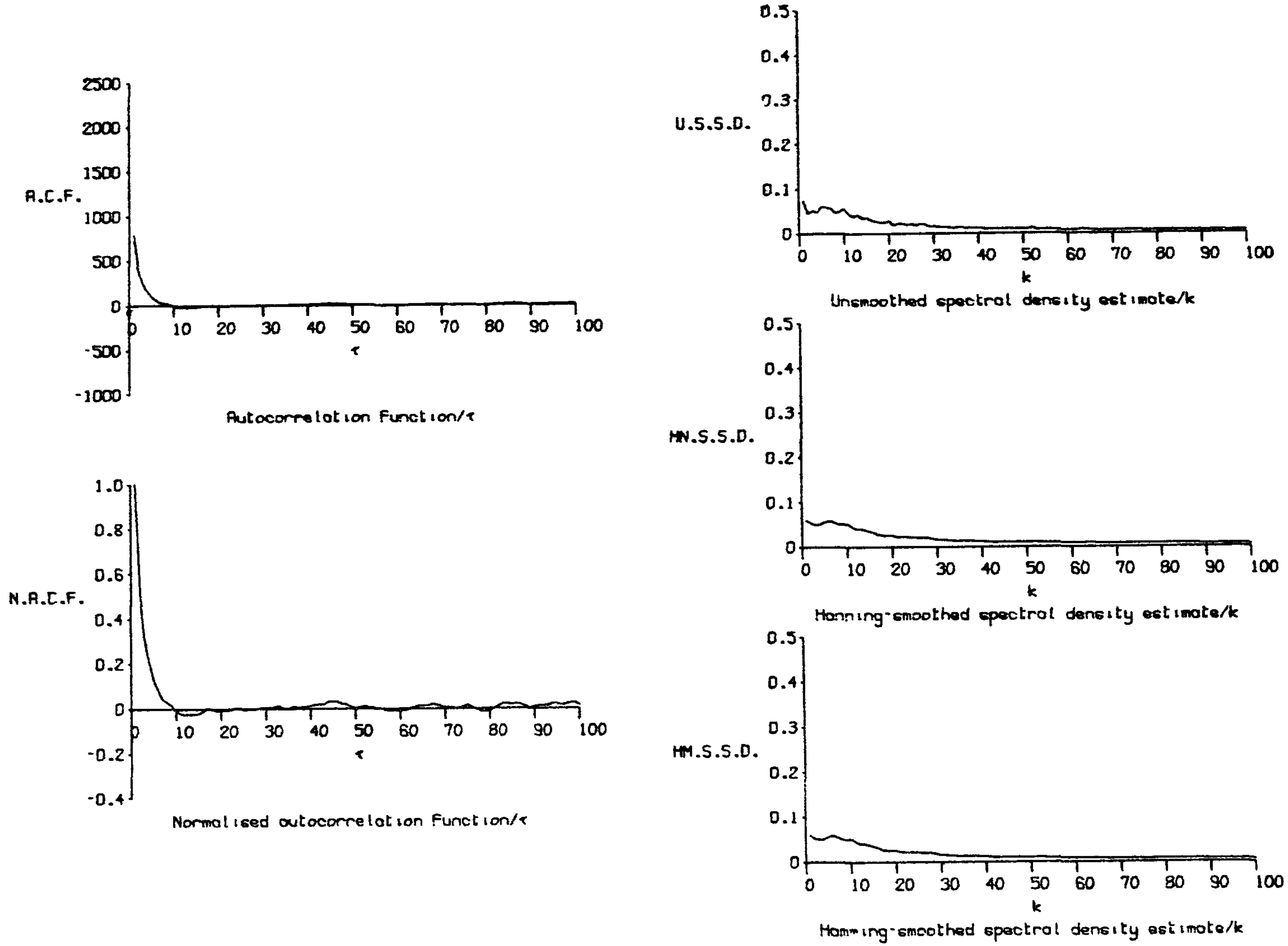


Fig. 6.46 Shark 3. Run 160. Rear station

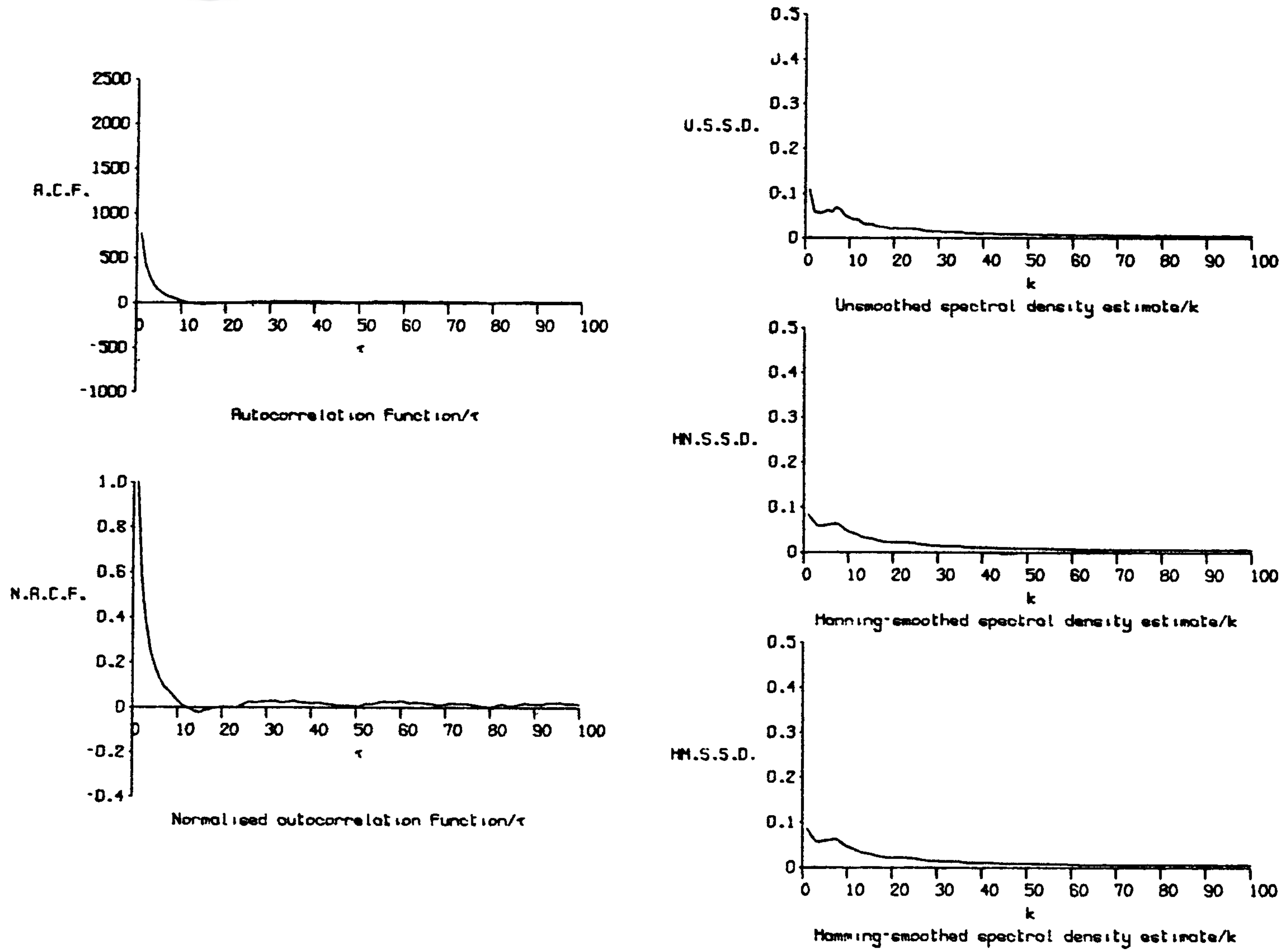


Fig.6.47 Shark 3. Run 175. Rear station

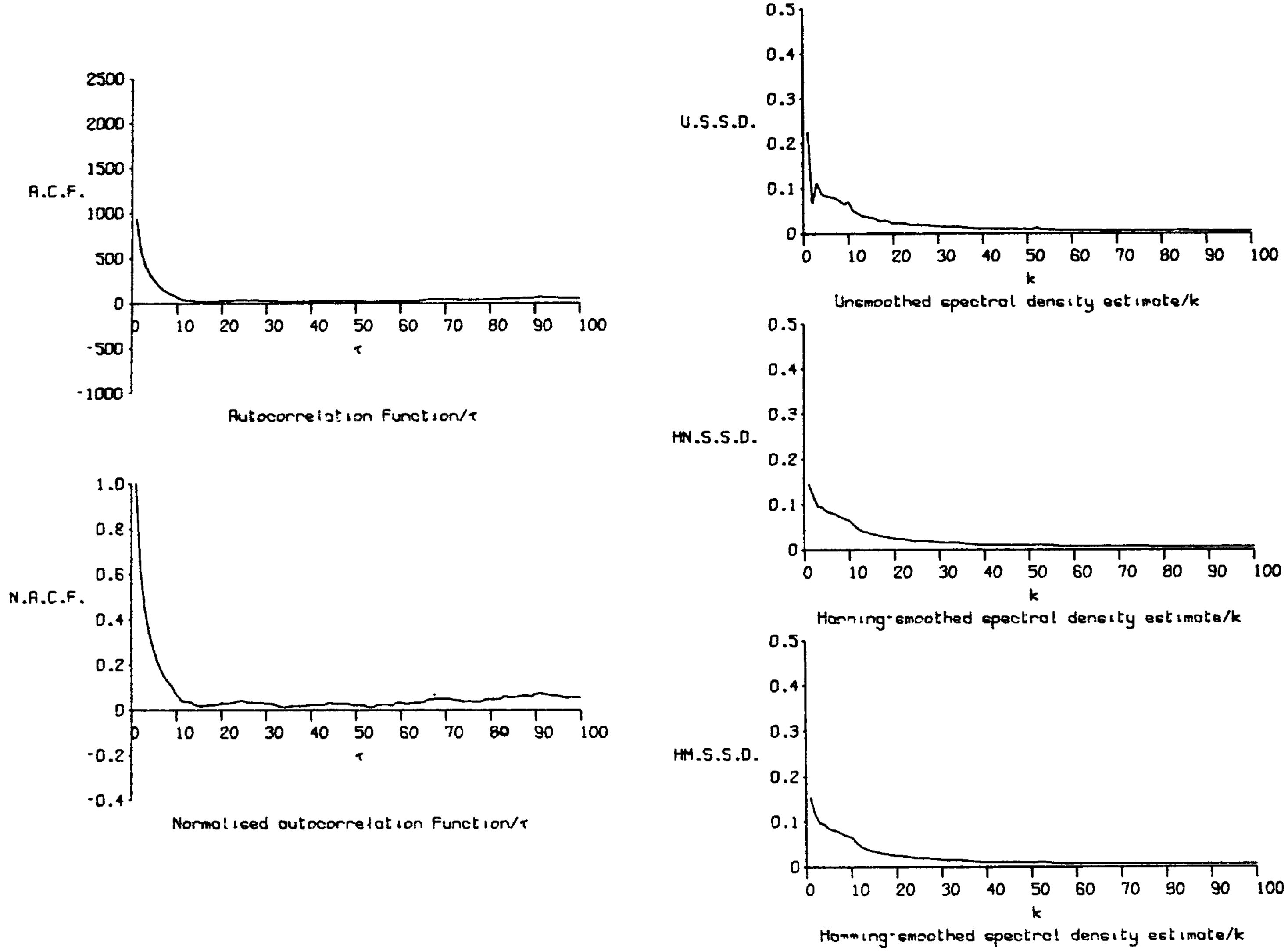


Fig. 6. 48 Shark 3. Run 190. Rear station

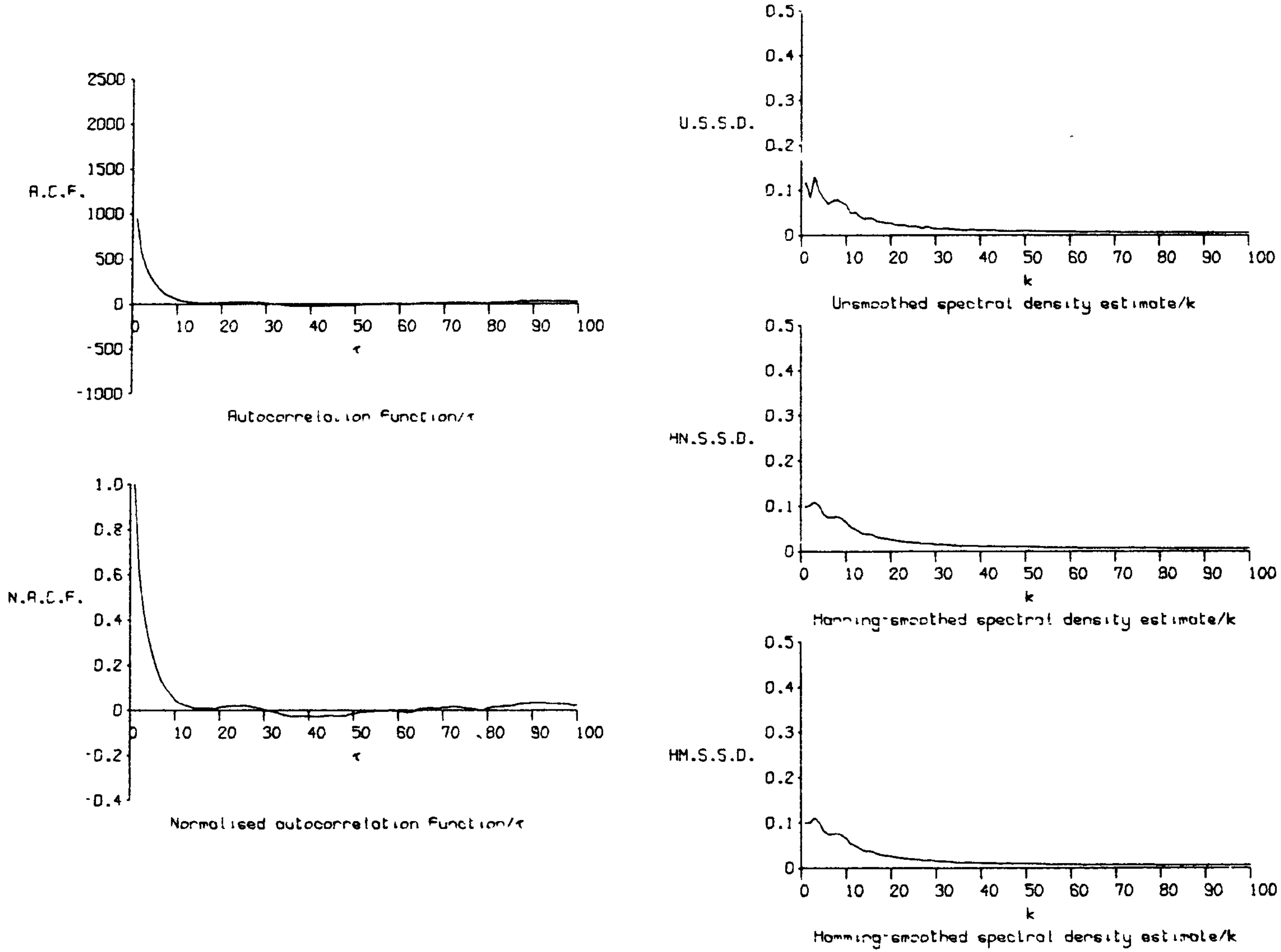


Fig. 6. 49 Shark 3. Run 205. Rear station

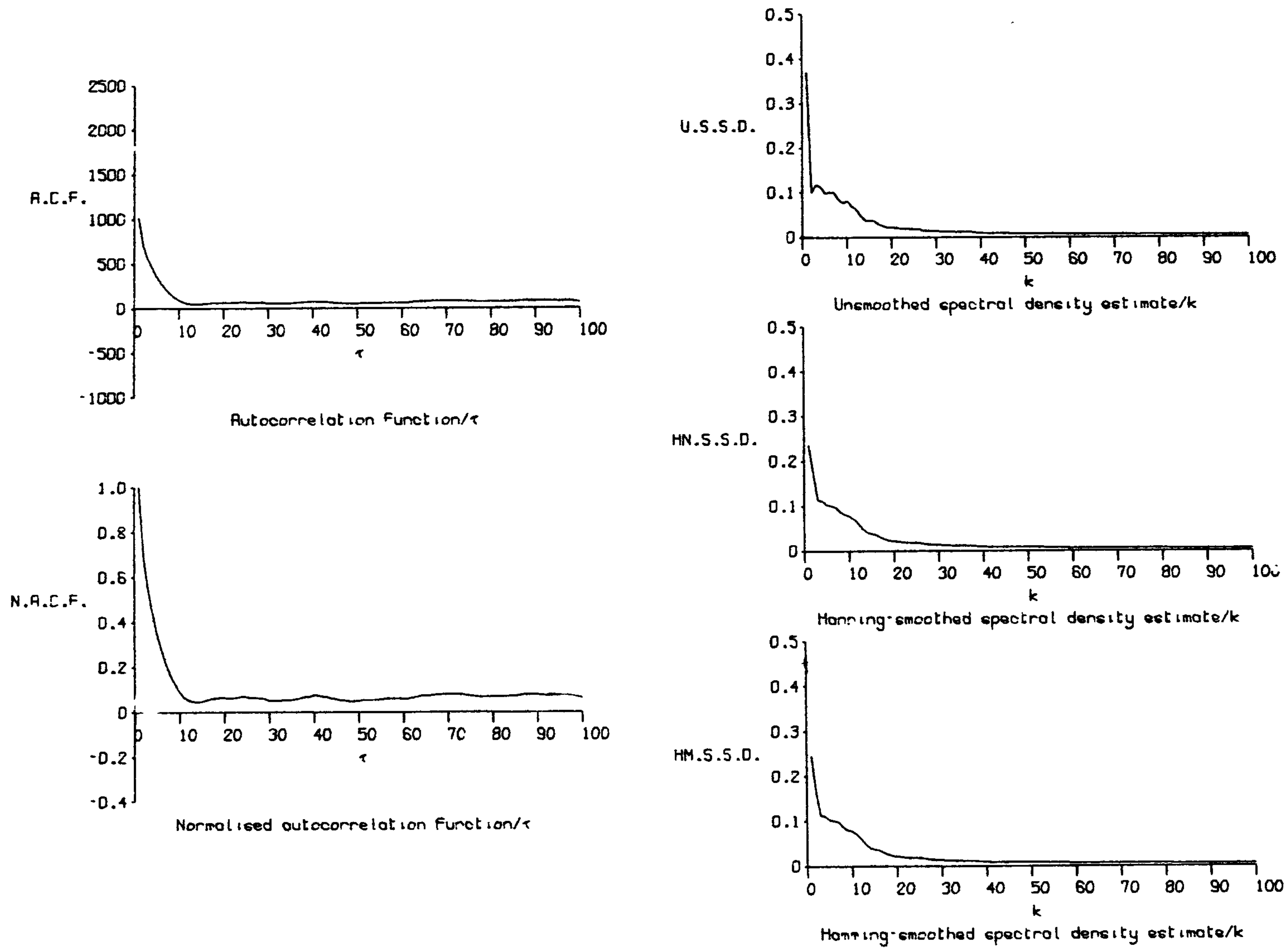


Fig. 6.50 Shark 3. Run 220. Rear station

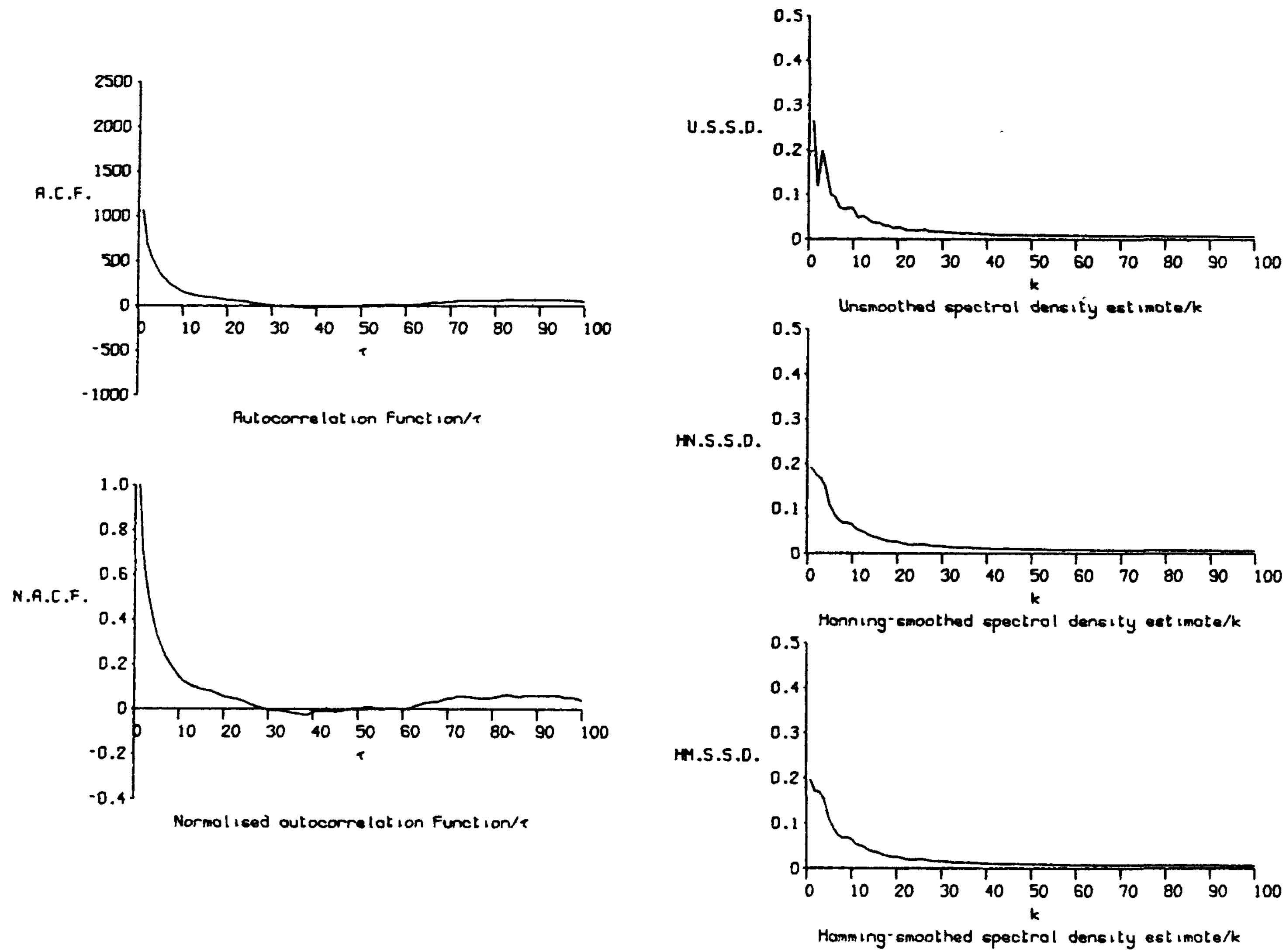


Fig. 6.51 Shark 3. Run 235. Rear station

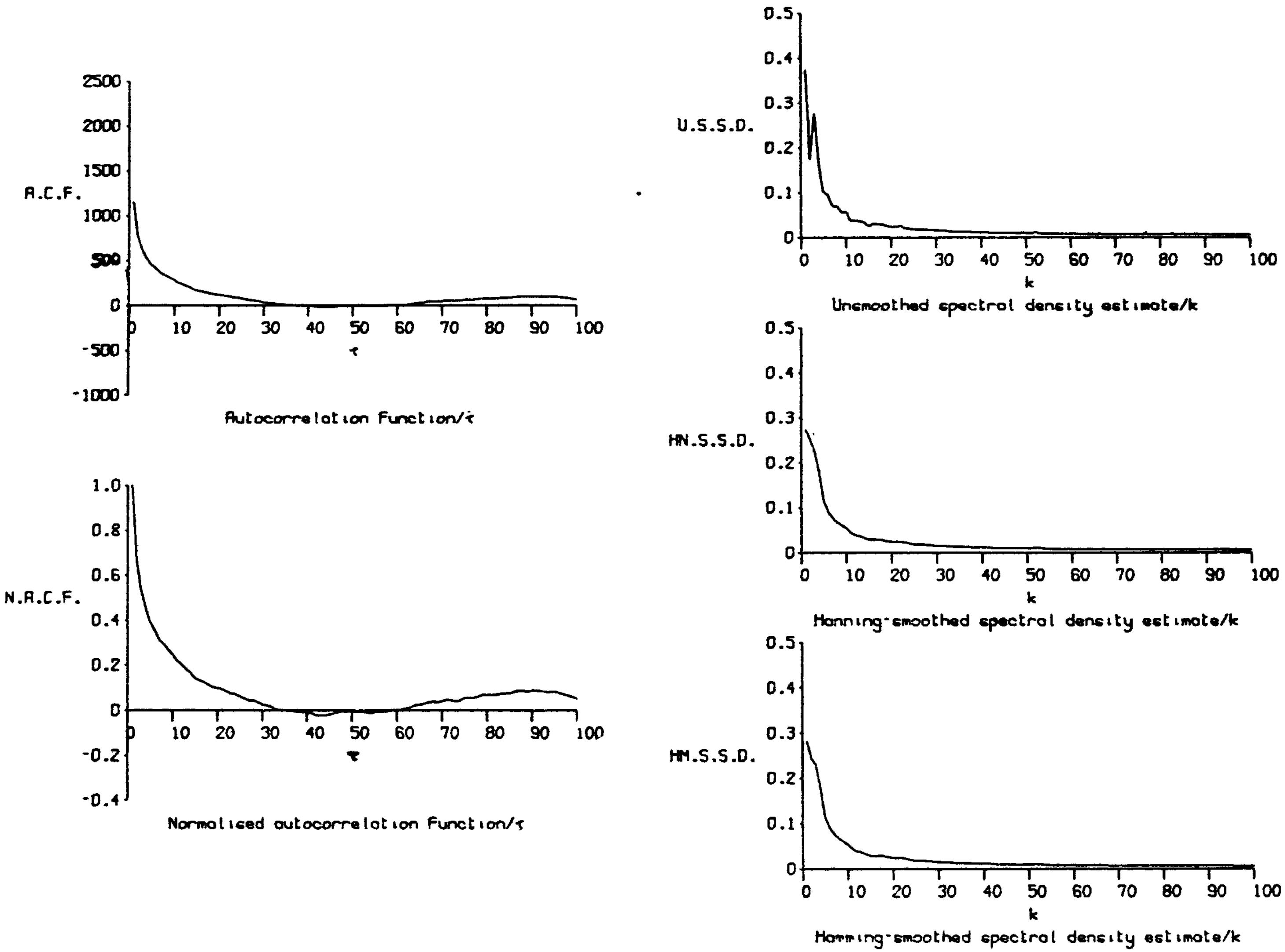


Fig. 6.52 Shark 3. Run 260. Rear station

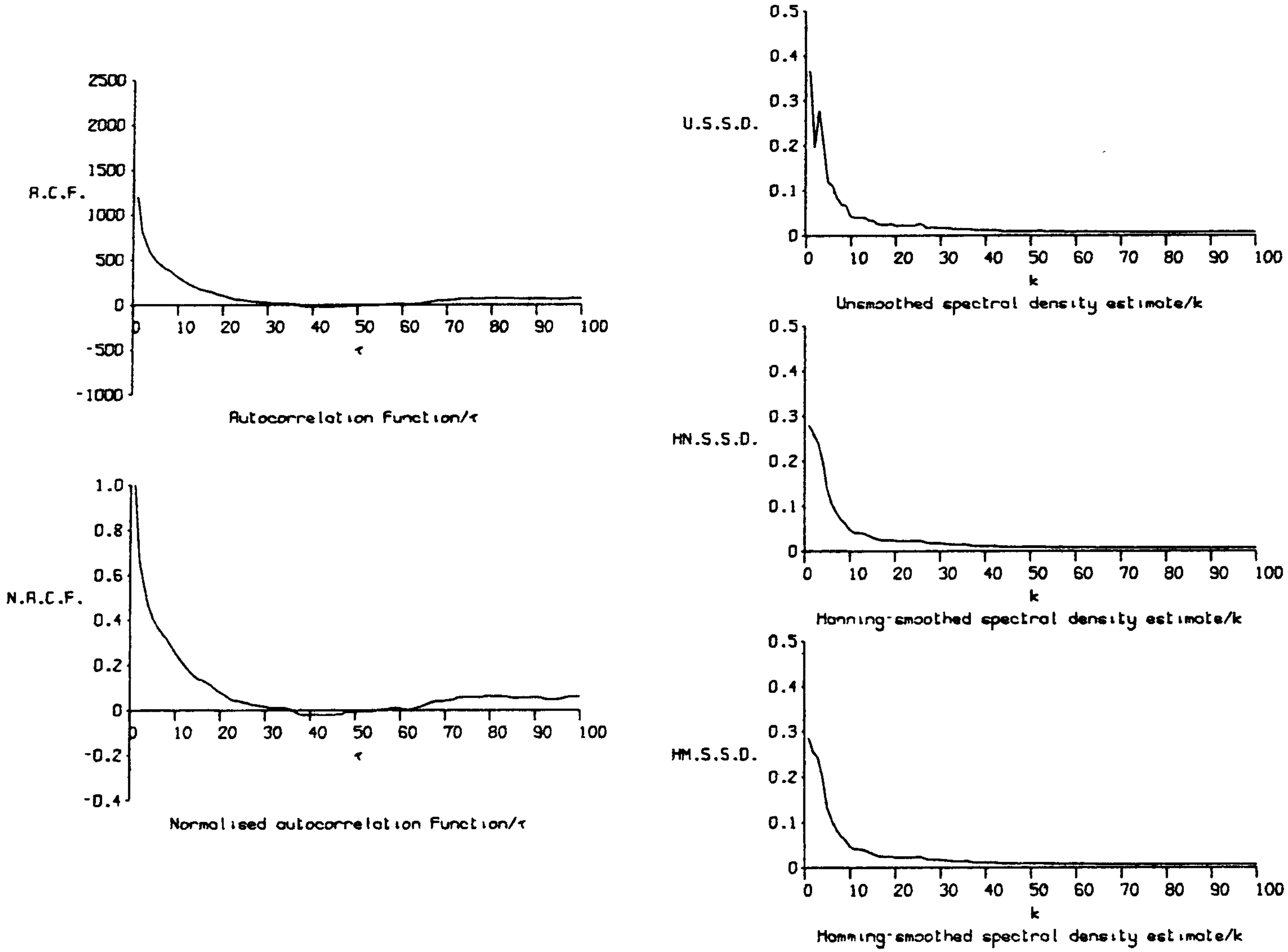


Fig. 6.53 Shark 3. Run 285. Rear station

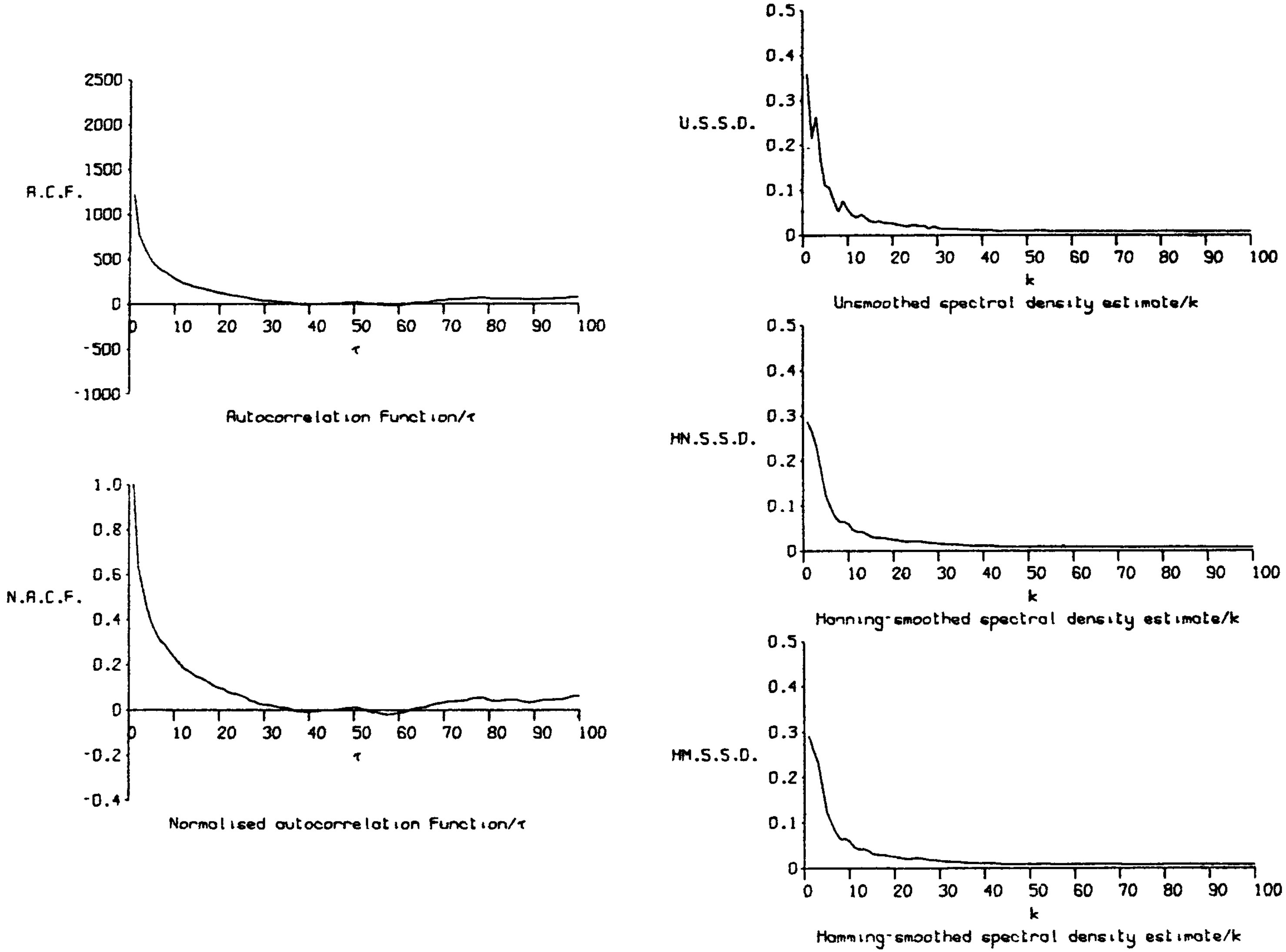
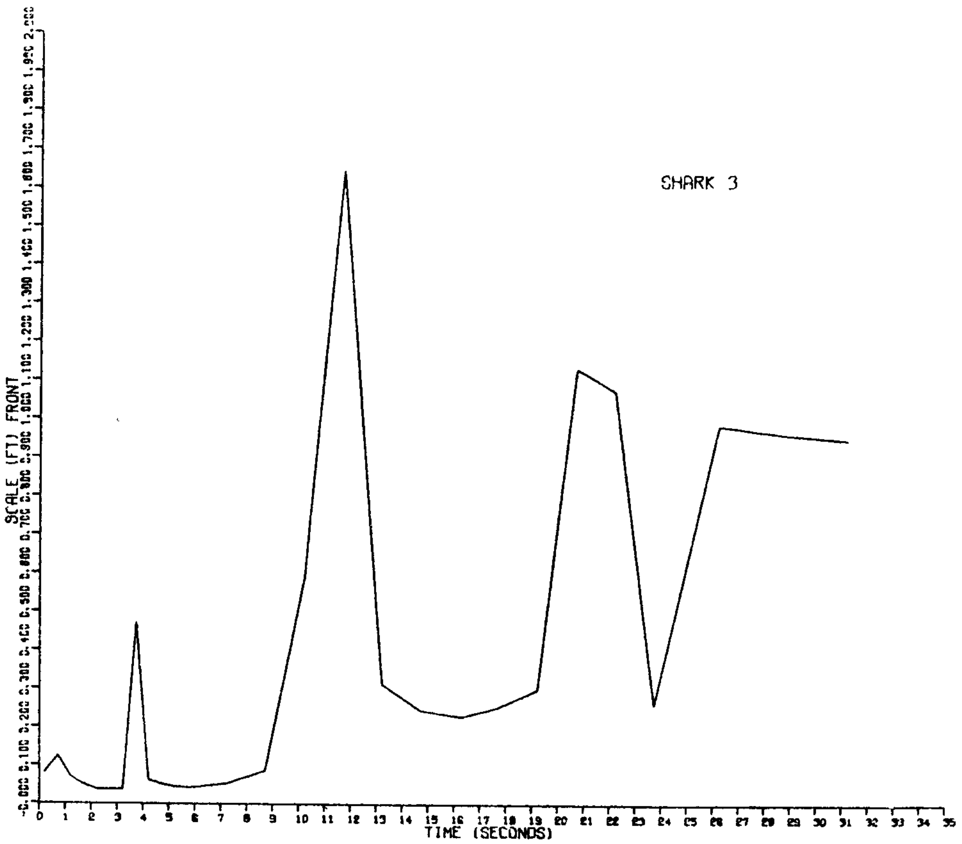


Fig. 6.54 Shark 3. Run 310. Rear station



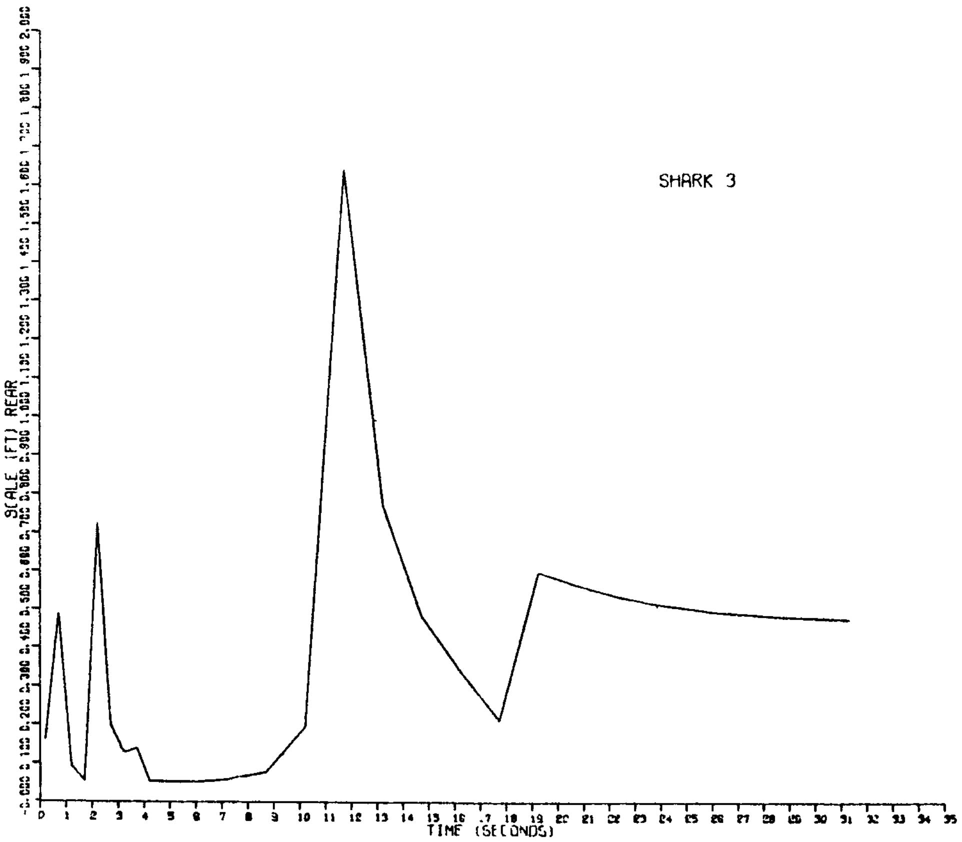
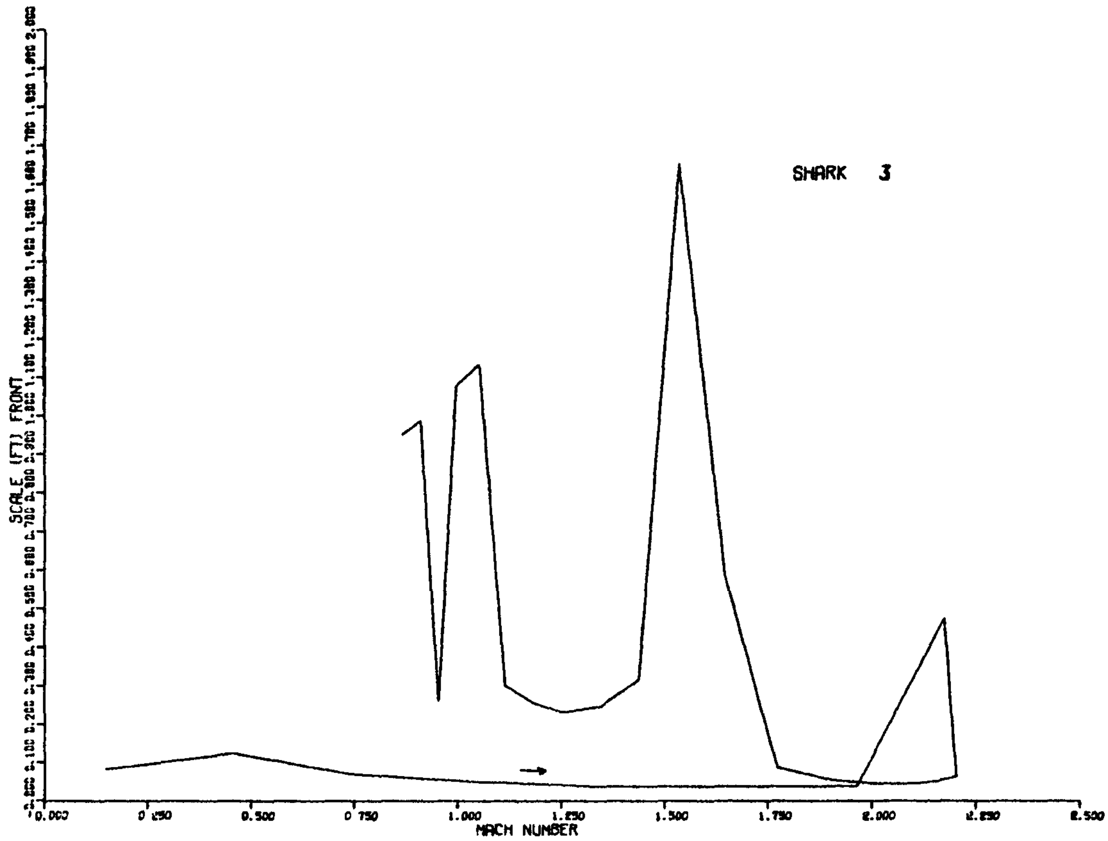


Fig. 7.1 Plot of scale / time



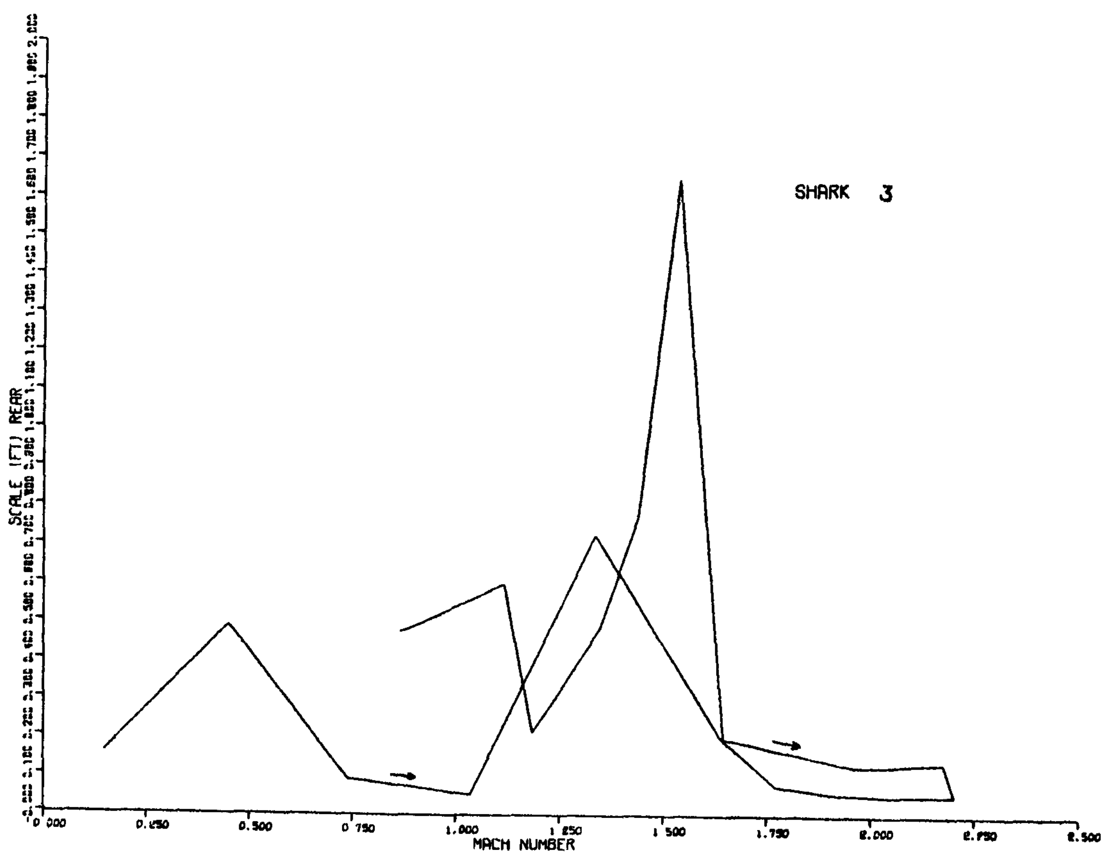


Fig. 7.2 Plot of scale/Mach No

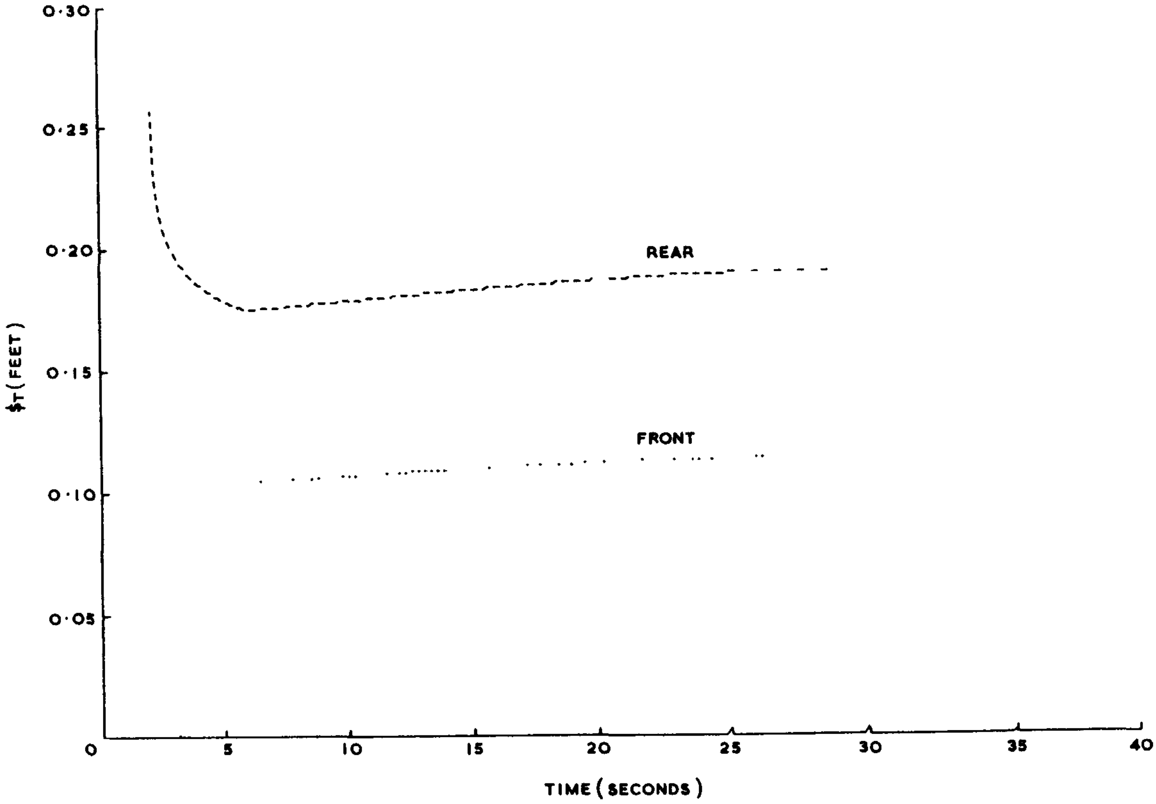


Fig.8a Plots of δ_T / time. Front and rear stations

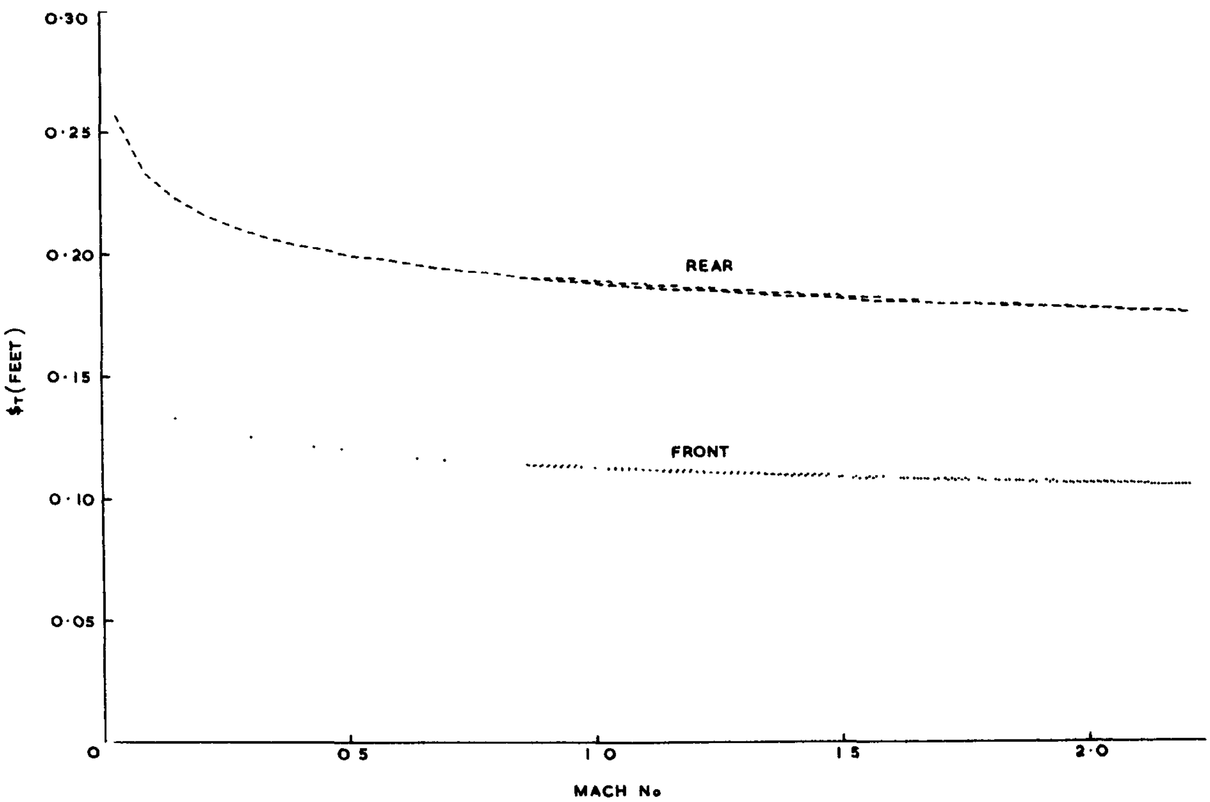


Fig.8b Plots of Mach No / time. Front and rear stations

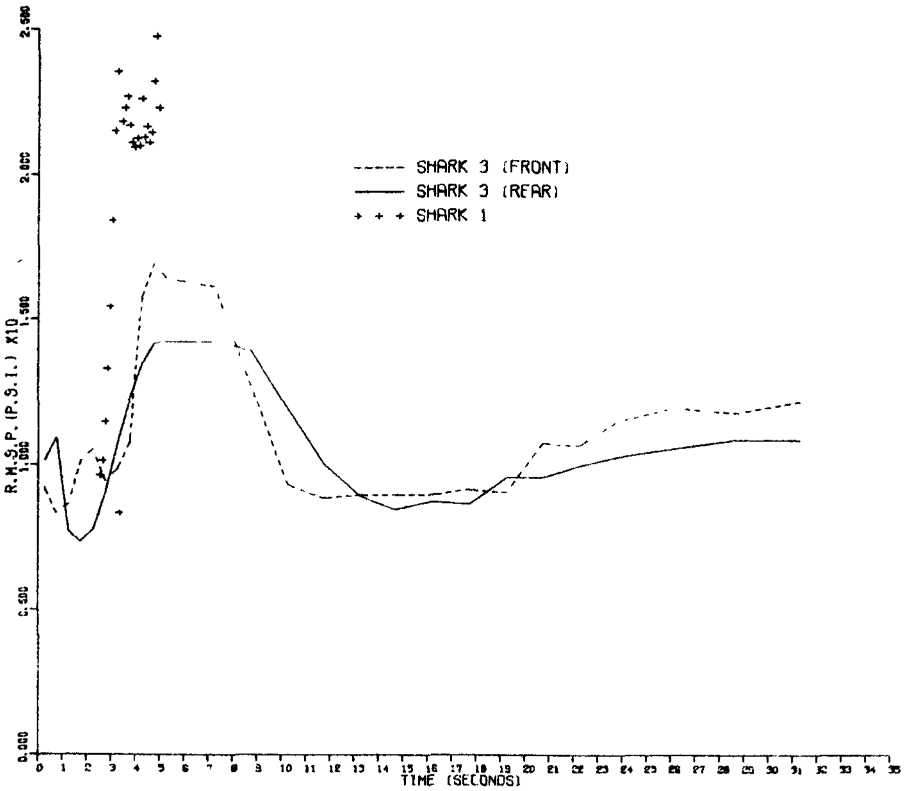


Fig. 9a rms pressure / time

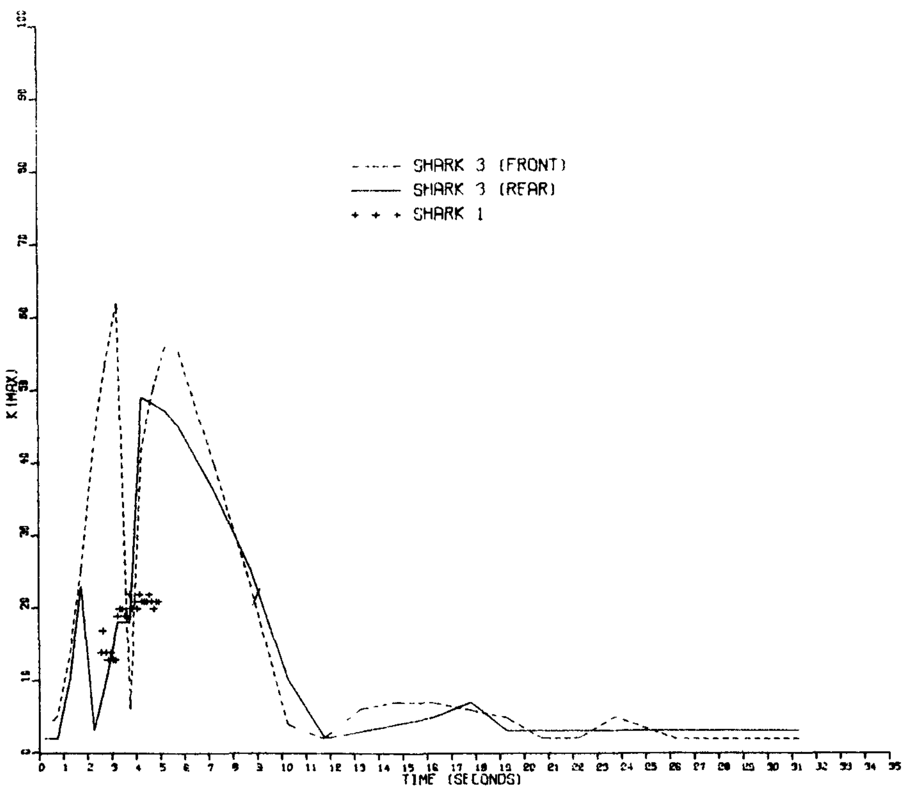
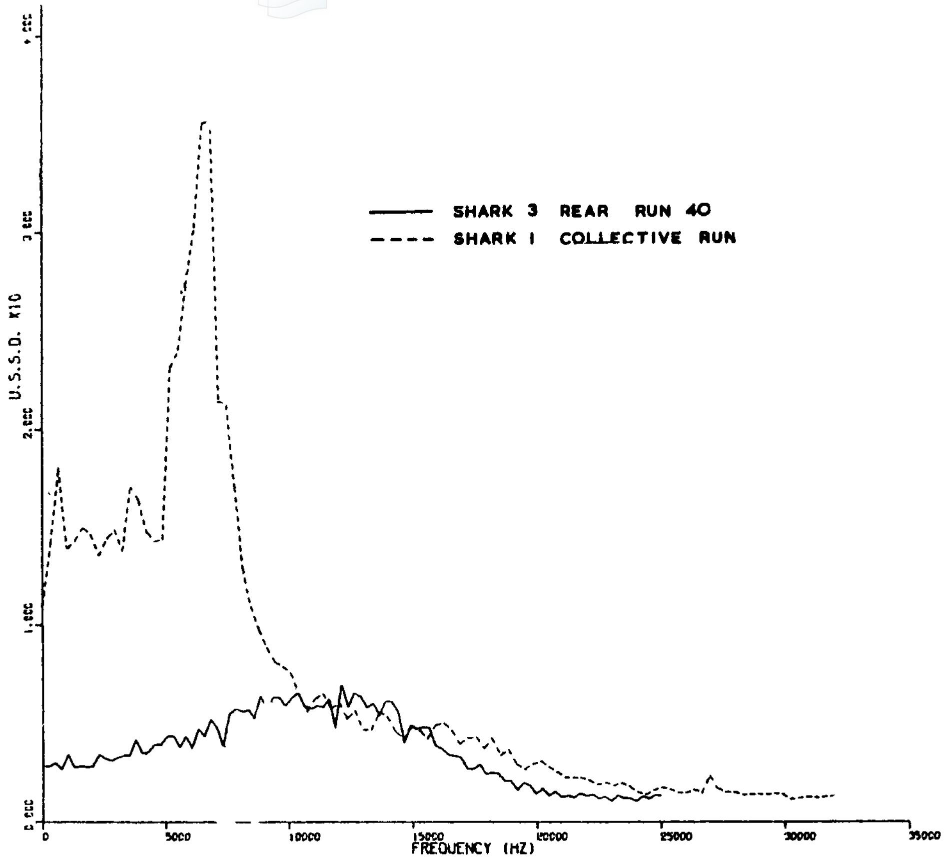


Fig. 9b Position of maximum spectral density



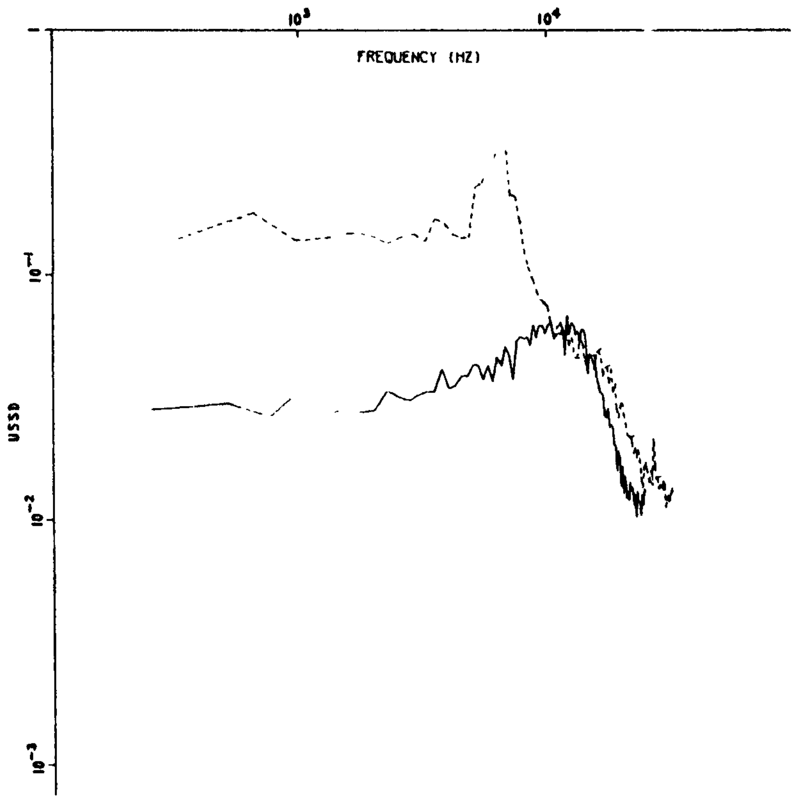


Fig. 10 Comparison of spectral density of Shark 1 and Shark 3 at Mach No 2.2

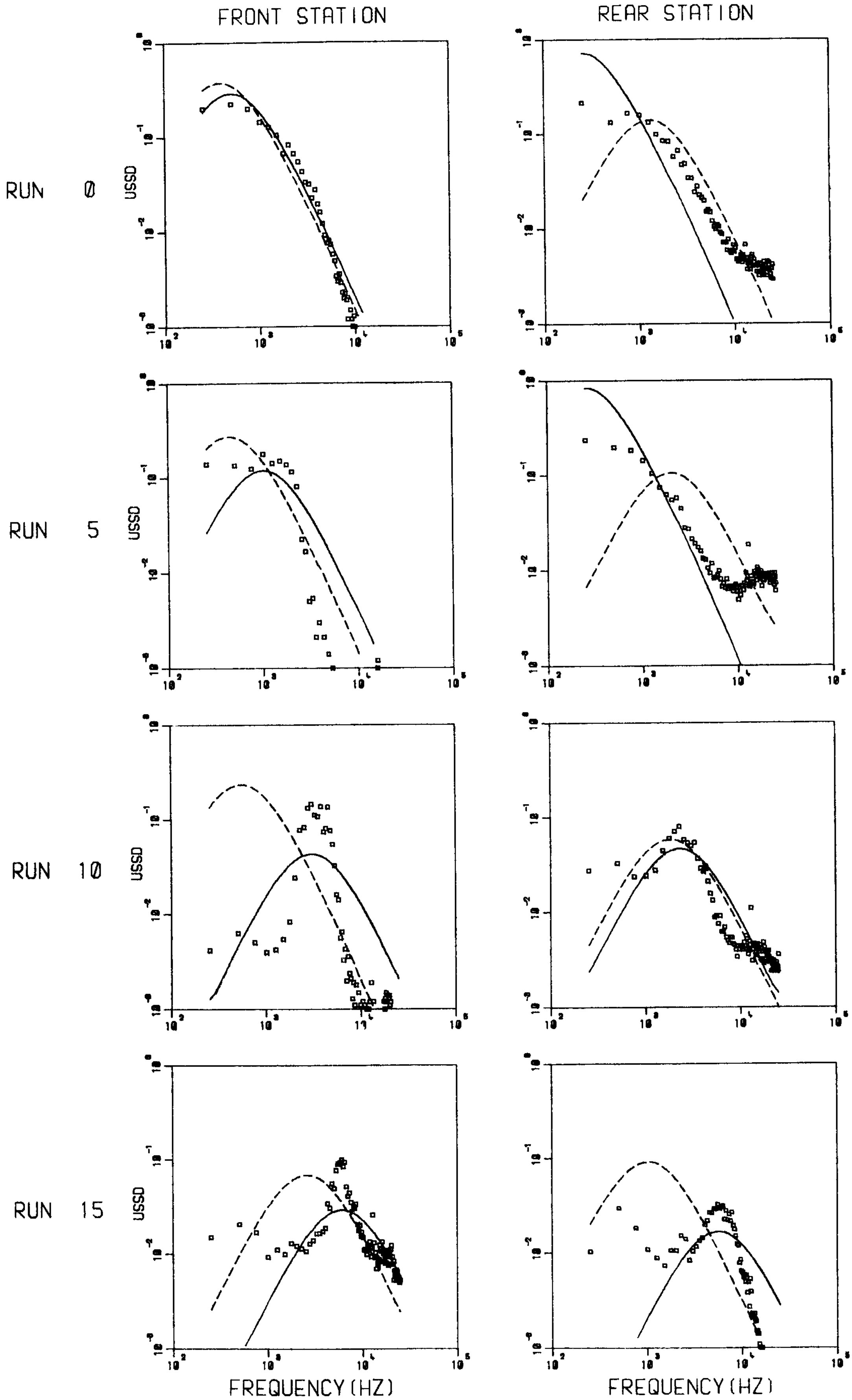


Fig. II. 1 Comparison of unsmoothed spectral density with theoretical distributions

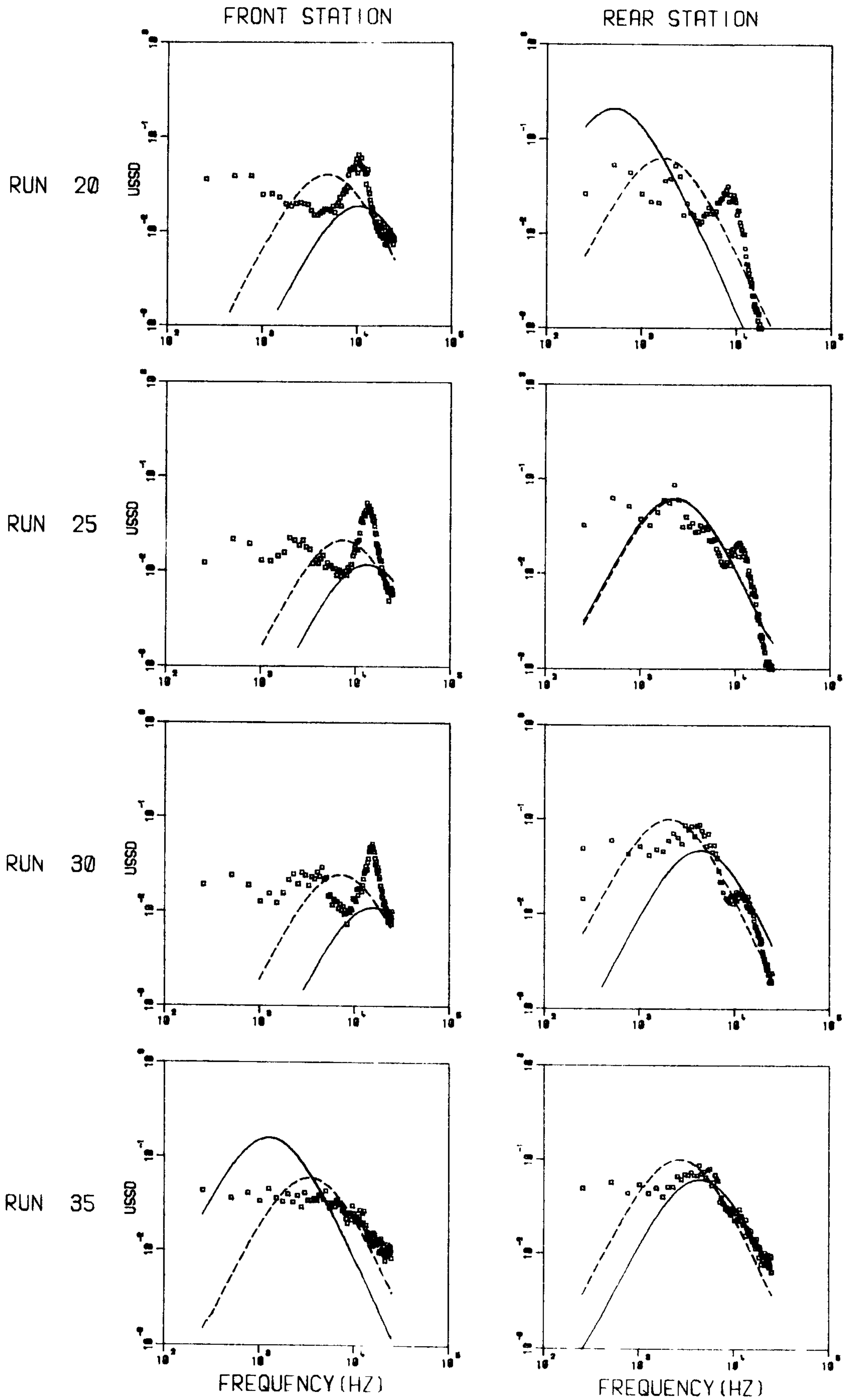


Fig. II.2 Comparison of unsmoothed spectral density with theoretical distributions

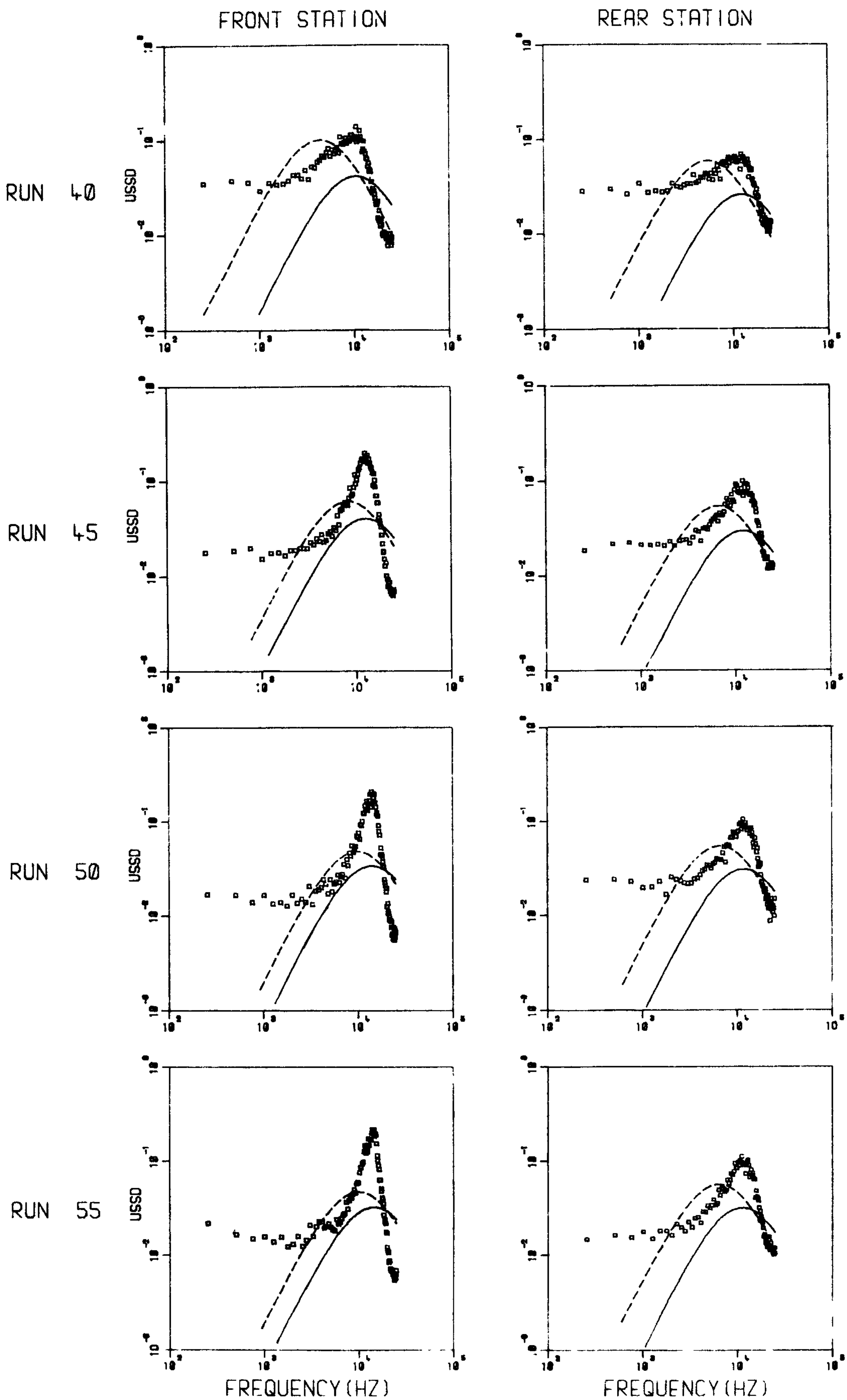


Fig.11.3 Comparison of unsmoothed spectral density with theoretical distributions

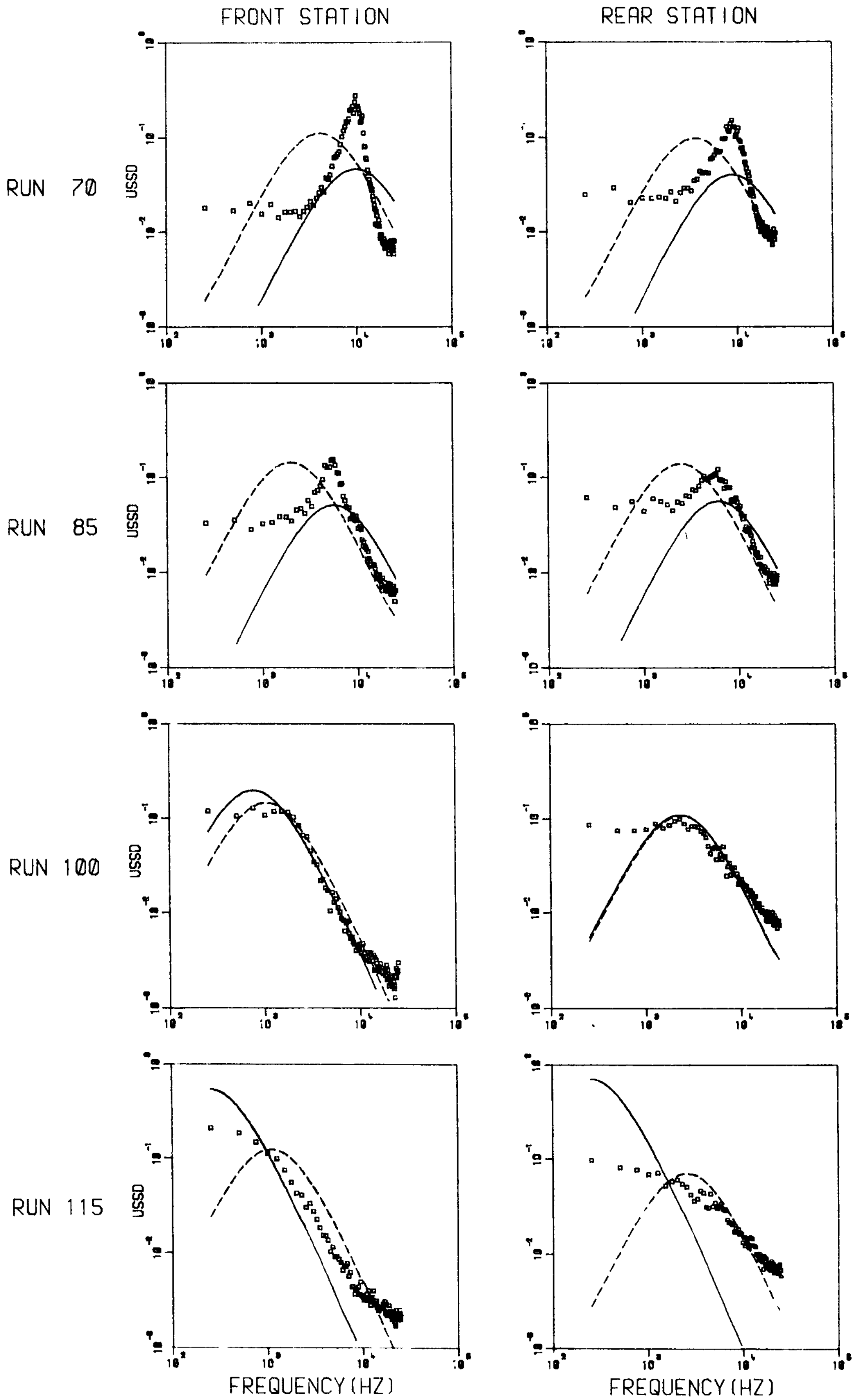


Fig.11.4 Comparison of unsmoothed spectral density with theoretical distributions

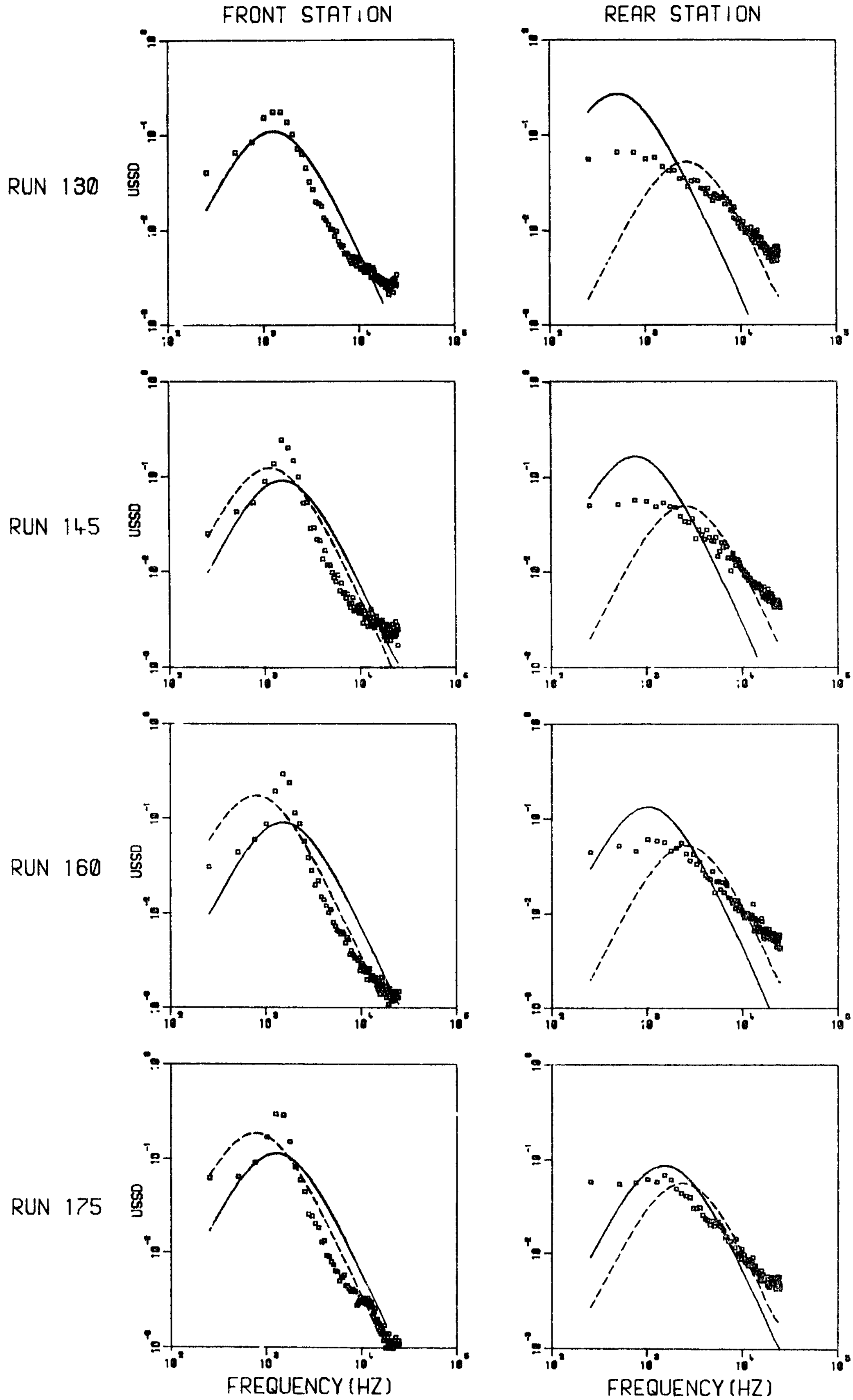


Fig.11.5 Comparison of unsmoothed spectral density with theoretical distributions

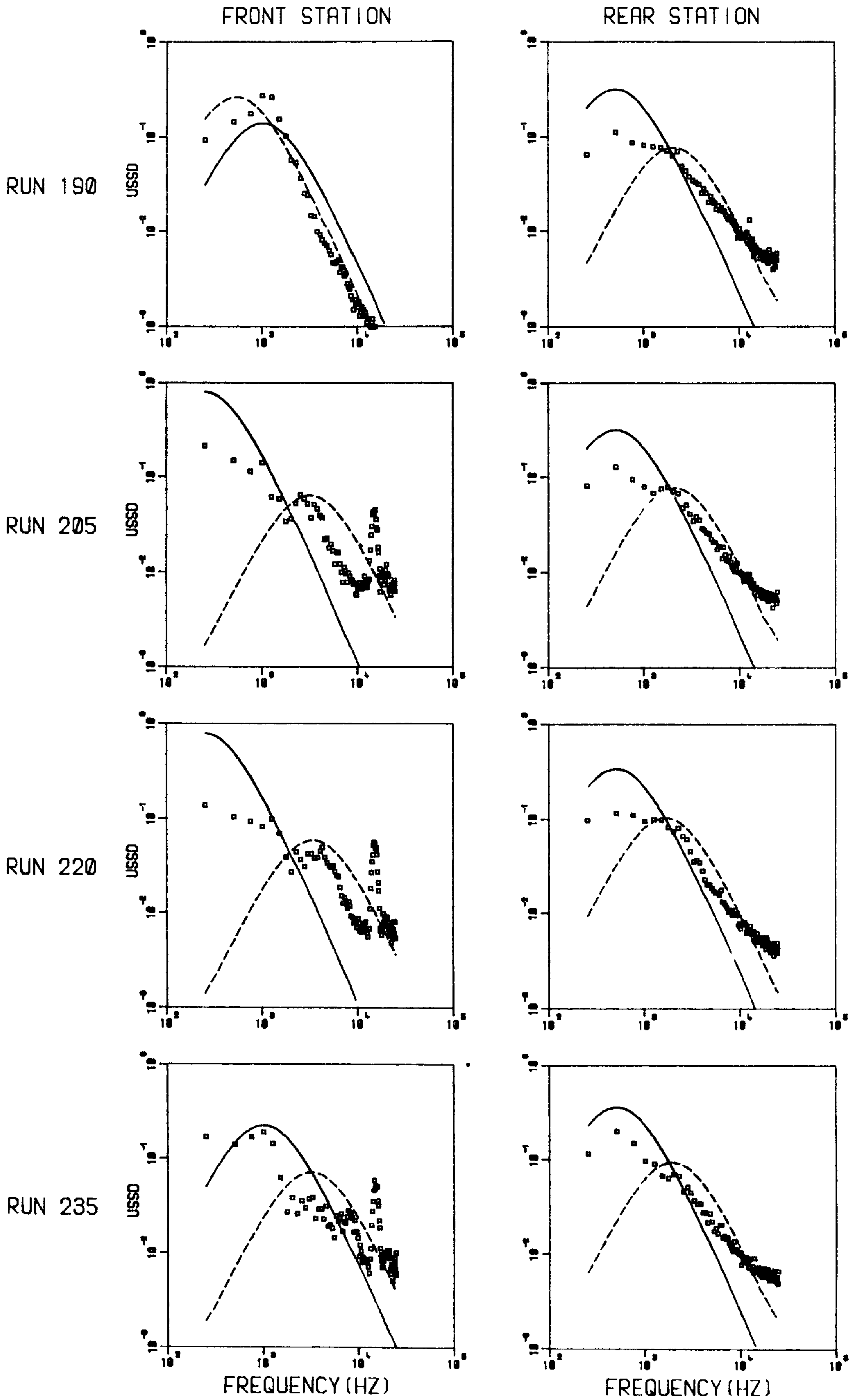


Fig. 11.6 Comparison of unsmoothed spectral density with theoretical distributions

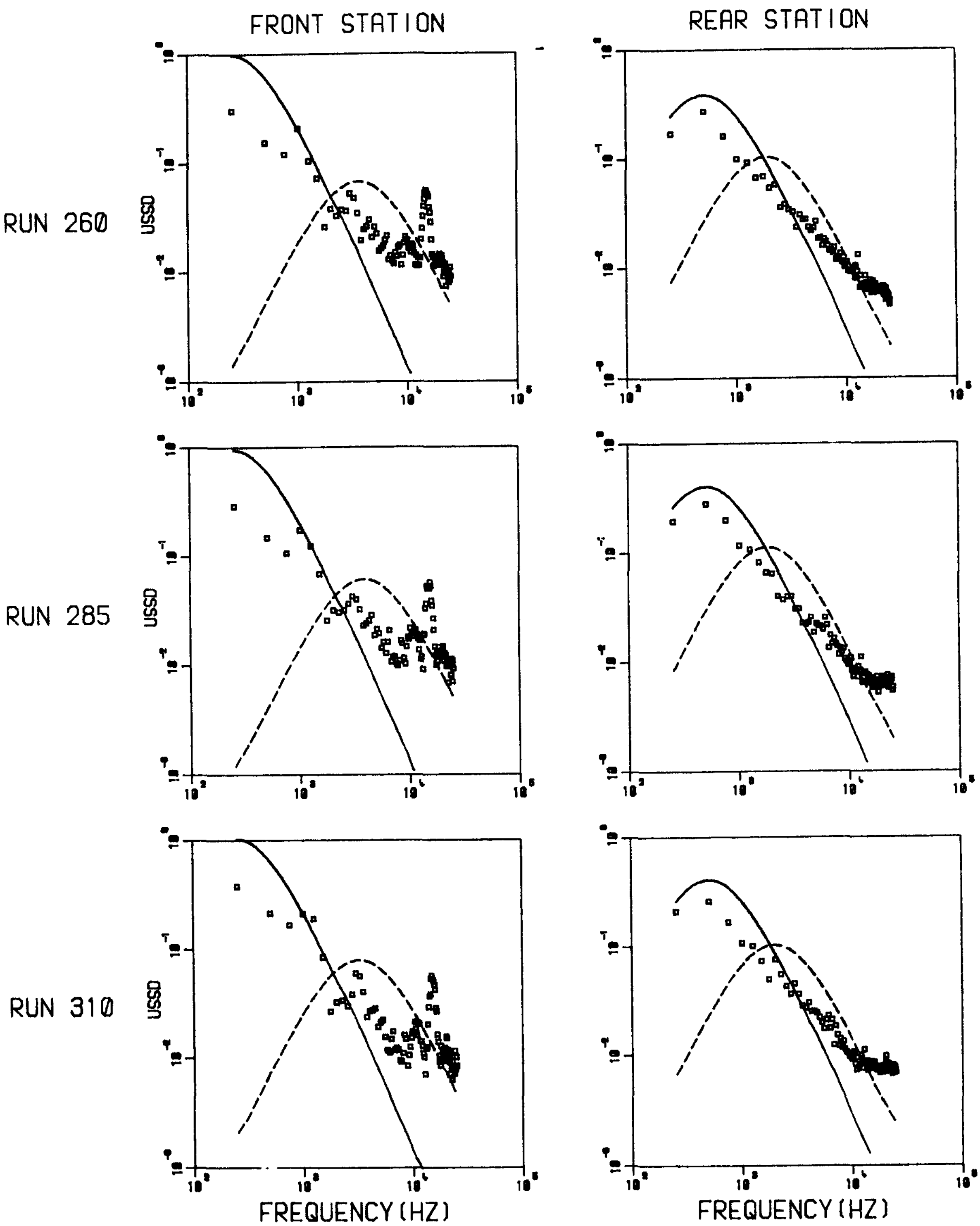


Fig. 11.7 Comparison of unsmoothed spectral density with theoretical distributions

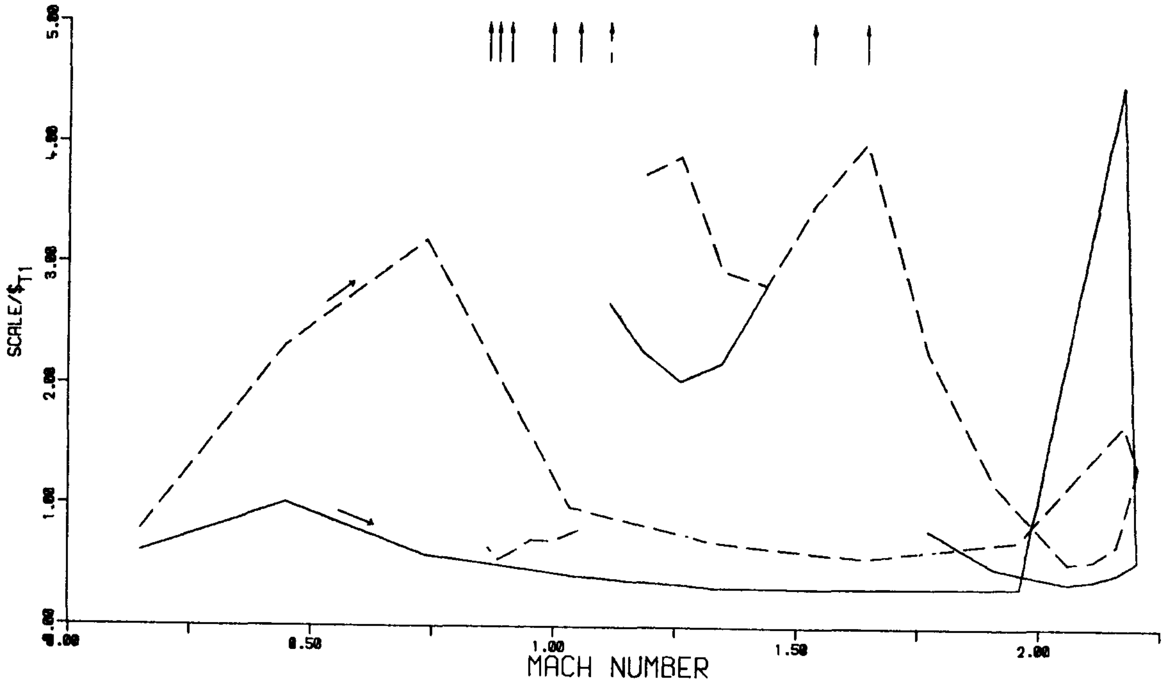


Fig. 12a Plot of $\frac{scale}{\$_T}$ / Mach No Front station

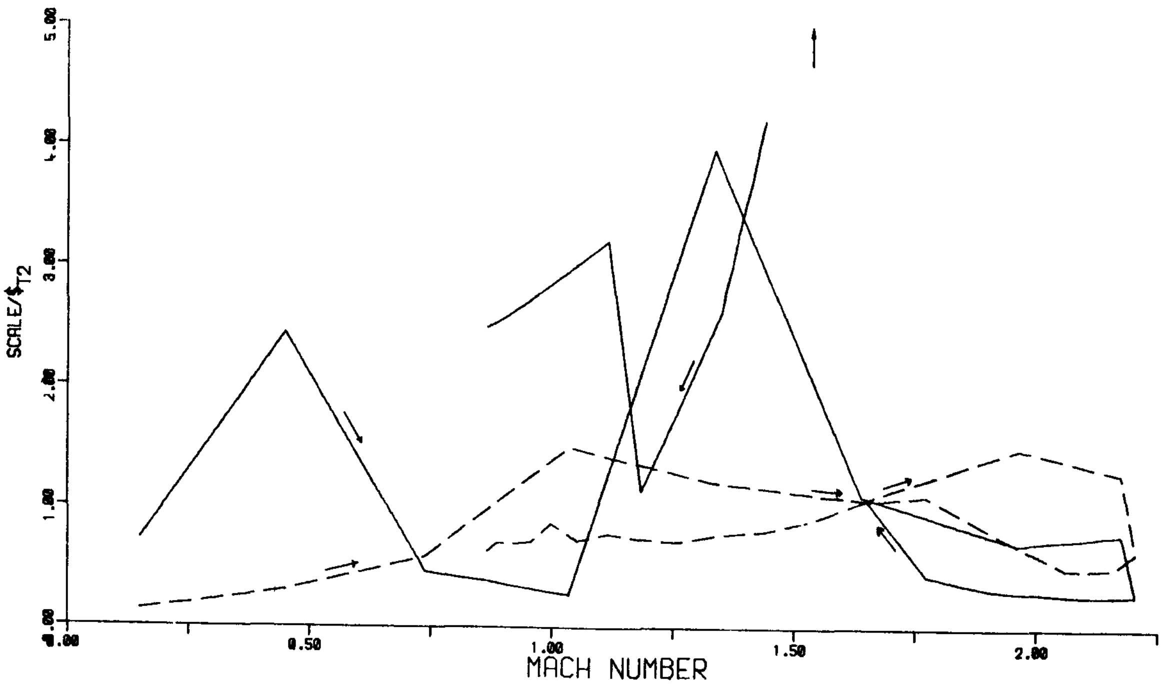


Fig. 12b Plot of $\frac{scale}{\$_T}$ / Mach No Rear station

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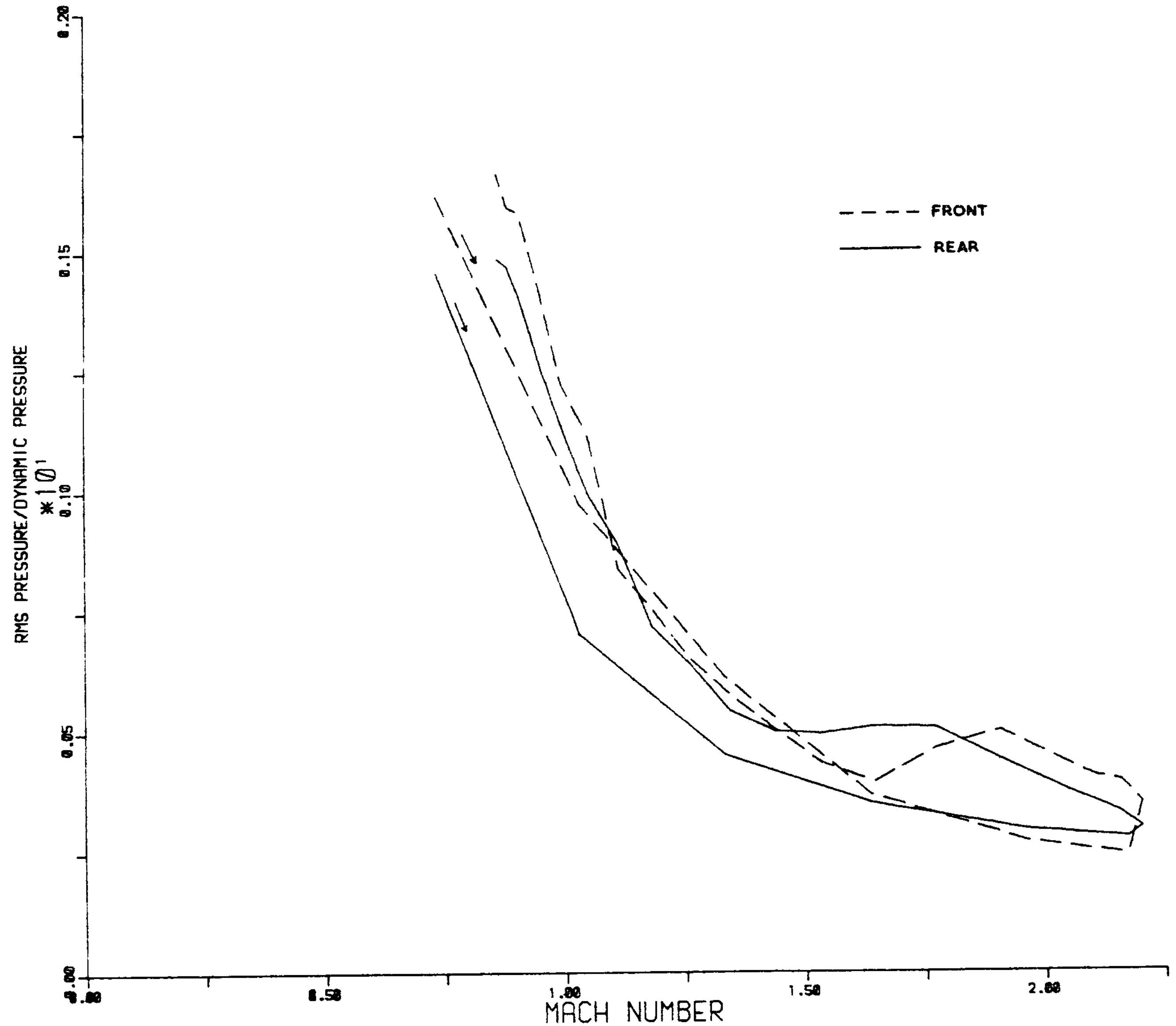

Fig.13 Variation of rms pressure with Mach No Shark 3.

ARC CP No 1302
February 1974

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Roberts, D R

BOUNDARY-LAYER PRESSURE FLUCTUATIONS AT HIGH REYNOLDS NUMBERS ON A SECOND FREE-FLIGHT TEST VEHICLE

Measurements have been made of the boundary-layer pressure fluctuations at two positions on the body of a free-flight aerodynamic test vehicle powered by a solid-fuel rocket motor The vehicle reached a maximum Mach number of 2.2 with a maximum Reynolds number of about 118 millions at the front measuring station and 207 millions at the rear

Pressure spectra have been deduced, and have been found to compare reasonably with a theoretical spectrum The scale of the boundary-layer turbulence fluctuates appreciably but is for the most part between 30% and 80% of the turbulence boundary-layer thickness for all Mach numbers up to 2.2 The root mean square boundary-layer pressure reduced with Mach number from about 0.01 times the free stream dynamic pressure at M = 1 to about 0 003 at M = 2.2, the front station tending to be slightly the higher at each Mach number

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