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LONG TERM STABILITY OF THE SPECTROSCOPIC PERFORMANCE OF THE STRATOSPHERIC SOUNDING UNIT

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LONG TERM STABILITY OF THE SPECTROSCOPIC PERFORMANCE OF THE STRATOSPHERIC SOUNDING UNIT

1. INTRODUCTION

Manufacture of the eight flight Stratospheric Sounding Units (SSUs) for the TIROS-N series of meteorological satellites has now been completed. At present SSUs are being launched at less than 1 per year so that it is unlikely that the last instrument will be launched before 1986, i.e. after at least 5 years storage on the ground. This memorandum summarises the evidence of long term changes in spectroscopic performance which have occurred during the storage of the earlier SSUs (i.e. D2 to F5) on the ground. The changes are the result of an increase of pressure within the pressure modulation cells (PMCs) which control the spectroscopic performance of the SSU. These cells are initially filled with carbon dioxide, but the increase in pressure is due to an ingress of water vapour and air from the SSU storage environment.

A rigorous examination of the evidence for PMC leaks (as follows) was necessitated by the apparent contradiction between the results of PMC leak testing during assembly at MSDS and the rates of leakage during storage. Similarly the verification of the amounts of water vapour in the PMCs (see sections 5 and 6) had to be performed in some detail.

Measurements of the change in spectroscopic performance induced by the increase in PMC pressure are summarised in section 7, and the results used to predict the spectroscopic performance of the two SSUs which have given operational service on TIROS-N and NOAA-6 (see section 8).

Revised storage procedures are suggested so that the leakage problems in the remaining SSUs can be minimised.

2. PRINCIPLES OF SSU OPERATION

An SSU is comprised of three channels, each of which observes radiation emitted by carbon dioxide in the atmosphere over the same spectral region (as defined by a bandpass filter centred at 668 cm^{-1} of equivalent width 60 cm^{-1}). However, each

channel also includes an optical cell (PMC) which is filled with carbon dioxide to a specified pressure (108 mb for Channel 25, 35.6 mb for Channel 26 and 10.8 mb for Channel 27, all at 30 C) which determines the spectroscopic performance as follows:-

The pressure in a PMC is modulated by about 25 per cent and the signal channel electronics amplify and select the signal component from the detector which is in phase with the pressure modulation (see Fig 1). Radiation from the spectral regions where the pressure modulation does not result in transmission modulation through the optical cell of the PMC, viz. - regions of very strong absorption close to the CO_2 line centres and regions of negligible absorption in the line wings - is therefore rejected. The regions of transmission modulation are located further from the line centres in a high pressure PMC than in a low pressure PMC so that, for instance, the radiation to which Channel 25 is sensitive is on average characterised by a lower CO_2 absorption coefficient than that to which Channel 27 is sensitive. This implies that on average the high pressure channel will observe to lower levels in the atmosphere than the low pressure channel. In fact, the heights of observation are centred at about 15 mb for Channel 25 and about 1.5 mb for Channel 27. Clearly, if the pressure in a PMC increases it will shift the levels of observation of that channel downwards in the atmosphere.

The requirement for long term spectroscopic stability in the SSU led to a design specification on PMC pressure stability with an aim of 1 per cent pressure change in 5 years (of which two years would be operation in space) and a maximum tolerable change of 10 per cent over the same period. In the worst case so far, (viz. F3 Channel 27) pressure increased by over 100 per cent in just over three years of storage.

The presence of water vapour in the PMC poses a particular problem in that water vapour transmission through the PMC is modulated in the far infrared in a spectral region across which the bandpass filters in the SSU do not provide adequate blocking (ie at wavenumbers less than 200 cm^{-1}). Worst case calculations

during the design phase of the SSU indicated that the amount of water vapour in a PMC should be restricted to less than 0.1 per cent by pressure if significant radiometric errors were to be avoided. However, in Appendix C it will be shown that for a variety of reasons the amount of water vapour which can be tolerated in a PMC is probably nearer 10 per cent.

3. USE OF PMC FREQUENCY TO DETERMINE PMC PRESSURE STABILITY

The pressure within a PMC is modulated by means of a piston oscillating in a larger cylinder to which the optical cell is attached (see Fig 1). The natural resonant frequency at which the piston is driven is mainly a function of the mean gas pressure within the PMC assembly and the mechanical constants of the Be-Cu support springs. To a first approximation this frequency can be expressed as:-

$$f = (A'.p + B')^{0.5} (F'.x^2 + G'.x + H') \qquad (3.1)$$

where A' and B' are Be-Cu spring constants which are measured during PMC assembly at MSDS (Frimley),

p is the mean pressure within the PMC,

and $(F'.x^2 + G'.x + H')$ is an approximation to the amplitude dependence of PMC frequency at an amplitude x, the constants F', G' and H' being measured during PMC assembly at MSDS.

Once a PMC is incorporated into an SSU it is driven to a set value of the back e.m.f. developed across its drive coil rather than to a set amplitude. As this back e.m.f. is proportional to the product of amplitude and frequency, increase in PMC frequency is associated with a decrease in amplitude. Consequently in an SSU the relationship between a change in mean PMC pressure and a change in PMC frequency becomes from equation 3.1 (using typical values of F', G' and H'):-

$$\frac{\partial p}{\partial f} = \frac{2f}{A'} \cdot \begin{matrix} 1.06 \\ 1.13 \\ 1.20 \end{matrix} \qquad \begin{matrix} \text{Channel } 25 \\ 26 \\ 27 \end{matrix} \qquad (3.2)$$

Values for individual PMCs are presented in Appendix A but typically:-

$$\frac{\partial p}{\partial f} = \begin{matrix} 7.3 \\ 5.9 \\ 5.5 \end{matrix} \quad \text{mb/Hz} \qquad \begin{matrix} \text{Channel } 25 \\ 26 \\ 27 \end{matrix} \qquad (3.3)$$

Before long term changes in PMC frequency can be related to changes in mean PMC pressure it is necessary to take account of the changes which may have occurred for the following reasons:-

(a) The PMCs are not operating at the same temperature. PMC frequency is temperature dependent because the mean gas pressure in the PMC is temperature dependent. Frequencies are compared once the PMCs have warmed up and reached their set thermostatting temperature. However, the operation of the PMC thermostats is such that the resultant overall operating temperature of the PMC is not entirely independent of the operating temperature of the SSU. These changes in instrument temperature have been found to lead to changes in PMC frequency at the set thermostatting temperature of as large as $\pm$ 0.05 Hz. This is not a problem in the UK since there is not much variation in the conditions of testing. However, once the SSU is mounted on the spacecraft at RCA (except in thermal vacuum) the SSU is run in air at a much higher temperature than normal operating conditions and this must be considered in frequency comparisons.

(b) The PMCs are not operating in the same orientation with respect to gravity. Changes in PMC frequency occur because the piston/main cylinder assembly is not of perfect cylindrical symmetry and gravity causes the piston to sit in different positions relative to the walls if the cylinder is rotated about its axis. The PMCs sit in the same position during vacuum testing at MSDS and the Met Office, are rotated through 90° during testing on the spacecraft and are rotated through 180° during bench tests and testing in the transit and storage cases. Frequency changes due to change in orientation are measured during PMC assembly and are rarely larger than 0.1 Hz. Comparison between measurements of frequency in vacuum tests and those from bench checks show that in only four PMCs (F3 channel 25 and 27, F5 channel 26 and F7 channel 26) is the frequency change associated with rotation through 180° systematically larger than 0.05 Hz.

(c) The mechanical constants of the springs have changed. The probability of such a change can be gauged from the performance of the life test PMC which was operated continuously for more than a year. In this test the frequency decreased by about 0.2 Hz in the first 100 days and then remained effectively stable for the remainder of the year. The PMCs in an SSU are only operated for a negligible time, by comparison, before launch. Thus it is unlikely that changes in spring constants will cause a significant increase in PMC frequency during periods of storage.

(d) There have been changes in the timing of the clock pulses which control the sampling in the SSU frequency counting electronics.

In Figs 2(a) to (c) PMC frequency at thermostatting temperature is plotted as a function of time since the PMC was first operated under vacuum in an SSU at MSDS for all the flight model PMCs in SSUs D2 to F5. Frequency increases associated with considerations (a), (b) and (d) above can be corrected for at all times except when the SSU is mounted onto the spacecraft and when the spacecraft is launched. The step changes in frequency which may occur at these times are less than 0.1 Hz in magnitude. The remainder of the frequency increase in Figs 2(a) to (c) must therefore be the result of an increase in mean pressure within the PMC, with gas pressure increasing during storage at a rate of about 10^{-9} torr.l.s^{-1} i.e. close to the limit of the design specification for Channel 25 and well outside specification for the other two channels.

Conclusive support for the large pressure increases within the PMCs was found as follows:-

(i) SSUs which have been stored or operated in vacuum for periods in excess of 40 days after prolonged storage in air (D2,P/F, F2 and F3) have been characterised by PMC frequencies which rose steadily in air but were effectively stable or decreased with time in vacuum. This is what would be expected if the frequency changes were the results of pressure changes caused by a leak in the PMC.

(ii) Measurements of the spectroscopic performance of the SSUs indicate that

effective PMC pressure has increased during storage in air (see Table 1).

(iii) Changes in the rediometric sensivity of Channel 27 during storage correlate with PMC frequency change and are consistent with an increase in PMC pressure. (Evidence for this will be reported elsewhere).

(iv) The increase in PMC frequency at the thermostatting temperature is found to be associated with a much higher rate of increase of PMC frequency with temperature than is expected on the basis of the temperature dependence of the pressure in a perfect gas. In section 6 it will be demonstrated that this is the result of the vapour pressure of water in the PMC increasing as the PMC temperature is raised, the water having originally leaked in from the SSU storage environment.

The sealing of the flight PMCs in F2 and F3 is typical of the succeeding models and so it is reasonable to conclude that all flight PMCs will have similar leaks. In contrast, the frequency stability of the two non-flight model PMCs in the development model radiometer, D2, are well within the design specification (see Fig 2(c), D2 channel 27). Thus PMC leak tightness appears to have degraded between the development and flight stages. Possible reasons for this are discussed in Appendix B.

4. COMPOSITION OF PMC LEAKS

As mentioned previously, water vapour in a PMC poses a special problem in that not only does it change the spectroscopic performance at 668 cm^{-1} but also gives rise to a pressure modulated signal in the far infrared in a region where the SSU filters are poorly blocked (between 200 and 60 cm^{-1}). If this water vapour pressure modulated signal is to produce a radiometric error of less than 0.05 $mw/(m^2.sr.cm^{-1})$ in a typical earth view it is estimated (see Appendix C) that the water vapour pressure in the PMC must be less than:-

6.0 ± 3.0 mb in Channel 25
3.0 ± 1.5 mb in Channel 26
1.4 ± 0.7 mb in Channel 27

Once the SSU is mounted on the spacecraft at RCA it is stored in air at a temperature of about 25 C and relative humidity around 50 per cent, so that the partial pressure of both water vapour and oxygen in the environment is much higher

than when the SSU is stored in its transit case. Close examination of the rates of frequency increase during storage revealed that the rate of increase when the SSU was stored on the spacecraft was typically twice that when it was stored in its transit case, (see Table 2). This implied that during the time on the spacecraft a gas which was not present in the transit case in significant amounts (probably water vapour or oxygen) was entering the PMCs at a rate comparable to that at which nitrogen had entered during storage in the transit case. This required that the conductivity of the leak for this additional gas be much higher than that for nitrogen.

From Table 3 it can be seen that when PMCs which had undergone pressure increases of between 5 and 10 mb were stored under vacuum for several months PMC frequency decreased at a rate which was similar for all three channels and which was at least a third of the rate of increase observed during storage in air. This suggested that the rate of outward leakage was related to the partial pressure of a contaminant gas in the PMC rather than the total gas pressure and that the outward leak would then be dominated by the gas for which the leak had the highest conductivity i.e. the contaminant gas other than nitrogen in the PMC. If it was first assumed that the rate of leakage was proportional to the difference in partial pressure of the gas across the leak, water vapour was clearly the most probable candidate for this gas. (For water vapour the ratio of partial pressure difference during storage on the spacecraft to that of the reverse gradient during storage under vacuum was about 4 whereas for oxygen it was about 50).

Thus it seemed probable that water vapour had entered the PMCs in amounts comparable to that of nitrogen.

5. MEASUREMENT OF WATER VAPOUR PRESSURE IN D2 CHANNEL 26.

In order to confirm the evidence in section 4, the Channel 26 PMC was removed from D2 so that its spectroscopic performance in the water vapour band around 1600 cm^{-1} could be examined in the Met. Office weighting function facility. This facility was originally described in Pick, et. al. (1976). The rig in which

individual PMC's are mounted includes a filter wheel positioned between the PMC and the detector so that either measurements at 668 cm^{-1} or between 1400 and 1800 cm^{-1} can be performed. A variable speed rotating chopper is located in front of the PMC and can be used to produce broadband measurements at the same frequency as the PMC, when required.

D2 Channel 26 was the first flight PMC and was incorporated into D2 when one of the development model PMCs was damaged during vibration testing. It is similar to the PMCs in P/F. When this investigation was performed, the increase of PMC frequency implied that the mean pressure at 30 C had increased by 10 ± 1 mb above the nominal PMC fill pressure of 35.6 mb.

With the PMC used in conjunction with the water vapour filters at 1600 cm^{-1} an apparent water vapour pressure modulated signal was observed at 30 C which was 0.0017 of the broadband signal obtained with the rotating chopper. Subsequent measurements in the carbon dioxide band at 668 cm^{-1} indicated that a misalignment of the optics meant that vibrations in the optics were generating spurious broadband signals during PMC measurements. Comparisons of PMC and chopper broadband transmission measurements through water vapour (see Figs 3(a) and (b)) and of the pressure modulated measurements with theory (see Figs 3(b) and (c)) indicate that the spurious broadband signal constituted about 8 per cent of the apparent water vapour pressure modulated signal, so the true water vapour PMC signal was 0.0015 of the chopper broadband signal.

The calculations used to model the transmission measurements were initially done using a Malkmus model for the water vapour band and a modification of the two parameter Curtis-Godson approximation to a four parameter model (see Rogers, 1976) to describe the path. This did not produce consistent fits to the measurements in Figs 3(b) and (c) so a line-by-line computation originally written by Eyre (unpublished) was used to check the results. In both cases a value of 4.5 was used for the self-broadening coefficient, β, of water vapour. This was derived by comparison with the chopper broadband measurements in Fig 3(a) and thus may not be totally appropiate for PMC calculations but is adequate here, given the

uncertainty in the transmission measurements from spurious broadband contamination.

The computations show (see Fig 3(d)) that the observed ratio of water vapour PMC signal to chopper broadband signal corresponds to a mean pressure of water vapour in the PMC of 5.9 $\pm$ 0.7 mb, where the uncertainty is primarily the result of spurious broadband contamination. This means that in D2 Channel 26 59 $\pm$ 12 per cent of the contaminant gas which had leaked into the PMC was water vapour, and is a clear demonstration that the conductivity of the PMC leaks for water is much higher than for gases such as nitrogen.

6. WATER VAPOUR ESTIMATES FOR FLIGHT SSU'S

As the PMC frequency increases during storage, the rate of increase of frequency with temperature also exhibits a marked increase, which is much larger than that which is predicted on tha basis of the perfect gas law and the frequency-pressure relationships in (3.2), see Table 4. Observations corresponding to the situation after prolonged storage, i.e. to the third set of samples in Table 4, are presented in Figs 4(a) to (c). These include the warming curve for D2 Channel 26.

In Fig 5 the variation of water vapour pressure modulated signal (normalised to the chopper broadband signal) with PMC frequency at both 668 cm^{-1} and 1600 cm^{-1} is plotted for D2 channel 26. The frequency range corresponds to the PMC temperature range from 5 to 35 C. Whereas the carbon dioxide signal at 668 cm^{-1} shows little variation with temperature, the water vapour signal increases markedly as the temperature increases. The increase between 5 and 30 C corresponds to an increase of water vapour pressure within the PMC of 4.6 $\pm$ 0.6 mb. The anomalous pressure increase within the PMC deduced from the anomalously high increase of frequency with temperature, as in Fig 4(b), was 4.8 $\pm$ 0.5 mb where the uncertainty reflects the uncertainty as to the correct value of $\partial f/\partial T$ to use in estimating the behaviour of a PMC in which the perfect gas law is obeyed. Clearly the anomalous frequency increase with temperature is the result of outgassing of additional water vapour into the PMC. Hence, PMC frequency against temperature plots can be used to estimate the water vapour pressure in any PMC. Results for all those

flight SSU's which have been subjected to extended periods of storage at atmospheric pressure are presented in Table 5. The uncertainty in the water vapour estimates is largest in Channel 25 PMCs since with these there appears to be more variation in the temperature dependence of frequency immediately after PMC assembly and the estimate of the temperature dependence of frequency for a PMC with gas pressure following the perfect gas law is less reliable. Estimates by this method represent a minimum limit as is well illustrated by the measurements of water vapour PMC signal on D2 Channel 26 (see Fig 5). Below a temperature of 7.5 C the temperature dependence of frequency is that expected of a perfect gas, but the water vapour PMC signal indicates that there is still 1.3 $\pm$ 0.5 mb of water vapour remaining in the PMC (see Fig 3(d)). It was also clear in D2 Channel 26 that there was additional water vapour, above the 5.9 mb measured at 30 C, absorbed internally within the PMC since the anomalously high frequency increase with temperature continued above 30 C and the water vapour PMC signal continued to increase in confirmation that additional water vapour was being desorbed. The continued increase of the frequency in this case was typical of the other PMCs.

It can be seen from Table 5 that the proportion of water vapour in the contaminant gases within the PMC was generally close to that in D2 Channel 26. Reference to the computations in Appendix C suggests that in the PMCs as shown in Table 5 radiometric errors from far infrared water vapour pressure modulated signals are unlikely to be in excess of

Channel 25 $\pm$ 0.08 mw/(m^2.sr.cm^{-1})

Channel 26 $\pm$ 0.1 mw/(m^2.sr.cm^{-1})

Channel 27 $\pm$ 0.3 mw/(m^2.sr.cm^{-1})

7. SPECTROSCOPIC MEASUREMENTS AT 668 CM^{-1}

The additional gas which leaks into the PMCs alters spectroscopic performance at around 668 cm^{-1} by increasing the pressure broadening of the carbon dioxide absorption, but decreasing the self-broadening of the carbon dioxide to a lesser extent. The effective mean pressure of carbon dioxide in a PMC can be determined from a comparison of transmission measurements through a mixture of carbon dioxide and nitrogen in the White Cell of the Met Office Weighting Function Facility with

the results of line by line computations, based on Drayson (1966) and using the line data of McClatchey, et. al. (1975).

Such measurements confirm that PMC pressure is increasing with time during storage, see Table 1, although it is only for D2 and F3 that reliable measurements bracket an extended period of storage in air. In Figs 6(a) to (c) increase in effective CO_2 pressure has been plotted against increase in PMC pressure derived from the increase in PMC frequency. The error bars on the spectroscopic measurements are estimates from the 1σ scatter of sets of measurements on particular SSU's (which had previously been adjusted to compensate for anomalies in the White Cell pressure stepping). The uncertainty associated with Channel 27 measurements is the smallest, but the plot in Fig 6(c) is not as well defined as that for Channel 26 in Fig 6(b), unless the measurements on F3 Channel 27 are taken to be anomalous and ignored for the present. If this is done the ratio of effective CO_2 pressure change to actual pressure increase derived from PMC frequency change (hereafter denoted as P*) is found to be 0.46 ± 0.04 for Channel 27, 0.45 ± 0.04 for Channel 26 and 0.42 ± 0.06 for Channel 25. These values are a little higher than the value of 0.4 which a simple theory of strong absorption, with no overlapping lines would predict.

On the basis of these measurements it is possible to estimate the effective CO_2 pressure in a PMC using the following extrapolation:-

$$P_c = P_o + P^* . \frac{\partial p . \Delta f}{\partial f}_c \qquad (6.1)$$

where P_c is the effective pressure of CO_2 in the PMC,

P_o is a measured value of effective CO_2 pressure

and Δf is the change in PMC frequency since the measurement.

Estimates of the effective pressure in P/F and F2 PMCs at intervals after launch are presented in Table 6. A value of P* of 0.46 has been used in all cases i.e. it has been assumed, for the present, that the effects of the additional gas are identical in all three channels, that water vapour and nitrogen influence the pressure broadening in an identical manner and that there has been no outgassing or leakage of carbon dioxide within the PMC. If the latter is the case, then in Table 6 it would be expected that extrapolation from the latest measurements on

an SSU would agree with extrapolation from PMC filling pressure to better than $\pm$ 0.7 mb for Ch. 25, $\pm$ 0.5 mb for Ch. 26 and $\pm$ 0.5 mb for Ch. 27. This is true for all Channels in P/F and F2 (except F2 Channel 26 where it is possible that significant outgassing of CO_2 has occurred).

The uncertainty in PMC pressure leads to an uncertainty in the match between measured radiance and that computed from measurements of atmospheric temperature profile (and hence in comparisons between different instruments). On average, the uncertainty in radiance for P/F from the uncertainty in pressure in Table 6 is, after Pick (1978):-

$\pm$ 0.05 mw/(m^2.sr.cm^{-1})	for Channel 25
$\pm$ 0.15 mw/(m^2.sr.cm^{-1})	for Channel 26
$\pm$ 0.20 mw/(m^2.sr.cm^{-1})	for Channel 27

These are of comparable magnitude to the radiometric error which may be introduced by the far infrared water vapour signal (see section 6). The increase in PMC frequency since the spectroscopic measurements on P/F was large in each channel ($\approx$ 0.7 Hz) and therefore it should be possible to increase the precision of the pressure estimate by about a factor of two if the frequency increase is limited to the more reasonable value of 0.3 Hz.

As noted above, in discussion of **Fig 6(c)**, the spectroscopic measurements on F3 Channel 27 show an anomalously large scatter. In each of the three pressure transitions in Fig 6(c) the water vapour change (as estimated from the anomalous temperature dependence of PMC frequency) has been of similar magnitude, **i.e. about** 3 mb in just over 6 mb total change. The simplest explanation for the large scatter is that both during the later stages of storage in air and also during the following extended storage under vacuum, CO_2 has been leaking out of the PMC. This idea is supported to some extent by the fact that the radiometric sensitivity of this channel has dropped during storage in air rather than increased as is the case for all the other Channel 27 PMC**s.** Use of the extrapolation technique from PMC crimp-off to November 1980 would have resulted in an estimate of effective PMC pressure of 13.7 mb for F3 whereas in fact the measured value was 11.0 mb $\pm$ 0.1 mb.

8. PMC STABILITY UNDER VACUUM

The variation with time of the PMC frequencies in P/F and F2 since the launch of TIROS-N and NOAA-6 respectively are shown in detail in Fig 7, whilst the behaviour of F3 PMCs during extended storage under vacuum can be seen in Figs 2(a) to (c). The estimates of effective CO_2 pressure in the PMCs one and two years after launch given in Table 6 were based on the assumption that the gases escaping from the PMC had the same effect on PMC spectroscopic performance as the gases which leaked in during storage in air.

From Fig 7 it is clear that it takes around 15 days from launch for the PMC leaks to reverse direction. After this time all PMC frequencies except F2 Channel 26 decreased with time (note that it was in F2 Channel 26 that there was a suspicion of internal outgassing of CO_2). Exponential fits of the form

$$\Delta f = \Delta f_0 + \Delta f^* . \exp(- t/r) \qquad (7.1)$$

where Δf is the frequency change since the PMC's first reached thermostatting temperature after launch, have been used on all P/F PMCs and on F2 Channel 27. The results over intervals of 320 days are presented in Table 7. In all cases the ultimate decrease in frequency during operation in space is predicted to be less than the frequency increase which occurred during storage on the ground. The P/F leaks during the first year were at least ninety per cent water vapour (see Table 8). The time constants in Table 7 indicate that the same process is still dominating in Channels 25 and 27 but that in Channel 26 the time constant of the leak has increased considerably with time, implying that a second leak process with longer time constant became significant at about 450 days from launch. The leak rate associated with this second process is about 0.025 mb/100 days.

The raising of the levels of observation in P/F due to the decrease in pressure in the PMC's would, on average, change the match with atmospheric temperature profiles over two years by 0.1, 0.5 and 0.7 mw/(m^2.sr.cm^{-1}) for Channels 25, 26 and 27 respectively.

The F2 PMCs appear to be sufficiently stable during operation in space that the

composition of the leaks is immaterial. On the grounds of similarity in manufacture the stability of the PMCs in succeeding SSUs ought to be more like those in F2 than in P/F, but the performance of the F3 PMCs during storage under vacuum does not bear this out. This may be explained if it is noted that all F2 PMCs and P/F Channel 25 are leaking to an ultimate state where just over 2 mb of water vapour remains in the PMC. If PMC stability is generally a function of water vapour pressure excess above 2 mb, none of the PMCs in F3 or F5 should be expected to be as stable in operation as those in F2.

9. CONCLUSION

A mixture of air (predominantly nitrogen) and water vapour in almost equal proportions has entered all the flight PMCs in the SSUs which have been stored for extended periods at atmospheric pressure. The size of the leaks is such that it is no longer adequate to use the nominal filling pressure to compute the spectroscopic performance, but instead the extrapolation technique outlined in section 6 must be used to estimate the effective pressure of CO_2 in the PMC. Otherwise in both Channels 26 and 27 discrepancies in excess of 1 $mw/(m^2.sr.cm^{-1})$ will result in intercomparisons with radiances computed from other temperature measurements. Uncertainty in the spectroscopic performance, once the extrapolation technique has been utilised, will only be significant when attempting to obtain the highest precision ($\sim$0.1 $mw/m^2.sr.cm^{-1}$)) from the SSU in monitoring long term trend of temperature over large areas of the stratosphere (eg zonal or global averages). Similarly, although the amounts of water vapour in the PMCs are much higher than were expected, the calculations indicate that the radiometric errors introduced by the far infrared signal are again only likely to be significant when aiming for the highest precision in large scale averages.

Good stability of spectroscopic performance during the operational life of the SSU in space requires that the amount of water vapour within the PMCs on launch be minimised. Otherwise significant changes will occur over a period of two years as has happened in the case of P/F on TIROS-N. To this end, F3 was stored in vacuum for nearly a year before its recent shipment to RCA. Experience from this

shows that it is not necessary to maintain the SSU in a very high vacuum as long as the water vapour present is negligible. This can be attained by storing the SSUs in the Vacuum Storage Cases which have been recently manufactured. From a spectroscopic viewpoint, storage in nitrogen or carbon dioxide at a pressure between 10 and 100 mb might be ideal. Furthermore SSUs should not be stored indefinitely on the spacecraft before launch. For most SSUs storage on the spacecraft for about 1 year before launch represents a tolerable limit, but for an instrument like F3 this must be reduced to a few months, see Fig 2(c).

Further work to be performed on the effects of the leaks is:-

(i) Direct measurements of the effect of known leaks of water vapour or nitrogen on the effective CO_2 pressure in the PMC. This would allow better interpretation of anomalous measurements and improve monitoring of the CO_2 in the PMC.

(ii) The completion of a satisfactory set of spectroscopic measurements for every SSU, so that anomalous performance can be identified. (A check during storage every 3 years may be desirable).

(iii) Direct measurement of the far infrared water vapour signal in order to check the calculations in Appendix C.

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Inst.	Increase in effective mean PMC pressure / mb			Δt/ days
	Channel 25	Channel 26	Channel 27	
D2	0.8 *	2.4	-0.0 *	900
P/F	1.4	1.5	0.9	270
F2	0.9	3.0	1.8	600
F3	3.4	3.6	3.4	1150
F4	1.1	0.2	0.5	455
F5	2.1	1.6	1.5	550
	$\pm$ 0.7	$\pm$ 0.4	$\pm$ 0.15	

Δt = Time interval between spectroscopic measurements.

The uncertainties quoted are estimates of precision to 1σ level for sets of spectroscopic measurements performed on D2, P/F and F3. The precision of the other measurements is less, (see Figs 6(a) to (c)).

Table 1 Increase in effective mean PMC pressure as determined from spectroscopic measurements in the Met Office Weighting Function Facility. (* indicates development model PMC's).

	$\Delta p / \Delta t /$ (mb/ 100 days)		
	Channel 25	Channel 26	Channel 27
Storage in air at RCA	1.0	1.1	1.4
Storage in transit case	0.5	0.5	0.4

Table 2 PMC leak rates during storage. (Values are averages for P/F, F2, F3 and F4).

	$\Delta p / \Delta t /$ (mb/ 100 days)		
	Channel 25	Channel 26	Channel 27
Storage in air at RCA	0.9	1.1	0.8
Storage under vacuum (after 200 days)	- 0.3	- 0.3	- 0.4

Table 3 PMC leak rates in air and under vacuum.

(Values are averages for P/F, F2 and F3, except that F3 Channel 27 has been excluded because of its anomalously high rates of frequency change).

	df/dT (/Hz/C)											
	Channel 25			Channel 26			Channel 27			Date		
Inst.	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
D2	0.072	0.072	0.072	0.026	0.056	0.072	0.011	0.010	0.010	Jul76	May78	Dec79
P/F	0.066	---	0.095	0.032	---	0.065	0.018	---	0.049	Jan77	---	Oct78
F2	0.054	0.060	0.080	0.023	0.028	0.047	0.006	0.018	0.042	May77	Jun78	Jun79
F3	0.049	0.074	0.087	0.019	0.043	0.067	0.020	0.060	0.092	Jun77	Nov78	Feb80
F4	0.060	0.069	0.102	0.025	0.035	0.069	0.009	0.015	0.044	Sep77	Jun78	Apr80
F5	0.060	0.070	0.112	0.025	0.029	0.055	0.010	0.010	0.034	Jun78	Aug78	Sep80
F6	0.060			0.023			0.010			Mar80		
F7	0.062			0.029			0.010			Apr80		
F8												

Where possible, 3 sets of data are presented for each instrument, the last set either being the data on launch of the instrument or the last set available to date. The values are derived from measurements covering the temperature range 20C to 30C.

Table 4 Rates of PMC frequency increase with temperature

Instrument	Channel 25			Channel 26			Channel 27		
	p+	Δp	$\%H_2O$	p+	Δp	$\%H_2O$	p+	Δp	$\%H_2O$
D2				4.8	10.	48			
P/F	4.9	7.9	62	4.0	9.7	41	3.8	8.1	47
F2	2.9	4.6	63	2.2	5.5	40	2.6	5.2	50
F3	3.6	5.5	65	3.7	8.5	44	6.0	12.6	48
F4	7.1	9.4	76	4.1	7.7	53	3.6	5.9	59
F5	8.6	10.2	84	3.5	6.1	57	3.0	5.0	60

Typical uncertainty in p+ = $\pm$ 0.5 mb

in Δ p = $\pm$ 0.7 mb

Δ p Overall increase of PMC pressure at 30C since PMC crimp- off as derived from PMC frequency change. (/mb)

p+ Increase in PMC pressure with temperature between 7.5 and 30C above that predicted by the perfect gas law, as derived from anomalous frequency increase with temperature. (/mb)

$\%H_2O$ This represents the lower limit of the percentage of water vapour in the PMC leak.

Table 5 Water vapour content of PMC leaks as derived from anomalous PMC frequency increase with temperature

		p_c / mb		
	SSU	Channel 25	Channel 26	Channel 27
Launch p_c (1)	P/F	111.7 ± 0.6	41.0 ± 0.5	14.5 ± 0.4
" " (2)	"	112.0 ± 0.8	41.2 ± 0.6	14.9 ± 0.5
After 1 year (1)	"	111.0	40.0	13.5
After 2 years (1)	"	110.6	39.5	13.1
Launch p_c (1)	F2	110.0 ± 0.6	40.8 ± 0.4	13.6 ± 0.3
" " (2)	"	110.4 ± 0.6	39.6 ± 0.5	13.5 ± 0.4
After 1 year (1)	"	110.0	41.0	13.5
After 2 years (1)	"	109.9 *	41.0 *	13.4 *

* Predicted value, extrapolated from that at 1.5 years.

Type (1) estimate uses PMC frequency change since the last set of spectroscopic measurements on the SSU.

Type (2) estimate uses PMC frequency change since PMC crimp-off and the mean filling pressure as determined spectroscopically.

Table 6 Estimates of effective mean pressure of carbon dioxide in P/F and F2 PMC's during operation in space

		Δf^* /Hz		τ /days		Δf_∞ /Hz		Δf^+ /Hz
Inst.	Ch.	(1)	(2)	(1)	(2)	(1)	(2)	
P/F	25	0.42	0.40	342	320	-0.37	-0.35	0.82
P/F	26	0.71	1.02	384	898	-0.67	-1.07	1.27
P/F	27	0.79	0.71	466	470	-0.74	-0.71	1.15
F2	27	0.14						

$$\Delta f = \Delta f_o + \Delta f^* . \exp(-t/\tau)$$

where Δf is the difference in frequency from that on initial storage under vacuum.

and Δf_∞ is the limiting value as $t \rightarrow \infty$.

$\Delta f+$ was the increase in PMC frequency during SSU storage at atmospheric pressure.

Sample (1) Day 40 - Day 360, Sample (2) Day 360 - Day 680.

Table 7 Characteristics of exponential decrease of PMC frequency whilst SSU's are kept under vacuum

	Channel 25			Channel 26			Channel 27		
	(1)	(2)	Δ	(1)	(2)	Δ	(1)	(2)	Δ
Water vapour estimate /mb	4.9	3.2	1.7	4.0	1.6	2.4	3.8	1.6	2.2
Total additional gas in PMC /mb	7.9	6.2	1.7	9.7	7.1	2.6	8.1	5.7	2.4
Ultimate water vapour pressure /mb	2.6 ± 0.6			0.0			0.3 ± 0.15		
Ultimate additional gas in PMC /mb	5.5 ± 0.7			3.4 ± 0.6			4.3 ± 0.5		

Sample (1) P/F warm up after launch on TIROS-N, Day 289 1978.

(2) " " " on Day 29 1980.

Table 8 Decrease of water vapour pressure in P/F PMC's during operational use on TIROS-N. (Derived from anomalous temperature dependence of PMC frequency).

	$\partial p / \partial f$ mb/Hz		
Inst.	Channel 25	Channel 26	Channel 27
D2	6.8 *	6.0	5.1 *
P/F	6.6	5.6	5.4
F2	7.1	5.7	5.4
F3	7.1	6.2	5.7
F4	7.1	5.9	5.6
F5	7.8	6.3	5.9
F6	7.3	5.7	5.4
F7	8.3	5.9	5.1
F8	6.8	5.7	5.1

* development model PMC.

Appendix A PMC Frequency - PMC pressure relationships as derived from mechanical constants measured during PMC assembly at MSDS.

Appendix B Degradation of leak tightness in flight model PMCs.

PMC leak tightness appears to have degraded between the development stage (eg. D2 Channels 25 and 27, the life test PMC) and the flight models. There are three main areas of the PMC in which leaks have been found during assembly at MSDS, viz. the electrical leadthroughs which take the current to the PMC drive coil, the area where the filling tube is brazed into the main cylinder of the PMC, and the crimped seal on the filling tube. The only clear difference in manufacture which affects the sealing of the PMCs between the development and flight PMCs is associated with the electrical leadthroughs so that these are the prime area of suspicion.

The central conductor of each leadthrough is hollow in order to facilitate the connection from the conductor spring within the PMC main cyclinder. The vacuum seal is formed when the external connection to the leadthrough is soldered into position. In most development PMCs a single strand wire was used for the external connection, but in all the other PMCs (except F8 Channel 27 and the refurbished D2 Channel 27) multistranded wire was used. With the multi-stranded wire it is possible that a leak may exist through the central strands if the solder does not flow uniformly around all the strands when the external connection is made. However, it is clear that multistranded wire does not necessarily imply a leaky PMC since D2 Channel 25 is well within the pressure stability specification and yet this has multistranded wire. A second change associated with the leadthroughs was that on the flight PMCs the external part of the central conductor was shortened (supposedly the length of the conductors in the development models had made the PMCs rather difficult to fit in position). The PMCs in P/F appeared satisfactory, but during the assembly of those for F2 a significant leak occurred through the leadthrough. This was attributed to the fact that the part of the central conductor which had been adequately tinned on the inside had been removed during the shortening of the conductor and consequently the external soldered connection did not take. In order to remedy this it was decided to solder a piece of copper tube over the end of

the conductor so that the external soldered joint was now made into the copper tube (see MRB No. 30, 18/11/76), and this has also been applied to all subsequent PMCs. It is possible that the extra machining or the heavy soldering close to the ceramic to metal seal required by this fix have damaged the seal. It should be noted that the internal ceramic face of the leadthrough was machined in both development and flight PMCs and it is possible that the ceramic to metal seals were damaged in some cases. During assembly into the SSU it was found that F3 Channel 27 did not fit into position and this problem was overcome by bending the external conductor of the leadthrough. It is fairly clear that this must have damaged the seals around the conductor since this PMC has by far the worst leak rate.

Leaks were found in the braze between the copper filling tube and the titanium body of the PMC in the PMCs for P/F. This was rectified by fitting a titanium collar over the suspect area and aralditing this in position. This has also been applied to all subsequent PMCs (see MRBs 16 and 25, 17/2/76 and 14/9/76 respectively).

The last area on which suspicion falls is the crimp seal on the PMC filling tube. This cannot be adequately leak tested and it is likely that only large scale failures in the crimp will be detected during PMC assembly.

There is one common factor which applies to all the suspect areas, viz. the use of a coating of araldite to stop small leaks and to act as an insurance against further leaks developing. The surfaces to which the araldite was applied (eg. titanium, copper, ceramic, ptfe coating, etc.) were not specifically prepared to take araldite and thus whilst the araldite might provide a temporary seal against a leak, it is less likely to provide a permanent mend in an area which is subject to considerable temperature fluctuation. In this context, the application of a fillet of araldite to the titanium collar around the filling tube braze to fill any leaks generated during the crimp-off of the filling tube and also the application of araldite during the bending of the leadthrough on F3 Channel 27 appear optimistic solutions.

Leak testing at MSDS during assembly failed to show the leaks in the PMCs. This may be because the sealing with araldite deteriorated after assembly, or the time scale of the testing (a few hours) was inadequate (In section 8 the time constants of the reversal of the leak are much larger than this), or that the leaks were generated during the crimping of the filler tube.

In conclusion, it is unlikely that there is one particular fault which can explain all the leaks. (Since e.g. it is unlikely that the development crimps would all be good and that flight crimps all bad). The leadthroughs look the most probable area, but the braze on the filler tube and the crimp seal itself cannot be ruled out. Adding another coat of araldite over the suspect areas is unlikely to significantly improve the leak tightness in the long term.

Appendix C The influence of water vapour pressure modulated signals in the far infrared on the radiometric performance of the SSU.

Computations of the magnitude of carbon dioxide and water vapour pressure modulated signals were originally produced during the design phase of the PMCs (see SSU Tech,Memo. No. 61, 1974), and are here updated in the light of the measured performance of the components of the SSU optics. The measurements on typical flight components were produced by Edinburgh Instruments and the results between 800 and 60 cm^{-1} are presented in Fig. C.1. An overall relative transmission for the SSU optics was then taken as the product of the transmission of the coated Ge component cubed with the transmission of the bandpass filter. This assumes that the reflectivity of the scan mirror and the performance of the light pipe and detector assembly (apart from the Ge lens) are to a first approximation independent of wavenumber over the region considered here. It also does not take account of the multiple reflections which may occur between the plane surfaces of the Ge windows of the PMC and also between the front surface of the filter and the back window of the PMC. These reflections will be most significant in regions where the anti-reflection coating is no longer appropriate and Ge absorption is small (eg. at wavenumbers less than 200 cm^{-1}). Consequently the overall relative transmission in the far infrared presented in Fig. C.1 may be too small by as much as a factor of two, however it is this transmission profile which will be used here.

The spectral distribution of energy in the pressure modulated signals is illustrated in Fig. C.1 for a high pressure PMC with one per cent water content with the SSU viewing a blackbody at a temperature of 200 K. The computations indicate that the variation of signal with scene temperature can be represented by using a wavenumber of about 669 cm^{-1} for the carbon dioxide and a wavenumber of around 156 cm^{-1} for the water vapour. Thus the radiometric error introduced by the water vapour signal can be written as

$$\epsilon_{Water} = \frac{B_{669}(T_{sc}) + b.B_{156}(T_{sc}^{*})}{B_{669}(T_{BB}) + b.B_{156}(T_{BB})} \cdot B_{669}(T_{BB}) - B_{669}(T_{sc})$$

where b is the ratio of the water vapour pressure modulated transmission to the carbon dioxide pressure modulated transmission,

$B_\nu(T)$ is the Planck function at wavenumber ν for a blackbody at temperature T K,

T_{BB} is the temperature of the SSU internal blackbody target,

T_{sc} is the effective scene temperature for the CO_2 PM signal

and T_{sc}^* is the effective scene temperature for the H_2O PM signal.

This expression simplifies to:-

$$\epsilon_{Water} = b. \; B_{156}(T_{sc}^*) - \frac{B_{156}(T_{BB})}{B_{669}(T_{BB})} \cdot B_{669}(T_{sc})$$

For one per cent water vapour in a PMC the computations indicated values for

b =	0.00050	Channel 25
	0.00042	Channel 26
	0.00037	Channel 27

It was found that to a first approximation the size of the water vapour signal was proportional to the amount of water vapour present and that pressure broadening effects were small, and so these computations have been extrapolated to the situation with 5 mb of water in each PMC. This gives values of

b =	0.0024	Channel 25
	0.0057	Channel 26
	0.0175	Channel 27

Computations using a Malkmus Band Model for the water vapour band and a four parameter Curtis-Godson approximation for the path showed that the values of T_{sc}^* were similar in each SSU channel, and that the values for T_{sc}^* lay between the scene temperature of Channel 26 and 10 C lower than the scene temperature of Channel 25. The wide range in T_{sc}^* is exacerbated by the uncertainty as to the distribution of water vapour in the stratosphere.

On average, T_{sc} =	230 K	for Channel 25
(global)	240 K	for Channel 26
	250 K	for Channel 27

whilst the lowest and highest daily zonal temperatures (polar winter and summer respectively) have approximately

T_{sc}	=	200 K	, T_{sc}	= 250 K	, for Channel 25.
(winter)		215 K	(summer)	260 K	Channel 26
		230 K		270 K	Channel 27

Using the values of T_{sc} and T_{sc}^* above, the radiometric errors introduced by 5 mb of water vapour in each PMC will be, in $mw/(m^2.sr.cm^{-1})$:-

	Channel 25	Channel 26	Channel 27
Global average	0.02 - 0.03	0.04 - 0.06	0.07 - 0.13
Polar winter	0.03 - 0.04	0.06 - 0.08	0.11 - 0.18
Polar summer	0.02 - 0.03	0.02 - 0.04	0 - 0.07

where the range is the result of the possible variation in T_{sc}^*.

If 0.05 $mw/(m^2.sr.cm^{-1})$ is taken as the largest tolerable radiometric error and remembering the factor of two uncertainty in the far infrared transmission then the largest tolerable water vapour pressure in the PMCs will be:-

Channel 25 6 ± 3 mb, Channel 26 3 ± 1.5 mb, Channel 27 1.4 ± 0.7 mb.

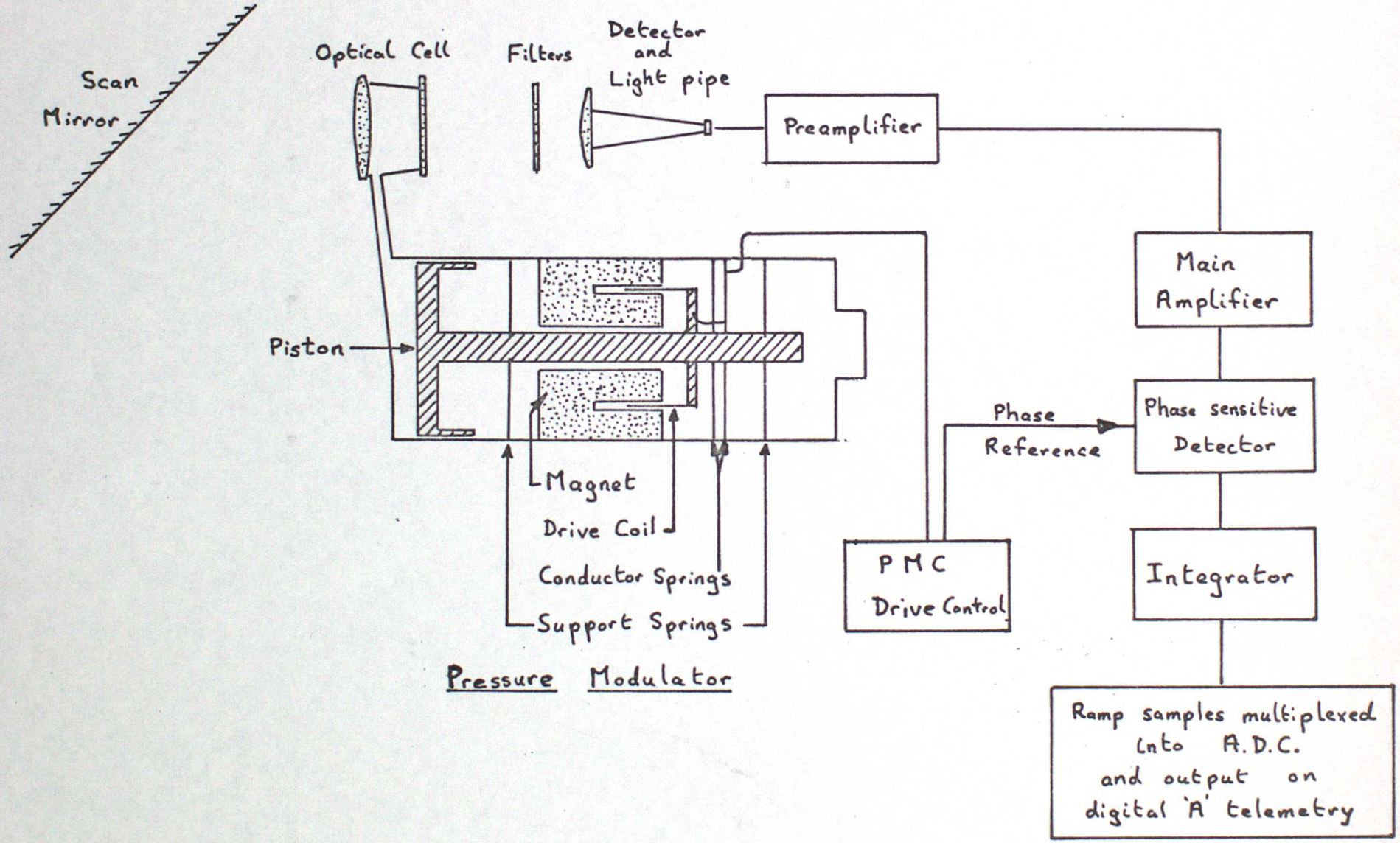


Figure 1. Schematic of the optics and electronics associated with an SSU signal channel.

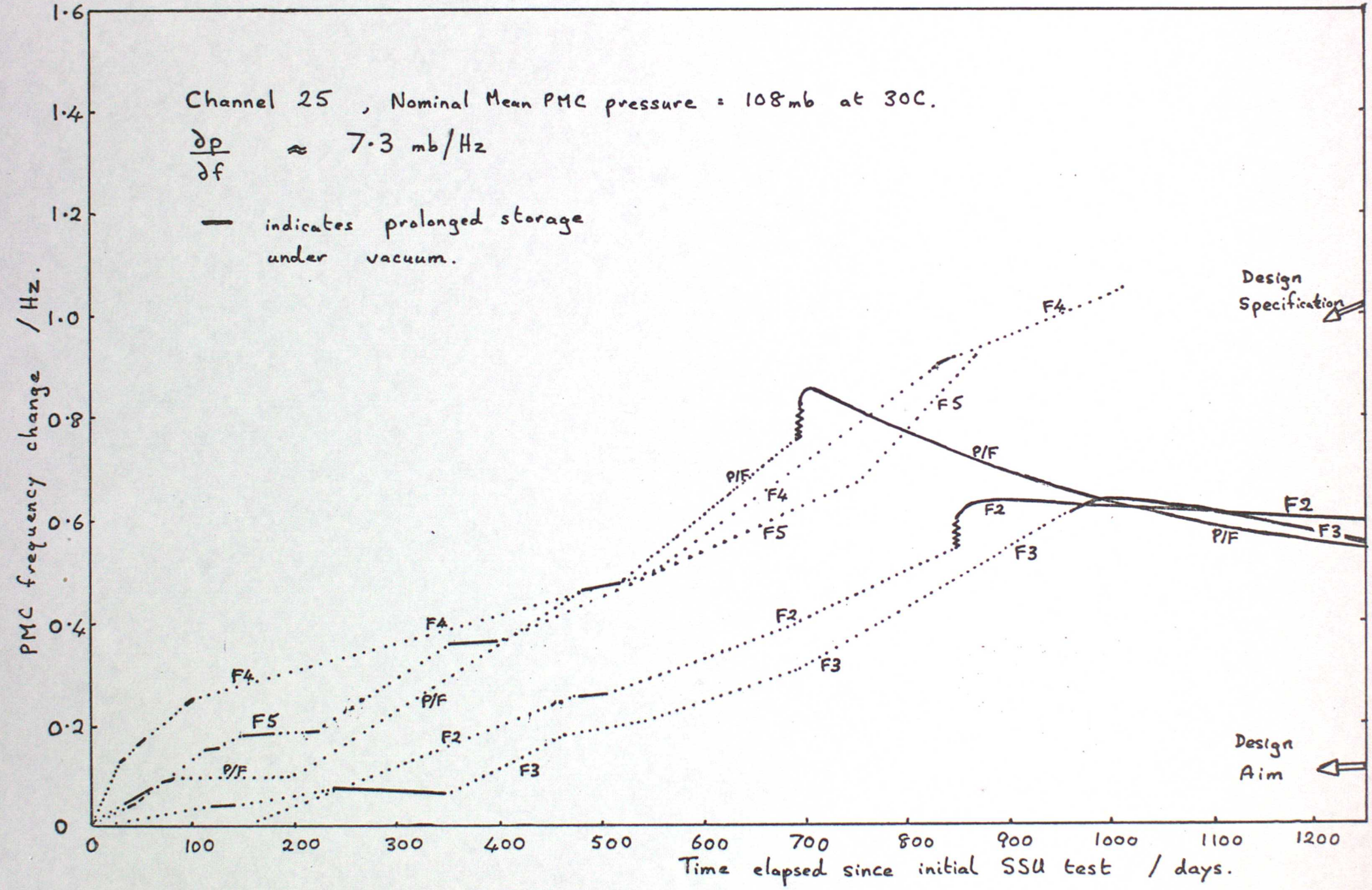


Figure 2 (a) Time dependence of PMC frequency [PMC Temperature ≈ 30C]

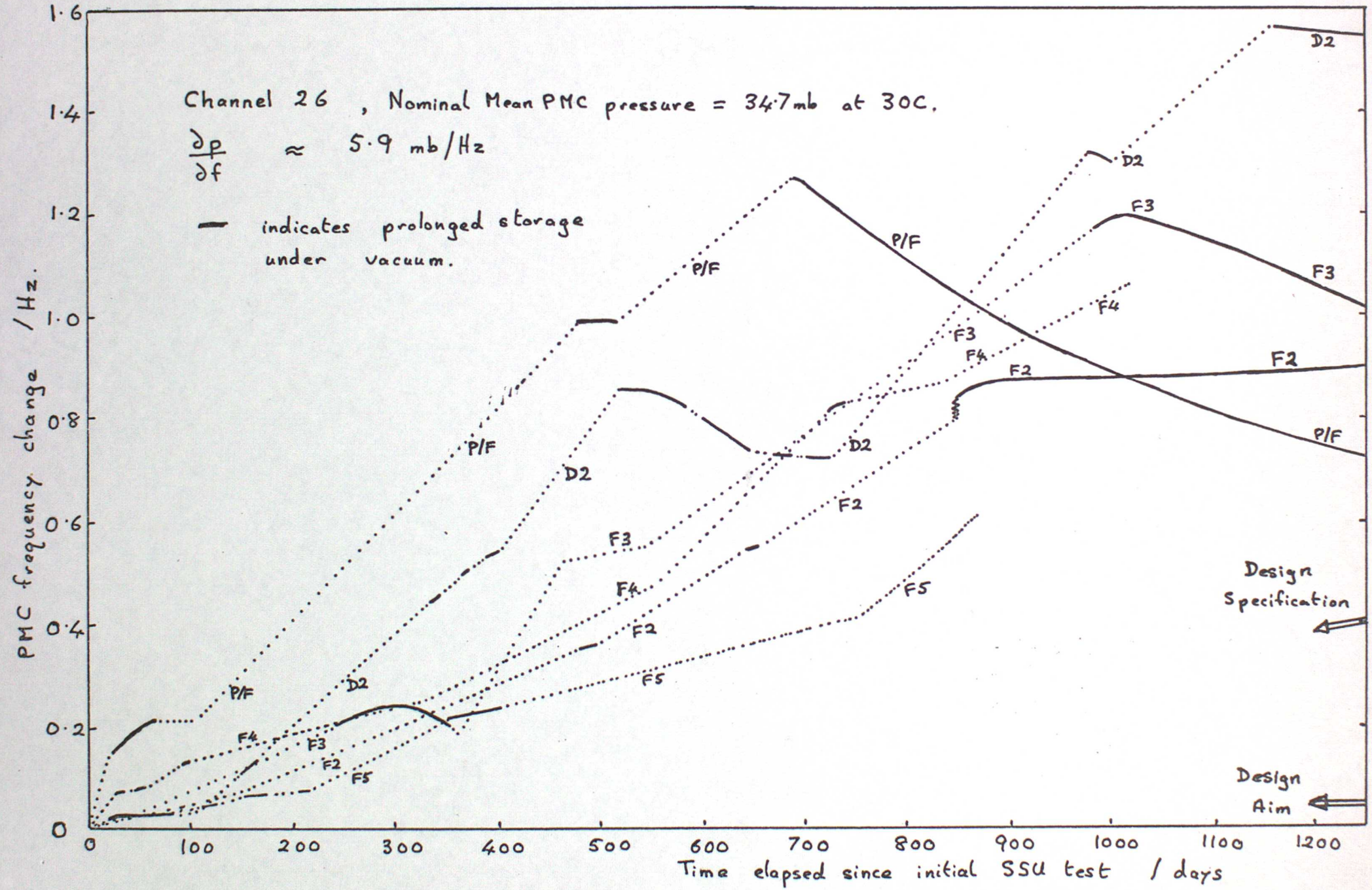


Figure 2 (b) Time dependence of PMC frequency [PMC Temperature ≈ 30C]

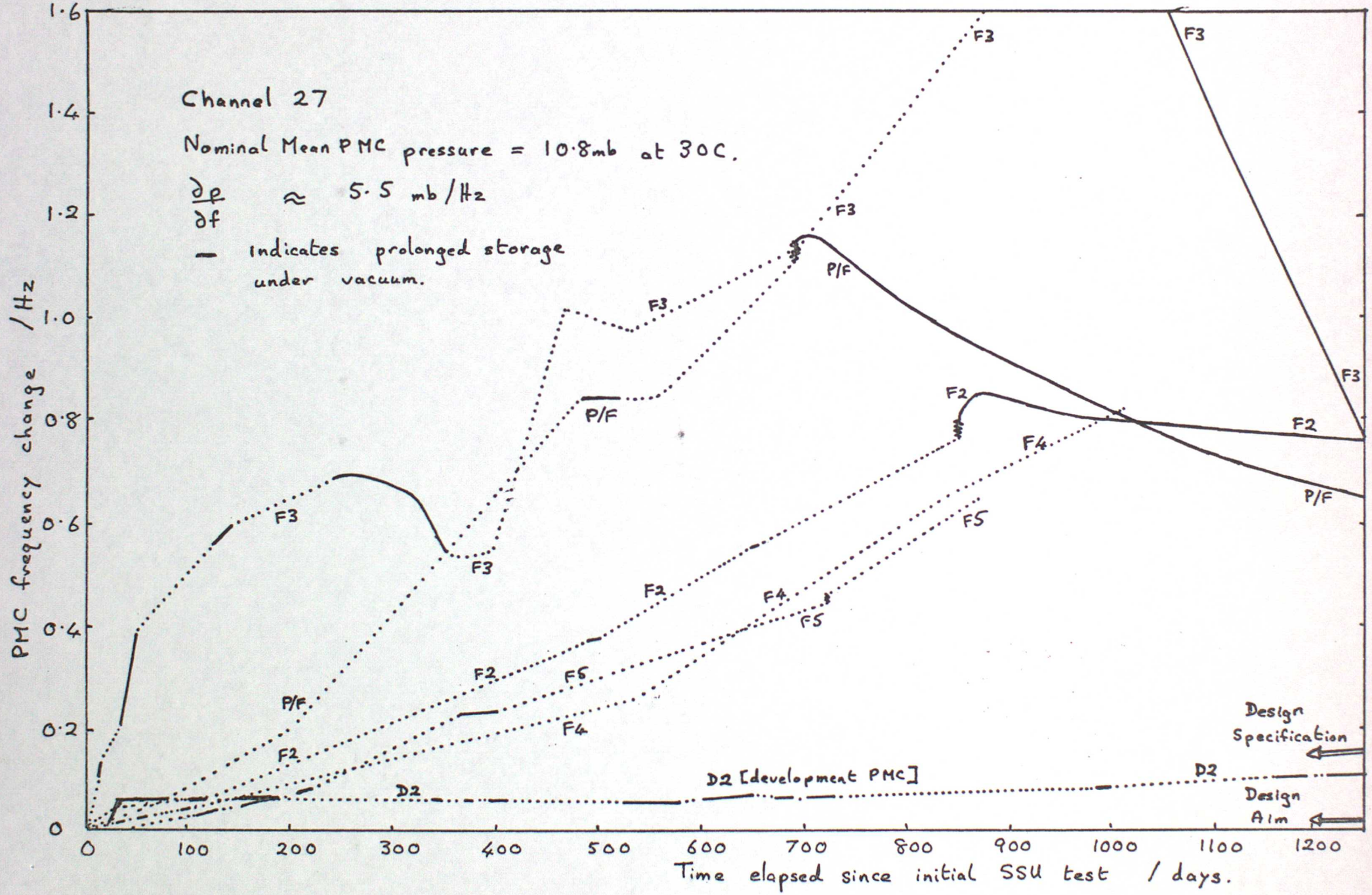


Figure 2 (c) Time dependence of PMC frequency [PMC Temperature ≈ 30C]

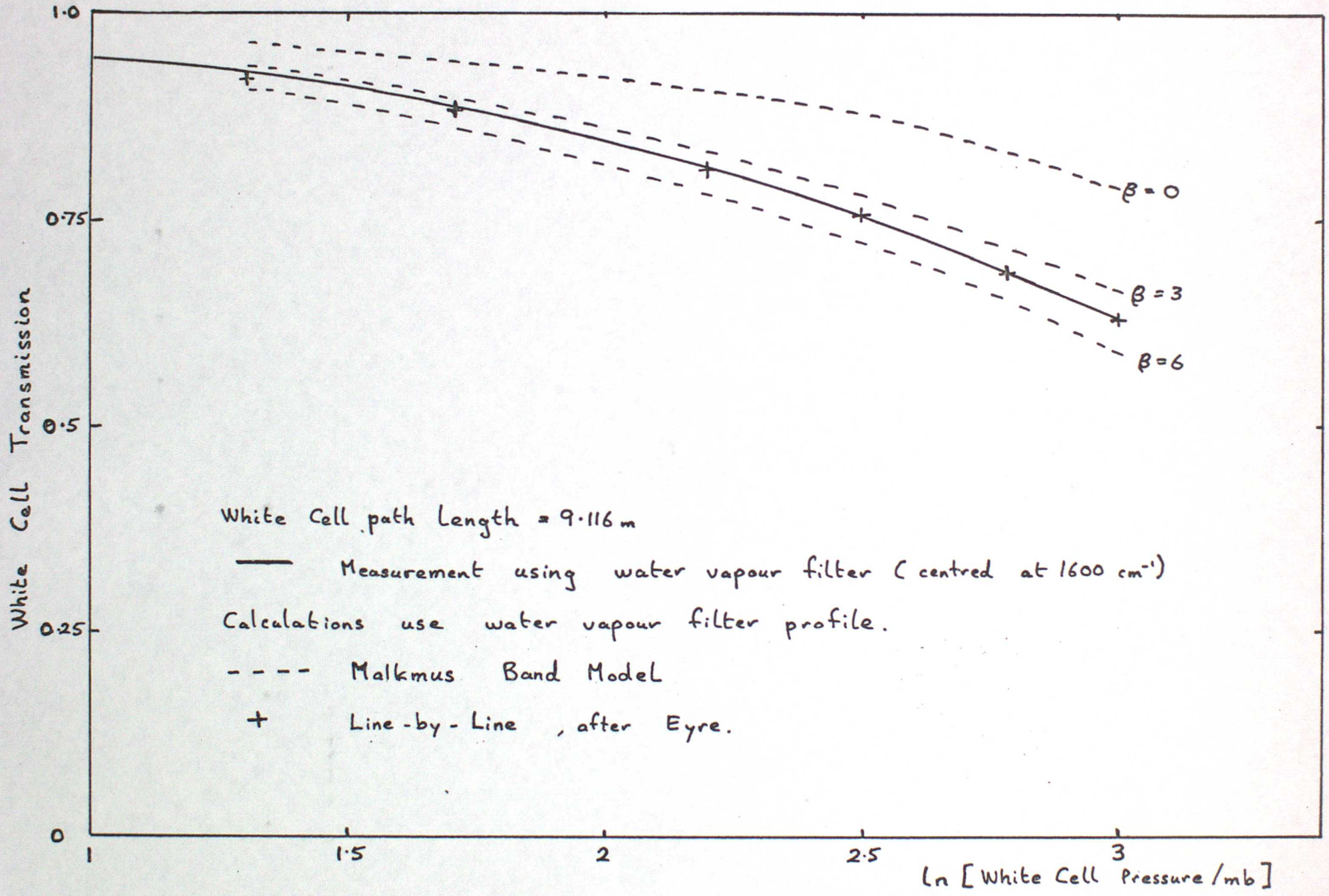


Figure 3(a) Broadband Transmission of pure water vapour between 1400 and 1800 cm^{-1}

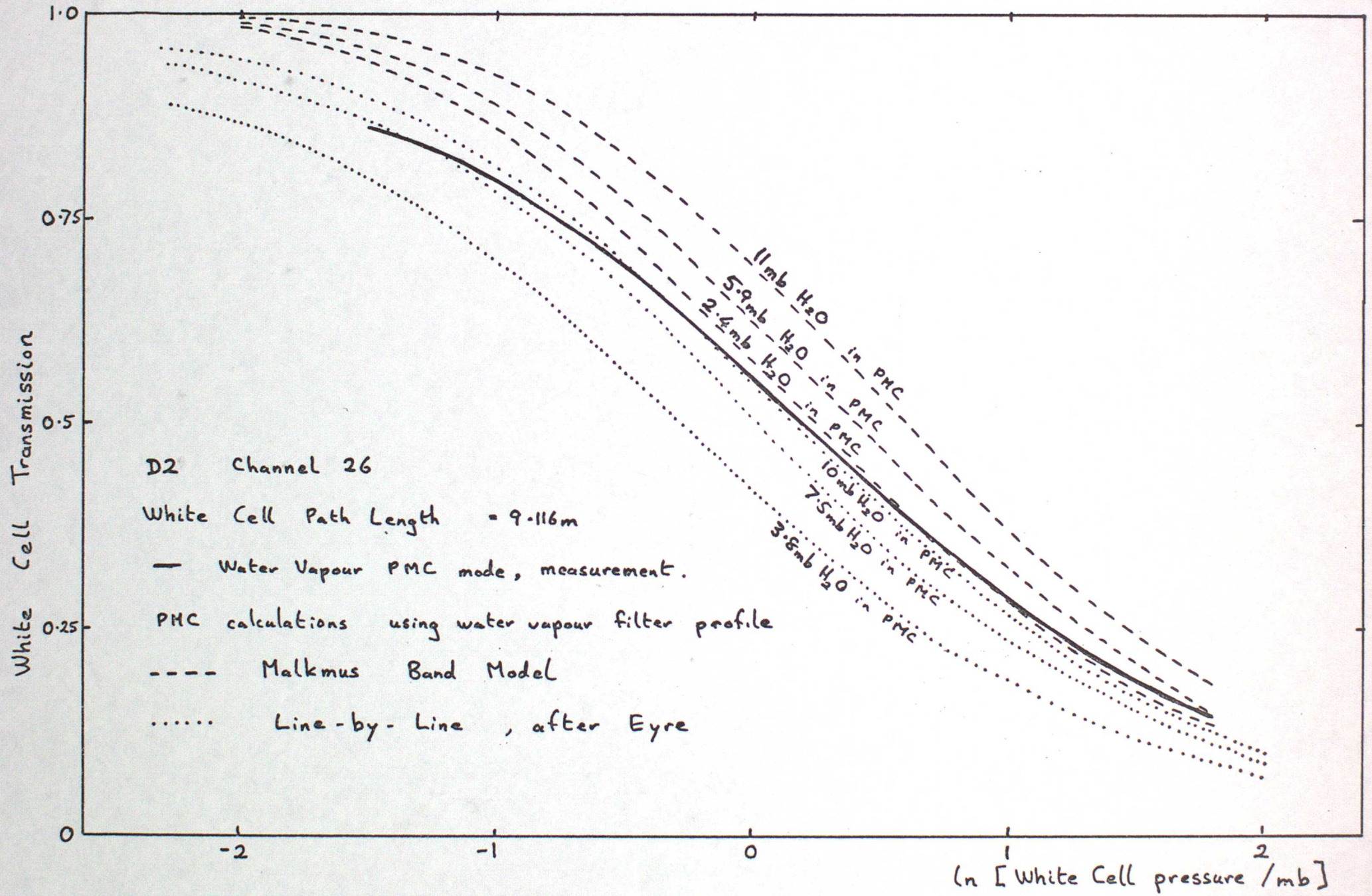


Figure 3(b) Transmission of pure water vapour, using D2 Channel 26 as a Water Vapour PMC, between 1400 and 1800 cm^{-1}.

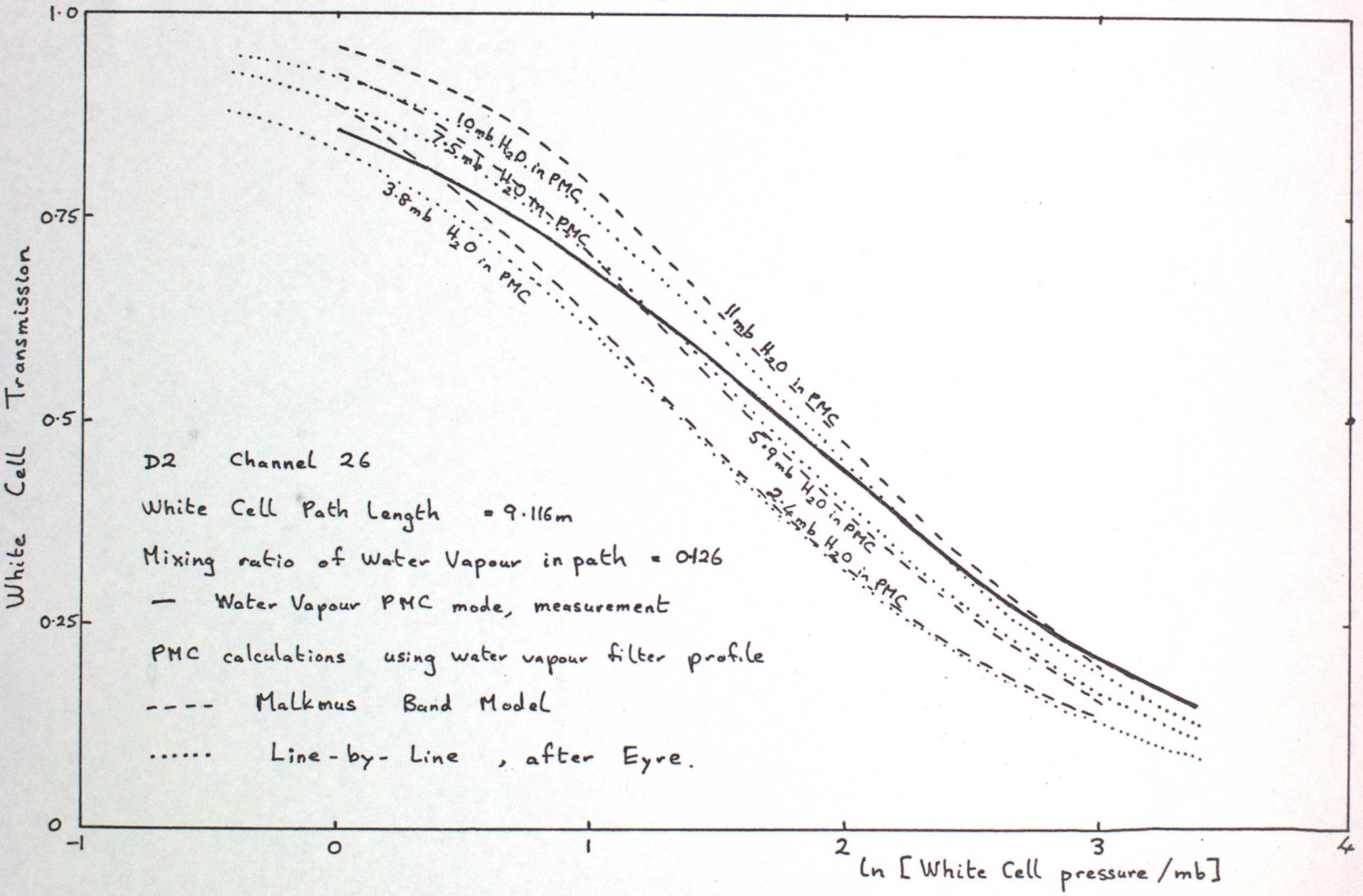


Figure 3(c) Transmission through a water vapour/nitrogen mix, using D2 Channel 26 as a Water Vapour PMC between 1400 and 1800 cm^{-1}.

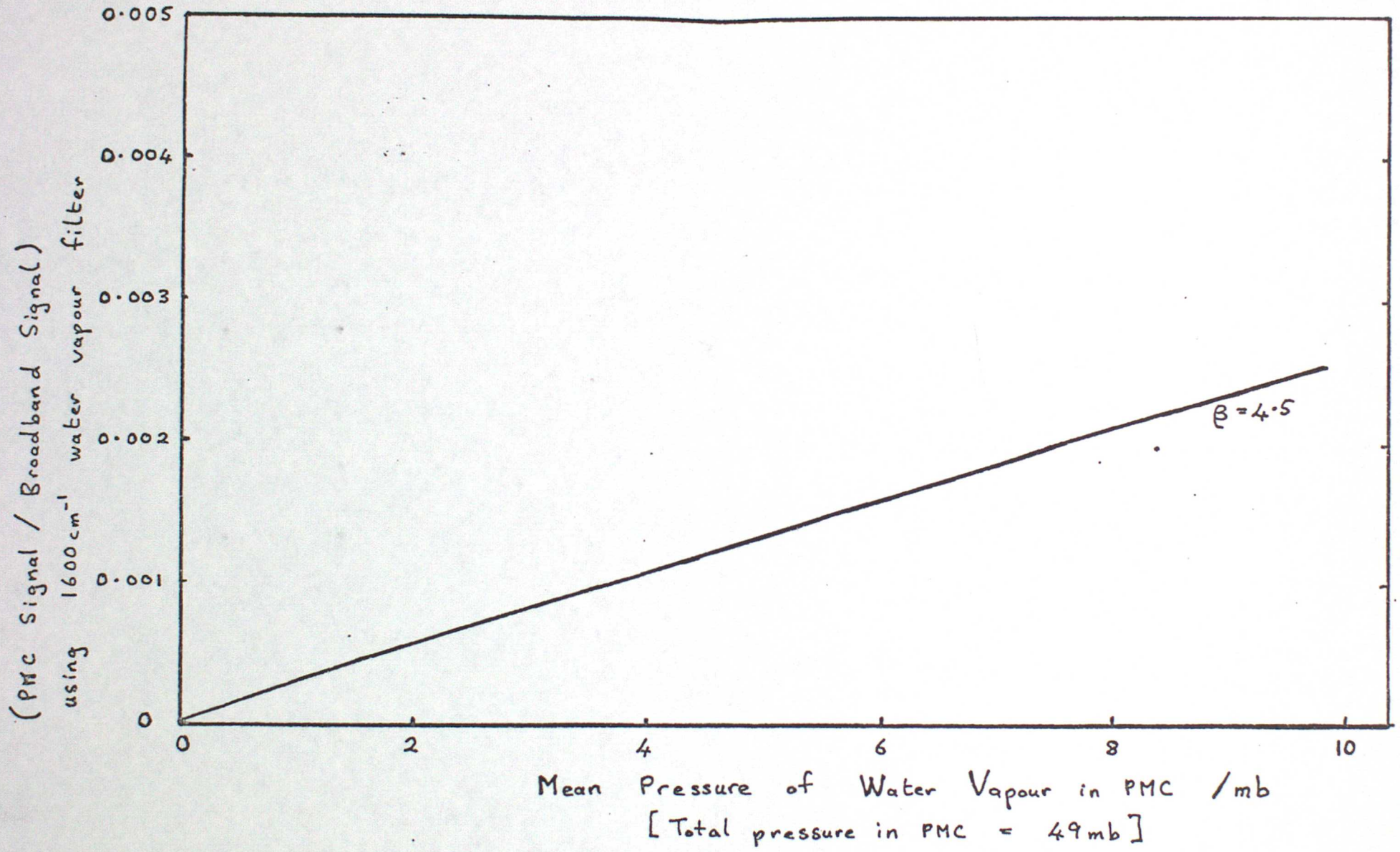


Fig. 3(d) Magnitude of Water Vapour Pressure Modulated Signal - between 1400 and 1800 cm^{-1} when using D2 Channel 26 in Met. Office weighting function facility.

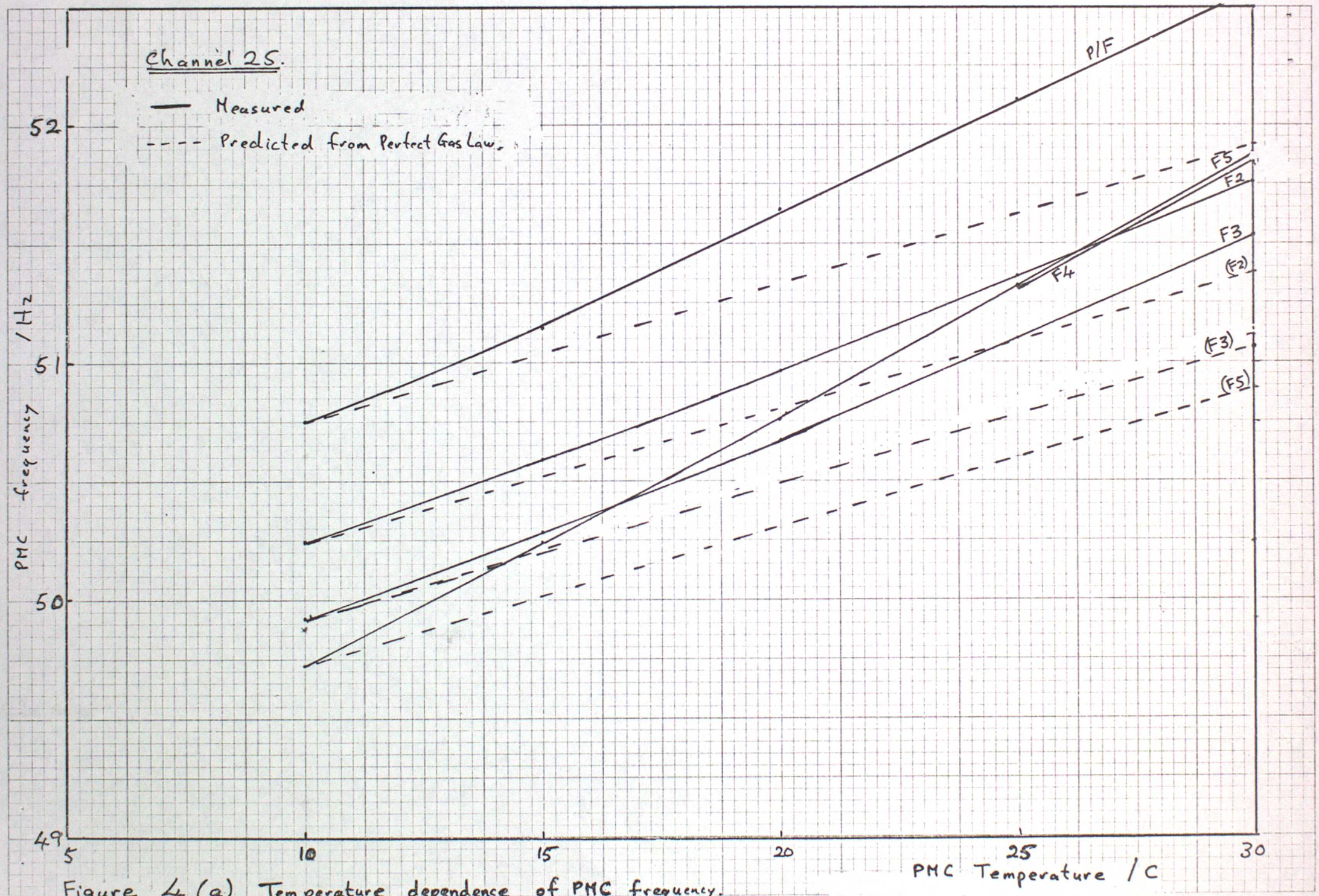


Figure 4 (a) Temperature dependence of PMC frequency.

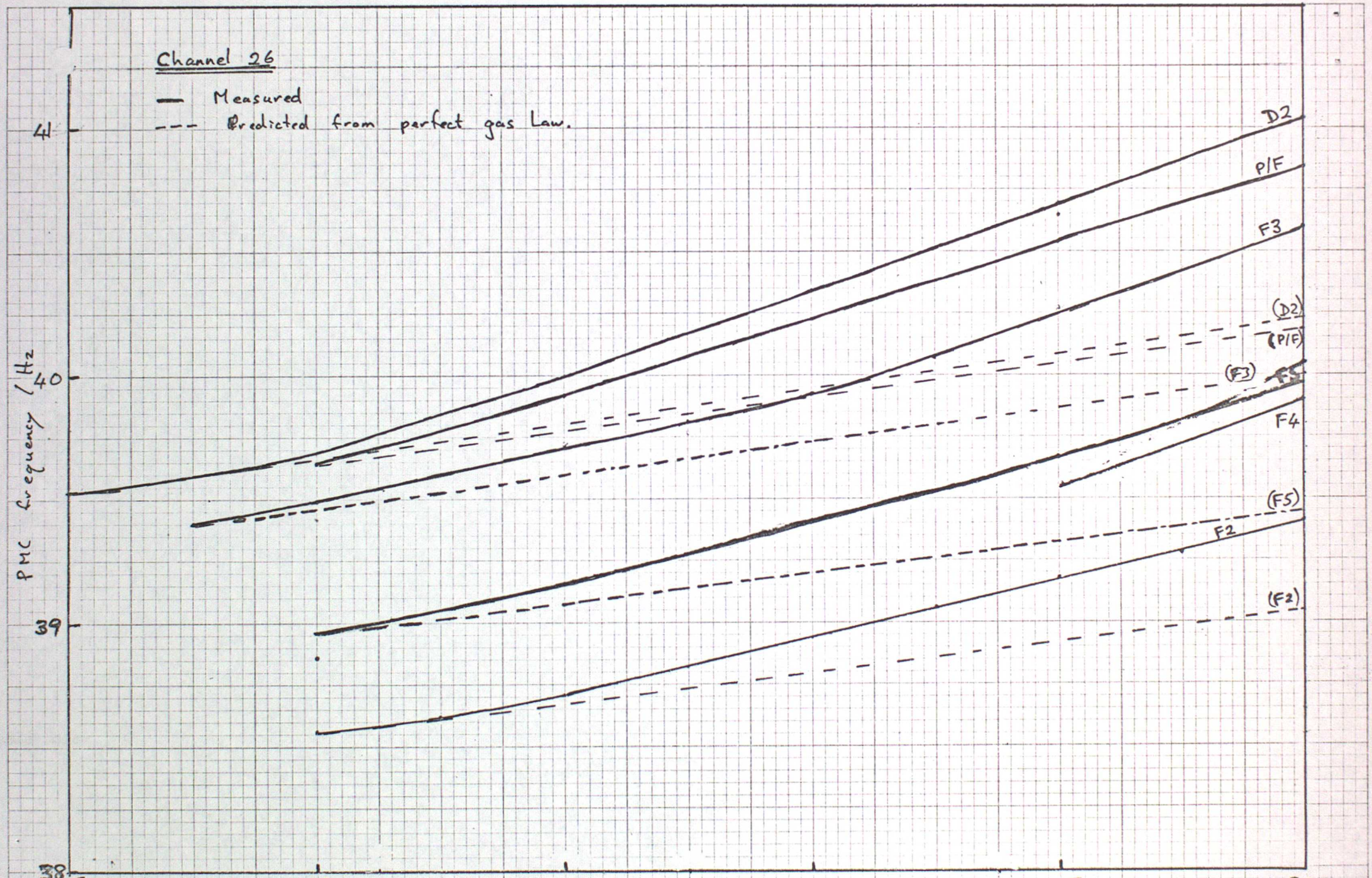


Figure 4(b) Temperature dependence of PMC frequency

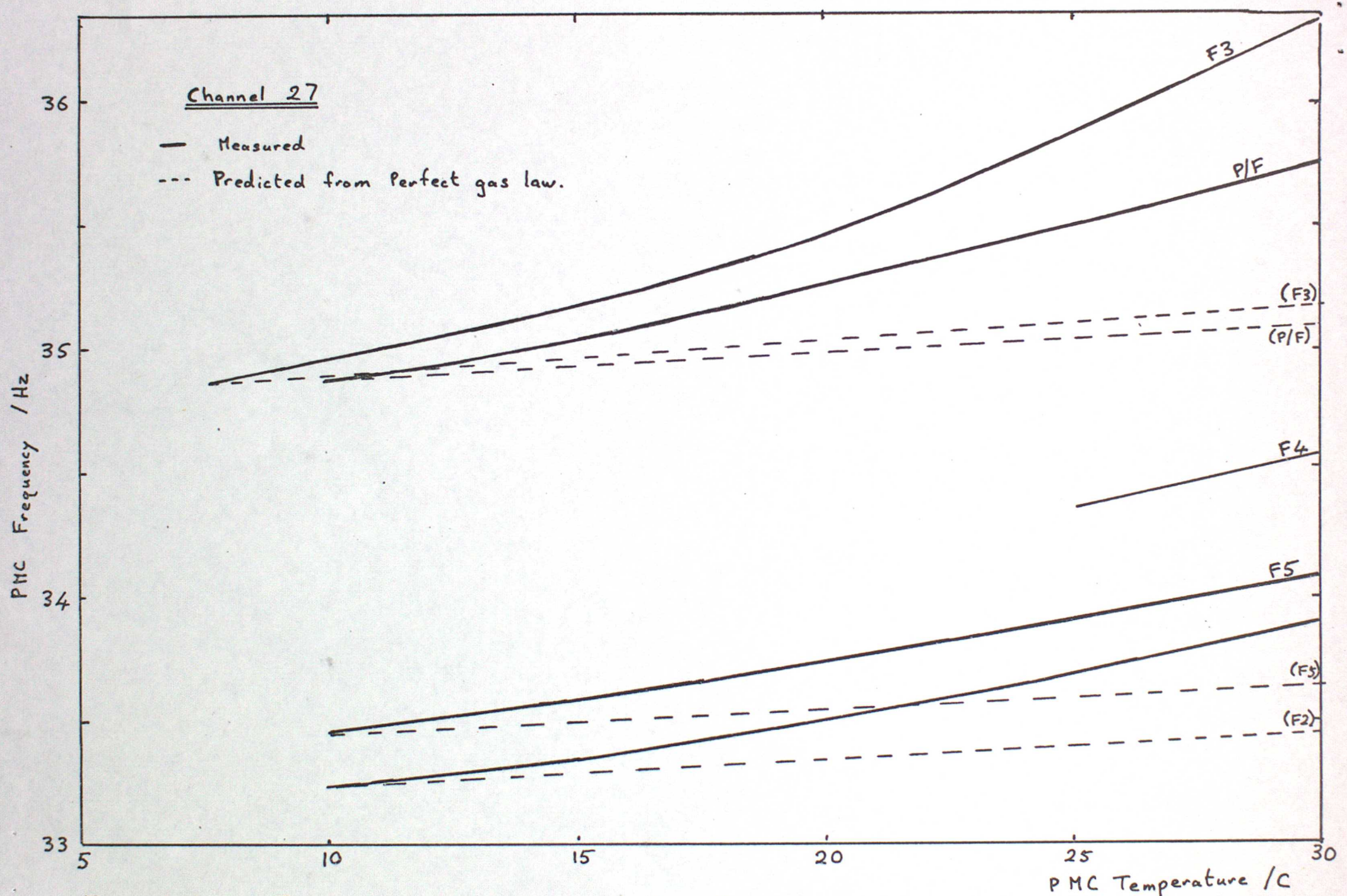


Figure 4(c) Temperature Dependence of PMC frequency.

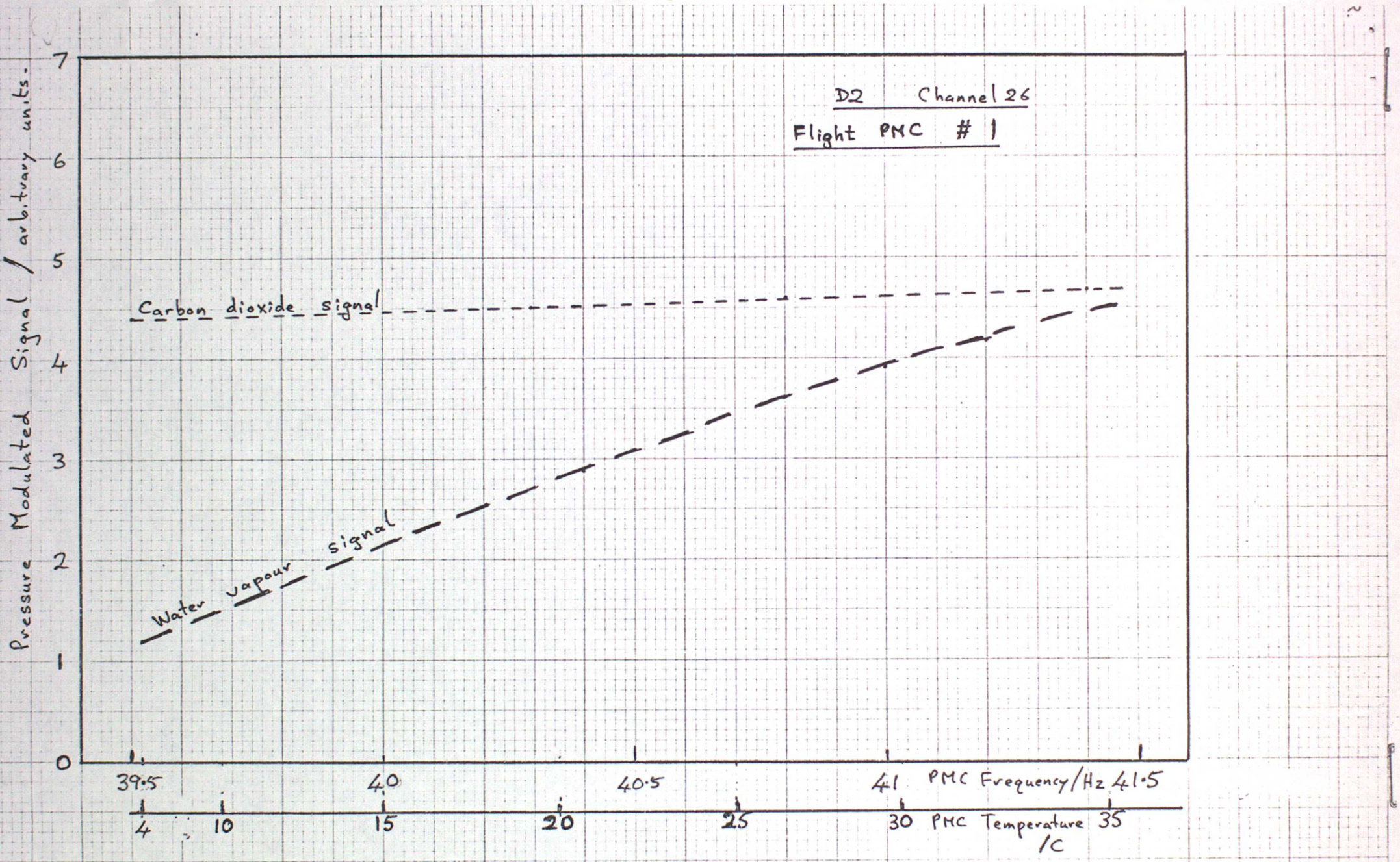


Figure 5 Variation of Pressure modulated signals with PMC frequency.
[Signal normalised with respect to broadband signals, PMC driven at a constant back e.m.f.]

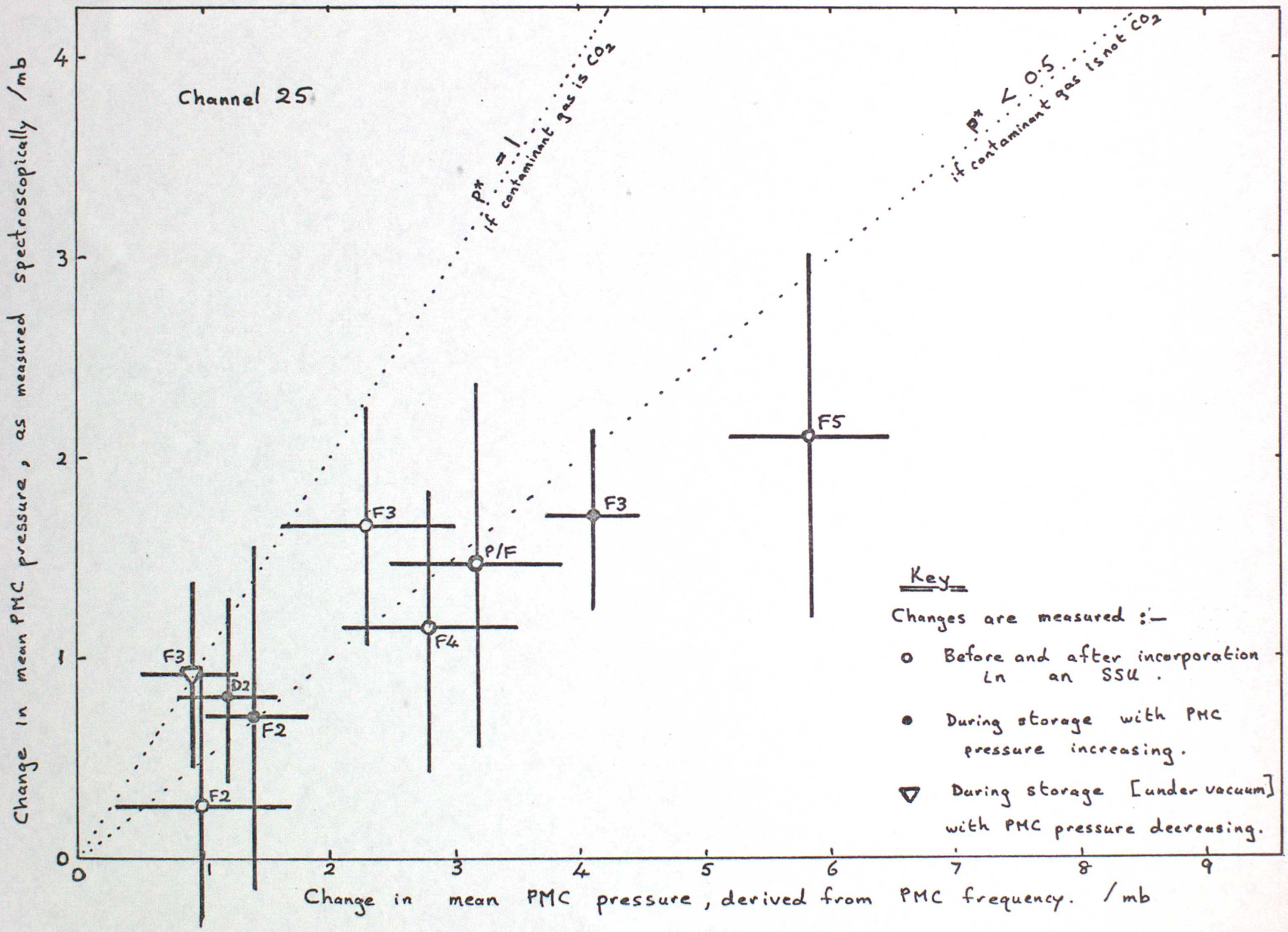


Figure 6 (a) Changes in SSU Channel 25 spectroscopic performance associated with PMC leaks.

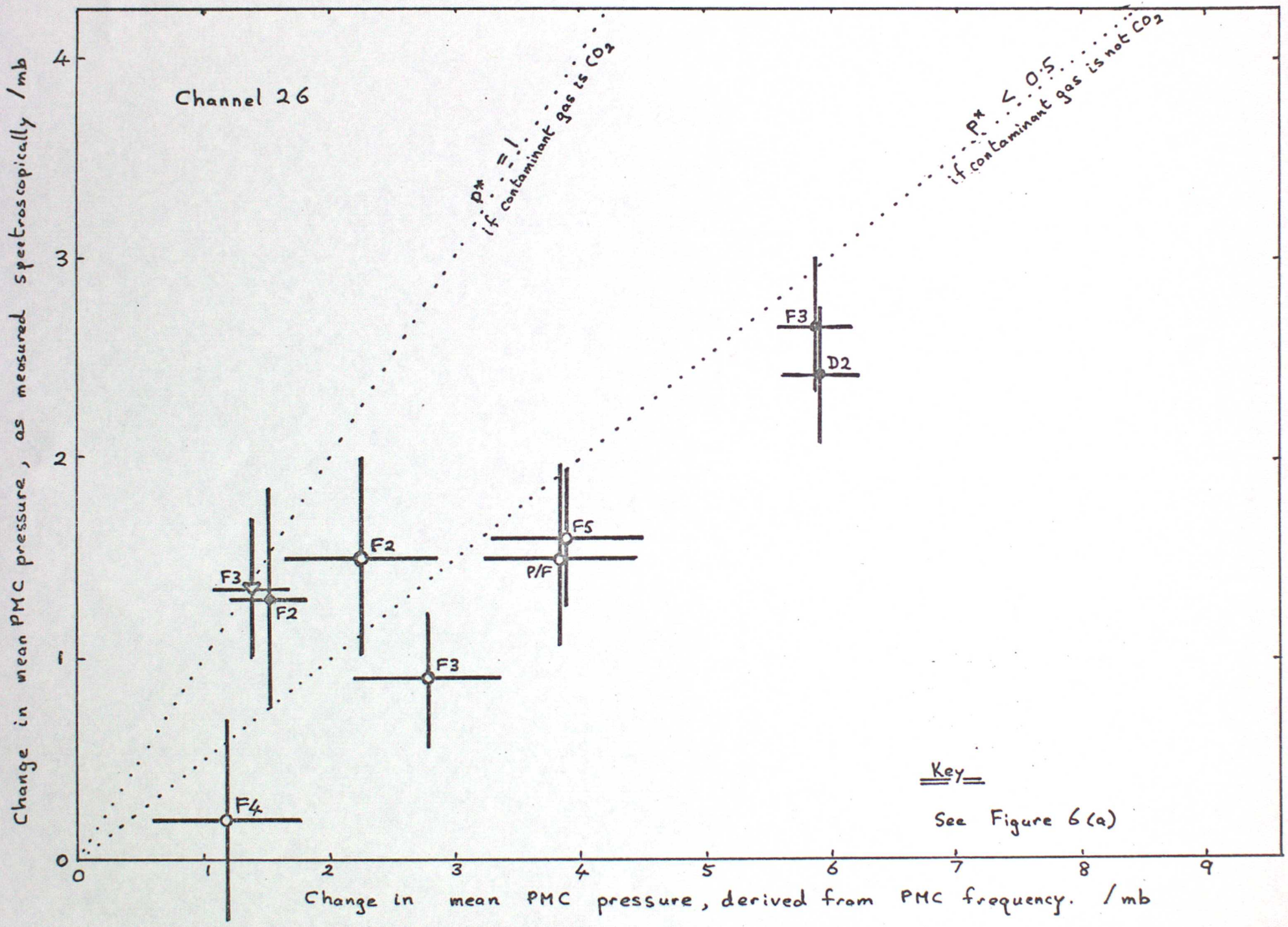


Figure 6(b) Changes in SSU Channel 26 spectroscopic performance associated with PMC leaks.

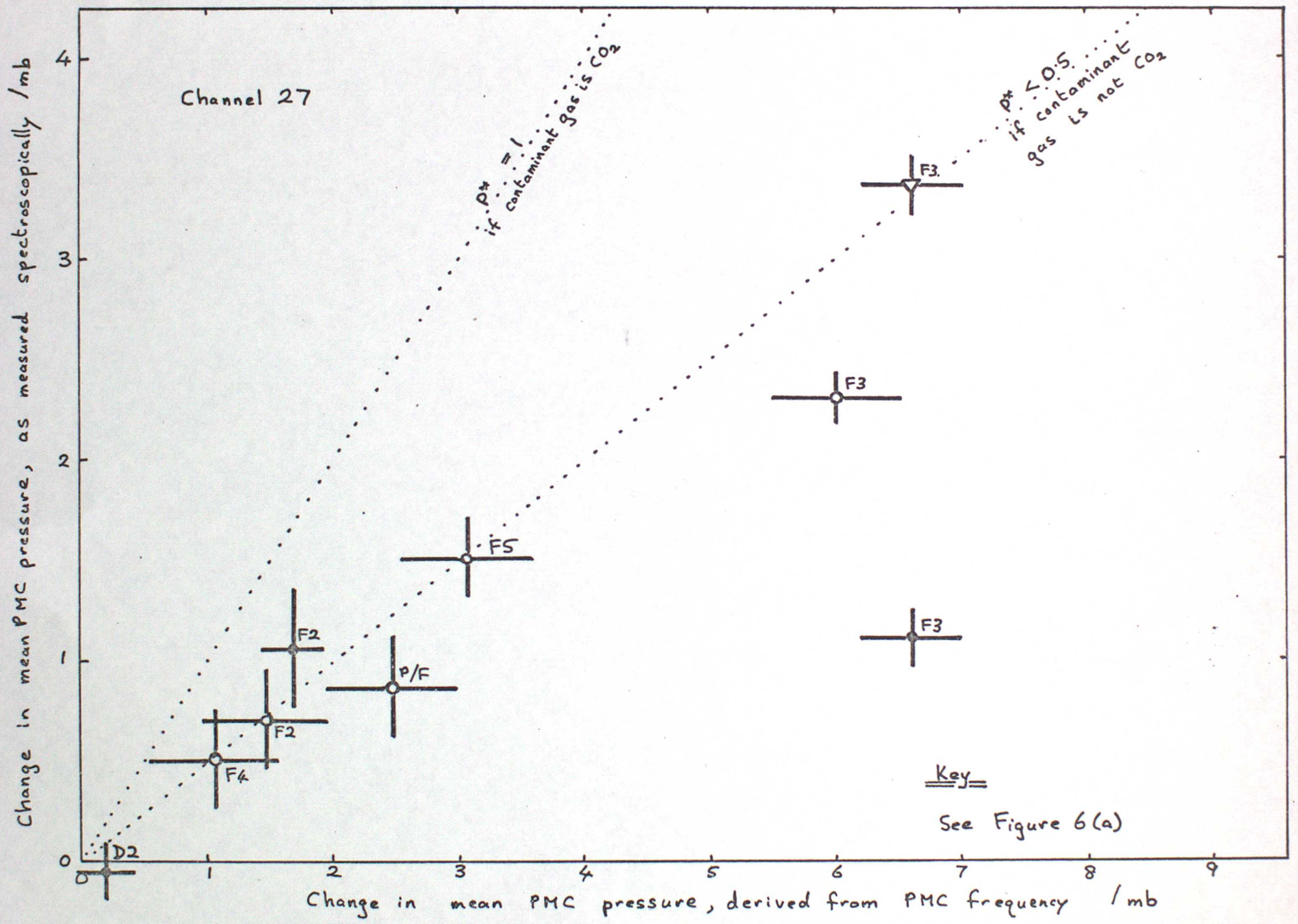
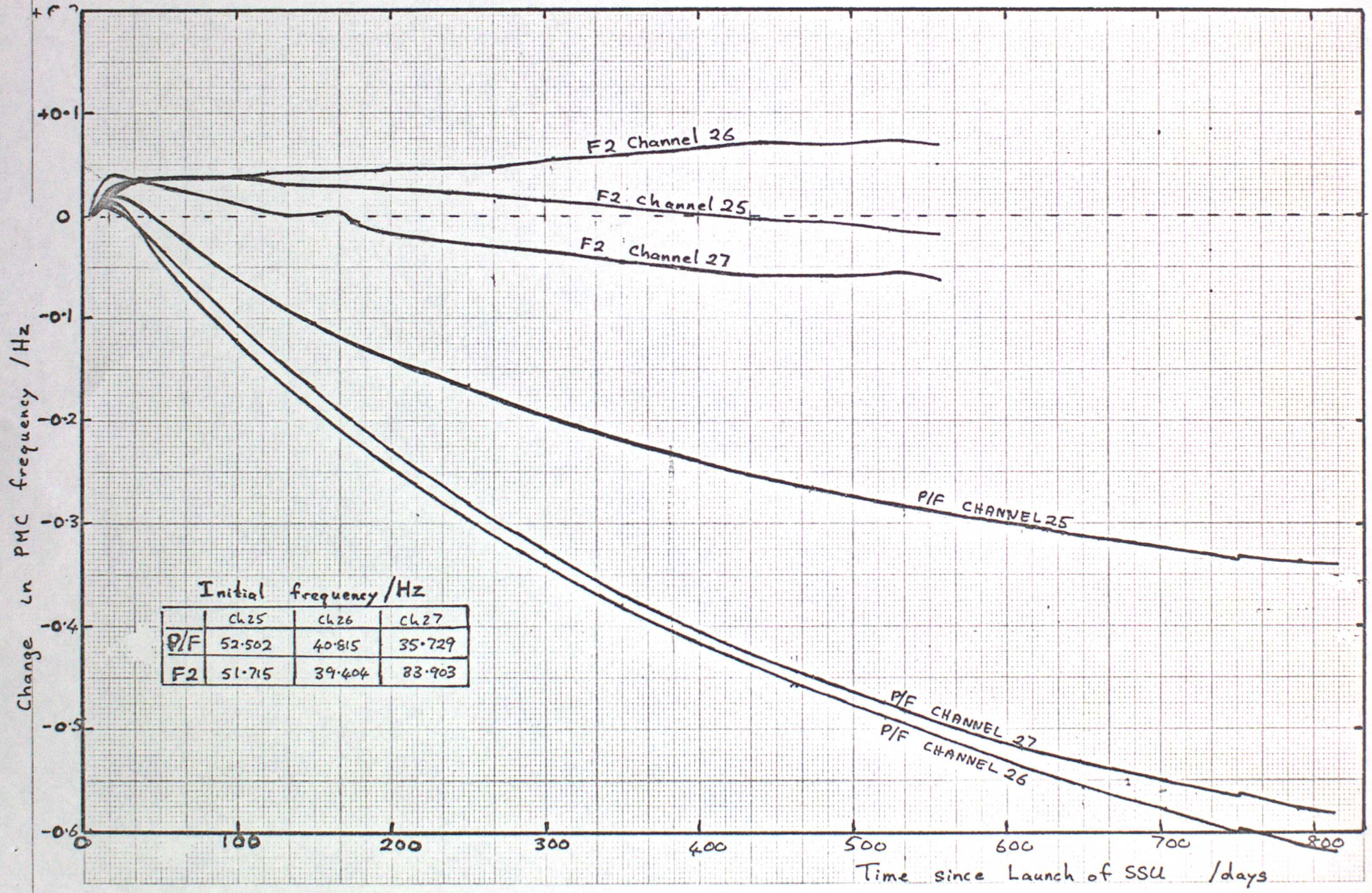


Figure 6(c) Changes in SSU Channel 27 spectroscopic performance associated with PMC leaks.



Initial frequency /Hz

	Ch25	Ch26	Ch27
P/F	52·502	40·815	35·729
F2	51·715	39·404	83·903

Figure . 7 Stability of PMC frequency during operational use of the SSU.

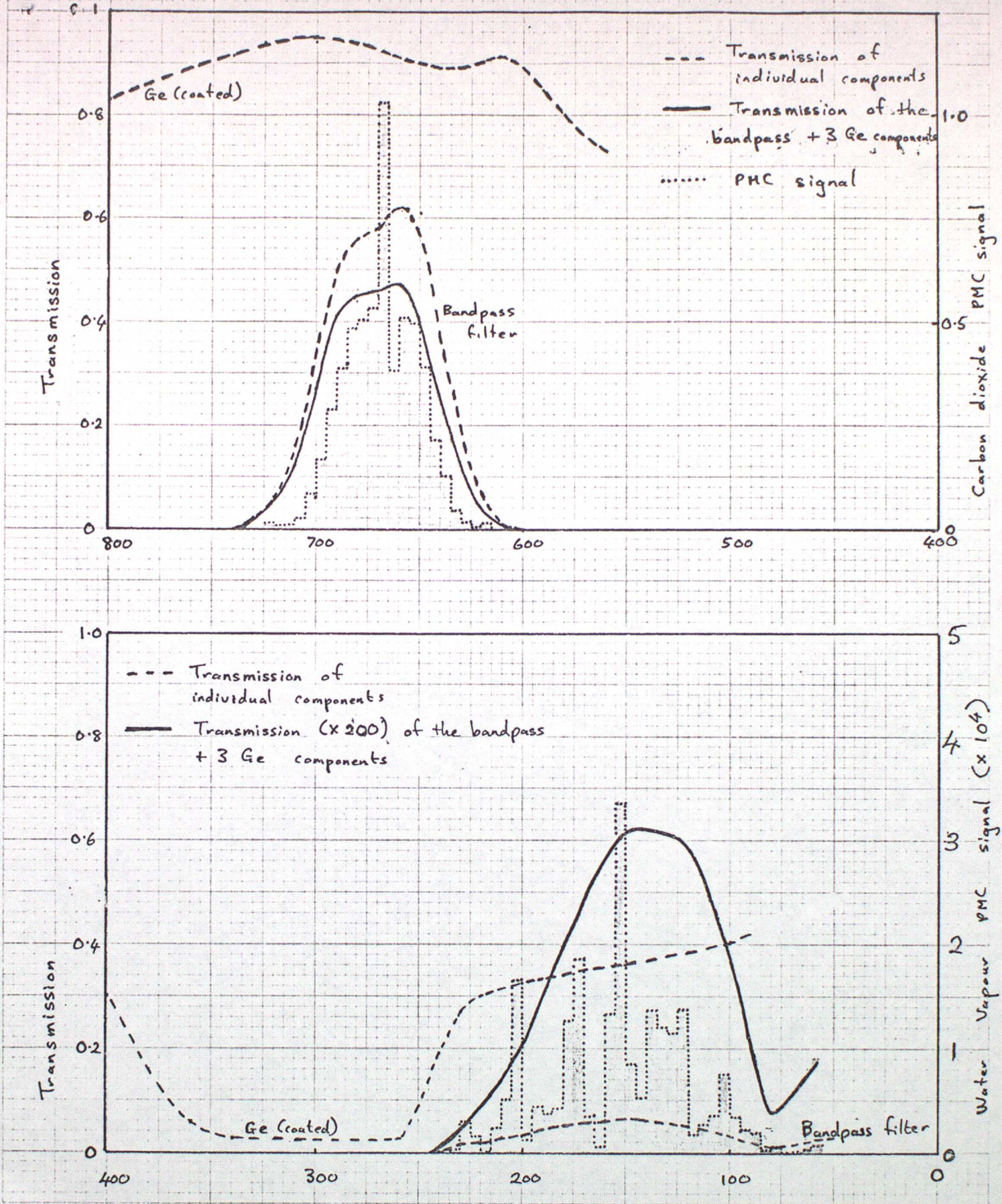


Fig. C1 Comparison of PMC signals at 668 cm^{-1} and in the far infra-red for a PMC with a mean CO_2 pressure of 100mb and 1mb of H_2O wapour. [The signals are scaled by the transmission curve and the Planck function for 200K, and correspond to a modulation depth of 0.2]