I.O.S.

RECORDINGS OF POTENTIAL DIFFERENCE ACROSS THE PORT PATRICK–DONAGHADEE SUBMARINE CABLE

D. PRANDLE AND A. J. HARRISON

REPORT NO. 21

1975

NATURAL ENVIRONMENT RESEARCH COUNCIL
INSTITUTE OF OCEANOGRAPHIC SCIENCES

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CONTENTS

ABSTRACT

Potential gradients generated by the flow of water through the North Channel of the Irish Sea were recorded for the period January to April 1974 using a submarine cable. The recordings formed part of an observational programme in the Irish Sea carried out by I.O.S. Bidston. A tidal analysis of the recordings showed that the magnitude of the induced voltage was in good agreement with earlier measurements of BOWDEN and HUGHES (1961). An examination was made of the correlation between the non-tidal flow indicated by the cable measurements and the wind as recorded at four stations in the Irish Sea. The various parameters in the equation relating wind induced flow to the wind stress were adjusted so as to maximise the correlation between the phenomena. By this means some features of the wind effects were identified.

1. INTRODUCTION

Potential gradients generated by the flow of water through the North Channel of the Irish Sea were measured by use of the Portpatrick-Donaghadee submarine cable (figure 1). The voltages were recorded at ten minute intervals and were later reduced to hourly values. This report includes a complete tabulation of these hourly values and plots of both the ten minute and hourly values.

A harmonic analysis of the data was made by separating it into 3 blocks, each of 29 days duration. The results of this analysis are compared with the corresponding values shown by BOWDEN and HUGHES (1961) which they obtained from recordings of the same cable in 1955. In addition, the correlation between the non-tidal component of cable voltage and the wind field over the Irish Sea is examined.

The data contained in this report forms part of an observational programme carried out in the Irish Sea during the early part of 1974. When all of the relevant data obtained during this exercise is available, a more exhaustive examination of the flow conditions throughout the area will be possible. The present data set should be of particular use in any future modelling of this period.

2. INSTRUMENTATION

The potential difference across the submarine cable was recorded on an analogue/digital battery-operated data logger kindly loaned by the Oceanography Department of the University of Liverpool. The instrument recorded 12 channels of data on quarter-inch magnetic tape at ten minute intervals. A 10 inch chart recorder was also used to monitor the signal, this was useful in providing a continuous check on the recording system and also enabled "noisy" periods to be readily identified (figure 2). The electrical circuit used to isolate the potential difference due to the flow of water from the high frequency communications signals on the submarine cable was similar to that shown by HUGHES (1969).

3. DATA PROCESSING

The cable recordings extended from 17 January to 17 April 1974. The format of the data, as originally recorded by the data logger, was incompatible with the IBM 1130 computer of IOS Bidston. An intermediate process was used in which the data on the original magnetic tapes was transferred to punched paper tape. The process introduced some spurious values and caused some loss of data: a full description of this problem has been given by PRANDLE and HARRISON (1975a).

The recordings, made at 10 minute intervals, were converted to hourly values using the filter $\alpha_6^2 \alpha_7 / 6^2 . 7$ described by QURAISHEE (1967), where α_n is a filter involving the summation of n consecutive observations of a time series. This filter incorporates all values up to 8 time increments (80 minutes) on either side of the central observation. The filter eliminates the contribution from frequencies above 1 cycle per hour, however it also leads to a reduction in the amplitude of the tidal constituents amounting to (a) 0.86% of species 1, (b) 3.69% of species 2 and (c) 14.07% of species 4. The application of the filter reduced the variance of the original time series by about 11%.

A final visual check on the data was made by plotting both the original 10 minute values and the computed hourly values together with the observed vertical tide at Portpatrick (figures 3a,b,c). This enabled a few spurious values to be corrected. The final list of hourly values, as used in the subsequent analysis is shown in tables 1a,b,c. The sign convention is such that flow towards the north-west produces a positive voltage. The precise timing of the values shown in this table are in error due to the inaccuracy of the data logger clock. Periodic checks on the timing error showed that it was a linear function given by $T = 2.28 (N - 14)$ where T is the number of seconds early at which recordings were logged on day number N.

4. TIDAL ANALYSIS

The hourly values of voltage, shown in table 1, were divided into 3 sets each of 29 days duration. A tidal analysis of each set was then completed by using the standard "TIFA" programme of I.O.S. Bidston. The separation of the close frequency constituents was facilitated by reference to the values of the vertical tide at Portpatrick. Table 3 shows the values for the principal constituents obtained from this analysis together with the corresponding results obtained by BOWDEN and HUGHES (1961). The phase values shown in table 3 include corrections for the timing error in the hourly values of table 1. Similarly the values of amplitude in table 3 include corrections for the reduction in amplitude introduced by the initial filtering (§ 3).

The noise:signal ratio for each tidal frequency band was calculated from a spectral analysis of (a) the time series predicted from harmonic constants and (b) the time series of the residual values obtained by removing this predicted tide from the actual recordings. The harmonic constants used to derive the first time series consisted of the values for 36 constituents derived from an analysis of 87 days of data. The variance in the appropriate frequency band of time series (a) reflects the power of the signal and that of (b) the noise. For a bandwidth of 9 cycles per month centred on the diurnal species the noise:signal ratio was 37.8%. Over the same bandwidth for the semi-diurnal species the ratio was 0.4%. Over a bandwidth of 11 cycles per month for the quarter-diurnal species the ratio was 59.0%. The large noise:signal values for the diurnal and quarter-diurnal species is reflected in the month to month variation of both the phase and amplitude of the corresponding constituents. By contrast the semi-diurnal constituents, with the exception of L2, are extremely consistent. The high noise value for the diurnal species could be partly attributed to electro-magnetic noise at the solar diurnal frequency. A significant contribution to the noise level might also be expected due to the inadequacy of the method of tidal analysis for a 29 day data set. However, the major reason is almost certainly due to the small magnitude of the energy in these bands - the diurnal:semi-diurnal energy ratio is less than 0.2% while the quarter-diurnal:semi-diurnal ratio is less than 0.1%.

A comparison of the present results with those of BOWDEN and HUGHES indicates good agreement for the semi-diurnal constituents. Manifestly, there is a discrepancy for the other frequencies of the same order as the month to month variations in the present results. However, the values for K1 are completely incompatible. The actual value for M_2 deduced from BOWDEN and HUGHES is 0.575v (assuming a calibration factor of 1v = 1.35ms^{-1}), the present study gives 0.502v. However, the former value was based on recordings made in July and August while the latter value applies to the period January to April. HUGHES (1969, Figure 5) shows that these two periods are at opposite extremes of the range of variation of the conversion factor C_1, relating induced voltage to mean velocity. This variation in C_1 is mainly a result of the annual variation in the conductivity, K_1, of the sea. LONGUET-HIGGINS (1949) showed that for a uniform stream of water flowing in a long straight channel of semi-elliptical cross-section the value of C_1 will be given by

$$C_1 = H_y L / (1 + K_o L / 2 K_1 D) \tag{1}$$

where H_y is the vertical component of the earth's magnetic field, L is the channel breadth or length of the major axis of the ellipse, Ko is the conductivity of the sea bed and D is the channel depth or half the length of the minor axis of the ellipse. The extremes of the range of values of K_1 are, according to HUGHES (1969, Figure 6), 3.4 $\Omega^{-1}m^{-1}$ and 4.1 $\Omega^{-1}m^{-1}$. By inserting these values into equation (1) together with the values Ko = 0.034 $\Omega^{-1}m^{-1}$, L = 34600m and D = 138.4m, as given by BOWDEN and HUGHES (1961), it is possible to adjust the value of M_2 to take account of the annual variation. By this means, the value of M_2 found in the present study was modified from the original January to April value of 0.502v to a July - August value of 0.554v. The latter value is within 4% of the value of BOWDEN and HUGHES. Preliminary results from a study presently being conducted at I.O.S. Bidston involving an analysis of a long term recording of the voltage on the Dover-Sangatte cable suggest that this figure of 4% is within the range of variability to be expected.

5. CORRELATION OF NON-TIDAL CABLE VOLTAGE WITH WIND DATA

The non-tidal or residual component of the cable voltage was obtained by removing the tidal component from the hourly values of recorded voltage shown in table 1. For the residual voltages shown in table 2 the tidal component was calculated using the technique of complex demodulation, HOWARTH (1975). In this way most of the energy in the main tidal frequency bands was removed from the recorded signal. The central frequency adopted for each tidal species was as follows; K_1, M_2, M_3, M_4 and M_6. This method of removing the tidal component has an advantage over the technique of simply removing the tide computed by harmonic prediction in so far as it is able to take some account of small phase shifts in the tidal motions. Similarly it is preferable to the use of a "tide-killer" such as Doodson's Xo filter. These filters substantially reduce the residuals due to the fact that the duration of the residual flow is often of the same order as that of the principal tidal constituents.

The recorded potential on a submarine cable includes contributions from several sources (PRANDLE and HARRISON 1975b). Thus, the recorded potential at any time t , denoted by E(t) , can be represented by

$$E(t) = E_o + E_1(t) + C_1 U(t) + C_2 UR(t) \qquad (2)$$

where Eo is a constant independent of water movements, $E_1(t)$ is a potential due to variable electro-magnetic effects, U(t) is the tidal flow, UR(t) is the non-tidal or residual flow and C_2 is the conversion factor, relating voltage to velocity for residual flows. The value of $E_1(t)$ can be disregarded, except during magnetic storms. Hence removing the tidal components from both sides of equation (2), as outlined above, the expression becomes

$$ER(t) = E_c + C_2 UR(t) \qquad (3)$$

The constant Eo can only be accurately determined by reference to an independent measurement of the flow in the channel. It is useful to obtain some estimate for Eo so that absolute values of residual flow can be calculated.

If it were assumed that, over the period of the exercise, the residual flow was negligible then Eo = 0.137 volts, i.e. the time averaged value of ER(t).

BOWDEN and HUGHES (1961) used cable measurements to make estimates of the flow of water through the North Channel due to wind over the Irish Sea. This procedure was repeated for the present exercise. Wind speeds and directions were obtained at six hourly intervals from the Daily Weather Reports of the British Meteorological Office. The wind stations chosen were Mull of Galloway, Ronaldsway, Valley and Aberporth, the locations of these stations are shown in Figure 1. Since the surface stress exerted by wind blowing over water may be expressed as a function of the square of the wind speed, it is appropriate to work in terms of W^2. Figure 4 shows the components of W^2 in two perpendicular directions, NW and NE, the former being aligned with the axis of the North Channel. The figure also shows the residual voltages as listed in table 2.

A relationship between wind stress and residual flow was assumed as follows

$$UR(t+\Delta t) = A\, W_{(t)}^{\lambda} \cos(\theta(t) - \alpha) + UR_o \qquad (4)$$

where Δt is the time lag between the wind stress and the resulting residual flow, A is a coefficient, θ (t) is the direction towards which the wind is blowing, α is the direction for which the wind is most effective in producing residual flows and URo is a residual flow not dependent on direct wind forcing. Equations (3) and (4) give

$$ER(t+\Delta t) = C_2 A\, W_{(t)}^{\lambda} \cos(\theta(t) - \alpha) + C_2 UR_o + E_o \qquad (5)$$

The four parameters Δt, α, (C_2A) and $(C_2URo + Eo)$ were estimated by maximising the correlation between the time series represented by the two sides of equation 5. The method adopted was to first assume Δt and α were known constants. Hence (C_2A) and $(C_2URo + Eo)$ could be calculated directly from a least squares fit for the two time series. The initial values $\Delta t = 0$ and $\alpha = 315^o$ were used. The value of α was then adjusted by using the Newton-Raphson technique to increase the correlation, r, between the time series. For the value of α corresponding to maximum correlation, $dr/d\alpha = 0$ hence a modified value, $\grave{\alpha}$, could be obtained from the expression

$$\grave{\alpha} = \alpha - \frac{dr/d\alpha}{d^2r/d\alpha^2} \qquad (6)$$

The derivatives were obtained by finite difference approximations using values of r corresponding to $\alpha - \delta\alpha$, α and $\alpha + \delta\alpha$. The value of Δt was then adjusted in the same manner as for α. The whole procedure was then repeated successively, using the adjusted values of Δt and α as the known constants, until the values for all four constants converged. In order to test this procedure it was repeated with different values for $\delta\alpha$ and δt. In the first case the values $\delta\alpha = 0.01$rad and $\delta t = 0.1$h were used and convergence to the precision shown in table 4 was obtained after about 5 iterations. In the second case the values $\delta\alpha = 0.002$rad and $\delta t = 0.02$h were used and convergence (to the same values as in case 1) was obtained after about 10 iterations. The results are shown in table 4. The value of the correlation coefficient, r, has the largest value, 0.67, at Ronaldsway. However, the results shown in the table are based on the application of equation (5) over the complete period of 3 months. When the above procedure was repeated for each month's data separately, the correlation coefficient reached a maximum of 0.78 at Ronaldsway. The largest correlations were found in the first month when the winds were strongest. By contrast, during the last month when the winds were extremely moderate the correlation coefficient was as little as 0.23. Better correlations might be expected for shorter periods of strong winds for two reasons:
(a) for shorter periods the value of URo should be less variable

and (b) the larger residuals due to strong winds should be more distinct in relation to flows arising from tidal interactions.

The value of C_2, the conversion factor for residual flows, may well vary with the direction, strength and distribution of the residual flow in the North Channel. However, if it is assumed that $C_2 = C_1$ it is possible to determine the strength of the residual current as a percentage of the wind speed. BOWDEN and HUGHES (1961) used the calibration factor $1v = 1.35ms^{-1}$ (§ 1), this corresponds to a value of $C_1 = 0.741vm^{-1}s$. This value must be adjusted for the variation in the value of M_2 between their study, 0.575v, and the present study, 0.502v. The resulting value of C_1 for the present study is $0.647vm^{-1}s$. Inserting this result into the value of C_2A at Ronaldsway gives a value of $A = 0.00100m^{-1}s$, in close agreement with the value $A = 0.000922m^{-1}s$ found by BOWDEN and HUGHES. On using this value of A in equation (1) the wind-induced residual velocity is given as W/10 per cent of the wind speed. Hence for a wind speed of $10ms^{-1}$ the flow is 1% of the wind speed and at $20ms^{-1}$ it is 2%.

The consistency of the values of (C_2 Uo + Eo) derived for all four wind stations suggests that the method used to determine the parameters in equation (5) was valid. By inserting the mean value of (C_2 Uo + Eo), namely 0.126v, into equation (5) together with the time-averaged value of ER(t), 0.137v, produces an estimate of the time-averaged wind induced flow. The value so obtained is $0.011/C_2$, so that assuming $C_2 = C_1 = 0.647vm^{-1}s$ the mean wind-induced flow is $0.017m^{-1}s$ out of the Irish Sea. The same procedure may be applied to each month of the data separately. The mean value of (C_2 Uo + Eo) for all four wind stations in each month respectively was calculated as 0.135v, 0.121v and 0.125v. The time-averaged values of ER(t) are shown in table 3 as 0.158v, 0.121v and 0.130v. Hence the value of wind-induced flow, calculated for each month separately, is $0.035m^{-1}s$, 0.000 and $0.008m^{-1}s$ respectively. By applying the equation of conservation of salt BOWDEN (1950) gave a value of $0.006m^{-1}s$ for the residual flow in the North Channel. There have been several other estimates, all of the same order of magnitude as the above results. It is difficult to ascertain the extent to which a particular observed residual flow is the result of wind forcing, either direct or indirect. A possible interpretation of the monthly figures is that the large outflow during the first month, due to strong winds, was partly compensated in the second month, subsequently returning to "normal" in the last month.

The parameter α shows a consistent change from 314° at Mull of Galloway to 337° at Aberporth. The direction at Mull of Galloway corresponds to the alignment of the Channel while the other values correspond to the change in the direction of the effective fetch. The values of Δt also vary in a systematic and logical manner. The values are much smaller than the figure of 2 hours given by BOWDEN and HUGHES (1961). However examination of their Figure 13, from which they obtained this value, suggests that the present values are almost equally valid. The indication that, for winds at Mull of Galloway, the residual flow is virtually coincident with the wind forcing is at first difficult to comprehend. A possible explanation may be derived by consideration of the effect on residual flows of atmospheric pressure disturbances which could precede the onset of the wind field (LENNON 1973). In addition, it is recognised that the resolution in time of the wind data, (values every 6 hours), is insufficient for an accurate determination of Δt. It is interesting to note that the values of Δt calculated for just the first month's data ranged from 19 minutes at Mull of Galloway to 92 minutes at Aberporth. In this case, the extreme values of both the residual flow and the winds were sufficiently large and continuous to enable the time lag to be more sensibly defined.

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Notation

A	coefficient relating wind-induced current to W^2,
C_1	conversion factor relating voltage to velocity for the tidal component,
C_2	conversion factor relating voltage to velocity for the non-tidal component,
D	channel depth or half the length of the minor axis of the ellipse,
E	recorded e.m.f.
Eo	constant potential or back e.m.f.
E_1	potential due to electro-magnetic effects,
ER	non-tidal potential,
Hy	vertical component of the earth's magnetic field,
Ko	specific conductivity of the channel bed,
K_1	specific conductivity of sea water,
L	channel breadth or length of the major axis of the ellipse,
r	correlation coefficient,
U	channel velocity,
UR	non-tidal velocity,
URo	component of non-tidal velocity,
W	wind speed,
λ	direction for which the wind is most effective in producing residual flows,
λ_n	a filter involving the summation of n consecutive observations of a time series,
Δt	time lag between the wind stress and the resulting residual flow,
θ	direction towards which the wind blows, relative to true north.

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POTENTIAL MEASURED BY PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0	100	200	300	400	500	600	700	800	900	1000	1100	DAY
1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	NO.
275	155	10	-125	-170	-152	-82	25	165	352	390	355	18
282	135	-15	-145	-262	-300	-242	-117	37	220	355	362	
325	220	75	-82	-217	-310	-295	-192	-25	167	320	390	19
370	290	177	17	-140	-255	-287	-212	-92	72	290	425	
480	432	287	115	-47	-212	-292	-255	-142	47	257	440	20
525	507	387	222	35	-132	-247	-227	-195	-52	180	400	
502	505	437	252	50	-155	-347	-415	-330	-137	102	352	21
517	572	507	365	170	-50	-227	-325	-317	-200	20	287	
505	610	592	455	240	-7	-225	-350	-350	-225	0	277	22
517	642	640	532	337	90	-155	-330	-380	-322	-130	112	
415	592	637	562	382	130	-137	-340	-412	-340	-160	117	23
400	595	655	577	400	147	-117	-330	-437	-407	-252	5	
305	547	650	622	465	225	-60	-327	-477	-472	-327	-60	24
267	552	700	697	555	327	60	-200	-377	-445	-385	-140	
147	417	632	687	625	427	95	-222	-390	-455	-357	-122	25
130	415	632	752	740	500	312	-45	-302	-365	-342	-265	
30	410	612	785	755	592	367	77	-180	-337	-335	-215	26
50	365	622	797	785	620	415	125	-127	-395	-487	-400	
-147	157	365	682	712	582	385	100	-185	-417	-492	-397	27
-207	87	405	642	725	677	577	222	-15	-107	-120	-127	
35	335	647	862	932	825	630	355	55	-195	-345	-342	28
-210	17	310	577	725	727	640	377	37	-170	-317	-420	
-462	-240	72	340	560	622	535	375	140	-140	-307	-372	29
-362	-177	87	332	605	707	715	667	462	210	15	-107	
-140	-65	102	377	635	772	772	672	497	295	87	-77	30
-170	-130	27	282	512	662	712	655	517	202	-20	-182	
-312	-287	-177	-17	205	375	485	487	405	265	62	-102	31
-240	-307	-237	-32	130	347	562	632	557	507	320	177	
62	5	0	82	235	377	545	617	610	582	450	290	32
115	-20	-57	-55	92	230	440	632	685	600	570	377	
125	57	-40	-82	-45	47	192	332	480	510	492	412	33
230	87	-37	-157	-175	-112	72	247	387	505	525	417	
322	187	-22	-162	-217	-212	-105	75	217	410	497	490	34
472	310	127	-60	-195	-285	-247	-105	145	395	522	577	
530	410	245	50	-112	-220	-230	-137	25	250	492	577	35
575	510	332	67	-230	-420	-425	-342	-175	107	387	557	
640	535	400	180	-97	-320	-452	-430	-292	-10	280	495	36
625	645	527	287	65	-157	-332	-450	-350	-162	135	472	
657	672	577	377	90	-210	-452	-500	-457	-277	0	367	37
607	660	657	535	275	-145	-435	-600	-567	-432	-145	220	
520	702	737	552	280	-42	-332	-537	-617	-462	-180	107	38
527	830	882	787	580	245	-152	-427	-555	-527	-340	10	
387	732	922	862	652	350	-22	-337	-497	-547	-382	-127	39
280	650	902	947	737	445	107	-235	-522	-597	-517	-247	
187	580	805	905	795	547	202	-167	-470	-630	-587	-335	40
-25	320	715	945	927	700	392	65	-305	-542	-582	-467	
-182	210	610	865	910	770	497	145	-180	-392	-485	-430	41
-205	165	565	822	895	852	682	362	90	-247	-535	-447	
-310	-40	277	587	755	757	567	272	-75	-357	-537	-542	42
-405	-147	197	532	717	777	715	560	152	-107	-380	-587	
-580	-352	-37	327	592	607	612	505	222	-27	-335	-455	43
-465	-277	-57	220	487	635	595	535	367	140	-147	-317	
-367	-300	-107	152	425	607	660	555	405	215	-35	-215	44
-322	-310	-155	37	265	435	547	525	437	325	117	-115	
-222	-247	-237	-122	100	327	472	515	440	330	185	87	45
-30	-65	-55	45	232	400	575	685	642	545	450	272	
87	-40	-92	-80	12	182	352	510	560	552	480	335	46
207	85	-2	-57	17	102	250	380	435	512	495	432	
305	130	20	-55	-80	-32	17	177	307	407	435	365	47
217	100	5	-47	-92	-120	-75	42	180	237	375	360	

TABLE 1a

POTENTIAL MEASURED BY PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0 1200	100 1300	200 1400	300 1500	400 1600	500 1700	600 1800	700 1900	800 2000	900 2100	1000 2200	1100 2300	DAY NO.
287	207	85	-75	-177	-205	-165	-72	72	235	350	367	48
355	267	167	30	-82	-130	-162	-135	15	197	340	460	
497	430	310	137	-37	-152	-205	-180	-40	95	275	405	49
477	427	302	185	10	-182	-260	-227	-210	-7	220	417	
540	507	400	242	40	-165	-300	-282	-205	-55	137	362	50
580	585	530	360	142	-77	-232	-290	-202	-87	127	380	
600	592	505	355	132	-90	-255	-325	-362	-180	62	282	51
525	600	552	377	210	-37	-272	-355	-310	-260	-60	252	
470	497	512	477	247	-45	-262	-415	-492	-385	-120	202	52
457	597	627	522	357	120	-160	-385	-495	-350	-172	105	
400	612	642	560	375	110	-145	-380	-480	-470	-277	30	53
340	592	645	600	420	167	-130	-352	-482	-437	-237	-120	
232	502	640	675	520	265	-102	-355	-480	-475	-357	-127	54
237	517	702	792	615	402	97	-192	-332	-475	-442	-237	
127	412	690	772	647	415	122	-205	-455	-517	-517	-242	55
120	432	680	732	665	527	282	-10	-392	-532	-500	-325	
0	335	537	685	695	522	285	-17	-352	-520	-510	-410	56
-140	232	500	710	780	600	417	160	-282	-480	-460	-370	
-157	117	460	647	702	645	485	220	-135	-422	-512	-465	57
-287	55	392	700	737	672	565	257	-12	-265	-460	-442	
-320	-52	272	510	692	667	517	347	7	-227	-382	-440	58
-370	-132	147	440	632	662	632	360	202	-70	-300	-375	
-327	-122	95	325	552	657	647	430	202	-12	-210	-330	59
-357	-155	60	352	580	687	667	542	377	165	-152	-282	
-410	-282	-97	120	340	442	512	510	390	170	-27	-180	60
-300	-310	-170	0	200	350	487	520	357	205	40	-170	
-310	-340	-255	-145	40	250	407	455	420	337	245	45	61
-125	-220	-255	-220	-67	127	335	475	520	475	312	142	
-15	-125	-182	-185	-100	17	175	305	397	470	417	255	62
132	-10	-125	-197	-207	-92	45	247	390	445	467	387	
202	85	-117	-207	-240	-225	-127	107	295	395	475	442	63
330	185	52	-90	-262	-250	-220	-60	197	430	540	552	
502	330	127	-45	-210	-305	-295	-177	0	230	477	570	64
560	497	327	77	-185	-360	-332	-292	-40	207	390	620	
625	525	392	157	-87	-262	-340	-337	-190	125	435	645	65
777	735	612	422	107	-180	-342	-447	-355	-72	310	600	
780	792	637	372	72	-222	-455	-515	-407	-185	112	495	66
747	767	735	547	270	-20	-312	-530	-507	-292	57	392	
665	837	782	557	275	-57	-392	-595	-567	-482	-185	232	67
595	817	810	702	455	107	-230	-452	-485	-365	-180	127	
477	807	877	747	490	212	-227	-515	-637	-612	-410	-32	68
357	717	895	845	655	395	35	-375	-697	-657	-460	-100	
222	580	795	867	695	375	-10	-325	-555	-677	-595	-287	69
97	477	780	917	780	570	227	-157	-460	-595	-582	-390	
-22	330	690	872	777	547	302	-35	-405	-567	-520	-420	70
-162	257	615	805	850	800	527	72	-222	-482	-540	-457	
-222	142	470	767	830	717	480	202	-100	-380	-492	-490	71
-315	40	402	650	780	777	522	302	40	-292	-440	-462	
-335	-85	232	537	685	710	625	345	62	-167	-350	-482	72
-372	-170	120	392	582	652	567	445	197	-85	-295	-405	
-372	-207	2	255	477	580	550	475	307	57	-170	-305	73
-375	-252	-55	142	375	527	570	557	370	160	-15	-170	
-270	-232	-102	67	262	420	487	502	422	267	60	-167	74
-270	-217	-197	-62	180	325	420	452	370	292	175	12	
-107	-170	-202	-107	27	167	292	350	300	230	115	-12	75
-155	-200	-215	-145	-10	110	247	320	340	300	195	125	
20	-102	-182	-165	-115	-70	72	210	270	287	302	310	76
170	42	-32	-112	-135	-70	-20	85	220	317	340	325	
252	132	-7	-120	-180	-170	-87	62	162	287	352	310	77
270	222	62	-25	-122	-192	-172	-80	45	205	360	445	

TABLE 1b

POTENTIAL MEASURED BY PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0 1200	100 1300	200 1400	300 1500	400 1600	500 1700	600 1800	700 1900	800 2000	900 2100	1000 2200	1100 2300	DAY NO.
382	275	175	37	-50	-160	-147	-25	140	275	457	532	78
500	447	302	125	0	-145	-202	-140	-42	127	315	487	
507	457	350	167	-75	-217	-232	-177	-77	122	347	487	79
525	520	385	182	2	-140	-202	-237	-157	-15	162	422	
582	540	465	295	15	-102	-227	-325	-267	-37	150	390	80
602	682	572	397	315	-25	-175	-272	-460	-267	0	300	
482	662	642	437	142	-127	-297	-395	-372	-245	67	442	81
582	632	647	495	225	-25	-295	-415	-445	-330	2	250	
425	567	640	552	245	5	-237	-447	-487	-405	-137	205	82
497	730	757	677	335	85	-187	-402	-450	-385	-182	120	
500	680	740	630	445	192	-150	-445	-580	-402	-255	-15	83
392	662	740	707	530	262	55	-367	-527	-457	-320	-22	
255	535	790	702	557	335	32	-317	-525	-562	-437	-122	84
237	560	727	750	645	387	172	-190	-497	-605	-457	-300	
80	410	680	747	660	472	190	-180	-387	-505	-500	-297	85
30	412	687	792	775	550	282	-12	-337	-515	-542	-382	
-40	247	610	747	727	542	277	60	-252	-497	-555	-425	86
-120	200	527	715	800	735	455	115	-145	-397	-507	-420	
-232	50	362	602	717	630	392	202	-2	-315	-480	-510	87
-370	-50	262	547	645	675	602	357	45	-222	-412	-432	
-285	-97	160	417	577	635	622	415	180	-85	-335	-412	88
-377	-182	62	255	540	692	617	432	265	17	-182	-282	
-320	-282	-62	150	397	560	580	512	372	152	-42	-180	89
-282	-307	-197	52	237	462	592	507	410	242	32	-125	
-235	-317	-225	-77	125	300	395	465	462	325	200	15	90
-155	-262	-272	-175	-12	222	375	467	537	437	262	115	
-52	-205	-257	-240	-150	0	182	350	427	485	402	292	91
210	17	-175	-200	-185	-75	157	342	435	495	527	397	
287	137	-30	-137	-192	-105	20	172	357	520	595	540	92
437	252	37	-90	-242	-202	-127	25	275	540	610	512	
377	220	152	-55	-257	-287	-267	-110	105	355	517	622	93
580	407	240	-7	-217	-417	-417	-215	-30	172	450	557	
520	435	290	80	-187	-367	-410	-342	-92	200	465	635	94
685	635	547	307	-5	-307	-452	-440	-280	42	440	680	
742	697	535	275	-25	-297	-440	-432	-342	-147	167	492	95
717	765	655	500	115	-235	-467	-547	-492	-230	127	470	
680	757	710	460	55	-177	-362	-460	-502	-350	-20	337	96
652	812	770	577	335	0	-377	-547	-457	-387	-147	287	
560	747	800	697	417	62	-240	-452	-565	-517	-240	67	97
435	757	830	752	515	230	-127	-415	-522	-540	-337	15	
410	687	845	780	585	267	-37	-335	-525	-552	-427	-162	98
210	602	805	805	670	435	97	-257	-500	-562	-437	-235	
85	487	745	815	720	435	130	-157	-410	-540	-532	-327	99
-30	387	657	747	722	610	367	-17	-365	-465	-522	-400	
-135	240	580	732	745	660	367	50	-225	-425	-460	-457	100
-232	135	477	670	712	657	540	237	-77	-342	-470	-445	
-277	30	285	577	692	632	537	300	-2	-237	-405	-380	101
-260	-40	265	517	697	697	527	407	162	-85	-267	-325	
-265	-72	185	432	592	665	622	447	230	-10	-187	-265	102
-217	-110	97	355	552	580	540	470	292	85	-90	-215	
-265	-152	0	190	427	555	575	527	345	130	-40	-192	103
-240	-177	-110	7	245	392	430	427	372	212	30	-160	
-237	-220	-167	-37	115	287	405	427	397	277	107	-80	104
-187	-172	-160	-52	42	197	322	370	417	340	215	85	
-25	-135	-165	-130	-25	95	232	355	390	360	245	137	105
32	-95	-115	-112	-82	30	142	232	297	345	337	270	
127	2	-95	-147	-125	-55	47	217	387	437	395	272	106
220	122	-22	-97	-140	-137	-60	57	200	317	385	400	

TABLE 1c

RESIDUAL POTENTIAL PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0	100	200	300	400	500	600	700	800	900	1000	1100	DAY
1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	NO.
****	****	****	****	****	****	****	****	****	****	****	****	18
****	****	****	****	****	****	****	****	****	****	****	****	
****	****	****	****	****	****	****	****	****	****	****	****	19
****	****	****	****	****	****	****	****	****	****	****	****	
****	****	99	110	145	141	132	132	111	97	82	88	20
103	127	127	132	138	148	143	176	122	91	97	104	
80	76	106	96	115	130	93	70	77	86	77	81	21
82	98	107	121	135	137	140	134	121	107	104	112	
118	127	143	146	151	157	161	158	151	142	130	126	22
126	128	139	154	161	161	152	138	133	112	111	82	
114	111	114	128	142	152	153	147	142	140	121	115	23
108	98	94	89	91	89	94	101	106	116	121	123	
126	119	98	94	91	104	112	98	90	92	91	98	24
114	129	127	121	108	113	132	142	148	134	107	137	
126	101	113	111	139	157	118	96	139	143	159	183	25
139	118	112	147	195	138	219	158	146	210	216	136	
161	226	164	202	195	195	232	244	251	245	251	226	26
229	232	215	229	206	171	198	187	198	118	87	85	
110	110	23	139	116	90	124	133	129	103	117	156	27
143	138	149	163	151	152	234	144	174	285	386	377	
393	419	420	392	346	265	238	237	234	220	209	242	28
270	252	228	219	202	167	174	126	62	101	117	90	
9	51	76	57	89	90	69	96	130	115	136	162	29
158	203	208	156	196	183	195	269	284	289	311	323	
332	334	307	317	335	329	299	281	286	316	331	326	30
306	310	312	321	293	251	219	196	198	96	101	121	
96	131	151	131	136	114	109	95	90	104	101	131	31
139	132	160	221	167	155	195	193	155	232	226	277	
317	345	344	352	363	326	327	294	260	286	276	287	32
290	295	326	308	343	291	287	309	281	214	285	253	
179	263	262	251	249	230	211	181	201	174	177	191	33
161	195	230	214	215	196	210	172	121	127	134	103	
145	182	145	142	154	142	147	155	97	120	115	106	34
168	158	177	195	208	168	141	113	123	139	114	132	
147	162	189	210	228	215	198	182	143	120	148	121	35
116	140	138	120	76	61	108	116	89	90	89	80	
119	84	111	131	124	116	84	84	77	107	95	65	36
77	107	107	87	156	213	218	143	145	99	70	94	
90	78	87	99	108	118	97	128	107	95	66	87	37
61	6	48	94	114	37	49	51	88	76	77	73	
42	46	87	59	55	71	105	111	78	122	155	87	38
132	167	139	143	171	170	142	166	177	159	139	151	
130	142	181	178	182	194	180	186	214	176	182	140	39
160	151	161	171	117	111	135	160	147	172	156	163	
222	214	138	139	142	155	151	139	134	123	127	171	40
146	96	140	176	173	136	133	168	147	151	170	151	
142	147	171	182	186	197	205	197	211	248	248	213	41
190	207	234	205	153	163	191	173	252	234	144	249	
222	183	129	118	114	126	101	81	63	84	98	126	42
132	126	131	146	121	120	132	170	52	119	119	54	
38	81	88	113	123	36	84	135	101	143	91	109	43
93	141	115	94	101	105	51	79	86	111	101	143	
180	197	213	204	193	179	176	135	130	148	136	153	44
138	128	161	148	129	90	101	84	81	119	119	108	
163	201	169	145	152	151	138	138	116	121	138	222	45
251	281	276	285	318	292	297	318	272	239	265	257	
251	257	269	268	264	266	248	263	251	260	270	256	46
276	276	256	212	240	218	219	207	162	199	205	231	
243	221	239	245	237	226	146	143	127	137	148	137	47
102	117	140	172	170	132	105	101	91	16	72	51	

TABLE 2a

RESIDUAL POTENTIAL PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0 1200	100 1300	200 1400	300 1500	400 1600	500 1700	600 1800	700 1900	800 2000	900 2100	1000 2200	1100 2300	DAY NO.
51	96	126	109	110	118	114	92	77	76	74	55	48
89	105	139	142	149	171	140	101	116	120	90	106	
139	153	176	178	176	179	159	131	146	101	86	76	49
110	117	111	153	158	117	112	126	46	76	83	88	
120	117	126	145	153	140	116	138	127	109	76	80	50
163	155	189	180	171	162	156	141	166	126	114	126	
178	129	117	128	126	141	162	170	91	122	126	78	51
114	106	101	65	110	111	88	118	155	82	59	101	
91	10	41	126	105	78	108	108	55	54	88	109	52
90	76	92	92	124	148	129	88	39	114	98	91	
96	114	95	97	101	103	133	118	113	73	77	88	53
76	89	51	63	57	61	53	73	76	115	173	32	
69	67	62	110	107	115	61	86	126	144	123	87	54
119	101	107	171	111	133	132	136	201	129	85	72	
123	91	149	162	116	97	117	120	114	143	73	130	55
167	139	140	96	74	105	138	178	77	81	101	116	
159	159	85	97	116	76	88	119	101	119	145	106	56
103	126	74	104	155	81	112	162	47	78	161	161	
157	122	146	118	115	131	146	152	123	106	134	130	57
114	154	151	192	120	101	149	84	117	148	117	136	
116	136	158	123	153	127	98	137	69	115	162	157	58
123	134	119	120	109	82	138	54	145	143	141	177	
182	215	185	151	160	158	178	104	87	113	143	172	59
155	226	212	243	234	189	147	127	154	176	95	151	
97	158	169	163	162	92	80	110	116	78	85	123	60
124	118	147	128	110	57	63	76	6	23	65	59	
70	92	122	97	101	117	118	87	63	69	124	103	61
103	122	119	97	110	110	121	121	120	128	102	115	
138	163	173	164	169	141	121	89	76	120	121	83	62
122	141	157	161	146	159	117	113	85	53	90	115	
93	153	108	131	146	121	90	137	127	76	89	83	63
77	92	144	177	129	172	120	96	113	127	109	113	
156	147	146	177	174	157	142	126	82	60	105	101	64
104	148	163	151	123	112	184	133	167	123	40	117	
110	115	173	185	195	216	226	185	157	191	194	170	65
203	191	207	248	222	209	223	151	116	127	162	148	
170	195	186	165	169	174	151	154	169	156	115	149	66
159	107	152	155	160	199	190	120	117	144	174	132	
98	141	147	121	132	151	139	130	167	94	96	130	67
124	121	89	120	123	108	124	164	214	232	170	126	
95	145	137	126	116	170	103	130	154	121	101	135	68
121	126	121	102	108	152	163	112	15	74	101	156	
97	91	81	137	132	101	70	114	146	107	78	116	69
127	108	106	129	79	111	111	105	121	146	121	99	
126	87	123	153	103	77	139	153	101	131	199	148	70
110	151	149	112	117	201	195	90	142	134	167	162	
151	164	132	176	157	133	116	143	165	147	166	139	71
129	178	189	147	131	152	63	110	162	116	151	159	
159	154	151	162	128	123	148	85	83	133	159	108	72
151	151	153	134	111	98	65	107	101	86	101	112	
133	159	136	123	124	104	72	104	130	123	130	155	73
126	161	168	120	122	122	119	163	117	105	142	158	
140	154	166	151	139	128	110	133	143	145	136	97	74
112	180	119	98	146	111	92	99	64	88	117	120	
138	147	106	121	119	97	84	69	23	16	11	29	75
30	81	87	105	133	112	106	78	61	42	3	40	
71	78	79	113	117	60	65	70	45	37	78	158	76
130	127	154	131	110	121	68	43	58	77	77	101	
123	135	133	127	112	95	83	95	49	58	67	37	77
66	129	99	138	135	103	91	87	67	68	98	134	

TABLE 2b

RESIDUAL POTENTIAL PORTPATRICK-DONAGHADEE CABLE IN MILLIVOLTS

0 1200	100 1300	200 1400	300 1500	400 1600	500 1700	600 1800	700 1900	800 2000	900 2100	1000 2200	1100 2300	DAY NO.
110	112	162	183	223	173	157	173	179	136	171	173	78
161	202	194	173	201	170	156	178	153	138	126	151	
126	142	183	191	136	130	167	174	132	127	139	119	79
92	130	127	107	115	136	188	185	187	149	94	138	
158	99	141	181	132	208	210	145	108	128	58	72	80
136	176	152	169	316	184	199	205	10	47	60	99	
81	160	176	155	131	119	136	138	140	93	114	193	81
123	76	112	116	106	131	77	89	92	101	186	130	
55	55	105	129	64	129	156	112	110	86	99	103	82
91	149	151	176	53	105	134	126	144	136	136	132	
190	149	149	115	114	142	130	103	77	191	137	70	83
126	118	88	116	111	101	216	102	113	166	134	156	
99	74	169	106	116	130	134	110	127	118	89	128	84
144	132	85	85	114	80	154	121	87	83	136	53	
110	99	114	105	117	138	126	69	148	181	138	121	85
126	155	137	106	141	108	107	123	103	130	123	117	
169	120	181	141	120	87	61	128	111	98	117	133	86
176	162	160	112	129	172	121	69	111	115	130	162	
138	126	133	128	130	90	27	83	154	105	116	103	87
92	142	139	138	58	72	137	128	93	92	99	140	
194	169	158	152	117	102	154	118	116	104	78	129	88
151	191	187	99	142	162	101	57	108	102	122	170	
169	122	158	136	156	157	120	111	120	99	116	162	89
171	145	129	162	101	119	138	62	83	101	94	118	
140	108	146	145	149	131	79	81	103	73	106	97	90
97	115	136	145	126	149	113	84	132	116	93	117	
113	101	129	132	114	101	107	113	80	116	105	124	91
201	185	152	202	171	133	172	161	99	97	181	179	
220	228	221	236	209	219	197	163	147	148	168	169	92
191	170	158	234	201	226	167	117	134	197	176	122	
112	104	210	201	160	181	130	126	114	113	83	126	93
138	96	121	127	168	114	101	153	94	11	51	59	
65	111	147	166	140	131	130	110	160	170	146	120	94
114	126	197	211	210	174	161	143	116	129	183	174	
154	172	174	161	152	134	136	159	135	84	66	83	95
122	130	115	186	129	113	115	120	101	123	119	103	
84	106	153	122	27	113	164	178	119	111	136	123	96
134	141	109	77	128	154	91	102	218	156	106	156	
83	80	123	164	149	133	151	153	118	99	154	108	97
95	144	120	118	101	147	147	138	163	119	131	147	
149	116	143	128	126	106	147	148	133	134	137	124	98
114	147	138	109	101	122	129	115	107	126	173	137	
91	116	124	131	132	69	84	135	137	126	108	140	99
119	157	129	87	85	126	157	118	76	153	127	132	
126	128	139	119	126	160	103	106	141	141	165	95	100
108	147	152	126	106	113	165	137	140	126	118	127	
143	169	89	122	130	101	143	139	131	157	132	166	101
174	168	174	156	190	180	101	157	164	181	186	193	
199	226	222	189	154	165	178	149	155	169	193	203	102
223	208	209	219	214	147	121	145	134	147	183	189	
164	208	206	173	183	162	146	161	120	108	152	147	103
147	170	132	83	126	117	82	87	108	92	99	79	
98	128	124	127	97	85	81	70	90	93	98	84	104
89	138	121	148	117	123	117	88	123	101	92	****	
****	****	****	****	****	****	****	****	****	****	****	****	105
****	****	****	****	****	****	****	****	****	****	****	****	
****	****	****	****	****	****	****	****	****	****	****	****	106
****	****	****	****	****	****	****	****	****	****	****	****	

TABLE 2c

Const.	AMPLITUDE						PHASE				
	1	2	3	4	4	5	1	2	3	4	5
Mean	158	121	130	137							
O1	12	6	10	8	1	1	102	148	121	118	155
K1	16	28	16	19	3	1	302	331	347	327	205
N2	93	99	103	98	19	22	14	16	14	14	13
ν2	25	27	28	26	5		28	30	28	28	
M2	502	502	503	502	100	100	43	43	43	43	42
L2	24	15	11	16	3		94	115	108	103	
S2	169	173	175	172	34	36	78	79	81	79	81
K2	48	50	50	49	9		78	79	81	79	
MN4	5	6	10	6	1		322	316	310	314	
M4	10	7	10	8	1	2	354	342	346	347	339
MS4	7	9	9	7	1	1	52	7	10	19	354
	millivolts				% of M2		Degrees				

1974 recordings:- 1 - days 19 to 47; 2 - days 48 to 76; 3 - days 77 to 105; 4 - vector mean; 5 - results of Bowden, K.F. and Hughes, P. (1961)

Tidal Analysis of voltages recorded on the Portpatrick - Donaghadee cable

Table 3

	$C_2A \times 10^4$ $(Vm^{-2}s^2)$	$C_2UR_o + E_0$ (V)	α	Δt min	r
Mull of Galloway	2.9	0.126	314^o	2	0.59
Ronaldsway	6.5	0.125	324^o	10	0.67
Valley	4.3	0.127	336^o	22	0.64
Aberporth	4.6	0.126	337^o	23	0.63

Table 4 Correlation between residual voltage and wind

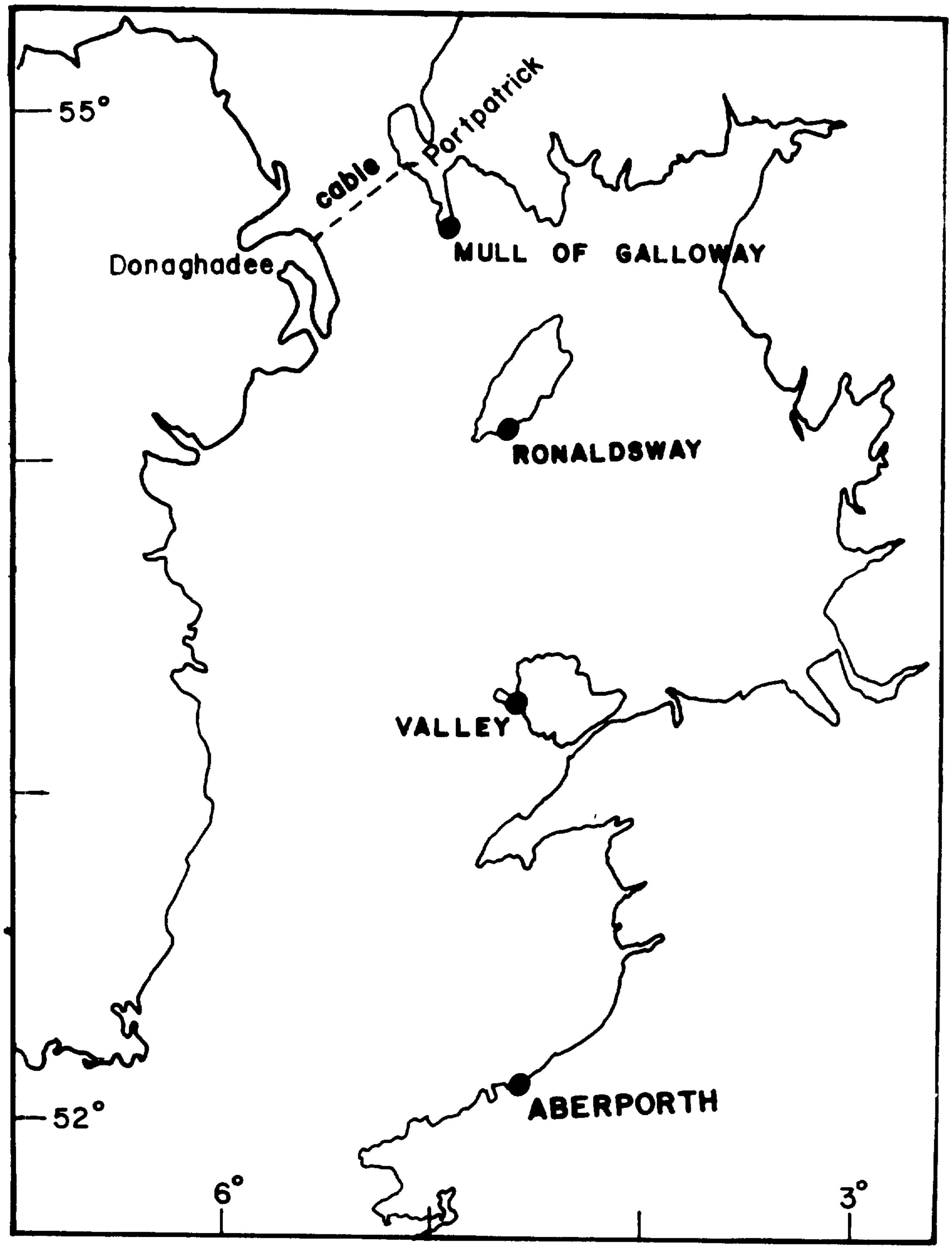
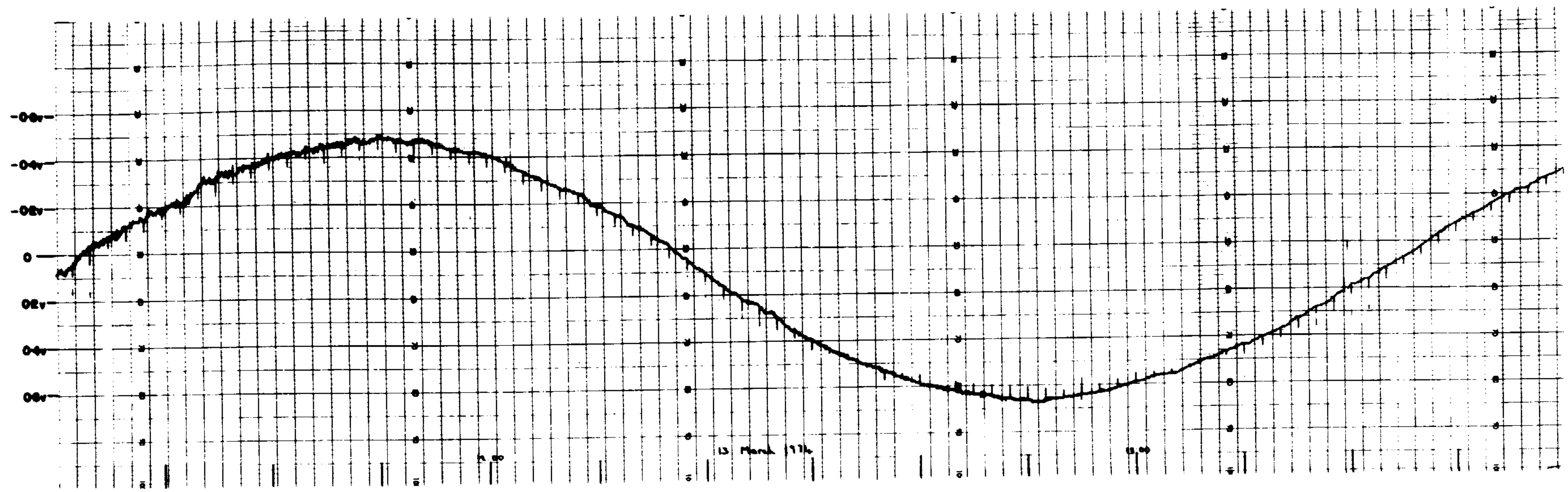
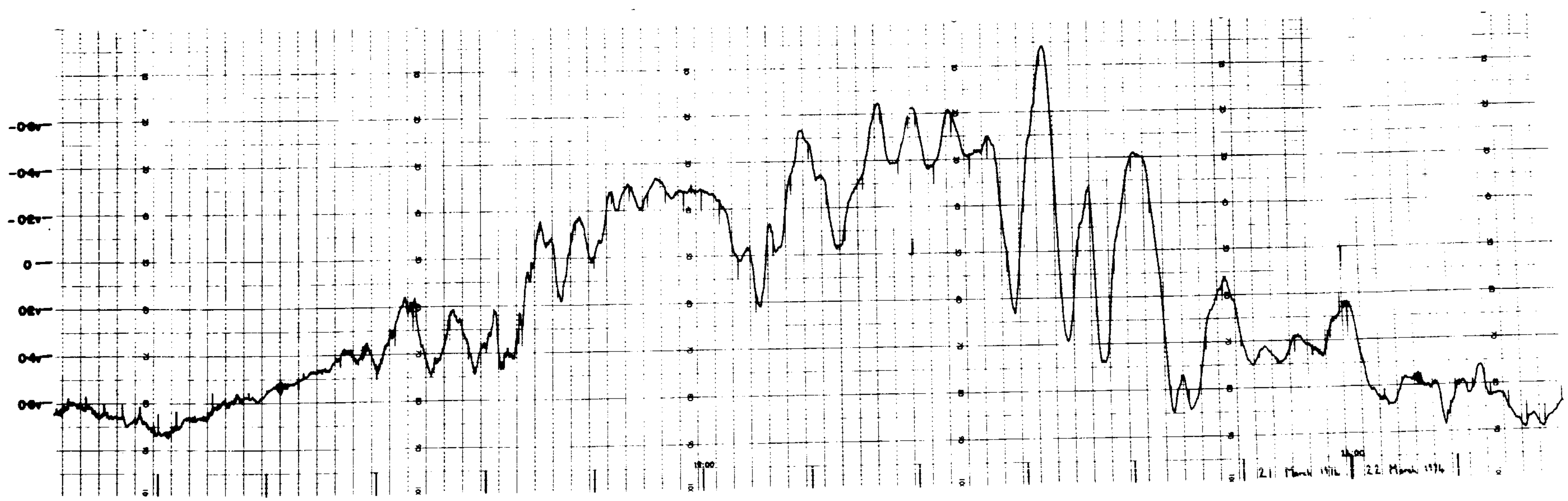


FIGURE 1 IRISH SEA



(a) Quiet Period



(b) Magnetic Storm

FIGURE 2 CHART RECORDINGS OF CABLE VOLTAGE

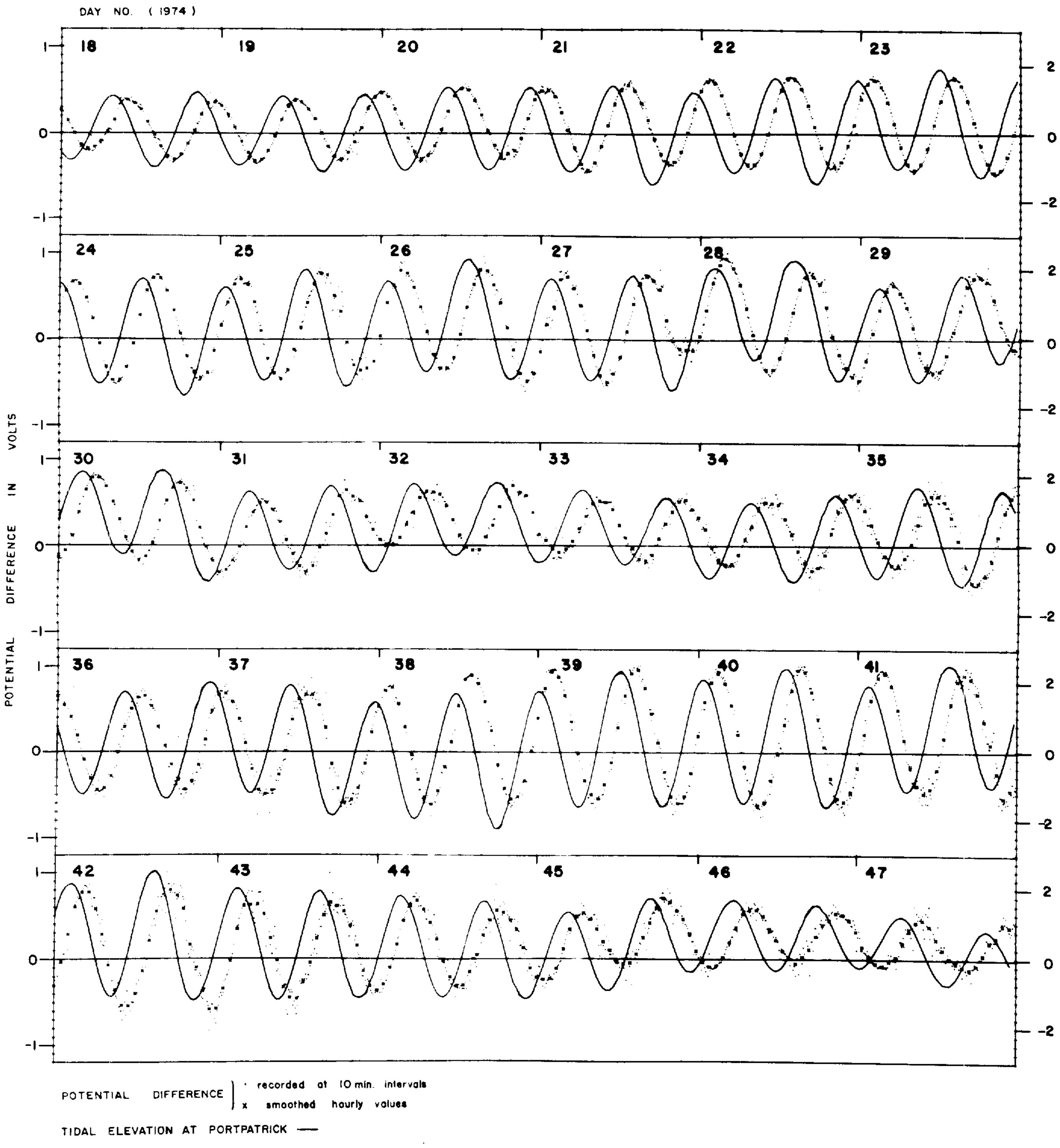
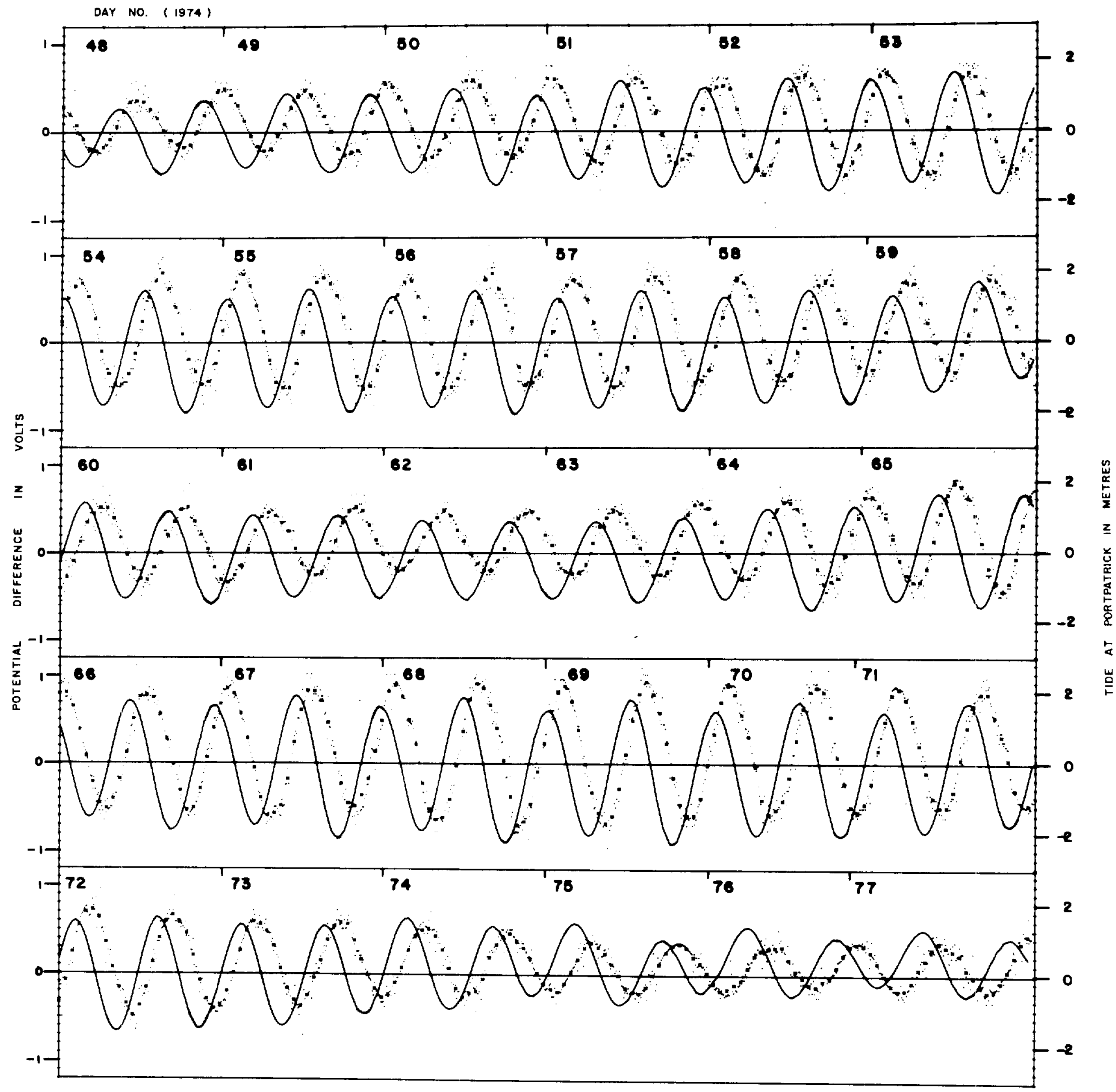


Figure 3a RECORDED CABLE VOLTAGES



POTENTIAL DIFFERENCE } · recorded at 10 min. intervals
x smoothed hourly values

TIDAL ELEVATION AT PORTPATRICK ——

Figure 3b RECORDED CABLE VOLTAGES

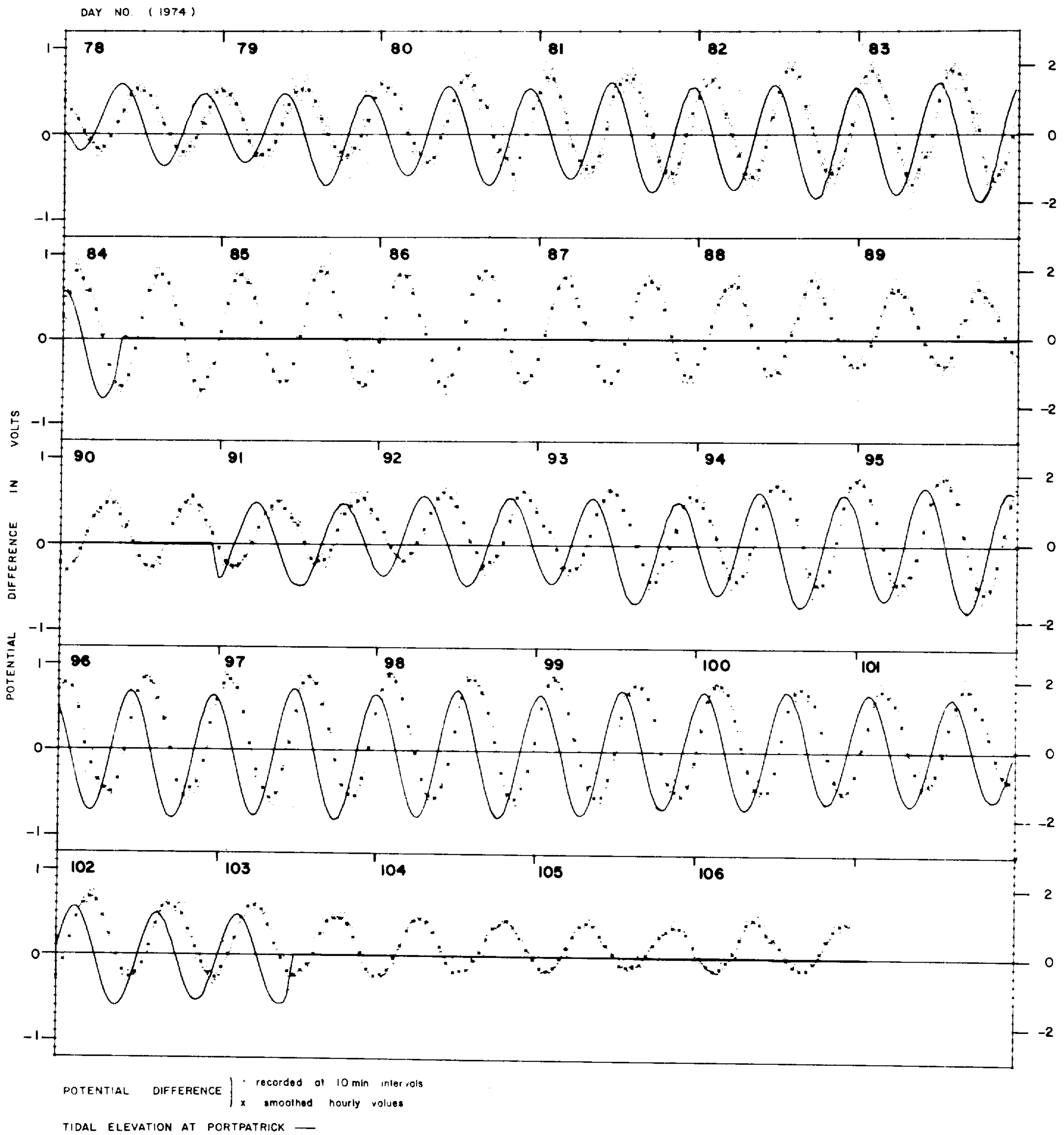


Figure 3c RECORDED CABLE VOLTAGES

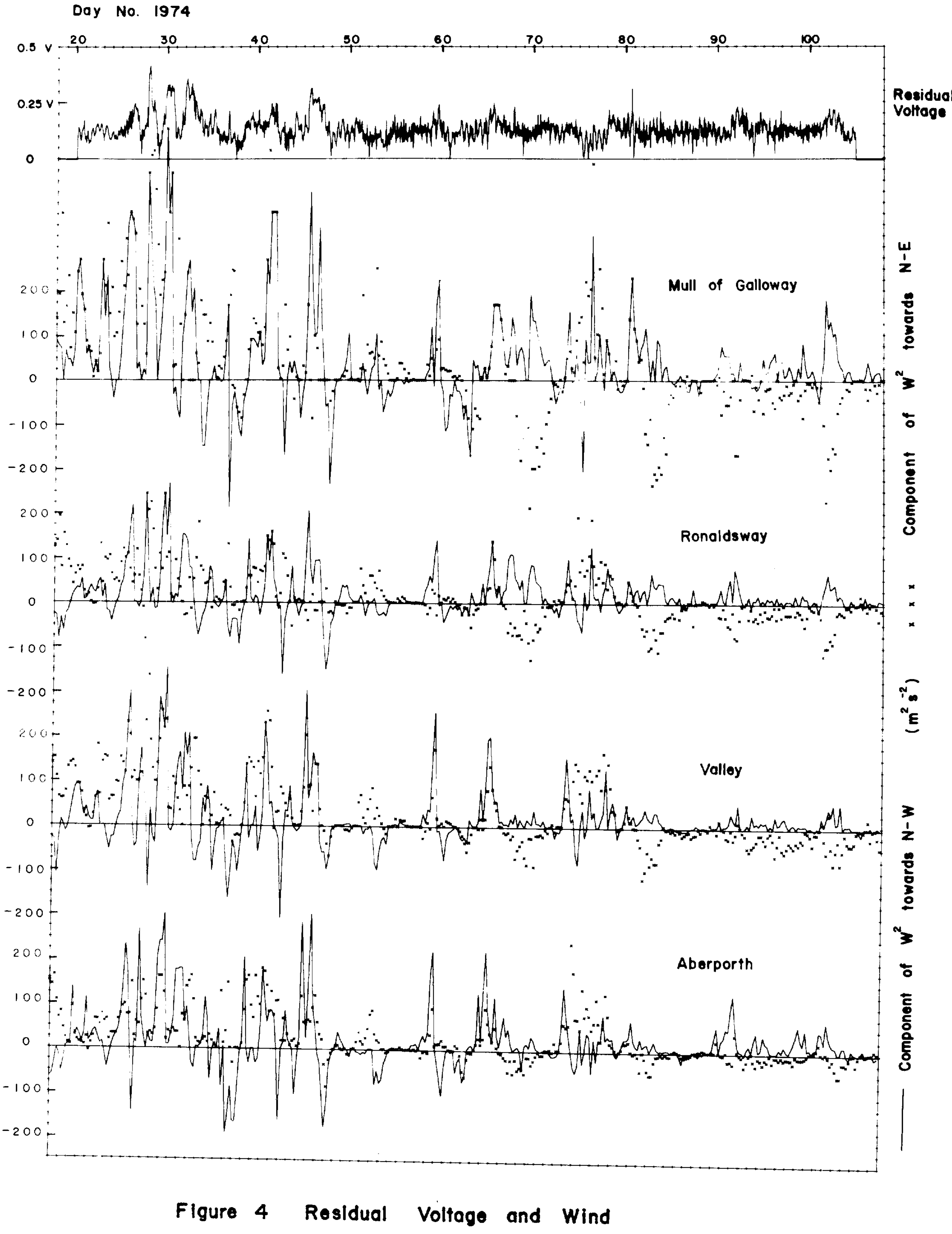


Figure 4 Residual Voltage and Wind