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Turbulence and Diffusion Note No 16 (June 1971)

EDDY-FLUX ANALYSIS OF DATA FROM JASIN, JUNE 1970

by N Thompson

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1. Introduction

JASIN was a joint oceanographic and meteorological expedition near OWS "Juliett" in June 1970: its purpose was to test various techniques intended to be used during the Royal Society - sponsored air/sea interaction experiment then planned for the same area in June 1973. The main Meteorological Office contribution was the operation from HMS "Hecla" of a turbulence-measuring system used in conjunction with a tethered balloon, by means of which it was hoped to obtain suitable data for estimating vertical eddy fluxes and turbulent energy budgets at several heights simultaneously. A description of the instrumentation has been given in TDN 12 and an analysis of some of the data in terms of turbulent energy budgets in TDN 15. This present note discusses in some detail the techniques of analysis which have been developed to estimate vertical turbulent fluxes from the data, and also considers the representativeness of these fluxes.

2. The experiment

Up to three turbulence-measuring instruments were flown at heights between about 45 and 200 m. The parameters measured were (1) the magnitude of the wind vector, (2) its inclination to the horizontal, (3) temperature, and (4) wet-bulb depression: a high-pass filtered temperature signal was also obtained. The signals were converted to an audio-frequency multiplex and after transmission were recorded on a multitrack magnetic-tape recorder. Measurements were usually made with the ship drifting broadside or else making way along the line of the wind. The main supplementary data (obtained by other groups) were a careful series of observations at hourly intervals of air and sea temperatures using a psychrometer and bucket thermometer both deployed to minimise the influence of the ship, and occasional radiosonde ascents.

A number of different groups had demands on ship time during the experiment and so it was not possible to make turbulence measurements at any instant. For example the ship's main transmitters produced enough power to adversely affect the instrumentation's performance. However there were opportunities to collect data on eight consecutive days. A wide range of meteorological conditions was encountered in this period: for the first three days winds were light and the near-surface stratification usually stable, but it then became unsettled with stronger winds, significant convection and rain or showers at times. Two of these later days were lost, one because of bad weather and the other (the final day of the exercise) when the balloon was damaged by a squall while on deck being topped-up. Thus (apart from a short period on 16/6) data were obtained on only three days of real meteorological interest (ie with significant air-sea exchange taking place) and the quantity was therefore substantially less than had been hoped for.

3. Data analysis

Prior to digitising, the analogue records were inspected and the apparently homogeneous record lengths were identified. Thus on occasions early in the excercise the ships have sailed up-and downwind to create sufficient relative wind to enable the instruments to function correctly: the periods when the ship was turning were found and discarded. The appropriate lengths of magnetic tape were then replayed, the outputs passed through a discriminator system and the resulting voltages were than low-pass filtered before being sampled by the higher-speed Cardington A-D converter: sampling rate was usually 1 scan per second (increased to 5 per second for the analysis described in TDN 15). The filtering was used to attenuate some of the higher-frequency telemetry and recording noise (including some of the tape flutter). The filters were 4-stage RC with attenuation therefore of 12 db at "cut-off" and ultimate slope of 24 db per octave. Cut-off was set at the Nyquist frequency (0.5 Hz) where the attenuation was a factor of 4: the factor was 25 at 1 Hz. Thus high frequencies were strongly attenuated and aliasing much reduced (this is well demonstrated by the composite spectrum shown in figure 1 of

TDN 15 which was plotted after correcting for filter attenuation). Multi-stage RC filters have the disadvantage of a comparatively slow decrease in attenuation with decreasing frequency: in this case for example the attenuation at 0.1 Hz is about 8%. This difficulty could have been avoided by using 4-stage Butterworth filters which have the same ultimate slope and only 3 db attenuation at cut-off, with very rapid decrease of attenuation at lower frequencies. On the other hand they produce overshoot when filtering signals with significant high-frequency content (ie step-like fluctuations) which is very undesirable if one wishes to perform spectral analyses on the resulting data.

The data on paper tape were read into the KDF 9 computer, converted to meteorological parameters (cubic functions were used to simulate the measured non-linearity of the combined sensor/signal conditioning/telemetry system - the discriminators and data logger were effectively linear) and then stored on magnetic tape in blocked digital form (Appendix, TDN 11). The digital data on magnetic tape were then used to deduce fluxes and variances, and spectra and cross-spectra as described in TDN 11. In each case a co-ordinate axis rotation was used to make $\bar{w} = 0$, and linear trends were removed. A further spectral and cross-spectral analysis was done after block averaging non-overlapping data lengths equal to N/1024 (rounded down) where N is the number of data, in order to obtain spectral estimates at lower frequencies.

4. Results and discussion

Some general information on the experiment is given in Table 1. The buoy data were obtained from a prototype self-recording buoy system moored in 2600 m of water at the centre of the exercise area (maximum distance of the ship from the buoy was about 17 km). A shielded but unaspirated thermometer system was used, giving air temperature, wet-bulb depression and air-sea temperature difference. Thus significant radiation errors were expected, especially earlier in the exercise when winds were very light, but a sea temperature deduced from the data should have been reasonably reliable. In the quiet conditions that prevailed at first there was a significant warming of the surface layer of the sea but this tended to be masked in the observations taken from the ship because of the stiring action of the ship: in these circumstances the buoy sea temperature (at a depth of 0.7 m) was often significantly higher than that measured from the ship in the afternoons - sometimes high enough to indicate unstable thermal stratification in the lower atmospheric boundary layer. The actual sea-surface temperature would probably have been several tenths of a degree centigrade higher than buoy sea temperature in these periods. In the unsettled spell that followed, the ship data on sea temperature are preferred because wave mixing then produced a well-mixed and nearly uniform upper ocean, and also because marked horrizontal temperature gradients were found and so buoy measurements were not necessarily representative of those at the ship.

The major difficulty in estimating turbulent fluxes and variances stems from the very large influence of ship motion on the measured turbulence (TDN 11). This affects all the measured parameters because of the periodic vertical and horizontal displacements of the sensors: in addition the inclinometer mount rotates to take up the apparent vertical and this makes the vertical velocity spectrum the one most affected by the ship motion. Typical magnitudes of the effects (which are mainly between frequencies of 0.07 and 0.25 Hz) are shown in spectra plotted in figures 1-4 (these are all corrected for filter attenuation): Clearly the w-spectrum suffers most and the q spectrum least from the influence of ship motion. The temperature spectrum shows considerable noise at frequencies above about 0.2 Hz. This is because the mean temperature at the instrument level cannot be predicted to much closer than about 1 degree C before an experiment and to allow for signal fluctuations a range of about $\pm$ 1.5 degree C from the predicted temperature is used: excursions outside this bandwidth must be avoided in order to prevent significant cross-talk with other channels in the telemetry system. The standard deviation of the temperature fluctuations is typically around 0.1 degree C, i.e. less than 5% of bandwidth, and so the signal-noise ratio is inevitably rather poor. Fortunately in most cases the contribution to the heat flux from these higher frequencies is small.

Corresponding cospectra are plotted in figures 5-7 (the points are estimates uncorrected for low-pass filtering: crosses are corrected estimates and it is seen that the corrections only become significant above 0.1 Hz). An overwhelming contribution to the apparent momentum flux comes from the obviously identifiable spurious perk (figure 5) as would be anticipated from the appearance of the component spectra. Bearing in mind too that characteristic tethered balloon motions will also produce spurious uw correlations almost certainly larger than the corresponding correlations that would affect heat and moisture fluxes, and also that tw (and presumably q w) correlation coefficients appear to be a little larger than those for uw (Haugen et al. 1971), it seems then that reliable estimates of vertical momentum flux will be the most difficult to obtain. Figures 6 and 7 certainly demonstrate that the contribution to heat and moisture fluxes due to ship motion are much less important. Another feature of interest is that substantially higher frequencies appear to contribute to heat flux than to moisture flux, in agreement with the findings of Miyake et al (1970 a, b). Over the height range of the present experiments one might anticipate that only reduced frequencies ($f = n\ z/U$) within fixed limits would contribute significantly to the fluxes, though the limits might vary from one parameter to another as pointed out above. However the corresponding reduced frequency range of the main contribution due to ship motion will vary according to height and wind speed and this makes it difficult to devise an objective scheme for filtering out the effects of this motion. The approach which has therefore been adopted is to use the plotted cospectra to identify noise, which is then smoothed out according to simple rules given below. Some subjectivity must remain and so the approach cannot be completely satisfactory.

Table 2 summarizes the results of the turbulent flux calculations and lists some relevant supplementary data. The wind speeds at 10 m were estimated from those measured at the lowest height on the balloon cable (and corrected for ship speed) by means of the relation

$$U_{10} = U_z - \frac{u_*}{k}\left(\log z/10 + \psi_M(10/L) - \psi_M(z/L)\right) \qquad (1)$$

Estimates for ψ given by Dyer and Hicks (1970) were used in unstable conditions. In stable cases ψ was approximated by $-5.2z/_L$ (Webb 1970). L was calculated from the expression (TDN 14)

$$L = -2.4 U_e^2 / (\theta_s - \theta_a + 175(q_s - q_a)) \tag{2}$$

where $\theta_s - \theta_a$ and $q_s - q_a$ were the measured air-sea differences of potential temperature and specific humidity. U_e was a rough estimate of the 10 m wind, in m sec^{-1}, typically about 90% of that measured by the turbulence instrument (this also determined u_* ($\simeq (C_D)^{1/2} \times 0.96 U_e$ where C_D was assumed to be 1.3×10^{-3})). If U_e was found to be significantly different from the calculated U_{10} then the latter was recalculated using the revised estimate for U_e. In most cases the lowest height of measurement was at least 90 m (apart from the buoy anemometer which was usually several kilometres from the ship and hence not necessarily measuring a wind representative of that at the ship) and hence above the constant flux layer and so the estimated 10 m winds will not be very accurate. In a few cases with very light winds on the 15th and 16th only rough estimates have been given, either because the measuring height was far too great for a constant flux layer treatment to be at all applicable, or else because measured wind speed and ship's speed were of similar magnitude and so the actual wind was poorly determined (the ship's speed could not be estimated with great accuracy).

The surface fluxes were obtained using the expressions

$$\tau = -\rho C_D (0.96 U_{10})^2 \tag{3}$$

$$H = \rho c_p C_{H,E} (\theta_s - \theta_a)(0.96 U_{10}) \tag{4}$$

$$E = \rho C_{H,E} (q_s - q_a)(0.96 U_{10}) \tag{5}$$

In near-neutral conditions it was assumed that $C_D = C_{H,E} = 1.3 \times 10^{-3}$, but corrections were applied for unstable stratification as described in TDN 14. The coefficients were corrected in stable cases using the data given by Deardorff (1968). The listed values for L were obtained using these surface fluxes from

$$L_{(m)} = -8.6 u_*^3 / (H + 175E) \tag{6}$$

(TDN 14): they differed from those given by eq (2) by less than 10% usually.

A fundamental difficulty, associated with the determination of moisture fluxes, is that to do so accurately requires absolute measurements of air and wet-bulb temperature. The calibration system used for JASIN was designed primarily to check sensitivities and not absolute values: also uninsulated wire was used in the wet-bulb elements and due to the shunting effect of the water film the measured wet-bulb temperatures were probably about a degree centigrade too low. In general then the calculated specific humidities and hence moisture fluxes were not very accurate, and were usually underestimates. More reliable estimates for mean specific humidity were obtained using the relation

$$q_z = q_0 - \frac{E}{\varrho k u_*} \left(\log z/10 - \psi_E(z/L) + \psi_E(10/L) \right) \qquad (7)$$

: ψ was again obtained from the data of Dyer and Hicks, and Webb. Corresponding corrections to the moisture fluxes were typically a few per cent, but reached 10% on one occasion where apparently the temperature offset of the instrument had been incorrectly noted (here the potential temperature calculated from the digitised data was about 1.5 degrees C lower than that measured on the ship at 10 m: a nearly adiabatic lapse above 10 m height would have been expected in view of the comparatively small air-sea temperature difference of 2 degrees C).

Columns 1-5 under "Method of flux estimation" in Table 2 show different ways in which the turbulence data may be used to estimate the eddy fluxes at the instrumental height. The results in method 1 were obtained by the conventional eddy correlation method and include therefore contributions from all frequencies between the cut-off due to RC filtering and the lower limit set by length of the sampling period. Inspection of figures 5 and 6 suggests that these estimates will be grossly inaccurate in the case of momentum, and to a lesser degree heat flux, but (figure 7) may be more acceptable for moisture flux. Method 2 involves simple numerical filtering (block averaging over overlapping 8-sec periods) which drastically attenuates the main contribution to the cospectra due to ship motion. The filter has a cut-off (-3 db) at about 0.05 Hz and the transmission decreases rapidly with increasing frequency to negligable amounts beyond about 0.2 Hz. Unfortunately in the present experiments there was often a significant contribution to the fluxes from frequencies around filter cut-off and so some loss of covariance must occur. Even so the resulting fluxes are usually a satisfactory first approximation.

Further refinement begins to introduce subjectivity but in spite of this it is felt that a plausible improvement on the second method can be made. The essential ingredient of methods 3-5 is knowledge of the expected range of frequencies contributing significantly to the various fluxes. If it is assumed that cospectral frequency ranges scale according to height up to about 200 m (Panofsky and Mares (1968) suggest that this is true up to 100 m at least, though there may be some stability dependance) then we may attempt to establish these ranges using data obtained comparatively close to the sea surface. Miyake et al (1970a) using data from a single run at 18 m and plotting the cospectra as n S(n) versus log n showed that the cospectral estimates for moisture and momentum flux became negligable outside the reduced frequency range 2×10^{-2} to 1, but 1×10^{-1} to 4 in the case of heat flux. Miyake et al (1970b) from a number of experiments at height between 1 and 5 m found virtually all the covariance contained between $f = 5 \times 10^{-3}$ and about 1 for uw, but again the high frequency cut-off for Tw was higher, around 3. Panofsky and Mares (1968) assembled uw cospectrum data given by Weiler and Burling (1967) and showed that the cospectral limits at a height of 2 m depended on stability but in unstable conditions the range of significant contributions was from somewhat larger than 1×10^{-3} to a little greater than 1. In general then the ranges $f = 1 \times 10^{-3}$ to 1 should contain most of the momentum and moisture fluxes but for heat flux the upper limit should be increased to about 4: it may be justifiable also to increase the low-frequency limit in this latter case to about 10^{-2}. It is not clear that these ideas can be extended unambiguously to heights of 200 m or so where reduced frequency scaling is probably no longer appropriate and where large scale systems e.g. cumulus clouds or helical rolls similar to those described by Hanna (1969), could introduce substantial flux contributions at comparatively low frequencies. However it will be assumed at present that the high-frequency cut-offs given above will be approximately correct: the fluxes listed under methods 3 and 4 in table 2.

were obtained by subjectively smoothing the cospectra to zero at these limits.

The final flux estimates (5) were calculated originally because of some surprisingly small (or even downward) heat fluxes in quite definitely unstable conditions. In many cases, after carrying out a cospectral analysis of the complete length of data when block-averaged as described earlier, this was found to be due to a substantial negative contribution at the lowest frequencies. Unfortunately the statistical reliability of the individual cospectral estimates is very low (S.D. of estimate $\simeq$ size of estimate) and so they had to be block-averaged to reduce the statistical variability: in practice values for the eight lowest frequencies were linearly averaged (the ratio of the actual estimate to that obtained from an infinite sample then lies between about 0.6 and 2.0 on 90% of occasions (Mercer 1968)). The higher frequency limit of this averaged estimate was typically 1×10^{-2} or greater and thus lay within the frequency ranges given above in many cases. It is possible then that these occasionally large contributions to the covariances are quite genuine. Thus updraughts would transfer heat upwards and because they originate near the ground would be of comparatively short periods whereas the major downdraughts would be associated with larger scale features, e.g. cumulus clouds, and would transfer heat downwards because of the sub-adiabatic lapse rate at higher levels. An alternative explanation may be instrumental errors producing spurious correlations. Changes in the apparent mean inclination of airflow to the horizontal, presumably due to ageing of the inclination sensors or perhaps drift in the electronic circuits, were certainly detected when data from consecutive runs were compared, typical values being around 5×10^{-3} radians. If these changes were correlated with temperature changes of the right magnitude and sign then spurious contributions to the heat flux of the right size and at low frequencies would have resulted. One occasion with a large negative heat flux at low frequencies was on 17/6, 1749-1922 (140 m). Here this flux was - 1.4 m W cm^{-2}, equivalent to $\overline{T'w'} \simeq 1.2$ cm sec^{-1} deg C. The mean inclination was found to have changed by 1.5×10^{-2} radians from the previous period (an apparent change of 12 cm sec^{-1} in w) and it would appear then that spurious low frequency temperature fluctuations of around 0.1 degree C if suitably correlated with the changing w would have sufficed to produce the flux. Such large temperature fluctuations would not have been expected as a result of instrumental drift and in any case would not correlate perfectly with spurious inclination fluctuations, and the trend corrections carried out in the data analysis should have further reduced the correlations. A final possibility is that of a sampling error, that is the lengths of record were too short to obtain reasonable statistical reliability, as would be the case if periods of organised motions were of the order of tens of minutes.

Similar estimates were made for momentum and moisture fluxes and they usually showed that there were substantial contributions below cut-off frequency but it was difficult to decide whether these were statistically significant because the cut-off frequency lay well within the energy-containing region of the cospectra. In general the apparent importance of low-frequency contributions to all these fluxes suggests that for statistical reliability the experiments in future should have the longest possible duration - for practical reasons this cannot be longer than about 200 minutes with the present system if all data are to be recorded on a single magnetic tape, but it is seen from table 1 that most of the analysed records are substantially shorter than this, and some only about 40 minutes. If contributions to fluxes at reduced frequencies less than about 10^{-3} are usually expected to be insignificant, then at a height of 200 m in a wind of 5 m sec^{-1} the record length would have to be at least 1300 minute to resolve this frequency and perferably several times longer (say 5000 minutes) for statistical reliability! However a simple physical argument suggests that the low-frequency cut-off of the cospectra may in fact be at much higher reduced frequencies than 10^{-3} at heights of a few hundred metres. Thus in convective conditions statistical reliability of measured fluxes is obtained if a sufficiently large number of individual cumulus clouds are sampled. If the clouds are randomly distributed and spaced say 2 km apart (the spacing would of course vary with the clouds' vertical development) then a sampling period of about two hours would probably be sufficient in a wind of 5 m sec^{-1}. This is two orders less than the earlier estimate which thus appears unduly pessimistic. Practically of course cumulus clouds are often larger and more widely spaced, or else organised into systems such as cloud streets, and a longer sampling period is then necessary to reduce statistical variability. It is therefore likely that at heights of a few hundred metres a sampling period of even 200 minutes will often be inadequate and the results of a single experiment may be misleading.

If it is assumed that the best estimates for the measured fluxes are those given by methods 3 or 4 above then inspection of the results from Table 2 shows that only in the case of moisture is there reasonably close correspondence between measured fluxes and those estimated at the surface. The momentum and heat fluxes are usually smaller than the surface values and an adequate explanation of this is required to evaluate properly the tethered balloon technique. Considering momentum first, we may write with the usual notation

$$\partial\tau/\partial z \simeq \rho f V_g \sin\alpha \qquad (8)$$

: here unaccelerated flow has been assumed, and also that the layer of interest is close to the surface so that baroclinicity can be ignored. The data of Mendenhall (1967) suggest that α is about 5 degrees in slightly unstable conditions at OWS "J", and taking $\rho \simeq 1.2 \times 10^{-3}$ g cm^{-3}, $f \simeq 1.1 \times 10^{-4}$ and $V_g = 10$ m sec^{-1}, then

$$\partial\tau/\partial z \simeq 1.2 \times 10^{-5} \text{ dynes cm}^{-3}$$

τ is about 1 dyne cm^{-2} in this case (assuming U_{10} = 8 m sec^{-1}) and thus the change of τ per 100 m is about 12%. In general the measured fluxes do not support such a slow variation with height. The low values for the fluxes appear to result from very small or even positive contributions to the uw cospectra over a broad frequency range centred close to 2×10^{-2} Hz (e.g. figure 5) or typically near a reduced frequency of 3×10^{-1} at 100 m. Two possible causes are periodic tethered balloon motions similar to those studied over land and reported in TDN 5, or a less obvious effect of ship - induced motion of the sensors (see below). Generally the balloon seemed to fly very stably with few of the characteristic crosswind excursions as are observed over the land and the likely explanation is the second. The ship has a characteristic period of about 6 seconds which is close to the peak of the wave spectrum in moderate winds. Usually the ship and dominent wave motions are not in phase but when correct phasing occurs the oscillation amplitude will increase for a few cycles. Thus the largest-amplitude oscillations of the ship tend to occur every minute or so, and while being comparatively isolated events none the less make a significant contribution to the measured uw cospectrum because of the associated large spurious velocities. Unfortunately it is not possible to smooth out the appropriate portion of the uw cospectrum to eliminate the effect with any objectivity. The balloon technique as it stands therefore seems incapable of producing data from which reliable estimates of momentum flux may be obtained.

Apart from occasional large contributions at low frequencies there appears to be no reason for doubting the validity of the measured heat fluxes. The effects of ship motion on the Tw cospectrum are clearly much less than those for uw and can be smoothed out with smaller resulting error, and so the observed tendency for comparatively rapid decrease of upward heat flux near the surface with increasing height in convective conditions is almost certainly real (the ATEX data (TDN 11), while admittedly of poorer quality, also support this conclusion). The measured fluxes were used in conjunction with eq (4) on the few occasions when air-sea temperatures were reasonably large to give a mean value for C_H around 1×10^{-3} which, bearing in mind the flux divergence between surface and level of measurement (and hence underestimation of C_H), agrees reasonably well with the value of 1.25×10^{-3} given by Robinson (1966). The validity of the tethered balloon technique for measuring heat fluxes appears thus to be confirmed.

The moisture flux data showed comparatively small variations with height on five out of six occasions on which measurements were made at two heights in convective conditions: this suggests that surface values may be adequately approximated by those obtained from measurements at 100 m or so. The cospectra are much less influenced by the effects of ship motion than those for Tw and only the uncertainty about estimating the mean specific humidity at instrument level prevents unqualified acceptance of the results. Table 3 lists measured fluxes and calculated values for C_E (eq. 5) for 10 unstable and two slightly stable cases when the surface wind could be estimated with reasonable accuracy. The final column contains estimates for $C_E(N)$ obtained by correcting the C_E's for stability as explained earlier. The mean of 1.72×10^{-3} may be compared with, for example, the value of 1.25×10^{-3} obtained by Robinson (1966) from heat budget considerations in predominantly unstable conditions, and 1.32×10^{-3} by Chamberlain (1968) from wind tunnel studies, and hence appears rather large. The mean in table 3 is however heavily weighted by the very large entries in the ninth and tenth rows and deleting these would reduce the value to 1.44×10^{-3}: the difference between this and the mean of Robinson's and Chamberlain's values is significant only at the 30% level (t - test).

In general the results are consistant with the idea that the main control of mixing in the convective boundary layer is due to the vertical flux of moisture rather than heat, in sharp contrast to typical conditions over land. A rudimentary model, into which the present results can be fitted, may be easily developed. The basis is that the convectively-mixed layer is capped by a dry inversion, and the mixing is maintained primarily by an upward flux of moisture. Typically there will be condensation and cumulus formation at heights greater than a few hundred metres, and the released latent heat will allow further vertical development. The cumulus clouds will of course decay continuously and if only sensible heat from within the well-mixed layer is available to evaporate the cloud droplets then the model is inadequate to explain the observed downward heat fluxes, and positive potential temperature gradients below cloud base. One way round this difficulty is to allow some precipitation and hence a net release of latent heat. Alternatively, or additionally, the moist rising elements will penetrate occasionally into the warm dry "lid" at the top of the mixed layer and entrain some of the air there. This will guarantee a source of sensible heat near the top of the layer, and subsequently this heat will be transferred downwards by mixing.

5. Conclusions

The present tethered balloon technique appears to be capable of measuring moisture fluxes from heights of about 50 m up to several hundred metres with reasonable accuracy, and heat fluxes also though with reduced accuracy because of the increased influence of ship motion on measured Tw correlations. Measured momentum fluxes while generally of correct sign were nearly all considerably smaller in magnitude than would have been anticipated from estimated surface values and expected variations with height: the cause of the discrepancies was apparently short periods of ship/wave resonance spaced a minute or so apart and introducing spurious positive uw correlations at frequencies around 2×10^{-2} Hz. Unexpectedly large contributions to fluxes at low frequencies were found occasionally, probably the result of too short a sampling period. It appears that even the longest period of continuous recording at present available (200 minutes) will sometimes be insufficient for adequate sampling of the turbulence.

Stabilisation of the tethering point of the balloon cable by a suitable servo-system is essential if momentum fluxes are to be measured reliably even in light or moderate winds, and if heat and moisture fluxes are to be obtained in winds in excess of about 10 m sec^{-1}. If the ship-induced motion of the tethering point were to be reduced by a factor of 3 an improvement of signal to noise ratio of about an order would be anticipated in the cross-correlations at frequencies clearly affected by ship motion, and this would probably be sufficient to allow the calculation of reliable momentum fluxes. Steps are being taken to acquire a suitable servo-system with a design performance superior to this requirement.

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Table 3. Values for C_E deduced from measured moisture fluxes

Date/Period		E (μg cm^{-2} sec^{-1})	$U_{10}(q_o - q_{1})$ (cm sec^{-1})	$C_E \times 10^3$	$C_E(N) \times 10^3$
16/6	1307-1347	2.25	0.90	2.09	2.04
	1914-2058	0.22	0.23	0.81	0.77
17/6	1057-1148	4.69	2.02	1.97	1.83
	1229-1317	2.97	1.70	1.47	1.40
	1610-1738	2.01	1.17	1.45	1.41
	1749-1922	3.28	1.31	2.12	2.03
	2143-0005	1.88	1.31	1.22	1.11
18/6	1530-1745	1.50	1.39	0.91	0.94
	1745-1845	5.44	1.36	3.39	3.46
20/6	1021-1147	8.45	2.48	2.88	2.76
	1830-1947	4.65	2.66	1.48	1.37
	2005-2137	4.25	2.27	1.59	1.47
				Mean	1.72

Table 1. General details

Date (1970)	Period (Z)	Instrument heights (m)	Wind Speed (a) (m sec^{-1})	Buoy wind (b) speed (m sec^{-1})	Air temperature at 10 m (°C)	Wet-bulb temp. at 10 m (°C)	Sea temp. by bucket (°C)	Sea temp. (buoy) (°C)	Weather etc	Notes
14/6	1330-1500	45 100 210								Not analysed: wind speed too low for satisfactory functioning of instruments
15/6	1259-1344	185	~ 2.8	1.7	14.3	12.3	14.4	14.7	Sunny, 3/8 cloud	Ship making 5-6 m sec^{-1} nearly across-wind to increase relative wind
	1400-1449	185	~ 2.0	1.9	14.3	12.4	14.3	15.0		
	1454-1534	185	~ 2.8	2.0	14.5	12.4	14.6	15.3		
16/6	1127-1307	90 185	4.5 4.4	4.2	15.0	13.0	14.6	14.5	Dry, 7 - 8/8 Sc.	Ship steering into wind at 2.1 m sec^{-1}
	1307-1347	90 185	6.0 6.0	5.0	14.8	13.1	14.7	14.9	Dry, 7 - 8/8 Sc.	Ship steering into wind at 2.1 m sec^{-1}
	1914-2058	90 185	2.7 2.8	2.4	14.8	13.7	14.2	14.8	Dry, 6 - 8/8 Sc.	Sailing into wind at 2.6 m sec^{-1}
	2106-2154	90 185	~ 1 ~ 1	1.1	14.8	13.8	14.1	14.8	Dry, 2 - 6/8 Sc.	Sailing downwind at ~ 5.0 m sec^{-1}
17/6	1057-1148	95	9.1	6.9	12.2	10.7	13.8	13.4	Dry, 8/8 St, Sc.	Drifting downwind at 0.6 m sec^{-1}. Sea temp. changed 0.8°C in 1 hr. Increase in temp. of 2.5°C at 95 m
	1229-1317	95	9.2	6.1	12.5	10.7	13.4	13.3	Dry, 8/8 Cu, Sc.	Drifting downwind at 0.6 m sec^{-1}.
	1610-1738	45 140	8.5 8.8	6.2	12.3	10.9	12.8	13.4	Occasional light rain, 7/8 Cu, Ac.	Drifting downwind at 0.2 m sec^{-1}
	1749-1922	45 140	7.6 8.1	6.3	12.3	10.5	12.8	13.3	Occasional light rain at first, 7/8 Cu, Ac.	Drifting downwind at 0.3 m sec^{-1}
	2143-0005	90 185	6.3 6.3	5.0	12.1	10.2	13.2	13.2	Dry, 2/8 Cu.	Drifting downwind at 0.3 m sec^{-1}
18/6	1530-1745	95	9.9	6.8	14.6	12.4	14.1	14.5	Dry, 6/8 Cu, Sc.	Drifting downwind at 0.7 m sec^{-1}
	1745-1845	95	10.6	7.7	14.5	12.5	14.1	14.5	Dry, 6/8 Cu, Sc.	Drifting downwind at 0.6 m sec^{-1}
	2020-2109	95	14.3	8.9	14.3	12.5	13.9	14.5	Dry, 3/8 Cu, Sc.	Headed into wind at 1.6 m sec^{-1}
20/6	1021-1147	95	8.3	6.3	11.9	8.3	12.3	12.3	Dry, except for light shower at end. 5/8 Cu, Cb.	Drifting acrosswind at 0.3 m sec^{-1}
	1830-1947	95	8.7	5.9	11.0	88.1	12.6	13.1	Dry, 5/8 Cu, Sc.	Hove to
	2005-2137	95	9.0	7.3	10.5	8.3	12.3	13.1	Dry, 5/8 Cu, Sc.	Hove to

Notes (a) At instrument height corrected for ship speed

(b) At 2m

Table 2. Vertical turbulent fluxes

Date	Period (Z)	Instrument heights (m)	$\hat{U}$ (a) (m sec^{-1})	$\hat{U}/z$ (sec^{-1})	U_{10} (m sec^{-1})	Flux (b) parameter	Method of flux estimation: 1. Direct: unaveraged data	2. Direct: 8-sec averaged data	3. Cospec smoothed to zero at $nz/\hat{U} = 1$	4. Smoothed to zero at $nz/\hat{U} = 4$	5. As 3, 4, with L.F. cut-off	$nz/\hat{U}$ at low-frequency cut-off	Estimated surface fluxes	L (m)
15/6	1259-1344	185	6.9	0.037	~ 2	τ(e)	0.36	0.10	0.10		(c)	0.11	-0.07	≈ -15
						H	-0.22	-0.21		-0.23	-0.14	0.11	0.1	
						E	0.40	0.37	0.38		(c)	0.11	0.9	
15/6	1400-1449	185	4.5	0.024	~ 2	τ(e)	-0.16	-0.13	-0.10		(c)	0.17	-0.08	≈ -10
						H	0.02	0.002		0.01	0.02	0.17	0.3	
						E	0.55	0.52	0.48		(c)	0.17	0.9	
15/6	1454-1534	185	7.8	0.042	~ 2	τ(e)	0.46	0.08	0.06		(c)	0.10	-0.08	≈ -10
						H	-0.08	-0.09		-0.09	-0.01	0.10	0.3	
						E	0.67	0.63	0.62		(c)	0.10	0.9	
16/6	1127-1307	90	6.6	0.073	2.6	τ	0.05	-0.10	-0.10		-0.09	0.023	-0.09	+55
						H	-0.09	-0.11		-0.13	-0.05	0.023	-0.2	
						E	0.90	0.81	0.85		0.52	0.023	0.5	
		185	6.5	0.035		τ	0.32	0.04	0.03		0	0.047		
						H	-0.15	-0.11		-0.12	-0.12	0.047		
						E	0.12	0.05	0.02		0.12	0.047		
16/6	1307-1347	90	8.1	0.090	5.3	τ	-0.49	-0.15	-0.15		-0.18	0.046	-0.42	-250
						H	-0.38	-0.38		-0.38	0.01	0.046	0	
						E	2.36	2.11	2.25		0.84	0.046	1.4	
		185	8.1	0.044		τ	0.47	0.15	0.16		(c)	0.094		
						H	-0.33	-0.36		-0.38	-0.03	0.094		
						E	1.47	1.32	1.34		(c)	0.094		
16/6	1914-2058	90	5.3	0.059	2.3	τ	0.25	0.07	0.06		0.06	0.023	-0.08	-130
						H	-0.27	-0.27		-0.29	-0.21	0.023	-0.05	
						E	0.26	0.21	0.22		0.31	0.023	0.4	
		185	5.4	0.029		τ	0.57	0.23	0.28		0.17	0.048		
						H	-0.39	-0.39		-0.41	-0.19	0.048		
						E	0.38	0.26	0.22		0.15	0.048		

Table 2 (continued)

Date	Period (Z)	Instrument heights (m)	$\hat{U}$ (a) (m sec^{-1})	$\hat{U}/z_1$ (sec^{-1})	U_{10} (m sec^{-1})	Flux (b) parameter	Method of flux estimation: 1. Direct: unaveraged data	2. Direct: 8-sec averaged data	3. Cospec smoothed to zero at $nz/\hat{U}$ = 1	4. Smoothed to zero at $nz/\hat{U}$ = 4	5. As 3, 4, with L.F. cut-off	$nz/\hat{U}$ at low-frequency cut-off	Estimated surface fluxes	L (m)
16/6	2106-2154	90	4.5	0.050	~1	τ(e) H E	-0.32 0.027 0.012	-0.003 -0.014 0.003	-0.03 0.010	-0.024	(c) -0.031 (c)	0.083 0.083 0.083	-0.02 0.2 0.2	≃ -30
		185	4.2	0.023		τ(e) H E	-0.09 0.022 0.036	0.05 -0.003 -0.010	0.06 0	-0.005	(c) 0.015 (c)	0.22 0.22 0.22		
17/6	1057-1148	95	8.6	0.091	8.1	τ H E	0.72 0.54 4.43	-1.20 0.30 4.40	-1.52 4.69	0.37	-0.37 0.45 1.52	0.030 0.030 0.030	-1.03 2.0 3.4	-80
17/6	1229-1317	95	8.5	0.090	8.1	τ H E	1.67 0.85 3.34	-0.43 0.53 3.09	-0.53 2.97	0.77	+0.51 0.60 0.71	0.046 0.046 0.046	-0.99 1.0 2.8	-130
17/6	1610-1738	45	8.3	0.185	7.7	τ H E	-1.96 -0.08 2.54	-0.80 -0.06 1.89	-0.80 2.01	0.12	-0.45 0.52 1.72	0.009 0.009 0.009	-0.90 0.5 1.9	-220
		140	8.6	0.061		τ H E	1.81 -0.63 0.57	-0.33 -0.77 0.52	-0.59 0.57	-0.76	-0.24 -0.19 1.09	0.027 0.027 0.027		
17/6	1749-1922	45	7.3	0.162	6.9	τ H E	-1.38 -0.52 3.22	-0.34 0.51 2.98	-0.39 3.28	-0.75	-0.30 0.83 2.20	0.010 0.010 0.010	-0.73 0.5 2.1	-145
		140	7.8	0.056		τ H E	1.14 -0.84 3.85	-0.49 -0.90 3.82	-0.56 3.80	-0.89	-0.29 0.48 1.80	0.030 0.030 0.030		
17/6	2143-0005	90	6.0	0.067	5.7	τ H E	-1.52 0.58 1.93	-0.39 0.55 1.81	-0.39 1.88	0.68	-0.21 0.54 1.32	0.015 0.015 0.015	-0.52 1.0 2.2	-55
		185	6.0	0.032		τ H E	1.01 0.34 1.91	-0.15 0.20 1.91	-0.23 1.88	0.19	0.02 0.15 1.05	0.032 0.032 0.032		

Table 2 (continued)

Date	Period (Z)	Instrument heights (m)	$\hat{U}$ (a) (m sec^{-1})	$\hat{U}/z$ (sec^{-1})	U_{10} (m sec^{-1})	Flux (b) parameter	Method of flux estimation: 1. Direct: unaveraged data	2. Direct: 8-sec averaged data	3. Cospec smoothed to zero at $nz/\hat{U} = 1$	4. Smoothed to zero at $nz/\hat{U} = 4$	5. As 3, 4, with L.F. cut-off	$nz/\hat{U}$ at low-frequency cut-off	Estimated surface fluxes	L (m)
						τ	0.07	-0.42	-0.45		-0.40	0.012	-0.87	
18/6	1530-1745	95	9.2	0.098	7.7	H	-0.30	-0.35		-0.36	-0.28	0.012	-0.7	+490
						E	1.61	1.26	1.51		1.38	0.012	2.1	
						τ	-0.17	-0.50	-0.64		-0.64	0.028	-1.06	
18/6	1745-1845	95	10.0	0.105	8.5	H	0.41	0.28		0.39	0.23	0.028	-0.7	+750
						E	5.67	5.15	5.44		5.20	0.028	2.1	
						τ	5.43	6.94)					-1.99	
18/6	2020-2109	95	15.9	0.167	11.6	H	1.72	1.63)	not evaluated (d)				-0.9	+1500
						E	-1.16	-1.45)					2.7	
						τ	0.61	-0.84	-0.78		-0.05	0.019	-0.81	
20/6	1021-1147	95	8.3	0.087	7.3	H	-0.02	-0.35		-0.07	1.22	0.019	0.4	-150
						E	8.41	8.32	8.45		3.21	0.019	4.1	
						τ	1.32	0.13	0.05		-0.38	0.024	-0.95	
20/6	1830-1947	95	8.7	0.092	7.8	H	2.81	2.41		2.74	2.65	0.024	2.0	-70
						E	4.68	4.22	4.65		4.54	0.024	4.4	
						τ	1.02	-0.10	-0.13		-0.55	0.017	-1.03	
20/6	2005-2137	95	9.0	0.095	8.1	H	2.61	2.19		2.50	2.15	0.017	2.3	-70
						E	4.30	4.05	4.25		5.02	0.017	3.7	

Notes

(a) $\hat{U}$ is measured wind at instrument height, not corrected for ship's speed

(b) Flux units:
- τ (momentum) — degrees cm^{-2}
- H (heat) — m W cm^{-2}
- E (moisture) — g cm^{-2} sec^{-1}

(c) Not calculated because of the comparatively high cut-off frequency

(d) Ship and sensor motion too violent for proper functioning of equipment

(e) Winds very light: some doubt whether ship was steaming accurately along line of wind and hence doubt about validity of calculated momentum fluxes

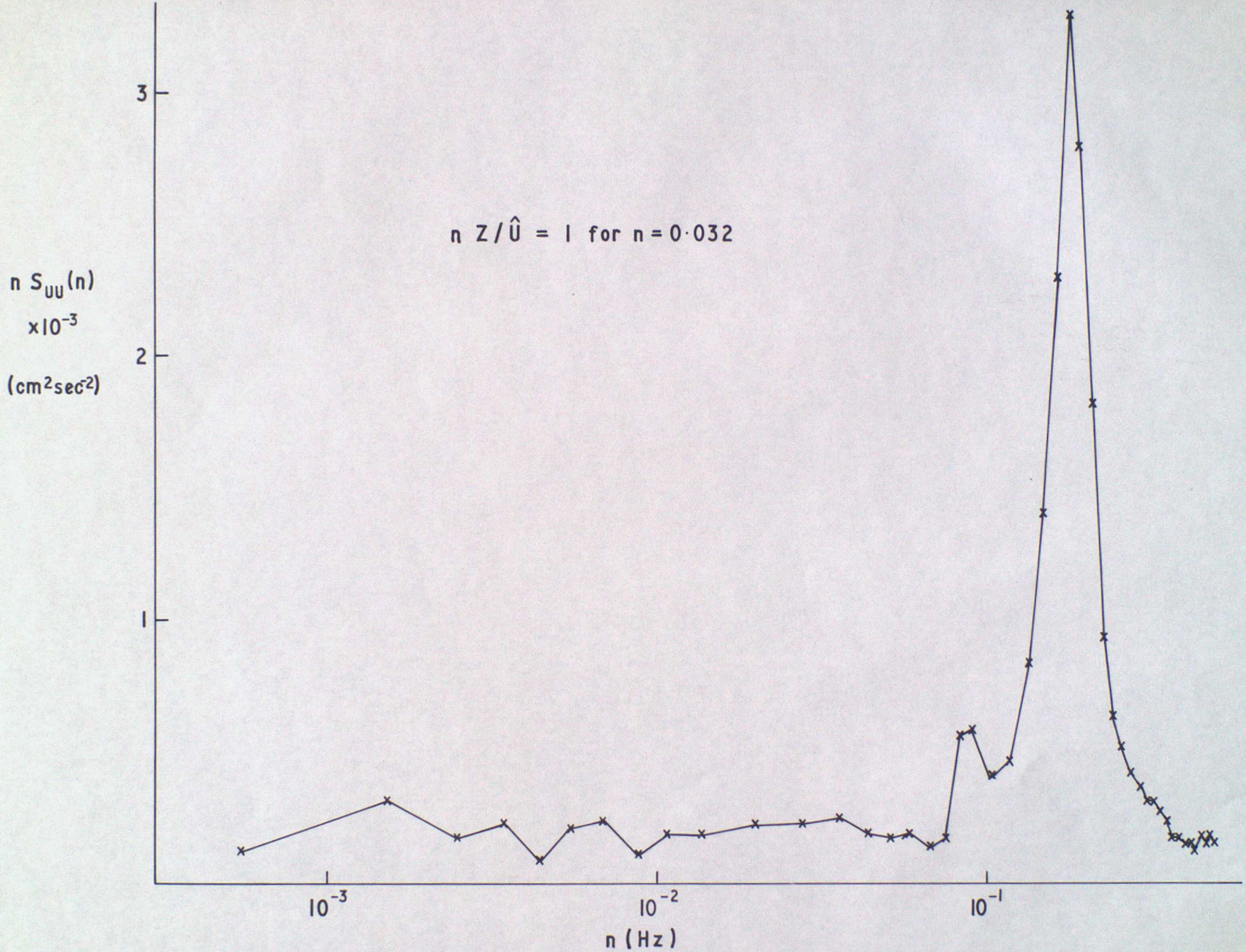

FIGURE 1. U SPEC, 185m, 17/6/70 2143,-0005

A4/5397 T1960 15·7·71

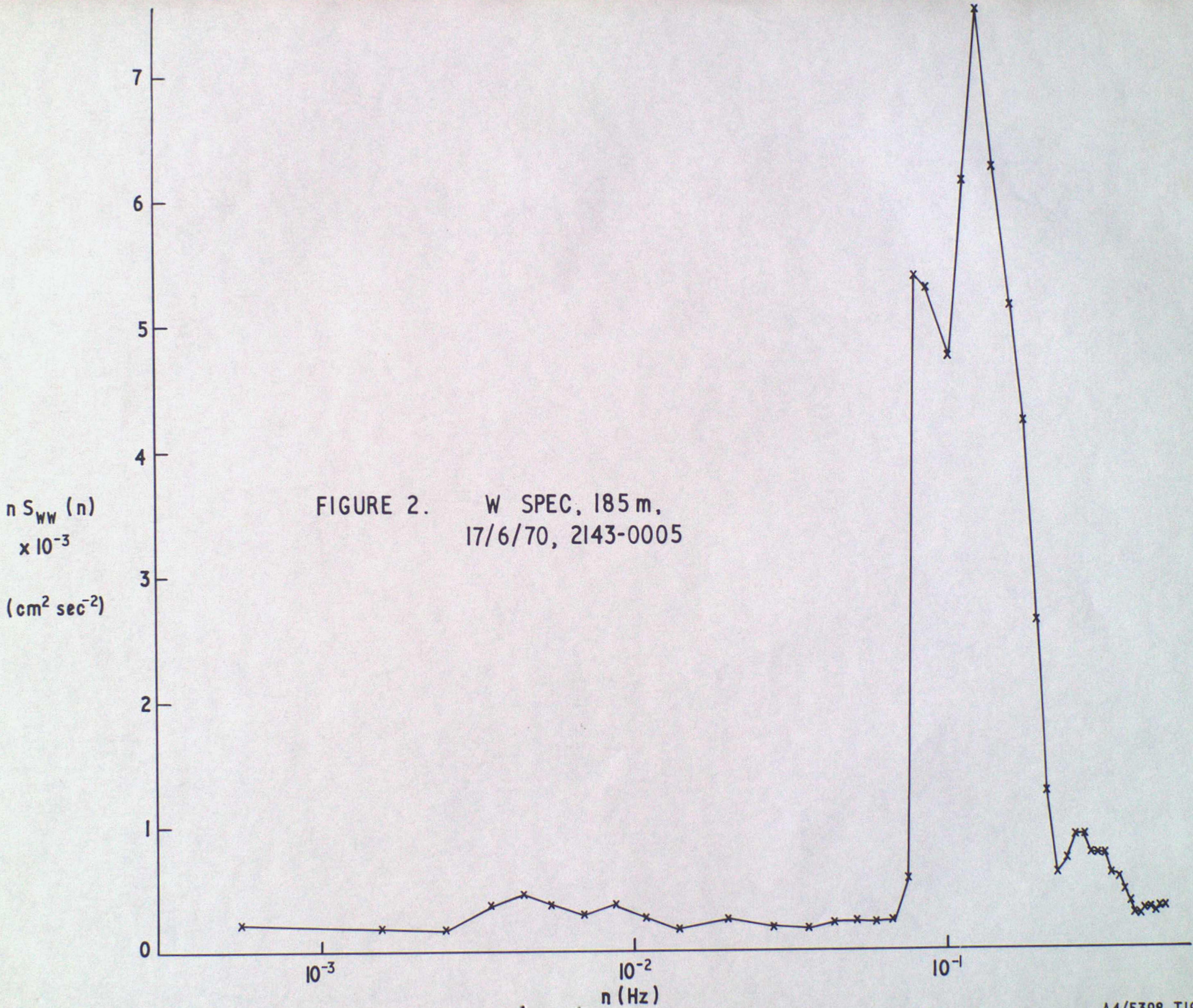

FIGURE 2. W SPEC, 185 m, 17/6/70, 2143-0005

A4/5398 T1960 15 · 7 · 71

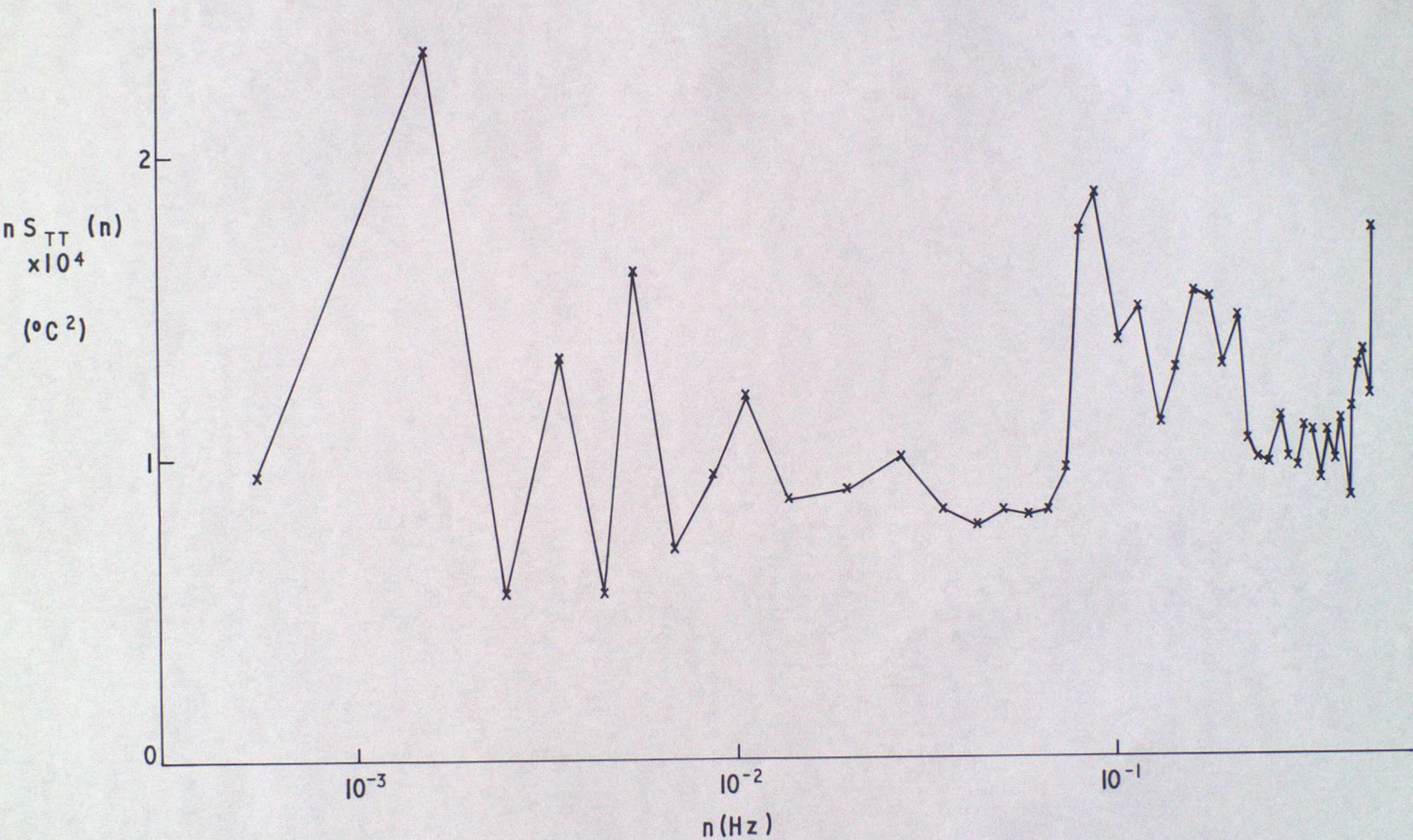

FIGURE 3. T SPEC, 185 m, 17/6/70 2143,- 0005

A4/5399 T1960 15·7·71

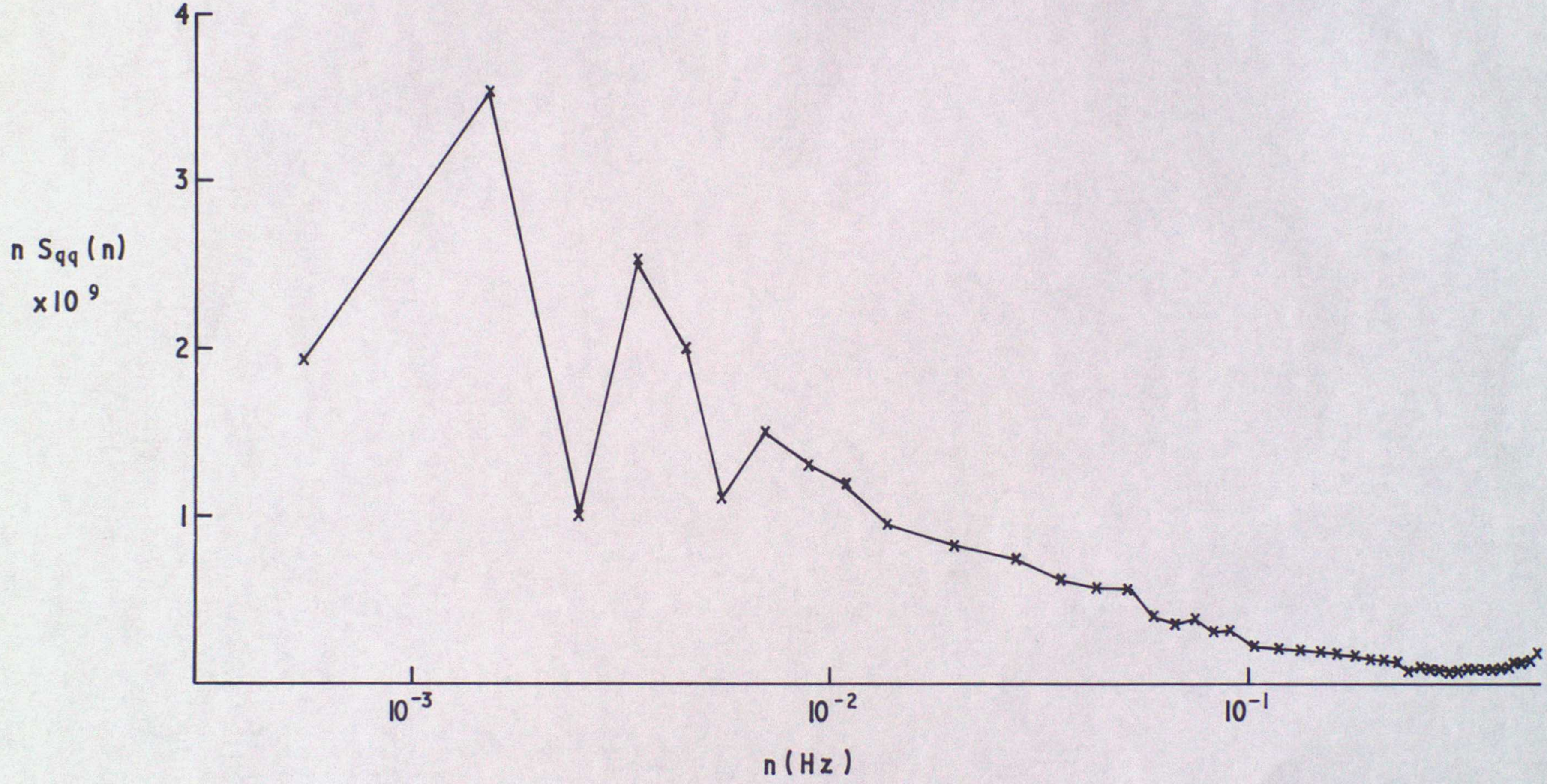

FIGURE 4. q SPEC, 185 m, 17/6/70 2143,-0005

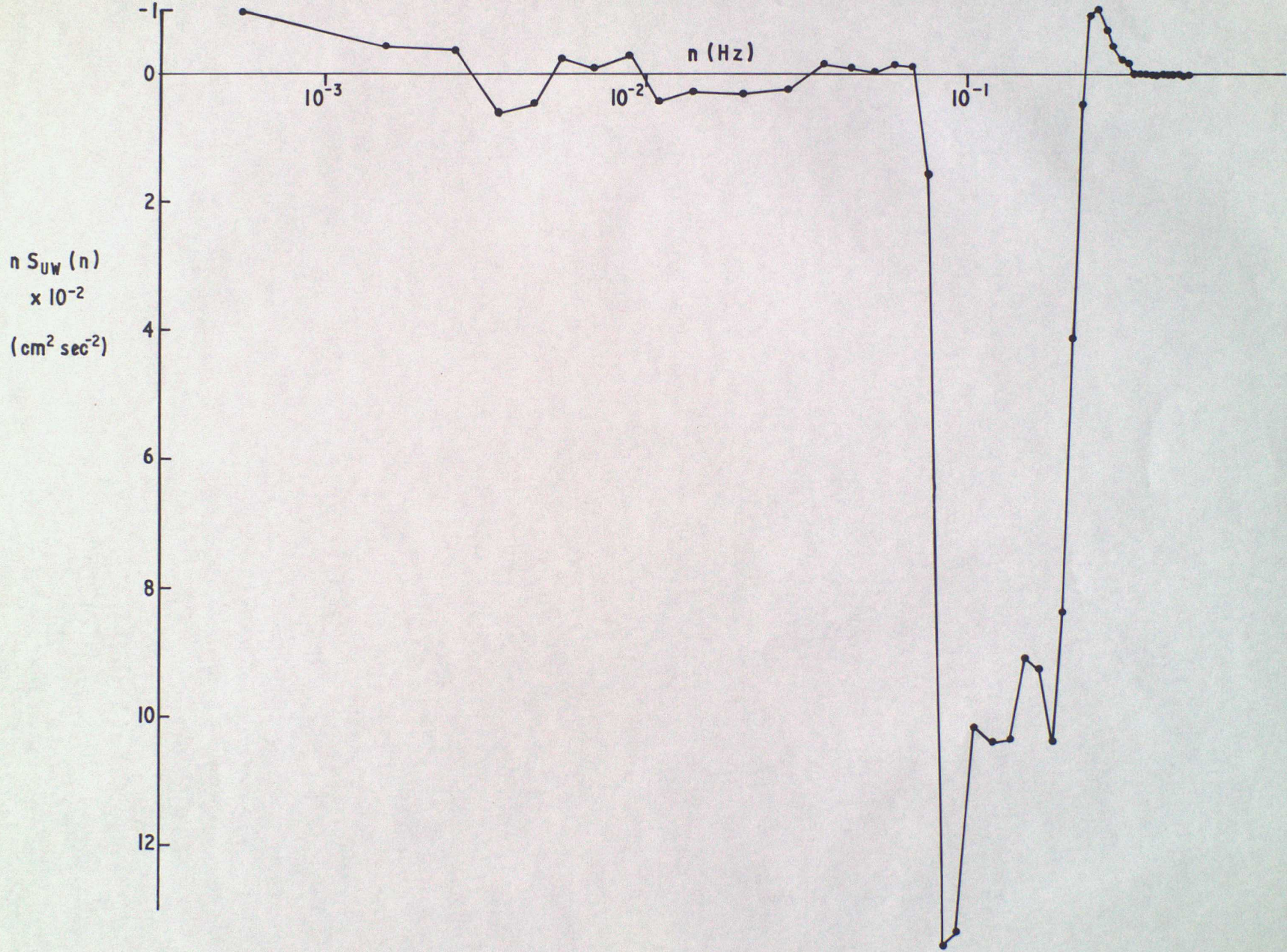

FIGURE 5. UW COSPEC, 185m, 17/6/70, 2143-0005

A4/5401 T1960 15·7·71

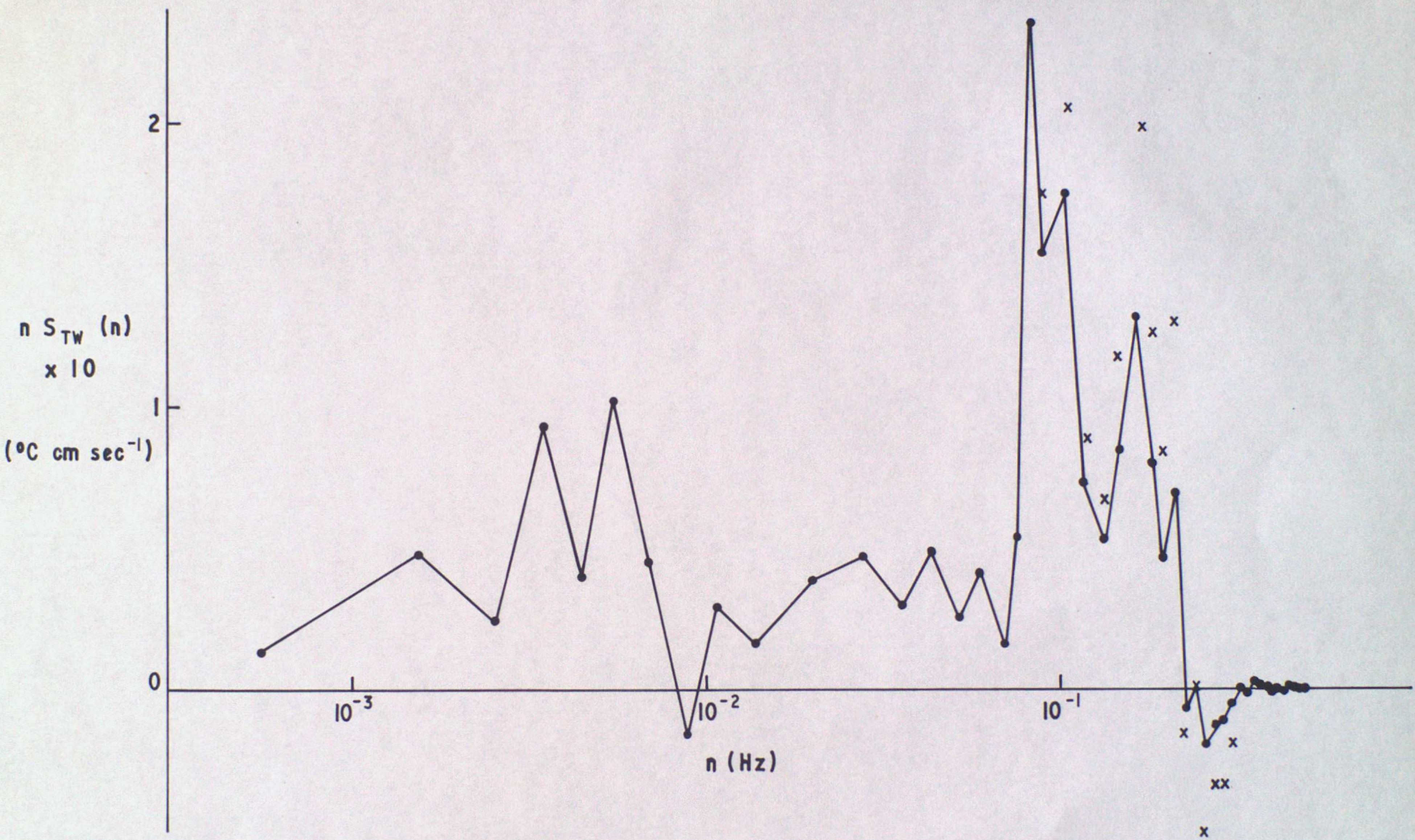

FIGURE 6. TW COSPEC, 185m, 17/6/70, 2143-0005

A4/5402 T1960 15·7·71

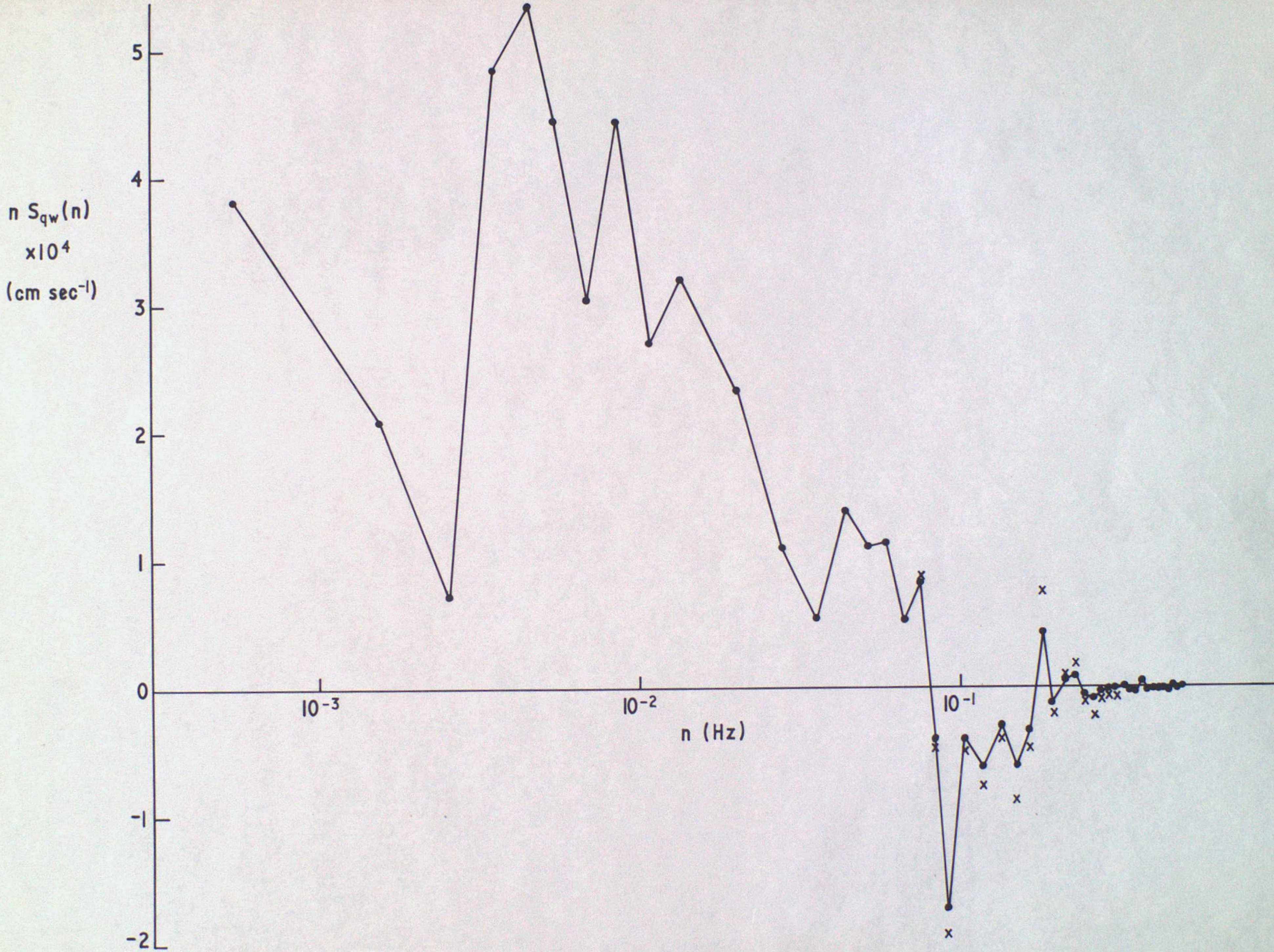

FIGURE 7. qW COSPEC. 185m, 17/6/70, 2143-0005

A4/5403 T1960 15·7·71