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MEASUREMENTS OF POTENTIAL DIFFERENCES ON NON-REPEATED AND REPEATED SUBMARINE CABLES ACROSS THE STRAIT OF DOVER.

by

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REPORT No. 62

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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INTRODUCTION

Within any flow of sea water, electric fields and currents will be established through geomagnetic induction, with the induced potential field depending on the spatial distribution of water velocity and electrical conductivity of the sea water and of the sea bed. Longuet-Higgins (1949) derived the potential difference, H, between two sides of a channel of semi-elliptical cross-section as

$$H = VZL\left[1 + \frac{K_o}{K_1}\frac{L}{2D}\right]^{-1}, \qquad (1)$$

where V is amplitude of the mean water velocity in the channel, Z is the vertical component of the Earth's magnetic field, L and 2D are the major and minor axes of the ellipse, and K_o and K_1 are the conductivity of sea bed and sea water respectively. At the latitude of Britain, the sense of the p.d. is such that the potential increases positively to the left of the water flow.

Therefore, the potential difference measured between two points on opposite sides of a channel connected by a submarine telephone cable can be used as an indicator of the water flow through the channel if the relationships between the cable e.m.f. and tidal and non-tidal parameters of the flow are known. Voltages measured on telephone cables have been used by Bowden (1956) and Cartwright and Crease (1963) in studies of water flow through the Dover Strait and comparison of the geodetic reference levels between England and France respectively. They used the usual method of calibrating the cable signals using a direct comparison between the recorded voltages and simultaneous water velocities measured by current meters. However, Robinson (1976), using a virtual current (electric) method to calculate a weighting vector for a given distribution of conductivity, has shown that velocity distributions associated with different tidal frequencies, storm surges, and long period residual flow will result in different responses at a given cable, and his computations were supported by measurements on the Dover-Sangatte no. 6 cable by Prandle and Harrison (1975). In a further paper, Robinson (1978) has applied his weighting vector model, in conjunction with a numerical non-linear dynamical model of the tidal flows, to the Dover Sangatte cable to investigate the contributions to the potential difference on the cable from water flow in the southern North Sea and the English Channel, and has compared his results with those from an analysis of ten years' voltage records from the cable made by Alcock and Cartwright (1978). Prandle (1978a) has also used this data in his estimates of residual flows in the southern North Sea and also in his computation (1978b) of monthly-mean residual flows through the Dover Strait.

All of the previous Dover Strait studies have used data from cables which were of the non-repeated type that are now becoming redundant and are scheduled for replacement by repeated type cables in the near future. A repeated cable running from St. Margarets Bay to La Panne, Belgium, has been in service for several years and this report includes a comparison of nearly two months signals measured on this cable with those measured simultaneously on non-repeated cables running from St. Margarets Bay to Sangatte and Audresselles in France. To the authors' knowledge, this is the first time that a telephone cable of the repeater type has been monitored for oceanographic purposes. Also ten months simultaneous records from the Sangatte and Audresselles cable have been analysed and the results are presented here.

2. INSTRUMENTATION

The location of the 3 cables is given in Figure 1; the St. Margarets Bay to Sangatte cable is number 6 previously monitored for part of 1968/1969 (Alcock and Cartwright 1978) and part of 1973 (Prandle and Harrison 1975). The circuit arrangement for both of the non repeated cables is given in Figure 2a, which shows that the tidal signal is developed across a 34 μF capacitor.

The circuit arrangement for the La Panne cable is given in Figure 3(a) and shows the two power units, one at each end of the cable, which provide a system voltage of 80V at 140mA constant current to power the two submarine cable repeaters in the normal "double end power feed mode". In the event of a failure of one of the power units, the remaining unit is capable of providing the full 80V in the "single end power feed mode". For the purposes of this experiment, the General Post Office kindly arranged for the system to operate in the latter mode from the St. Margarets Bay end of the cable so that any tidal signal developed in the system could be measured at this location by monitoring changes in the mean supply voltage, V, and current, I.

The schematic arrangement of the system in the "single end power feed mode" is given in Figure 3(b) and the equivalent circuit in Figure 3(c), with an 8.06Ω resistor added to monitor the 140 mA constant current. The total circuit resistance, R_T, shown in the circuit, is made up of cable resistance, cable repeater resistance, earth return path resistance, etc., and the internal resistance of the power unit constant current generator is R_I, so the tidal signal, V_T, is given by

$$V_T = (V + \Delta V) - (I + \Delta I) \times R_T, \tag{2}$$

where V and I are the mean operating voltage and current respectively. Therefore,

$$V_T = V_{in} - I_{in} \times R_T, \tag{3}$$

where $V_{in} = V_1$ and $I_{in} = V_2/8.06\,\Omega$.

Hence by monitoring V_1 and V_2, the tidal signal, V_T, can be computed if R_T is known. The value of R_T can be calculated from the data at any time by averaging over several tidal cycles to make V_T zero and hence R_T equal to the ratio of mean operating voltage to mean operating current. The mean operating conditions may change when the G.P.O. operators adjust the system controls but their ratio should be unchanged, with a nominal value of 80V/140 mA = 570Ω. However the actual computed value of R_T may change over the long term due to the cable resistance being affected by seasonal variations in sea bed temperature etc.

In both of the two voltages measured, V_1 and V_2, the tidal signal is in the presence of a large D.C. off-set which is removed by comparing it with a known stable reference source in a differential amplifier, and the circuit arrangement is shown in Figure 4 for both the voltage and current measuring circuits. If V_v and V_c are the voltage inputs to the logger of the system voltage and system current respectively, then

$$V_{in} = (3 \times V_v/0.99) \times 0.001 + 80 \text{ V}, \tag{4}$$

and

$$I_{in} = V_c/(110 \times 8.06) + 140 \text{ mA}. \tag{5}$$

The arrangement of the recording equipment to monitor the signals from the 3 cables is shown in Figure 2(b), and consisted of a Rapco multichannel digital data logger, type T112 which recorded data sequentially on 0.25 inch magnetic tape at 200 bpi, and a 2 pen 10 inch potentiometric chart recorder to provide direct analogue records. The 4 inch NIO chart recorder shown in Figure 2(b) was being used by IOS Wormley to obtain a long series record and so was left undisturbed during this experiment. When the two non-repeated cables were only being monitored, the voltage output from each was recorded on ±1V, ±2V, and ±10V channels of the data logger and also on the analogue recorder. When all three cables were monitored simultaneously Vv and Vc from the La Panne cable were each recorded on ±1V channels of the logger and on the analogue recorder, the voltage signal from the Audresselles cable was recorded on ±1V and ±2V channels, and the voltage signal from the Sangatte cable was recorded on ±1V, ±2V, and ±10V channels. The logger sampled the voltage channels at ten minute intervals and recorded cable voltage data, year number, day number and scan time sequentially on 0.25 inch magnetic tape at a density of 200 b.p.i.

3. DATA PROCESSING

The magnetic tape from each recording period was translated onto 8 channel paper tape in Ascii code using a Rapco translator and the data listed and stored on disk using the Bidston inhouse IBM 1130 computer. Any scans with incomplete data were padded out with maximum channel readings and the data then transferred, using the 1130 as a Remote Job Entry terminal, into disk storage on the IBM 370/165 computer of the SRC Daresbury Nuclear Physics Laboratory on which all subsequent data reduction and analysis was carried out. The data file was edited for errors in continuity by checking the time channel count for correct differences of ten minutes; any missing scans were inserted with voltage channels set to 999. The final data set for the Audresselles and Sangatte cables from 30 July 1975 to 31 May 1976 was 97.8% complete with 939 scans lost due to translation errors and 58 scans not logged out of 44,734. In addition there were lacunae of 8 hours on 7 November 1975 and 39½ hours on 27/29 January 1976 when the logger was switched to a fast sampling time of ten seconds. For the period from 29 January to 25 March 1976, when all 3 cables were monitored, the data set was 98.1% complete with 151 scans lost due to translation errors and 1 scan not logged out of 7996.

Values of the voltages logged every ten minutes from the Audresselles and Sangatte cables were computed from the appropriate ±1V, ±2V, or ±10V channels, and missing values over short periods were evaluated by reference to adjacent records. Longer lacunae, such as 0825 GMT to 1135 GMT on 11 August 1975 or 0725 GMT to 1025 GMT on 13 August 1975 were subsequently interpolated manually. The ten minute values were converted to hourly values using an interpolation program which incorporates a low pass filter, FLP05, to smooth the data and a cubic spline to interpolate the data at hourly intervals. The filter has a half length of 27 and therefore each hourly value was computed from values spanning a period of 9 hours. The filter response characteristic is shown in Figure 5 and the reduction in amplitude of tidal constituents is 0.1% for the diurnal band, 0.2% for the semi-diurnal band, and 0.6% for the quarter-diurnal band. The program also incorporates a linear time correction based on exact times of scans at the beginning and the end of the record (the clock only gained 8 seconds in a period of 55.5 days from 29 January to 24 March 1976). After the hourly data record had been obtained, the two lacunae in November 1975 and January 1976 were filled by extracting the ten minute values from the fast-sampled record and averaging to obtain the required hourly values.

Ten minute values of the input voltages, Vv and Vc, from the La Panne cable were computed from the appropriate $\pm$1v channels and converted to hourly values using the interpolation program. Hourly values of the system voltage Vin, and system current Iin, were computed using the relations (4) and (5), and relation (3) used to compute the total voltage signal, V_T. Relation (3) involves a knowledge of the total circuit resistance, R_T, and this was computed as the mean of the values of Vin/Iin over the whole record. (The value of R_T may change seasonally and longer records from the repeated cable may need a more sophisticated computation of R_T to remove seasonal variations). Premature failure of the measuring system used for the La Panne signals restricted the common period of measurement of the 3 cables to a period from 0932 GMT 29 January 1976 to 0812 GMT 16 March 1976.

Figure 6 shows plots of the hourly values of the input voltages Vv and Vc (labelled as "voltage signal" and "current signal" respectively) and total voltage signal, V_T, of the La Panne cable. (In this and subsequent figures, day numbers are given under the tick for 1200 GMT). The larger proportion of the total signal occurs in the system voltage signal but the system current signal improves the result by approximately 1%. The fact that the current signal is not a constant value indicates the inability of the power feed system to regulate perfectly. The total signal record shows an initial upward drift which may be due to a settling of electronic components, although the period of approximately 9 days is rather long.

4. COMPARISON OF HOURLY VOLTAGE RECORDS

4.1 10 months data from Audresselles and Sangatte cables.

Figures 7(a) and 7(b) show the records of hourly voltage obtained from the Audresselles and Sangatte cables for the periods from August to December 1975 and from January to May 1976 respectively. The Audresselles record is the noisier of the two but some major spikes occurring during 22 November, 26 March and 3 May are common to both although less pronounced on the Sangatte record; according to data supplied by the I.G.S. Geomagnetism Unit (Miss K Dyson - personal communication), these coincided with periods of high disturbance of the earth's magnetic field. The large negative excursion of both records on 3 January is a consequence of the storm surge of that time.

The Audresselles record is noisiest at periods of neap tides, when the signal due to the tidal currents will be least and the flow more variable; the record is especially noisy at the first neaps of January, February, and March when the tidal cycle was at its least during the monitoring period from August 1975 to May 1976. Robinson (1976) has shown that the induced cable emf depends on the water velocity distribution over an area of the order of the channel width upstream and downstream of the cable, and hence any variability in the water flow during these periods will have more effect on the Audresselles cable than on the Sangatte cable because of the geometry of the Dover Strait with its diverging coastlines. Magnetic storms around the 10/11 January could have contributed to the noise of the January record around the first neaps.

It is apparent that the Audresselles cable record has a smaller amplitude response than the Sangatte cable record, as predicted by Robinson (1976) using different sink points in his virtual current model to compute the response of cables from St. Margarets Bay to different points on the French or Belgian coast. In fact, his computations showed that the position for a maximum response in voltage to a prescribed water current flow system in the Strait is when the end of the cable is near Sangatte.

4.2 45 days data from Audresselles, Sangatte and La Panne cables.

Figure 8 shows the records for the Audresselles and Sangatte cables replotted for the period from 29 January (day number 029) to 24 March (day 084) 1976, together with the record of total voltage signal from the La Panne repeated cable from 29 January to 13 March (day 073) when the record prematurely terminated due to a failure of electronics. The La Panne record is very noisy, especially at the first neap tide period of February and March, and therefore hydrodynamic noise from the variability of water flow seems to be greatest for the La Panne cable. This is not a surprising result as the La Panne cable is the longest of the three and hence responds to a greater area of water flow, including large areas of shallow water in the southern North Sea. However, electromagnetic sources of noise also have to be considered.

Axe (1968) has studied the effect of the earth's magnetic field on submarine cables and concludes that the maximum voltage caused by earth currents between two earthing points is proportional to

a) the distance between them,

b) the resistivity of the earth between them,

c) an intensity factor determined by the geomagnetic latitude (0.21 at the geomagnetic latitude of 53°N of the Dover Strait),

and

d) the cosine of the angle between the line joining the two earthing points and the direction of induced current flow, which is most likely to be along the geomagnetic latitude and therefore inclined at an angle of approximately 71^{o} to the north in the vicinity of the cables. Taking the orientation of the Audresselles, Sangatte and La Panne cables to be 159^{o}, 131^{o}, and 94^{o} to true north respectively the cosine factor is 0.03, 0.50, and 0.92 respectively. Therefore, assuming a uniform rock structure and hence similar resistivity, and a constant intensity factor in the vicinity of the cables, the La Panne cable is the most susceptible to noise from electromagnetic disturbances through factors a) and d). However, the cosine factor for the Audresselles cable is much lower than that for the Sangatte cable, and, as the distance between their earthing points is approximately the same, the noisier signal on the Audresselles cable compared with the Sangatte cable is presumably more attributable to hydrodynamic effects than to electromagnetic effects. It is thus considered that the very noisy signal of the La Panne cable is primarily due to variable water current flow in the large area to which it responds (especially in the shallow water areas near Dunkerque), but that electromagnetic sources of noise may also have a significant effect on the La Panne cable because of its close alignment to the orientation of the geomagnetic latitude and to the axis of the Dover Strait, along which the earth-currents may be concentrated.

5. HARMONIC ANALYSIS OF CABLE VOLTAGES

5.1 General method

Tidal analyses of 29 day periods of the hourly records of cable voltage were carried out using the T.I.R.A. (Tidal Institute Recursive Analysis) program which utilises the harmonic method of analysis. For all analyses, the amplitude and phase lag, relative to Greenwich epoch, of 27 major and 8 related harmonic constituents were computed, the time zone being Greenwich Mean Time, S = O. Related constituents used were π_1, ρ_1, ψ_1 and ϕ_1 all related to K_1; $2N_2$ and ν_2 both related to N_2; and T_2 and K_2 both related to S_2; and all relations were computed from an analysis of one year of vertical tide data at Dover during 1974/75. No attempt was made to resolve S_1 as it can only be unambiguously resolved from the harmonic constituent K_1 with one year of data, and any attempt to relate it to K_1 using the vertical tide at Dover is unsatisfactory because of the solar diurnal nature of the principal constituents of the geomagnetic tides (Malin 1973).

5.2 Results from Audresselles and Sangatte

Tables 1 and 2 summarise the vector means of amplitude and phase of the principal harmonic constitutents from the results of 9 separate monthly analyses of the Audresselles and Sangatte cable data. The periods used were P1, 03 to 31 August; P2, 02 to 30 September; P3, 03 to 31 October; P4, 12 November to 10 December, 1975; P5, 31 December 1975 to 28 January 1976; P6, 02 February to 01 March; P7, 21 February to 20 March; P8, 29 March to 26 April; and P9, 29 April to 27 May, 1976. In order to determine the noise to signal ratio of each tidal frequency band, an analysis was made of the power spectrum of the recorded voltage series and a residual voltage series. The residual voltage series was computed as the difference between the recorded series and a predicted series computed using the vector means of the harmonic constants of each cable. A band width of 9 cpm was used for both diurnal and semi-diurnal species, and 11 cpm for the fourth- and sixth-diurnal species. Noise to signal ratios are shown in Table 3(a) for 10 month period from August 1975 to May 1976 for the Audresselles and Sangatte cables.

Within the diurnal band, K_1 is much more variable than O_1, reflecting the difficulty in resolving the S_1 constituent. Noise to signal ratios were 38.3% and 29.4% for Audresselles and Sangatte respectively.

In the semi-diurnal band, all constituents are fairly consistent except for the small constituent L2 which usually shows variability in tidal analyses. Noise to signal ratios were 1.1% and 0.5% for Audresselles and Sangatte respectively.

Constituents in the fourth- and sixth-diurnal bands are more variable for the Audresselles cable than for the Sangatte cable, and this may be attributed to the fact that it is more susceptible to the shallow water effects producing these tides. This is also reflected in the noise to signal ratios for the two cables which were 25.0% and 5.6% for Audresselles and Sangatte respectively in the fourth-diurnal band, and 86.2% and 29.6% respectively in the sixth-diurnal band.

It is clear that the response of the Audresselles cable is noisier than that of the Sangatte cable in all tidal bands, and that the conclusion of Alcock and Cartwright (1978) that the residual spectral levels of the Sangatte cable are low is confirmed. They also found that there was a decrease in phase of the M_2 constituent from 6° to 1° when they analysed a year's record from cable number 6 compared with an analysis of 9 years data from cable number 5 which has the same terminal points but whose path is, on average, some 2½ Km to the east of number 6. Prandle and Harrison (1975) obtained 1° from number 6 and Bowden's result (1956) of 3^{o} is from measurements predominately on number 6 but also on number 5 when breaks occurred in the former cable. Our result of 2^{o} is further evidence that cable number 6 has a difference in phase lag for M_2 when compared to number 5, and that it seems to respond to semi-diurnal tidal currents further into the English Channel, as inferred by Alcock and Cartwright (1978). (Their statement that number 6 seems to respond to currents further into the North Sea is an error).

5.3 Results from Audresselles, Sangatte and La Panne

Table 4 shows the amplitude and phase for the principal harmonic constituents from an analysis of a 29 day period of the Audresselles, Sangatte and La Panne records from 30 January to 27 February 1976. Predicted series of voltage for the 3 cables were computed using these constants and the residual series computed as the difference between observed and predicted series. An analysis of the power spectra of the observed and residual records gave the noise to signal ratios presented in Table 3(b); the same frequency band widths for each tidal species were used as before.

It is clear that the La Panne repeater cable has the noisiest response of the 3 cables, with an overall signal to noise ratio of only 53.4% compared to 85% and 94.9% for Audresselles and Sangatte respectively, and that it is very noisy in all of the tidal bands. It is thus apparent that it is difficult to extract a useful tidal analysis from just one month of recordings on the La Panne cable, due to the high noise level from the hydrodynamic and electromagnetic sources discussed above. It is intended to monitor the La Panne cable over a period of at least one year, and to use an integration time of 15 minutes in an attempt to reduce the noise level on the signal.

6. RESPONSE OF THE CABLES TO LOW FREQUENCY SIGNALS

In order to examine the response of each cable to low frequency signals, the records of observed hourly voltages were filtered using a numerical filter previously used to remove drift from records from Off-shore tide gauges (Alcock and Vassie 1975). This filter, whose response characteristic is shown in Figure 5, was designed with a cut-off frequency (half-power point) of 0.027 $c.h^{-1}$ (9.8^{o} h^{-1}), and had a half length of 72 values, so three days of data were lost at the beginning and end of the record. The low frequency response of the cables was obtained by subtracting the filtered tidal signal from the observed record.

The low frequency response of the Audresselles and Sangatte cables during the period of 01 to 24 January 1976 is given in Figure 9 and shows the signals on the 2 cables during 02 to 05 January when there were several storm surges along the English and European coasts (Flather and Davies 1978). An intense depression was centred off the west coast of Scotland at 1200 GMT on 02 January and strong S/SW winds (force 7 at 1800 GMT at Gorleston) ahead of it caused water to flow through the Straits into the North Sea, thus giving a large positive cable voltage, and a consequent negative surge at Southend at 0000 GMT. As the depression moved south of east to reach Denmark by 0600 GMT on 03 January, very strong W/NW gales (force 8 at 2300 GMT 02 January at Gorleston) caused positive surges at Southend at 0930 GMT and 2100 GMT on 03 January and a flow out of the North Sea into the English Channel during this period and a consequent large negative voltage on the cables. A ridge of high pressure crossed Britain during 04 January followed by a frontal trough with strong SW winds ahead of it (force 7 at 1800 GMT at Gorleston) which produced a strong flow into the North Sea, shown by the large positive cable voltage, and a second negative surge at Southend at 0000 GMT on 05 January. A smaller positive surge occurred at Southend at 1800 GMT on 05 January, and there was a flow of water out of the North Sea and a consequent increase in negative voltage.

The low frequency response of each of the 3 cables for the period from 1400 GMT 01 February (day 032) to 1400 GMT 10 March (day 070) 1976 is given in Figure 10 and shows the signals in the cables corresponding to the surge events of 12 to 14 February 1976 (days 043 to 045) and 29 February to 02 March 1976 (days 060 to 062).

The former was due to a deep depression centred NW of Britain which moved SE from north of Scotland into the southern North Sea and produced a strong W/SW airstream over that area throughout the 11 January (SW force 6 at 1200 GMT 11 January at Gorleston), hence there was a strong residual flow into the North Sea and a large positive voltage on the cables. As the depression moved further SE into Germany, strong N/NE winds blew over the southern North Sea (NE force 7 at 1200 GMT on 12 January at Gorleston) with a consequent flow out of the North Sea and large negative cable voltages.

The latter was due to a depression which moved NE between Iceland and northern Scotland towards the Norwegian Sea, giving a strong NW airstream over the northern North Sea and producing an external surge which caused flow out of the North Sea and hence a large negative voltage on the cables. The following negative surge caused a return flow through the Straits and a consequent positive cable voltage, which was most marked on the Audresselles cable.

All three records of low frequency response are quasi-periodic with a period around 2.2 days. The plots of power density of the three records given in Figure 11 indicate that the energy associated with these low frequency oscillations is spread out over a broad band, and probably reflects the character of the meteorological forcing.

7. CONCLUSIONS

Simultaneous recordings of potential differences over a 10 month period during 1975 and 1976 from the St. Margarets Bay to Sangatte number 6 cable and the St. Margarets Bay to Audresselles cable show that the latter has a noisier signal, especially at periods of small neap tides when any variability in the water flow will be more pronounced. An analysis of the variance density of the raw data and tidal residuals shows that there is a better signal/noise ratio for the Sangatte cable over all tidal bands.

Simultaneous records over 45 days during 1976 from the Sangatte and Audresselles non-repeated cables and the La Panne repeated cable show that the latter has the noisiest response in all tidal bands. The noise is from two sources: hydrodynamic because the cable is the longest of the three and responds to the largest area with the most variable flow conditions; and electromagnetic, because the La Panne cable is aligned most parallel to the Dover Strait and therefore is most susceptible to noise of earth current origin.

The time series of low frequency response from the three cables show well-correlated quasi-periodic oscillations and so the repeated cable seems to respond to low frequency signals in a similar manner to the non repeated cables, and could therefore be used to monitor the long period non-tidal flow through the Dover Strait in place of the Sangatte and Audresselles non repeated cables which have now been removed from the sea bed.

REFERENCES

ALCOCK, G.A. and CARTWRIGHT, D.E. 1978. An analysis of 10 years' voltage records from the Dover-Sangatte cable. pp. 341-365 in, A Voyage of Discovery, George Deacon 70th Anniversary Volume, (edited by M.V. Angel). Oxford: Pergamon. 696 pp.

ALCOCK, G.A. and VASSIE, J.M. 1975. Off shore tide gauge data. Institute of Oceanographic Sciences, Data Report, No.7. 38 pp.

AXE, G.A. 1968. The effects of the earth's magnetism on submarine cables. Post Office Electrical Engineers' Journal, 61. pp 37-43.

BOWDEN, K.T. 1956. The flow of water through the Straits of Dover related to wind and differences in sea level. Philosophical Transactions of the Royal Society, A, 248, pp. 517-551.

CARTWRIGHT, D.E. and CREASE, J. 1963. A comparison of the geodetic reference levels of England and France by means of the sea surface. Proceedings of the Royal Society, A, 273, pp. 558-580.

FLATHER, R.A. and DAVIES, A.M. 1978. On the specification of meteorological forcing in numerical models for North Sea storm surge prediction, with application to the surge of 2-4 January 1976. Submitted to Deutsche Hydrographische Zeitschrift.

LONGUET-HIGGINS, M.S. 1949. The electrical and magnetic effects of tidal streams. Monthly Notices of the Royal Astronomical Society. Geophysical Supplement, 5, pp. 285-307.

MALIN, S.R.C. 1973. Worldwide distribution of geomagnetic tides. Philosophical Transactions of the Royal Society, A, 274, pp. 551-561.

PRANDLE, D. 1978a. Residual flows and elevations in the southern North Sea. To be published in Proceedings of the Royal Society of London, A.

PRANDLE, D. 1978b. Monthly-mean residual flows through the Dover Strait; 1949-1972. Submitted to Journal of the Marine Biological Association.

PRANDLE, D. and HARRISON, A.J. 1975. Relating the potential difference measured on a submarine cable to the flow of water through the Strait of Dover. _Deutsche Hydrographische Zeitschrift_, 28, pp. 207-226.

ROBINSON, I.S. 1976. A theoretical analysis of the use of submarine cables as electromagnetic flow meters. _Philosophical Transactions of the Royal Society_, A, 280, pp. 355-396.

ROBINSON, I.S. 1978. A theoretical model for predicting the voltage response of the Dover-Sangatte cable to typical tidal and surge flows. pp. 367-391 in, _A Voyage of Discovery_ , George Deacon 70th Anniversary Volume, (edited by M.V. Angel). Oxford:Pergamon. 696 pp.

Constituent	AMPLITUDE (mV)			PHASE (degrees)		
	Vector mean	S.D.	S.E.	Vector Mean	S.D.	S.E.
Mean	-70.7	27.2	9.1			
O_1	64.1	19.0	6.3	38.6	8.6	2.9
P_1	20.9	13.2	4.4	128.8	26.4	8.8
K_1	54.4	34.9	11.6	144.7	26.4	8.8
N_2	121.4	10.7	3.6	341.0	2.1	0.7
ν_2	30.0	2.6	0.9	331.7	2.1	0.7
M_2	655.3	44.3	14.8	1.5	1.4	0.5
L_2	50.5	15.3	5.1	350.4	27.9	9.3
S_2	260.6	31.9	10.6	49.4	3.9	1.3
K_2	72.4	8.9	3.0	46.0	3.9	1.3
MN_4	28.2	9.8	3.3	249.8	20.1	6.7
M_4	69.5	15.0	5.0	277.6	11.2	3.7
MS_4	52.5	10.3	3.4	324.1	12.1	4.0
M_6	9.1	6.0	2.0	158.9	36.6	12.2
$2MS_6$	11.6	5.8	2.0	209.0	61.5	20.5

TABLE 1: Principal harmonic constituents of Audresselles cable voltage. Vector mean, standard deviation, and standard error of 9 monthly analyses.

Constituent	AMPLITUDE (mV) Vector mean	S.D.	S.E.	PHASE (degrees) Vector mean	S.D.	S.E.
Mean	-33.4	30.3	10.1			
O_1	69.5	12.0	4.0	39.4	7.3	2.4
P_1	27.5	12.9	4.3	171.9	18.7	6.2
K_1	71.8	27.5	9.2	187.8	20.5	6.8
N_2	133.9	5.6	1.9	341.7	2.8	0.9
ν_2	33.0	1.4	0.5	332.4	2.6	0.9
M_2	717.9	39.0	13.0	2.1	0.7	0.2
L_2	59.3	14.3	4.8	357.4	17.6	5.6
S_2	253.4	10.6	3.5	51.2	0.9	0.3
K_2	70.7	2.9	1.0	47.8	0.9	0.3
MN_4	35.0	7.5	2.5	256.5	19.8	6.6
M_4	89.0	6.1	2.0	285.7	3.6	1.2
MS_4	63.5	8.8	2.9	338.0	11.5	3.8
M_6	17.2	1.4	0.5	183.4	7.3	2.4
$2MS_6$	16.8	2.6	0.9	226.9	16.2	5.4

TABLE 2: Principal harmonic constituents of Sangatte cable voltage. Vector mean, standard deviation, and standard error of 9 monthly analyses.

BAND	AUDRESSELLES Total signal $(mV)^2$	Residual signal $(mV)^2$	Noise/ Signal %	SANGATTE Total signal $(mV)^2$	Residual signal $(mV)^2$	Noise/ Signal %
Total	323636	35984	11.1	357713	22122	6.2
Diurnal	4418	1694	38.3	5124	1508	29.4
Semi-diurnal	281130	3173	1.1	323685	1586	0.5
Fourth-diurnal	6445	1614	25.0	7690	427	5.6
Sixth-diurnal	694	598	86.2	270	80	29.6

TABLE 3a: Variances of cable signals for period 01 August 1975 to 31 May 1976

BAND	AUDRESSELLES Total $(mV)^2$	Residual $(mV)^2$	Noise/ Signal (%)	SANGATTE Total $(mV)^2$	Residual $(mV)^2$	Noise/ signal (%)	LA PANNE Total $(mV)^2$	Residual $(mV)^2$	Noise/ signal (%)
Total	270273	40425	15.0	314597	16061	5.1	85978	40554	46.6
Diurnal	3752	1677	44.7	3245	1281	39.5	955	598	62.6
Semi-diurnal	229233	4699	2.0	289042	1645	0.6	44618	1480	3.3
Fourth-diurnal	3788	1945	51.3	6589	476	7.2	5164	2129	41.2
Sixth-diurnal	1032	837	81.1	298	93	31.2	1926	1337	69.4

TABLE 3b: Variances of cable signals for period 29 January 1976 to 14 March 1976.

	AUDRESSELLES		SANGATTE		LA PANNE	
Constitutent	H (mV)	G (°)	H (mV)	G (°)	H (mV)	G (°)
O_1	73.1	50.2	74.4	50.0	13.9	52.6
K_1	58.6	117.8	48.5	160.1	16.9	223.9
M_2	611.2	1.3	674.0	2.6	231.5	3.0
S_2	220.8	53.5	246.3	50.3	110.5	31.7
MS_4	61.6	350.2	70.5	356.9	26.2	29.7
$2MS_6$	20.7	197.9	18.7	255.5	31.8	325.1

Table 4: Principal harmonic constituents of the 3 cables for period 30 January to 27 February 1976.

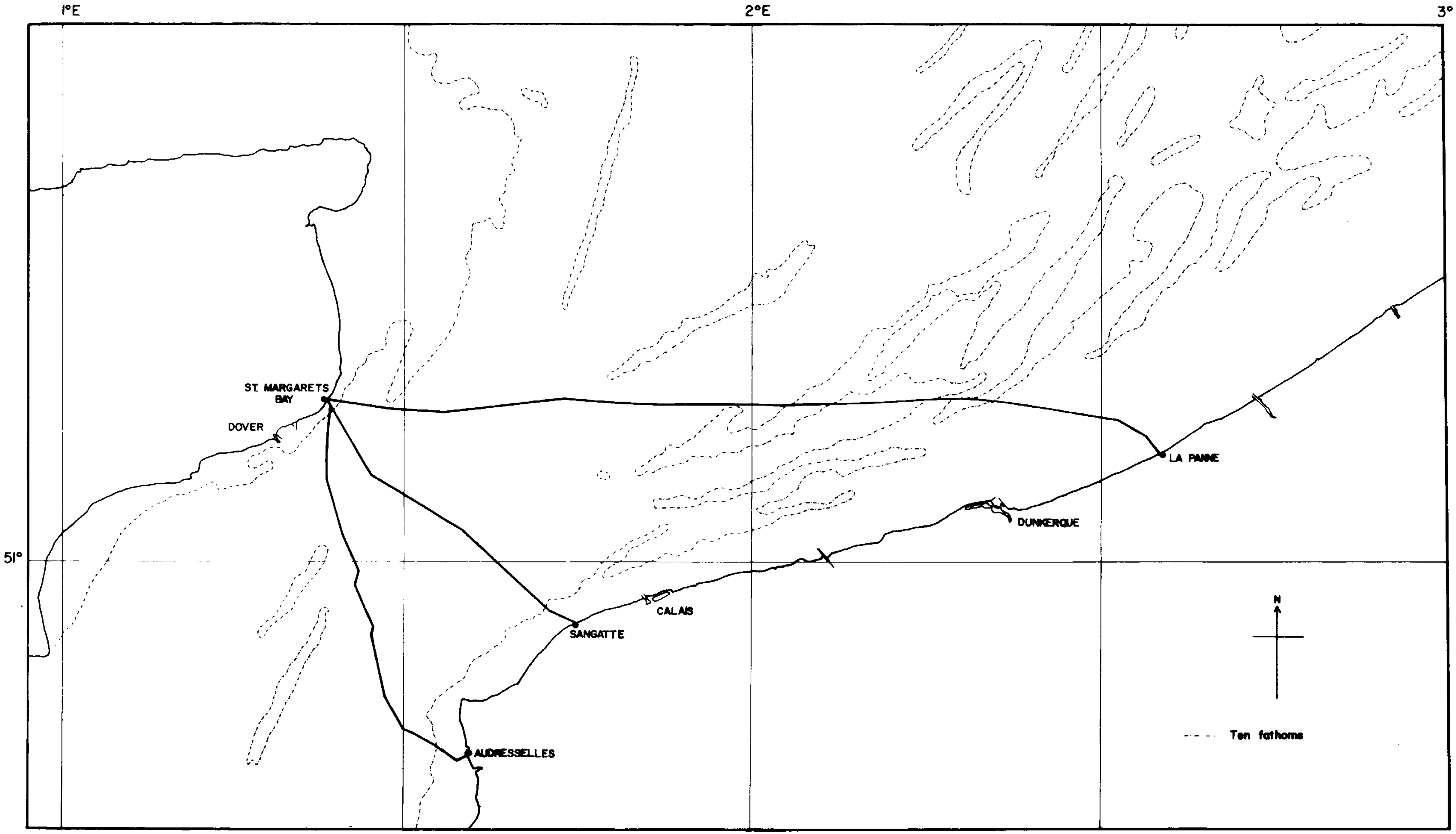


Figure I. LOCATION OF CABLES.

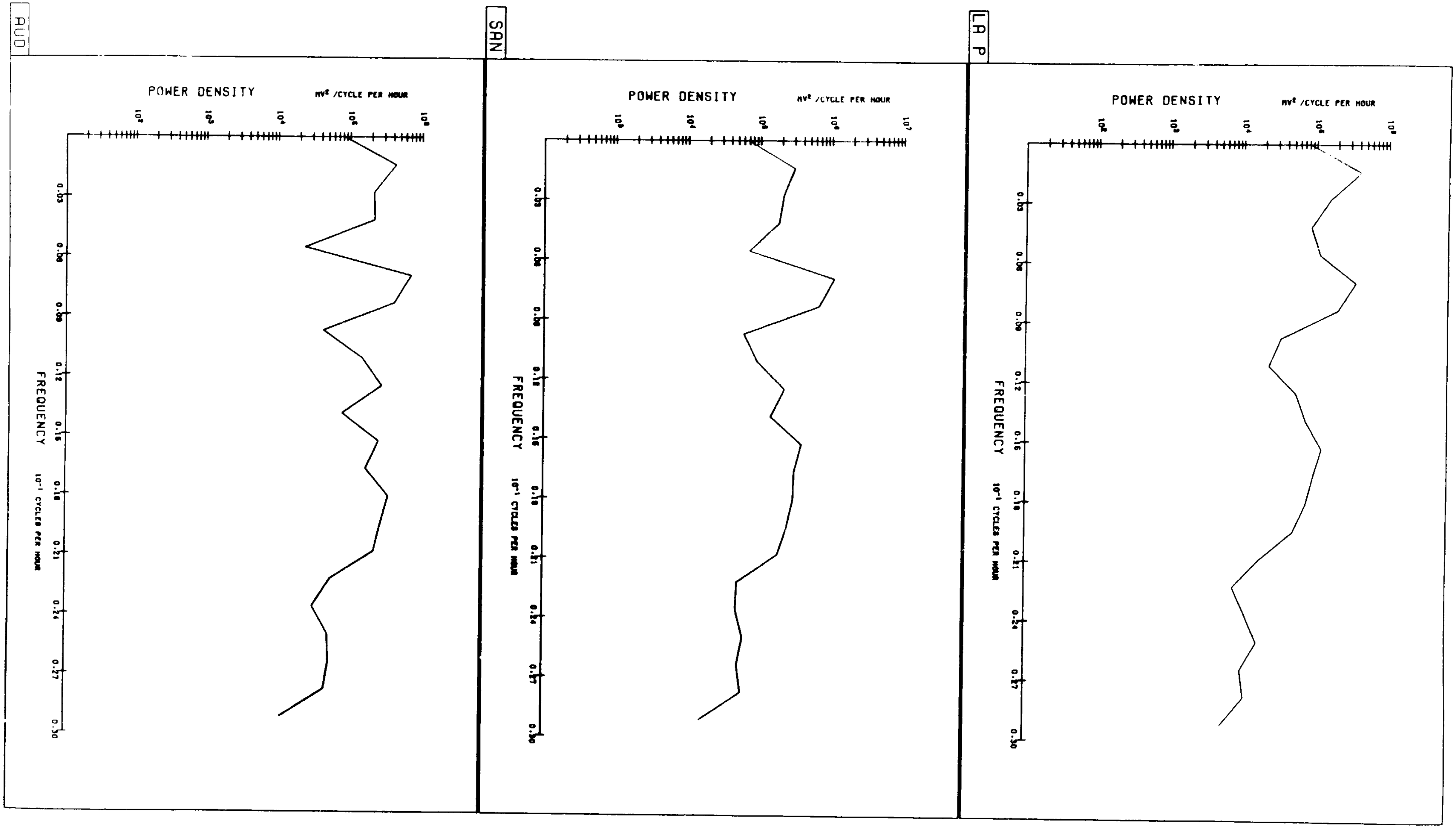


Figure 11. POWER DENSITY OF LOW FREQUENCY RESPONSE.

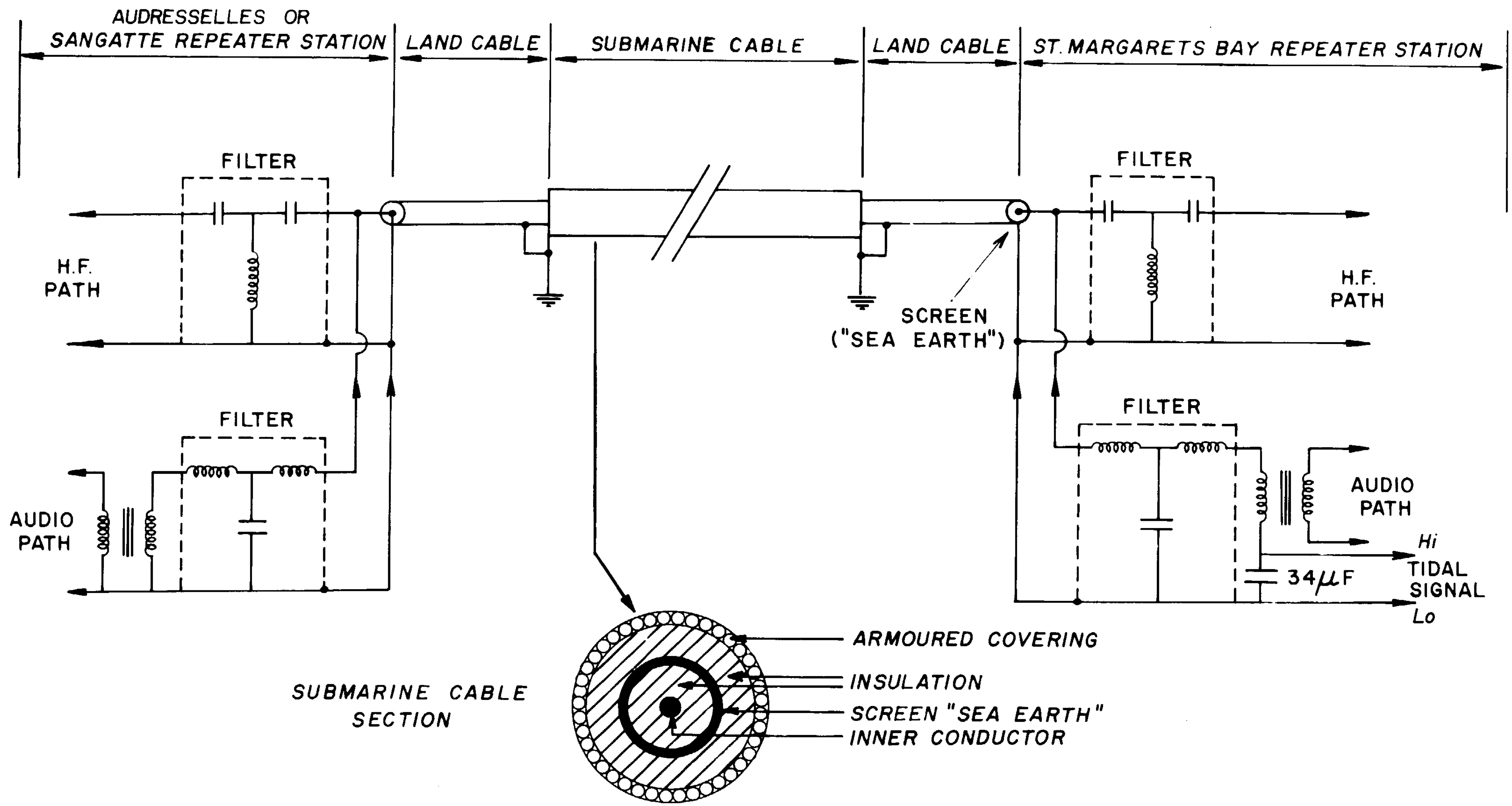


Figure 2 (a). CIRCUIT DIAGRAM FOR NON-REPEATER CABLES.

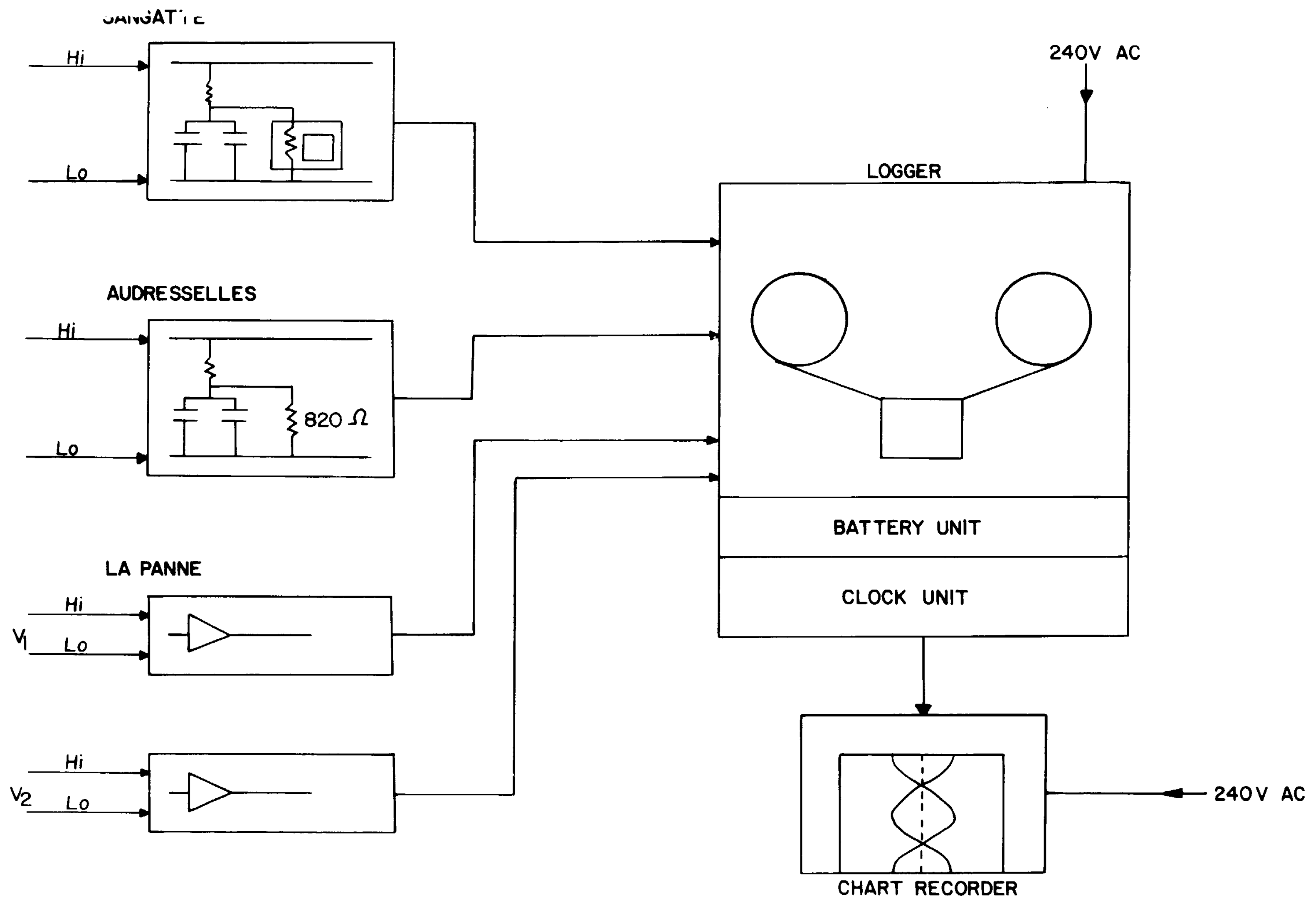


Figure 2(b) ARRANGEMENT OF RECORDING EQUIPMENT.

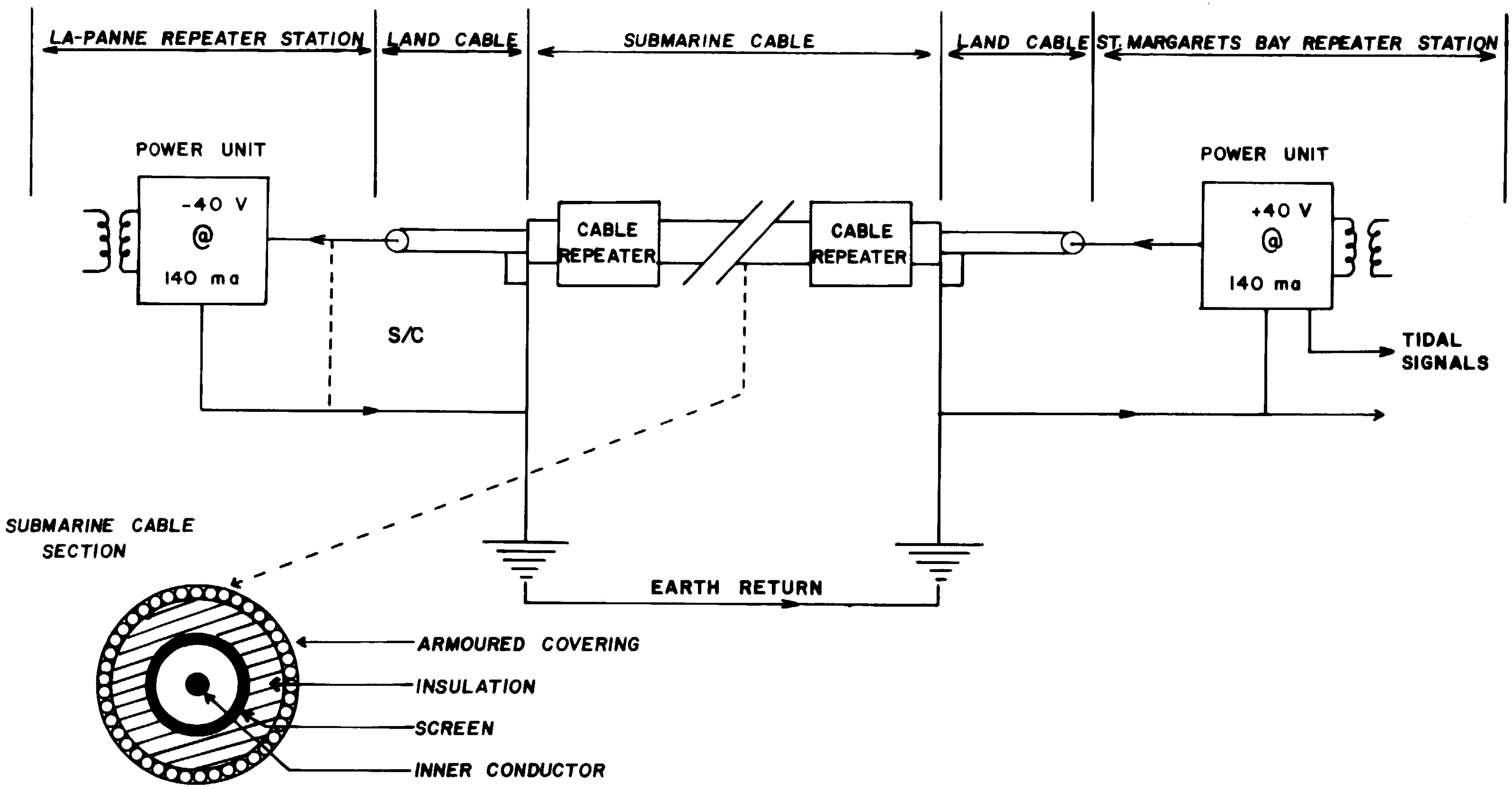


Figure 3(a). CIRCUIT DIAGRAM FOR REPEATER CABLE.

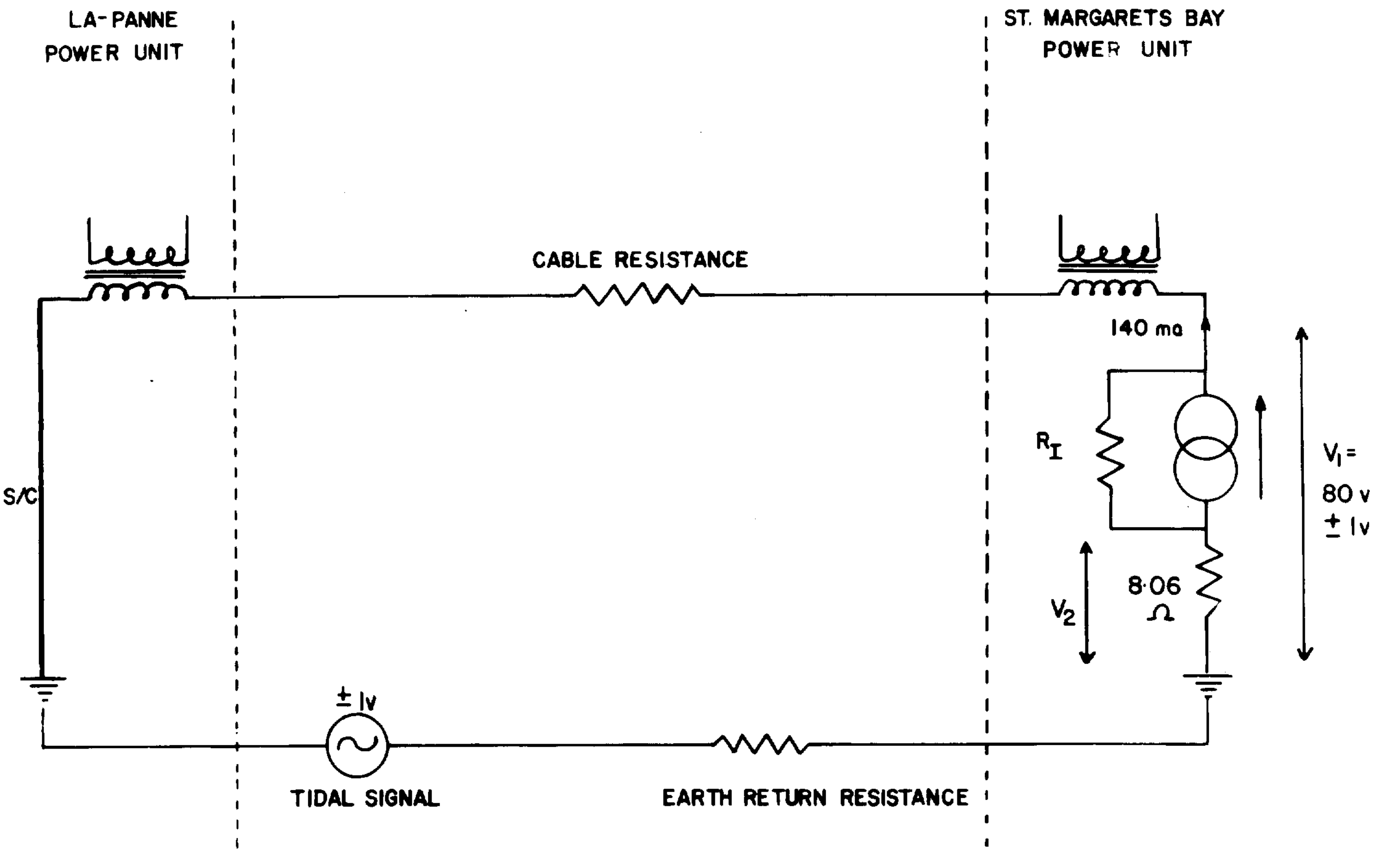


Figure 3(b). SCHEMATIC ARRANGEMENT FOR SINGLE END POWER FEED MODE.

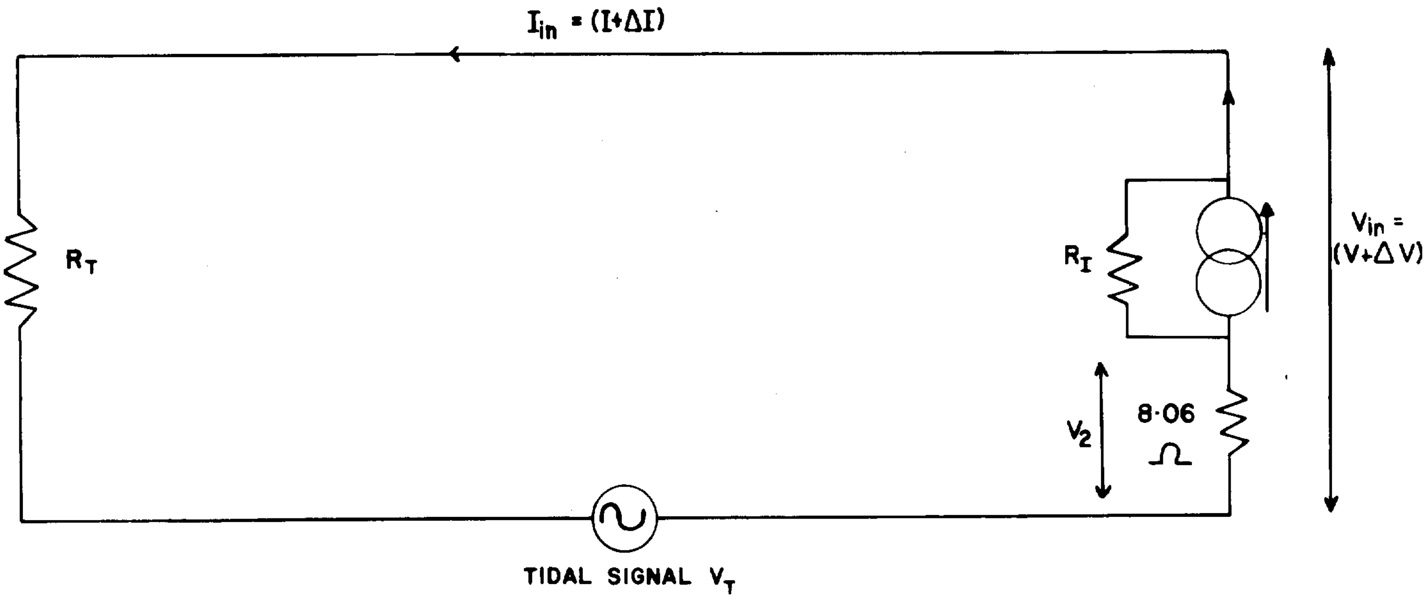


Figure 3(c). EQUIVALENT CIRCUIT FOR REPEATER CABLE.

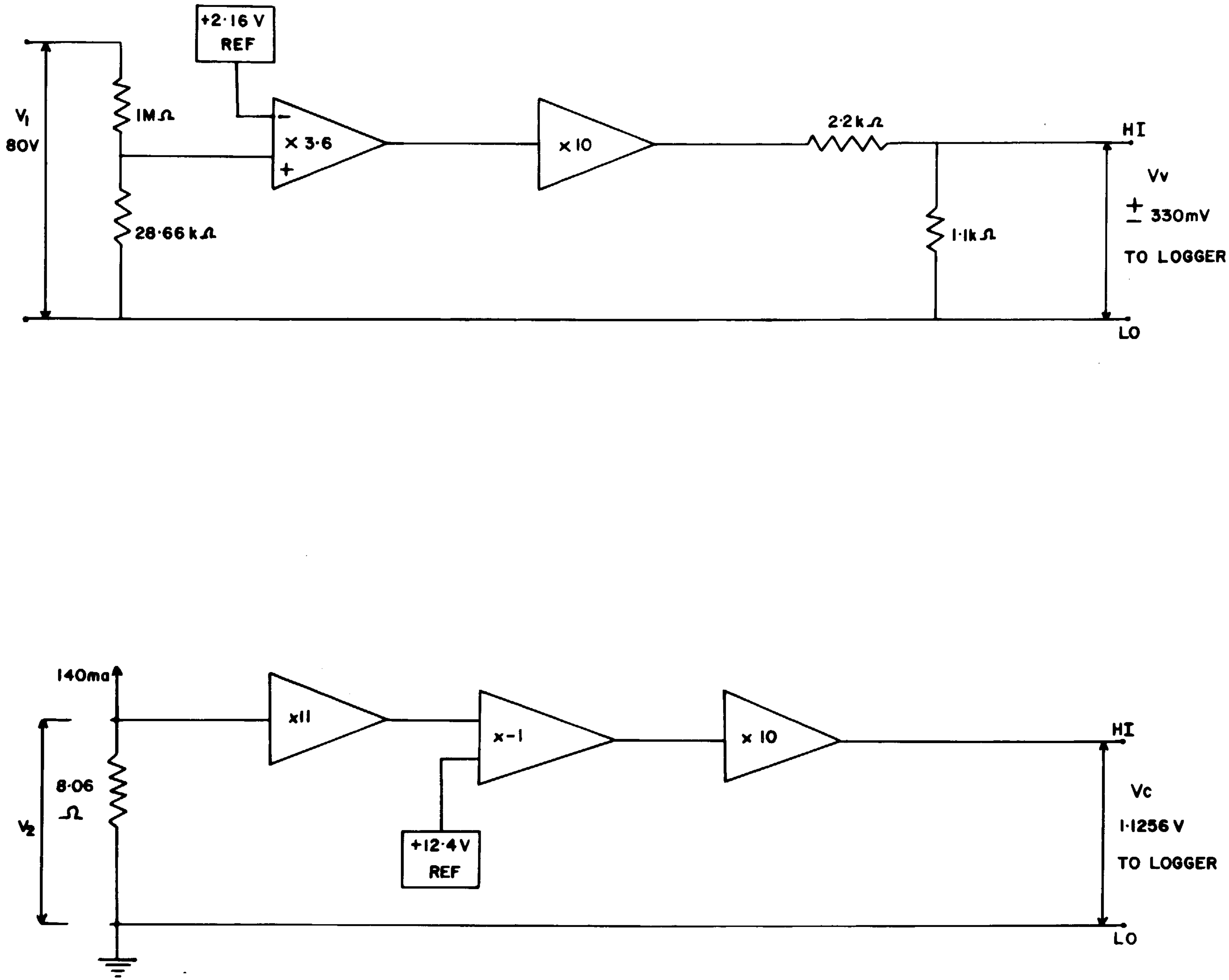
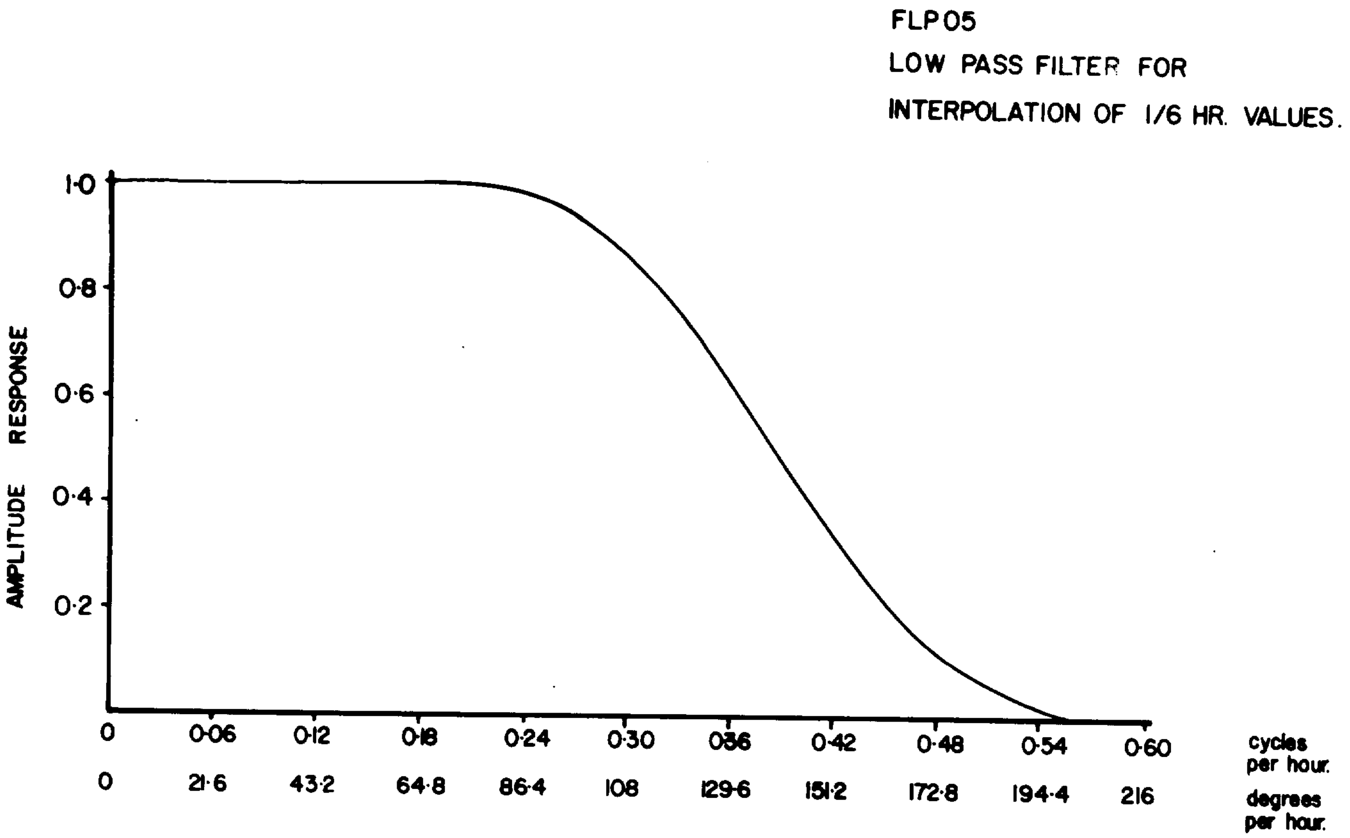


Figure 4. VOLTAGE MEASURING CIRCUITS.



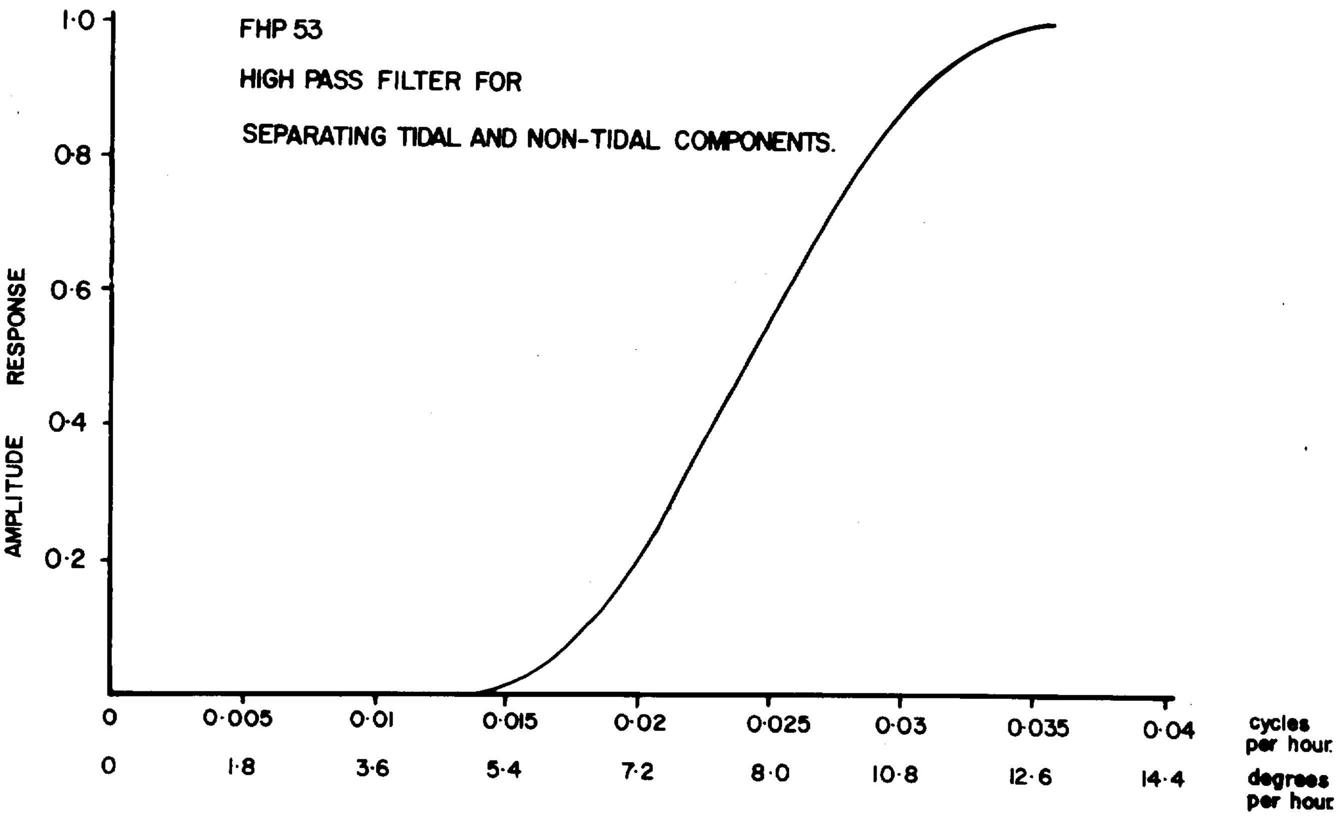


Figure 5. FILTER CHARACTERISTICS.

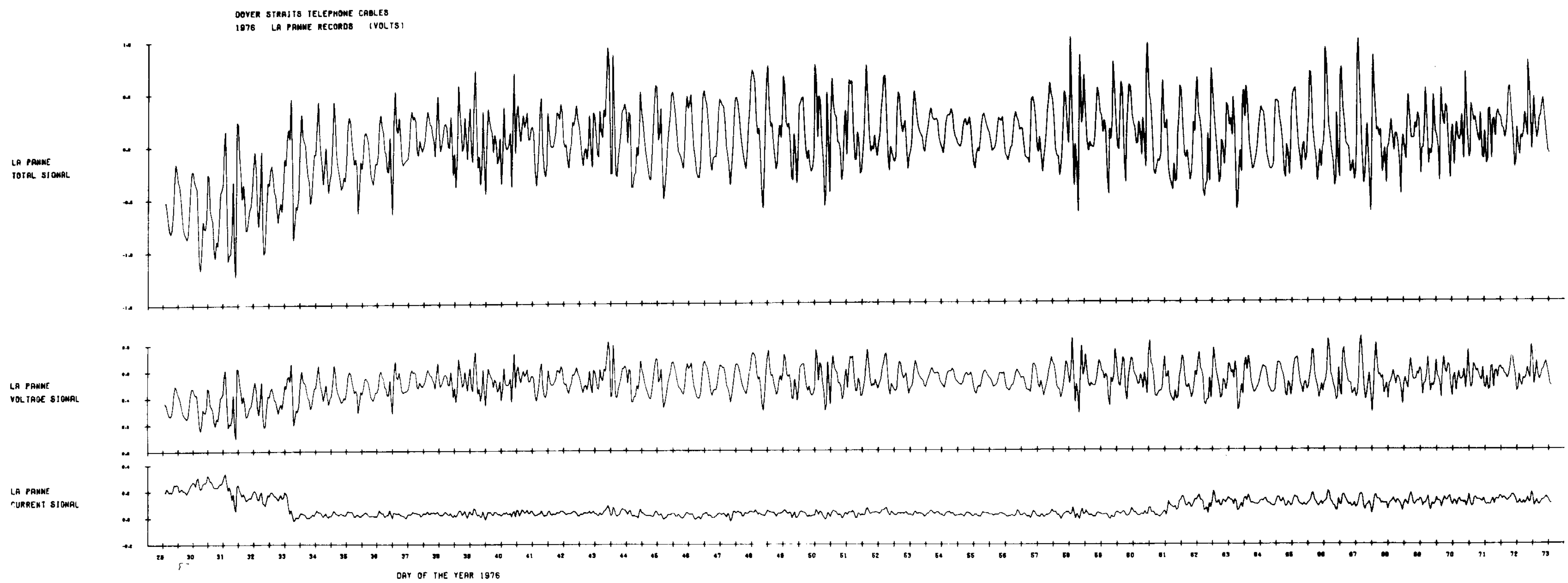


Figure 6. LA PANNE CABLE VOLTAGES.

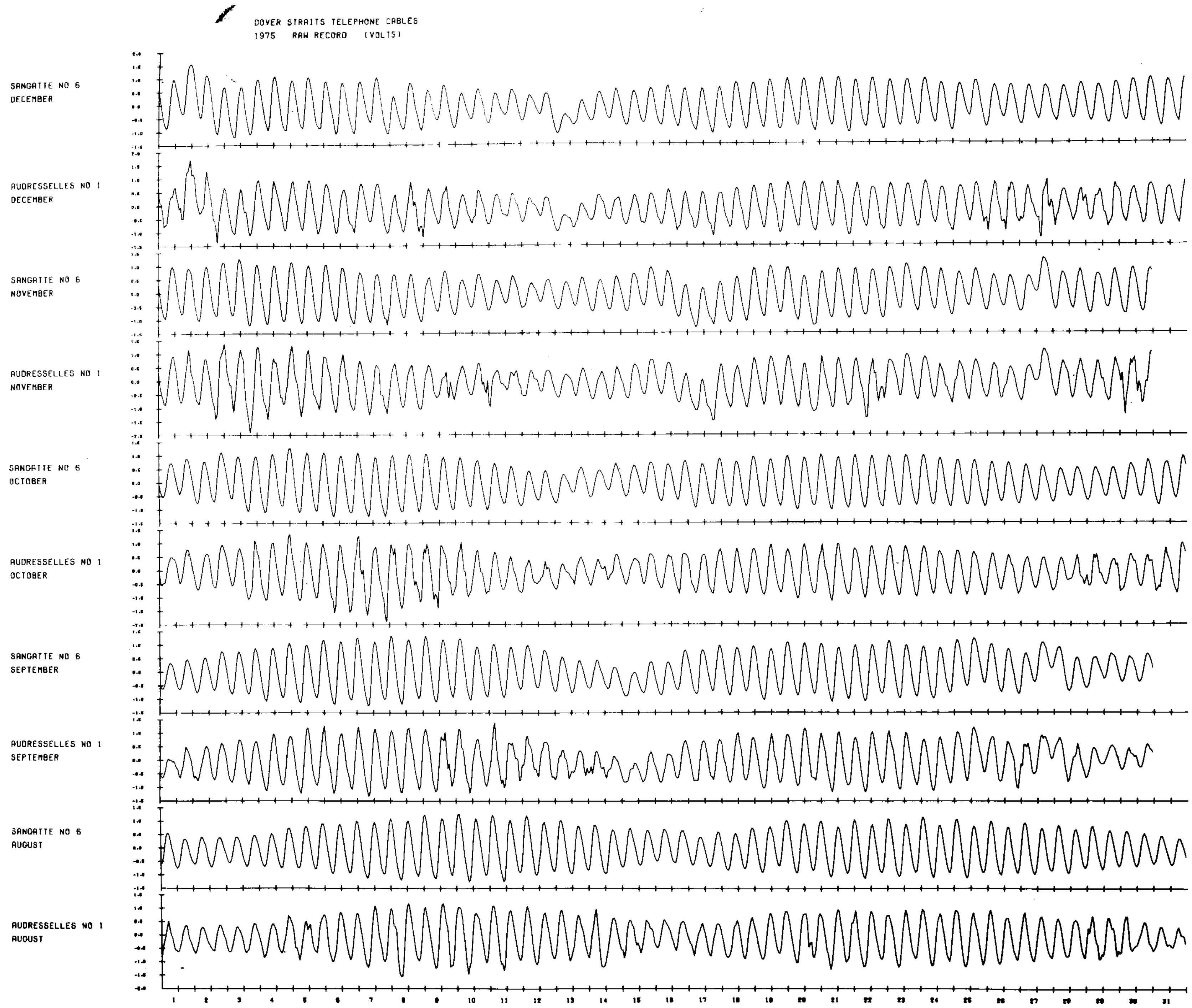


Figure 7a. AUDRESSELLES AND SANGATTE CABLE VOLTAGES.

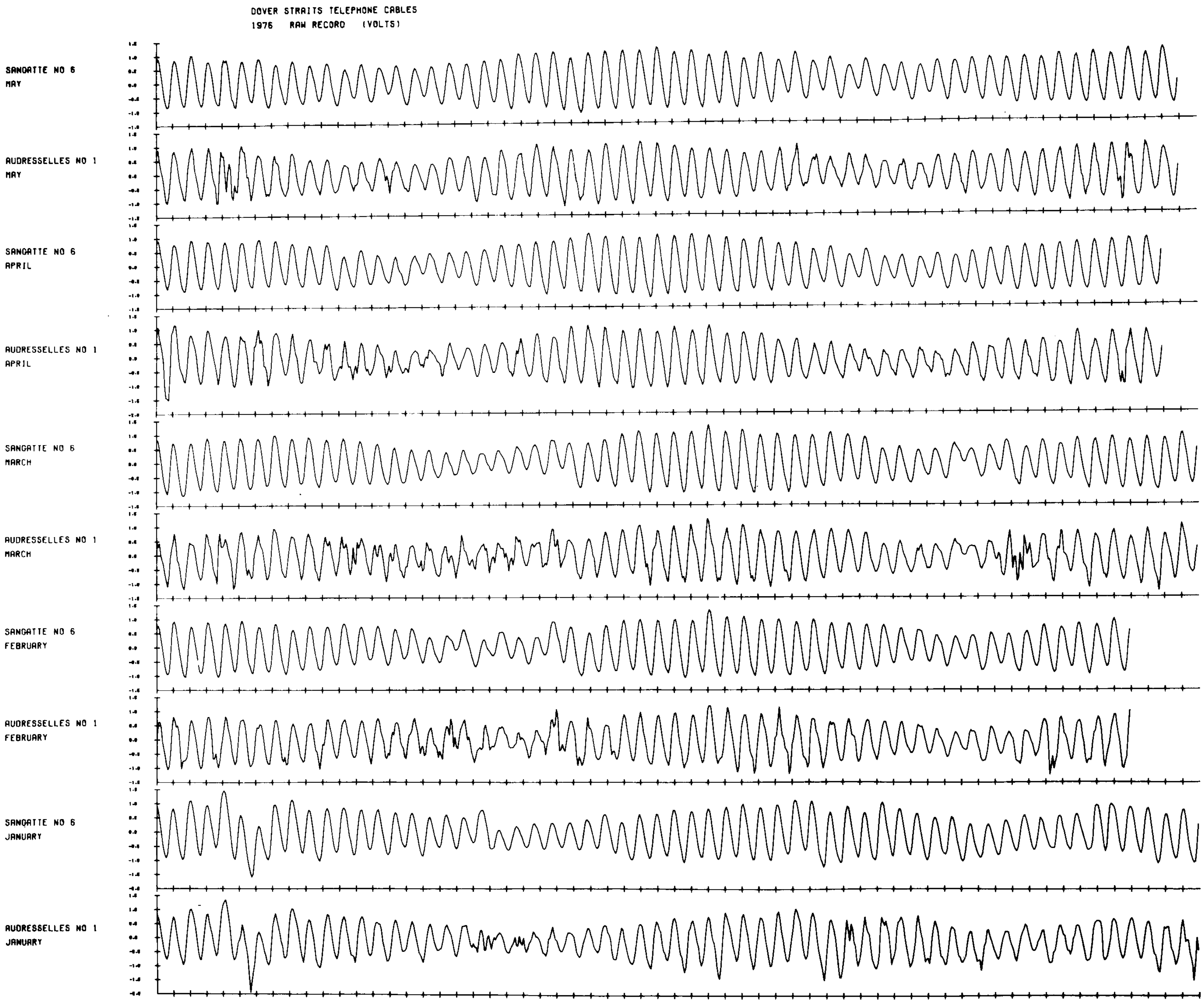


Figure 7b. AUDRESSELLES AND SANGATTE CABLE VOLTAGES.

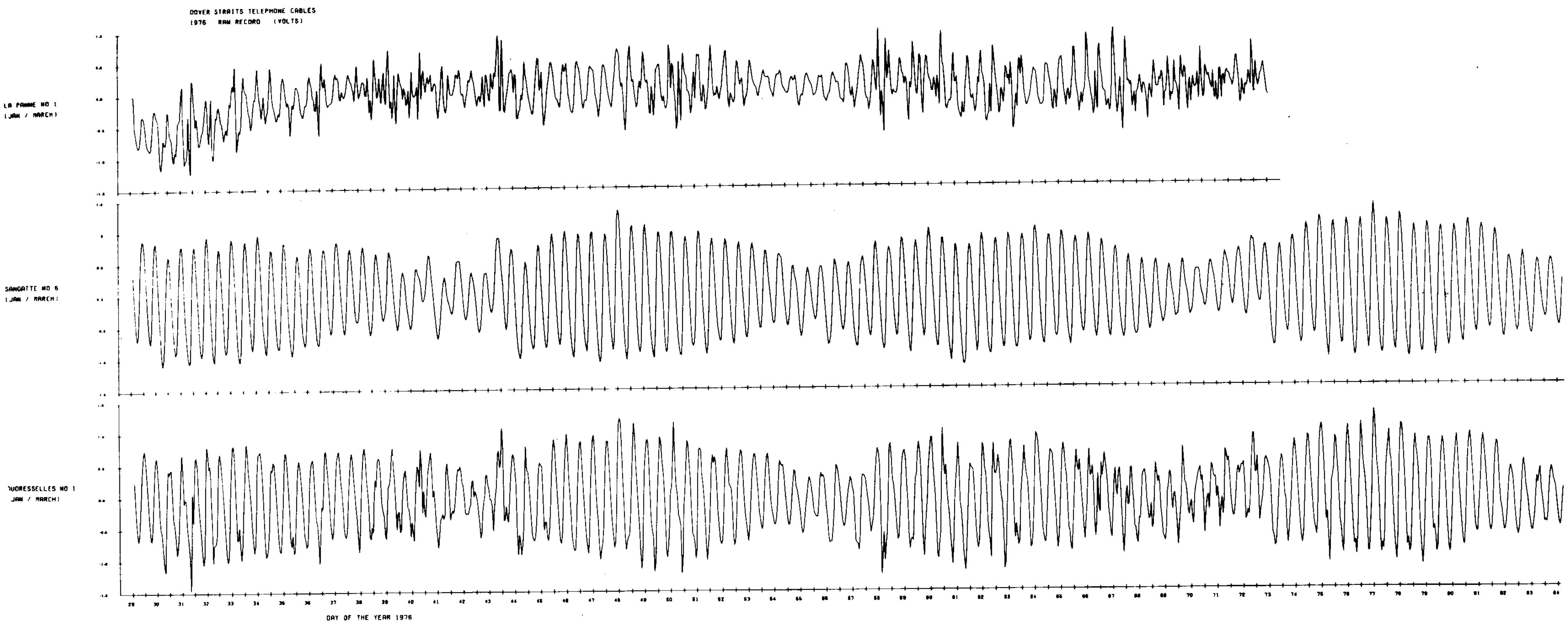


Figure 8. AUDRESSELLES, SANGATTE AND LA PANNE CABLE VOLTAGES.

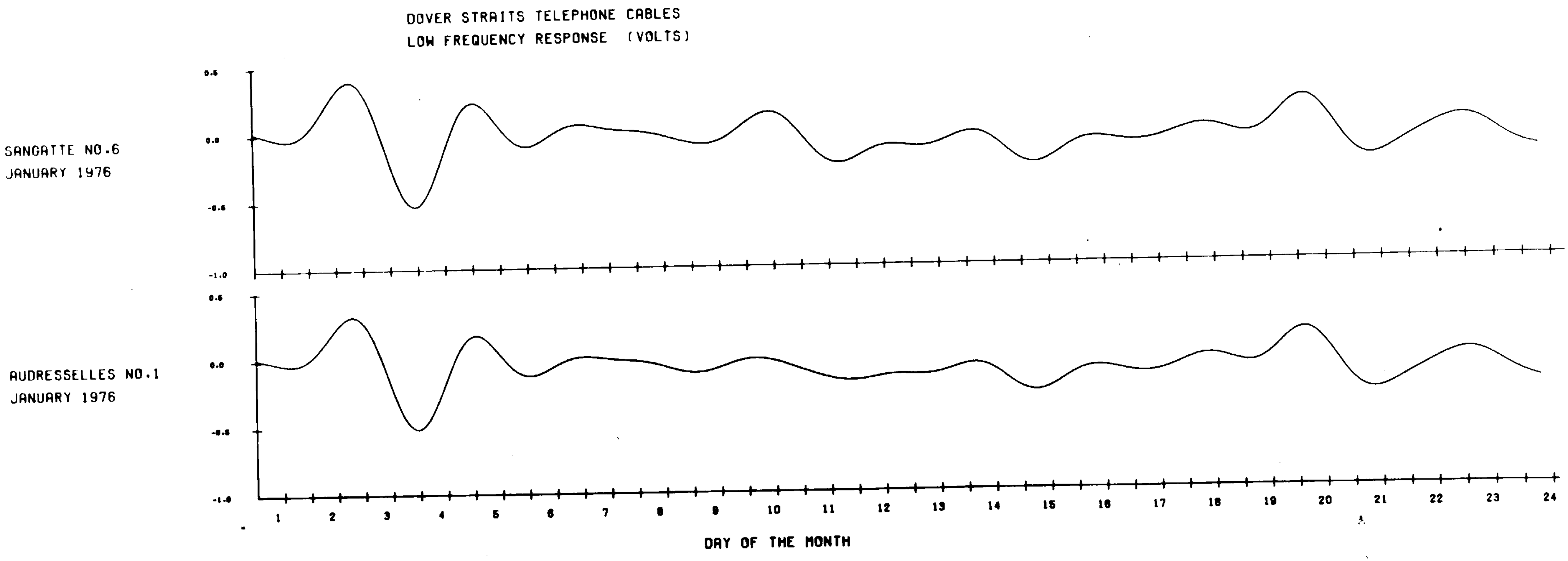


Figure 9. LOW FREQUENCY RESPONSE OF AUDRESSELLES AND SANGATTE CABLES.

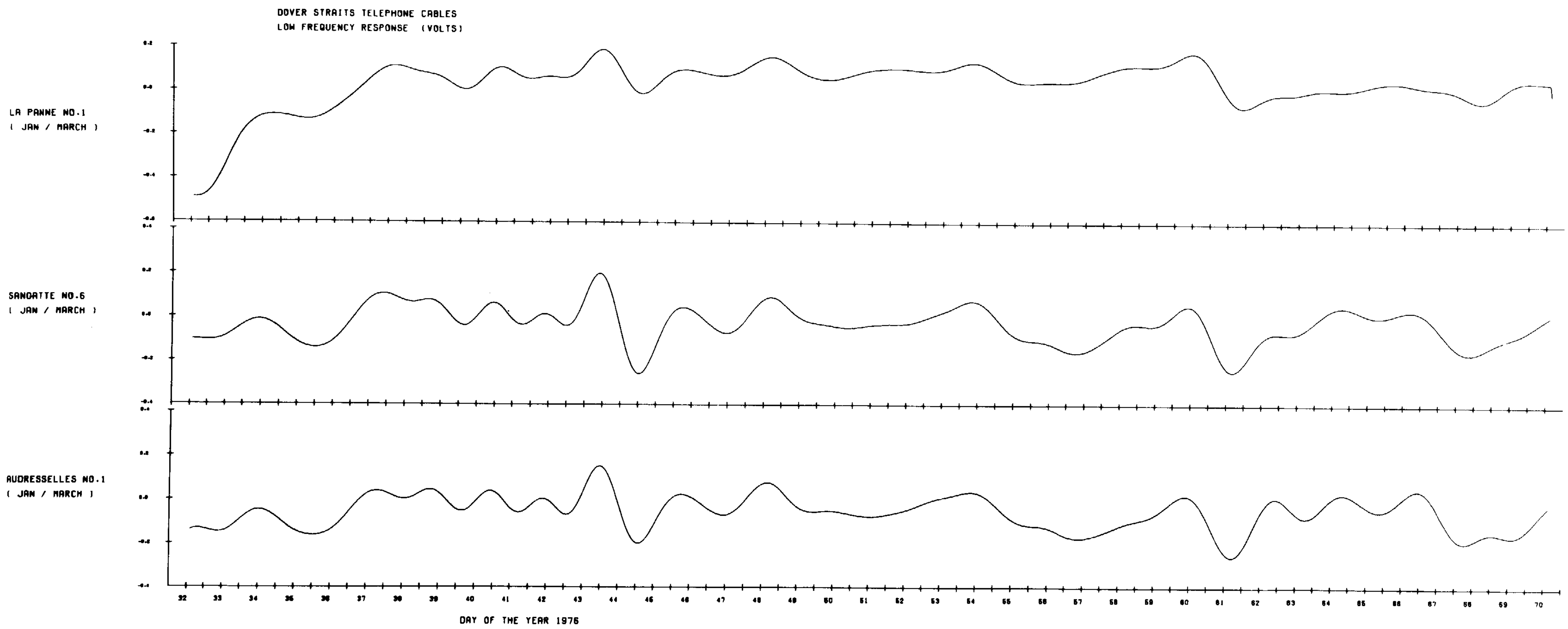


Figure 10. LOW FREQUENCY RESPONSE OF THE 3 CABLES, 01 FEBRUARY TO 10 MARCH 1976.