REAL-TIME CHANNEL ESTIMATION OF HF DATA CIRCUITS - FIELD TRIAL ANALYSIS

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ABSTRACT

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REAL-TIME CHANNEL ESTIMATION OF HF DATA CIRCUITS - FIELD TRIAL ANALYSIS

by Ronald Sherwood Broom

HF communications systems in operation at the present time are dependent upon the frequency prediction method to establish operational parameters. This field trial analysis provides results in support of a much improved method of determining operational conditions by real-time channel estimation.

Interrogation of the HF (3-30 MHz) spectrum can be carried out in several ways. The structure of the ionosphere may be examined by ionospheric sounding but such a macroscopic analysis does not disclose the prevailing conditions for individual channels. A microscopic analysis will show the quality of an individual channel in terms of propagation, noise and interference conditions and can be achieved by equipment under development in this research. This equipment has been subjected to a number of field trials and results show encouraging correspondence between the system theory and its practical behaviour.

The quality of individual channels is examined by transmitting low-power pilot tones alongside the main data signals, and measurement of their phase perturbation is translated as a pilot tone error rate. A relationship between this pilot tone error rate and the data signal error rate, also measured by the system, is then used as the basis of the decision making process for frequency management of the link. During a field trial using a United Kingdom/Gibraltar link a digital read out of pilot tone phase errors and data signal errors was used to assess the quality of the channels under interrogation and acquire analysis data.

In operation the system functions as a diagnostic probe of channel quality and can be developed to operate in a hybrid (man/machine) or automatic mode.

Both the theory and the field trials equipment are discussed prior to presentation of the field trial analysis results. These results indicate that progress to date now justifies long term trials under operational conditions to research into aspects not yet investigated.

The cost/benefit to the user will depend on the category of user, but the 'add-on' peripheral equipment will represent only a small fraction of the cost of a complete HF communications system.

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1. INTRODUCTION

Interrogation of the HF (3 - 30 MHz) spectrum can be carried out in several ways. A macroscopic analysis is represented by true ionospheric sounding which examines the structure of the ionosphere but does not disclose the prevailing conditions for individual channels. A microscopic analysis will show the quality of an individual channel in terms of propagation, noise and interference conditions.

The macroscopic analysis provides information, via the observed layer structure, on the MUF and multipath situation. By comparison, a microscopic analysis will give real-time data on the quality of a channel which can be applied as a tool for accurate channel estimation.

The macroscopic technique is exercised by the well established oblique-incidence pulse sounding method (1)(2), and the two ionograms of Figures 1.1 and 1.2 clearly illustrate the expansive aspect of true sounding. Figure 1.1 shows how MUF, multipath etc. can be verified, and also shows that the vertical traces, depicting noise as a function of time, aggravate a resolution too crude to ascertain the quality of a given channel. Figure 1.2, which was obtained with a reduced brilliance setting, gives an excellent picture of the layer structure but nothing else.

There are two methods of microscopic analysis:

(a) Channel Estimation from an Analysis of Normal Traffic or Test Data Sequences on Assigned Frequencies (3).

(b) Monitoring the Amplitude and Phase Perturbations of Pilot Tones on Assigned Frequencies (4).

It is method (b) above which is the concern of this thesis and the work described is one contribution to the research effort of a Group led by Dr. J.A. Betts, investigating real-time channel estimation of HF circuits for data transmission. The system under development operates as a diagnostic probe for channel quality and, as such, first requires a

IONOGRAMS BY OBLIQUE-INCIDENCE PULSE SOUNDING

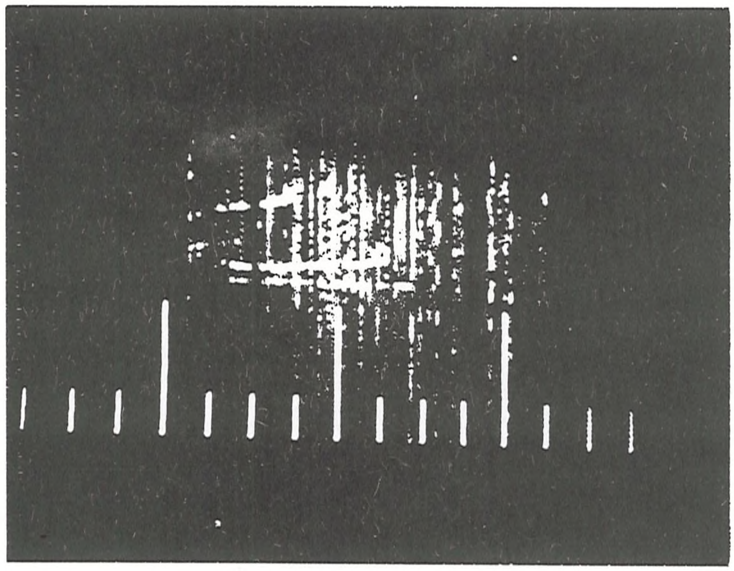


Figure 1.1

Ionogram for 1530 5 October 1971

Normal control settings

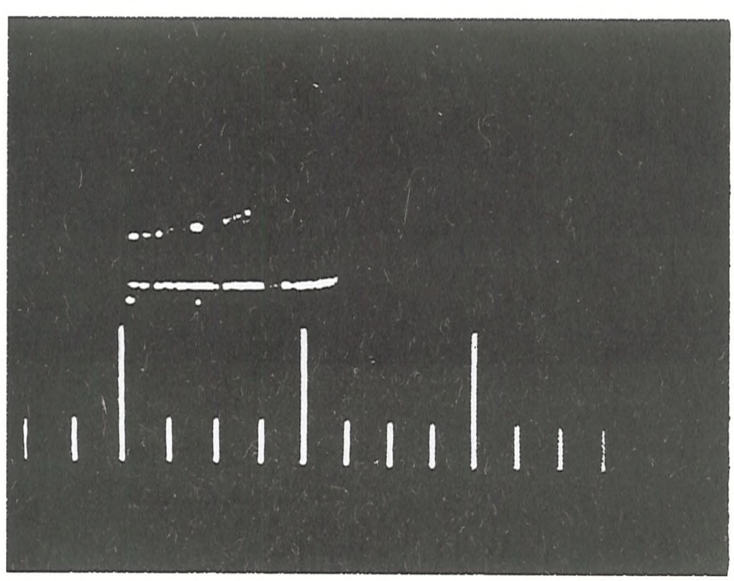


Figure 1.2

Ionogram for 2014 6 October 1971

Control settings to emphasize layer structure presentation.

modulator with pilot tones included in the baseband signal generated. Design of this modulator was the Author's initial assignment. Analysis of results from field trials testing the system was the second assignment and the outcome of both tasks is presented in Chapter 3 and Chapter 4.

The work of the Group began in late 1967 (1) and the first part of the research programme is covered in detail in references (1)(2)(5)(6)(7). Progress through this stage, and developments stemming from it, gave a more precise orientation of the work objectives and brought about the transition from preparatory study of ionospheric sounding techniques to concentration upon the needs for channel interrogation. Discussion of ionospheric sounding (1)(2)(7) was a requisite feature of the early programme as the vehicle of 'sounding' is inherent in channel investigation by pilot tone phase analysis. However, previous paragraphs have now drawn a distinction between true ionospheric sounding and the Group viewpoint, focussed on the transmission of pilot tones as a means of providing for rapid and accurate channel estimation by HF communications users through a method of processing the phase perturbations of low power pilot tones on assigned frequencies. In a manner explained in Chapters 2 and 3 these phase variations are interpreted as error rates which will indicate the real-time quality of a channel. Simultaneously additional pilot tones can keep the quality of standby channels under surveillance and complete the concept of frequency management by providing the operator with fast-access information for all the frequencies of the system's operational plan. Pilot tones monitoring the channel in use are normally transmitted alongside the main data.

Sufficient work has been done to foresee the implementation of a relatively cheap automated system of frequency management for HF systems, with an open loop arrangement that retains the human operator in a supervisory role. A completely automated system which would close the loop and exclude the human operator is a viable proposition, but this would greatly increase the cost of the system and the immediate aim is to achieve economic frequency management giving a significant performance improvement over the existing technique of frequency prediction for HF systems.

As the important item in the quality of an individual data channel involves the error rate relationship to signal-to-noise power ratio and interference level, the macroscopic nature of oblique-incidence pulse sounding does not measure up to the needs of channel interrogation for frequency management. Oblique-incidence pulse sounding was, however, used for a feasibility study on automatic frequency management (the 'CURTS' study; Reference (8)) and a brief reiteration of the outcome is very relevant at this point since it endorses the Group research policy in the method of channel interrogation. The following conclusions from the CURTS study make this clear:

(a) The number of communication circuits available increases with frequency management.

(b) Frequency management revealed the availability of a range of operating frequencies higher than those provided by frequency prediction methods.

(c) Outages due to interference were significantly more frequent (five times as many) than those due to propagation conditions.

The results have been summarised (Betts, (3), p. 110) by pointing out that the CURTS feasibility study proved conclusively that the problem on HF is one of interference and not of propagation and that the requirement is for a continuous estimate of signal to noise ratio where the noise includes interference. The implementation of this concept is referred to later, but before leaving pulse sounding in the context of frequency management the objection to the high cost of the CURTS system must be recorded.

Another category of channel estimation arises from analysis of normal traffic or transmission of special test sequences and is covered by two possible methods.

(a) error rate check of a known data sequence.

(b) a measure of the rate of cycling of an ARQ system.

This category classifies into the microscopic process of examining a single channel and the probable order of preference for the two methods would place cycling of an ARQ system first, use of a known data sequence second. The relative merits of the two methods are well known and comparison with the next category of channel estimation outlined below will suffice to emphasize its advantages compared with these methods.

This thesis presents real-time channel estimation using the phase perturbation characteristic of the pilot tones (6). An indication of the method was given on page 3 and is covered in detail elsewhere (4)(6) and (7), all that remains for these comments is to repeat its advantages as follows:-

(a) employment of low power pilot tones in a method having diagnostic capability.

(b) simultaneous estimation of the data channel in use and the suitable standby channels.

(c) the availability of low-cost, modular 'add-on' units which can easily convert existing standard HF equipments to control by frequency management.

Examination of the state of a single channel(s) with simple modulation techniques provides microscopic information enabling the benefits of frequency management to be realised giving a significant improvement in performance over systems controlled by frequency prediction. By contrast with the macroscopic process of pulse sounding used in the CURTS study it also offers an enormous economic advantage.

The research has thus taken a path through the work described in (1) (7) to emerge with a particular version of real-time channel estimation as a means of frequency management (4). It is the Group's interpretation of this latter objective that must now be stated more directly. The frequency management envisaged will come out of a practical system capable of repeated accurate assessment of the quality of a channel, and which uses a sampling period optimum for the decision making involved in selecting operating frequencies for HF communications. The analysis of Chapter 4 deals with this basic question - What period is required for an accurate estimation of channel quality? Previous work indicated a sampling period in the range of 200 to 1000 seconds so the analysis offered included summation of the FSK bit errors and the pilot tone phase errors over periods of 200, 300, 500 and 1000 seconds for reasons explained in Chapter 4. If the results of the analysis are significant for a practical system, then the decisions as to which frequency to use and time to change frequency will be based on measurement of a maximum allowable error rate for the current data transmission Earlier research and field trials have shown the feasibility of establishing such a criterion and the decision making process will be a function of the effects of noise and interference on the channel being estimated.

Hence the interpretation of 'frequency management' takes account of:-

(a) the real-time state of usable frequencies in the HF band

(b) the most significant cause of channel degradation in the HF band - interference.

(c) a method which indicates advantageous change of working frequency with earlier warning of the need to change than could be applied by a human operator.

Eventually the project will relieve the operator of decisions on when to change frequency and develop towards adaptive techniques by means of variation of information rate (e.g. from low speed parallel operation to 2.4 k bits/s in series operation) or change of modulation to suit prevailing propagation conditions. However, adaptive control as exemplified by adaptive reception techniques previously established, is not the concern of the present investigation because such systems fail to be realistic as cost-effective equipments, especially when their operational dependence on frequency prediction is taken into consideration.

It is apposite to note at this point that so far in the development of HF communications efforts to improve system efficiency have concentrated upon coding techniques. Relevant publications on the various methods have been widely referenced, but of such methods it is possible to list the ARQ system (9) as the leading method of practical significance. This technique, however, operates at high power and, of course, is subject to the limitations of frequency prediction in its operational management. By comparison, the present approach is exploring new methods of improving HF communications systems performance.

All the preliminary theoretical analyses of the signal processing requirements for the system to yield frequency management information were carried out by Betts (1) (6) (7) and Ellington (1) (2) (6). This was followed by development of a laboratory simulation of the initial concept of the system (1) (7)to evaluate the method with a closed loop. In this simulation,transmission path of the practical case was replaced by an Ionospheric Simulator (10) which subjected the baseband input signals to the various degrees and types of fading and noise of the kind encountered in practical transmissions. Results obtained from these closed loop tests gave encouraging correspondence between the results of the theoretical treatment and the behaviour of the practical system model, enabling proposals for field trials to be formulated (7).

The first of these field trials met with mixed success, largely due to over ambitious intentions to examine the effects of a number of modulation methods simultaneously. For this field trial which used a United Kingdom/Gibraltar link only 4 pilot tones were used alongside a single data channel of wideband FSK forming one composite SSB signal. Results from this field trial, discussed and analysed in Chapter 4, will be found to extend the principle, already outlined, of using the phase perturbation characteristics of pilot tones for channel estimation, to the use of a relationship between these phase perturbations and the error rate of the data signal transmitted. Chapter 2 explains this elaboration and the way that a linear relationship between the FSK/pilot tone errors is used as a measure of channel estimation. It will be shown that the results given in Chapter 4 confirm this error rate relationship as being more closely linear, irrespective of time of day or frequency, than would have been expected from a theoretical standpoint. However, these results refer to a 4 day period in mid-winter and further trials are required to verify the existence, or otherwise, of a general condition. Data transmitted during the trial was received in Gibraltar and recorded on magnetic tape for the convenience of off-line processing.

The modulator unit whose development is described in Chapter 3 is the fourth generation of such units, a sequence which began with two designs for multiple modulation facilities and ISB/SSB operation. Information on the previous types of modulator unit used in the Group project is contained in reference (4) which also explains (p.1) the various research requirements which have dictated the modulator specifications. Chapter 3 is concerned with a comparatively simple specification detailed on page 31.

Updating of the pilot tone phase analyser/demodulation unit (see also (4)) has been carried out by Betts. A description of the version used to analyse the tapes obtained from the United Kingdom/Gibraltar field trial is available in (4), but as WBFSK was the only type of data signal analysed from this trial all significant information on this unit is now contained in Chapters 2 and 3.

2. AN OUTLINE OF THE SYSTEM

Research into methods of achieving optimum channel selection for data transmission over HF communication systems has been extensive. Considerable literature exists and the most relevant publications have been included in the Reference lists of (1)(6)(7)(11)(12). The work has assessed the effects of propagation, noise and interference on different types of transmission, covered the measurement of channel parameters and error rates and produced a number of systems which alleviate the effects of propagation and interference on digital transmissions by using coding and sounding-assisted techniques. The system of interest here, as described in the introduction, has developed along a new path and aims to select high quality channels by the microscopic examination of the one in use and of standby channels. A brief explanation of how the system works is therefore required to serve as a preamble for the following chapters.

Assessment of the prevailing propagation, noise and interference conditions is inherent in the system technique of measuring error rates of pilot tones and data channels suitably associated within the baseband signal. Subject to the choice of system parameters, as discussed later, validation of the system is being carried out by relating these two error rate measurements in a manner to be described and using the relationship as the basis of the decision making process for frequency management. Before proceeding with further detail of the system an explanation of the meaning of 'error rates of pilot tones and data channels' is necessary.

2.1 Pilot Tone Errors

For the pilot tones, the 'Introduction' mentioned concentration upon their phase perturbation characteristic as a main aspect of this channel estimation method, and it is the phase perturbations of the received pilot tones that are interpreted directly as 'errors'. Hence, in the system, an error for a pilot tone refers to the phase shift occuring between the incoming pilot tone and a locally generated reference. To establish the presence or otherwise of pilot tone errors continuous sampling of this phase differential is maintained. In operation the time difference between the zero crossing of a received pilot tone and a locally generated reference marker is stored as a digital count to give a measure of the instantaneous phase difference θ with respect to the reference marker. This measurement of instantaneous phase is repeated at intervals of τ seconds, designated the sampling interval for pilot tone analysis, each count being subtracted from the previous count to indicate the phase change θ_{τ} between measurement times. If θ_{τ} exceeds a preset threshold value θ_{Th}, digital phase change counters pass an 'error' pulse to a visual display and a printer.

For the work in question τ may be 10 or 20 ms and logic circuitry has been provided to examine threshold values of $\theta_{Th} = {}^{\pi}/2$, ${}^{\pi}/4$ and ${}^{\pi}/8$.

Immediately before the measurement of instantaneous phase the pilot tones are separated from the information signals by narrow bandwidth (10 Hz) band-pass filters whose shape factor is another parameter of the system. The effect of changing the system parameters τ , θ_{Th} and the shape factor is included in the subsequent discussion on the shape of the curves yielded by the theoretical study of this method of channel estimation.

2.2 FSK Errors

This is the straightforward process of detecting reception of a false signal element, and in this system it is achieved as follows. Measurement of digital error rate requires a test signal which resembles the kind of digital signal that a system handles in normal usage, hence, for the field trials, the FSK data channel was keyed by a pseudo-random pulse generator since its random pattern of '1's' and '0's' meets this requirement by

(a) closely approximating the need for equal probabilities of 1 and 0 occuring, and

(b) the sequences also have long runs of 1's and 0's.

The circuit arrangement used provided a maximal length pseudo-random pulse train output before repetition of the pattern which, in this case, contained 255 bits.

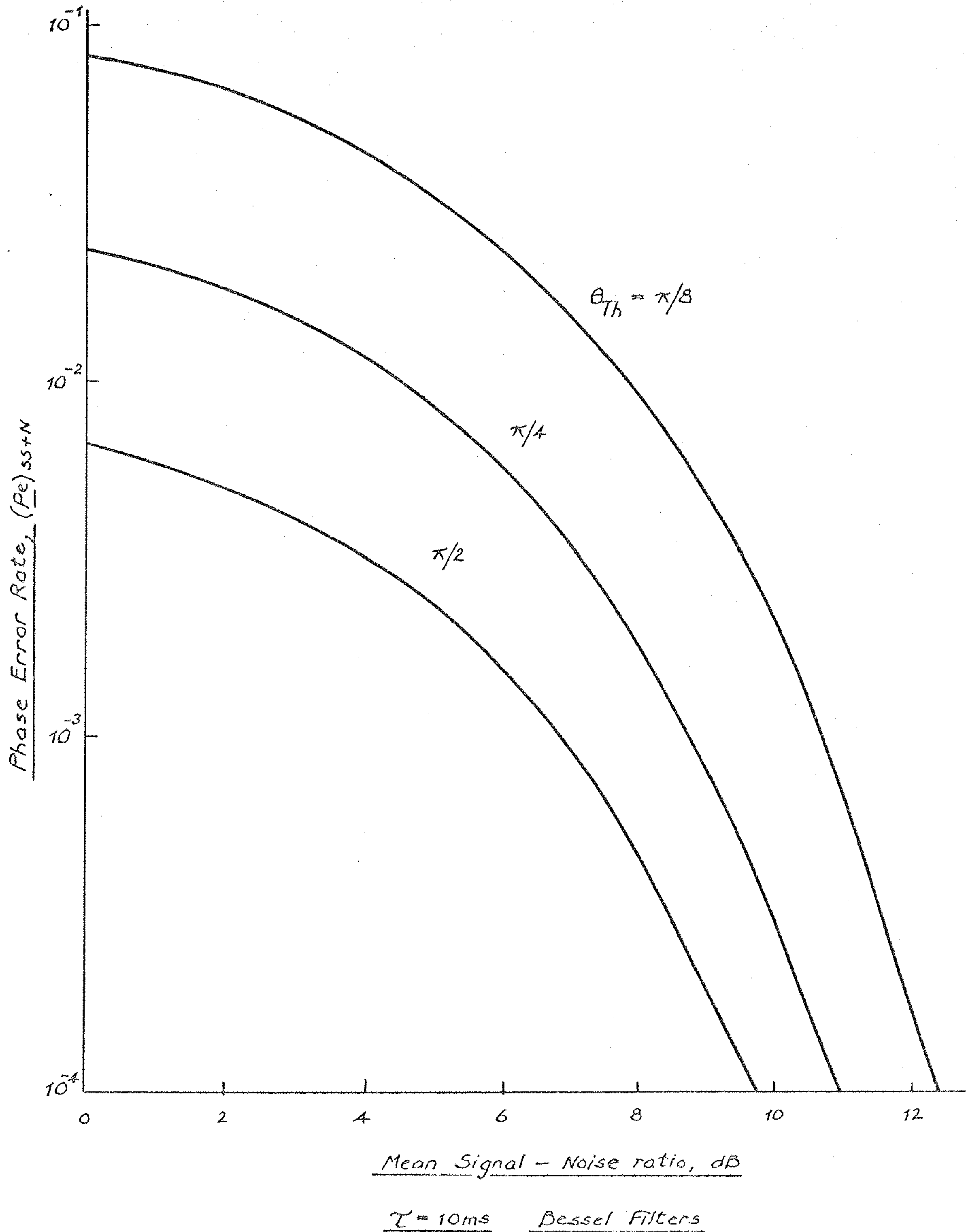
The laboratory demodulator/pilot tone analyser which simulates the final reception techniques of a future practical system, uses a pseudo-random pulse generator of identical characteristics to establish data synchronisation and effect error detection. This latter function is carried out by an 'error comparator' arrangement which, using digital circuitry, feeds the demodulated WBFSK data and the pseudo-random pulse generator output to an exclusive -OR gate. With effective data synchronisation, this gate will give an output only when the pseudo-random pulse generator signal is different from that of the incoming data signal. Thus the exclusive-OR gate functions as an error detector. The output of error pulses is processed to the visual display and the printer facility.

2.3 A Precis of System Operation

Having described the system interpretation of an error in the transmissions and how such errors are measured it will be appropriate to present an introductory explanation of how the system works.

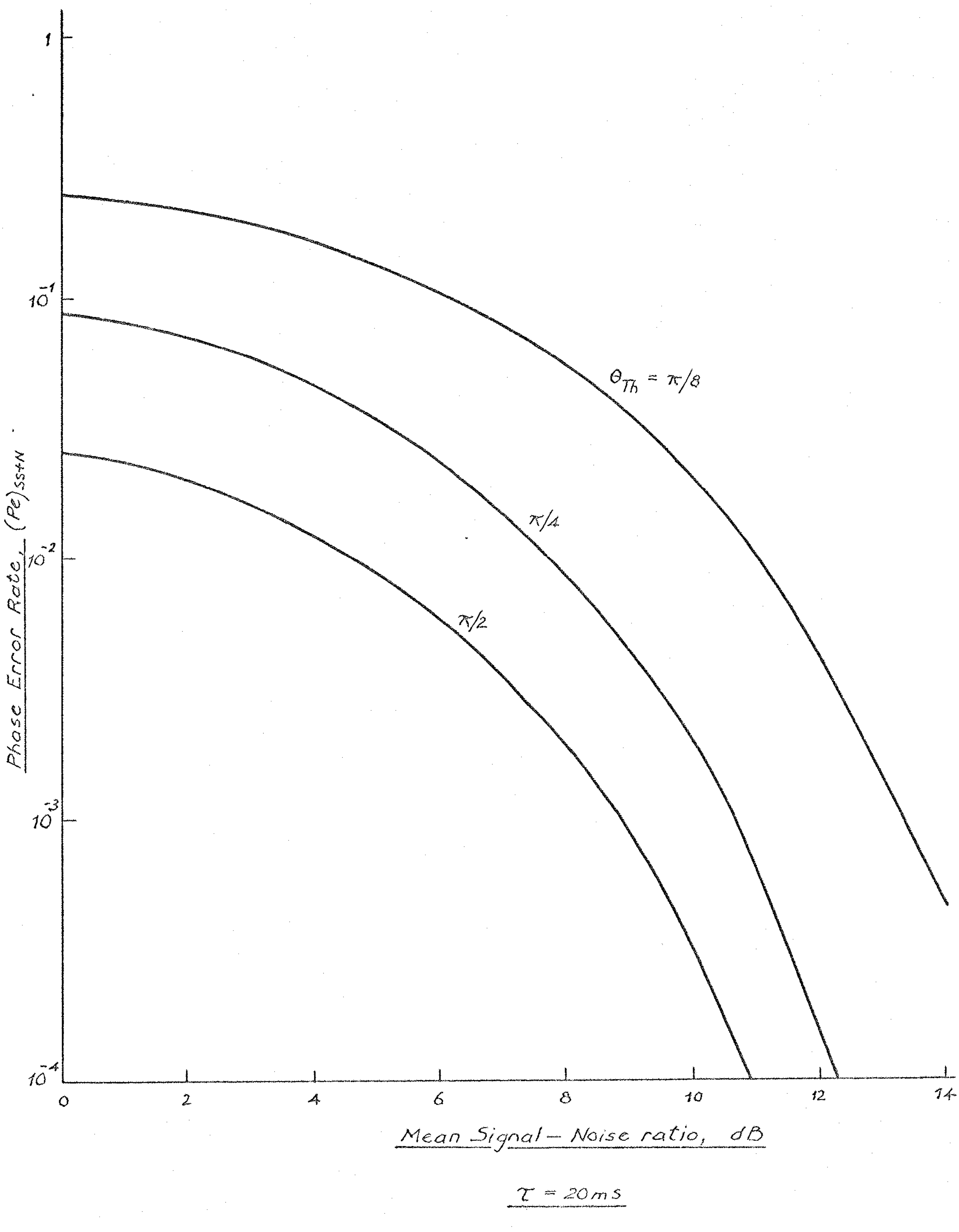
2.3.1 Preamble on the Theoretical Investigation

The theory developed by Ellington (1, Appendix 7) applied to the deduction of error rates in a TDPSK system under various transmission conditions. Results computed from this theory were presented graphically (7) and compared with practical results taken using the laboratory simulation of the system (1). Continued development of the work by Betts extended the analysis and provided theoretical error rate curves for the pilot tone phase perturbations against mean signal-to-noise ratio under steady-signal conditions and flat fading with Rayleigh distribution (4). The parameters for these curves are τ = 10 and 20 ms $\theta_{Th} = \pi/8$, $\pi/4$ and $\pi/2$. (Figures 2.3.1-1 to 2.3.1-4).



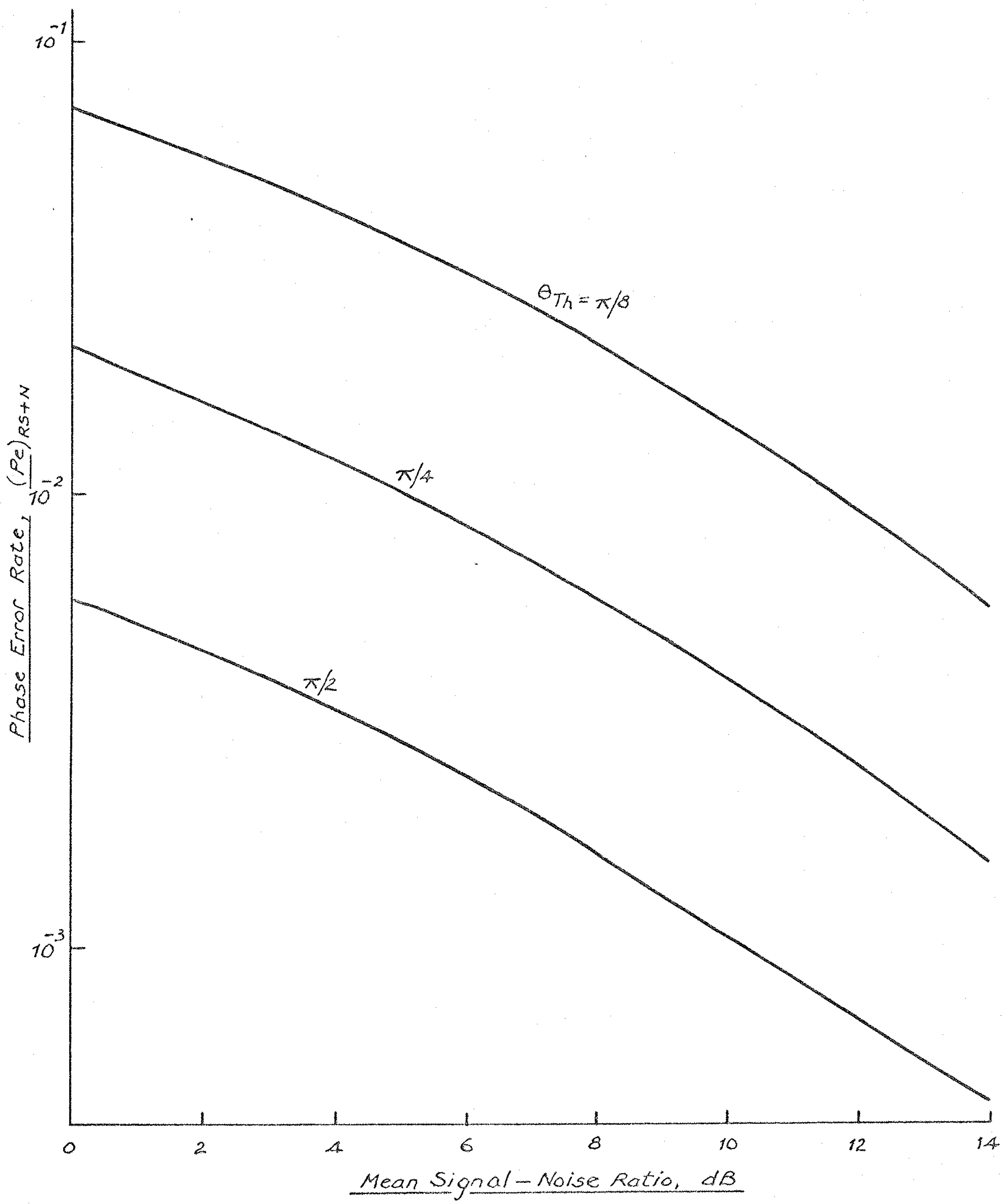
THEORETICAL ERROR-RATE CURVES FOR THE PILOT TONE PHASE PERTURBATIONS — STEADY SIGNAL CONDITION

FIG 2.3.1–1



THEORETICAL ERROR-RATE CURVES FOR THE PILOT TONE PHASE PERTURBATIONS — STEADY SIGNAL CONDITION

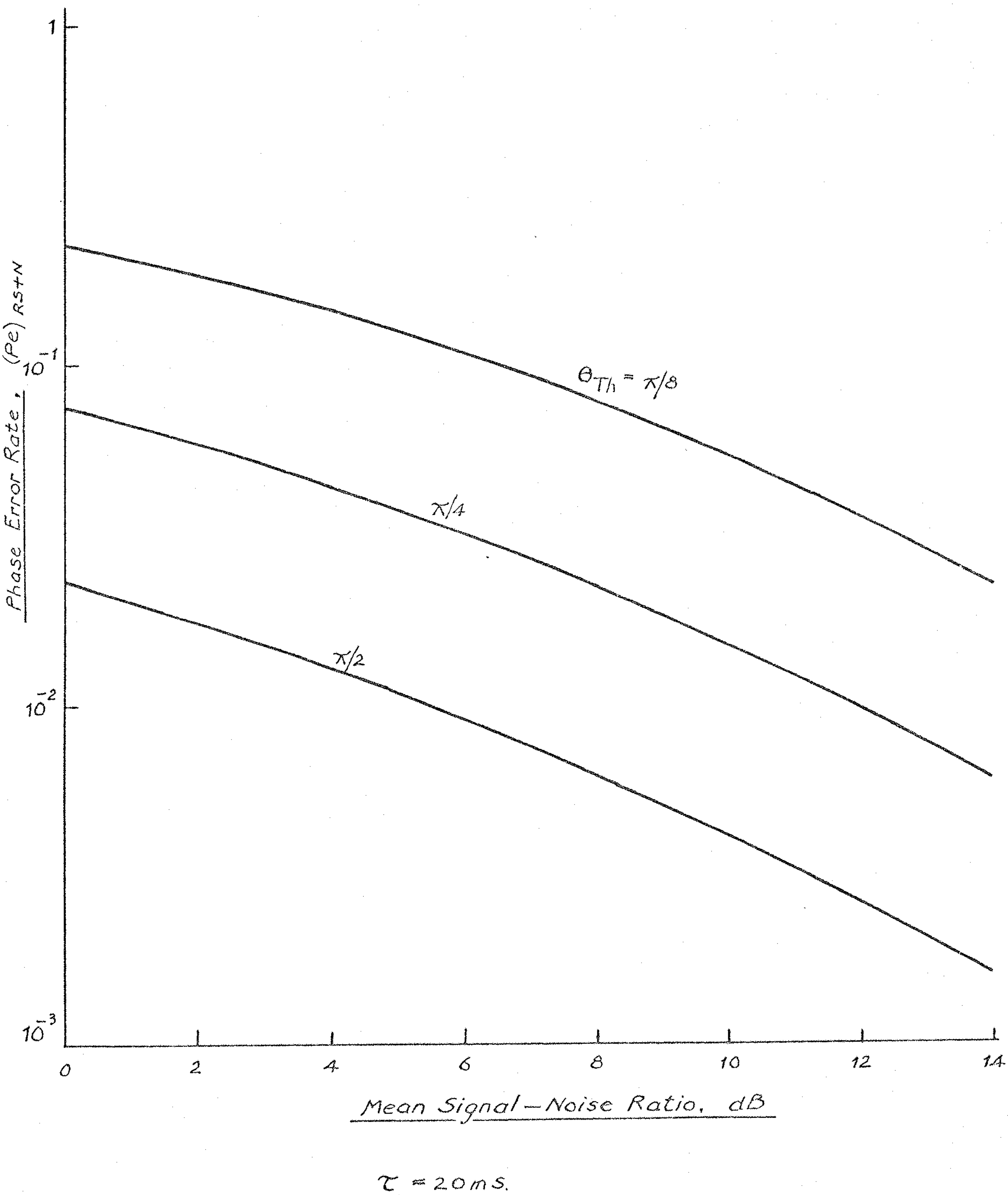
FIG 2.3.1—2



τ = 10 ms. Bessel Filters

THEORETICAL ERROR-RATE CURVES FOR THE PILOT TONE PHASE PERTURBATIONS — RAYLEIGH FLAT FADING

FIG 2.3.1 – 3



THEORETICAL ERROR–RATE CURVES FOR THE PILOT TONE PHASE PERTURBATIONS – RAYLEIGH FLAT FADING

FIG 2.3.1–4

The basis of the present work, however, rests upon the relationship between pilot tone phase error rates and data channel error rates, where, in this exercise, 'data channel' refers only to wide band, discontinuous phase FSK. Curves for the error rate performance of FSK are shown in Figures 2.3.1-5 and 2.3.1-6. Ellington demonstrated that the relationship between these two classes of error rate can be obtained via the ratio of their associated signal-to-noise ratios (2, Appendix 9.2). Graphical versions of this relationship are produced from combinations of the two separate families of error rate against signal-to-noise ratio curves; pilot tone curves are available from the theoretical investigation and the FSK error rate curves are available from various authors in standard texts (13) (14). An outline of this combination process is given below and the curves relating to the field trial computed for steady signal conditions and Rayleigh flat fading are shown in Figure 2.3.1-7.

Demodulation of the FSK data in the laboratory unit uses the filter-assessor method and the well established error rates for this method (13) are given by

$$P_e\Big|_{\text{steady signal}} = \frac{1}{2}\exp\left[-\frac{1}{2}\frac{S}{N}\right]$$

and

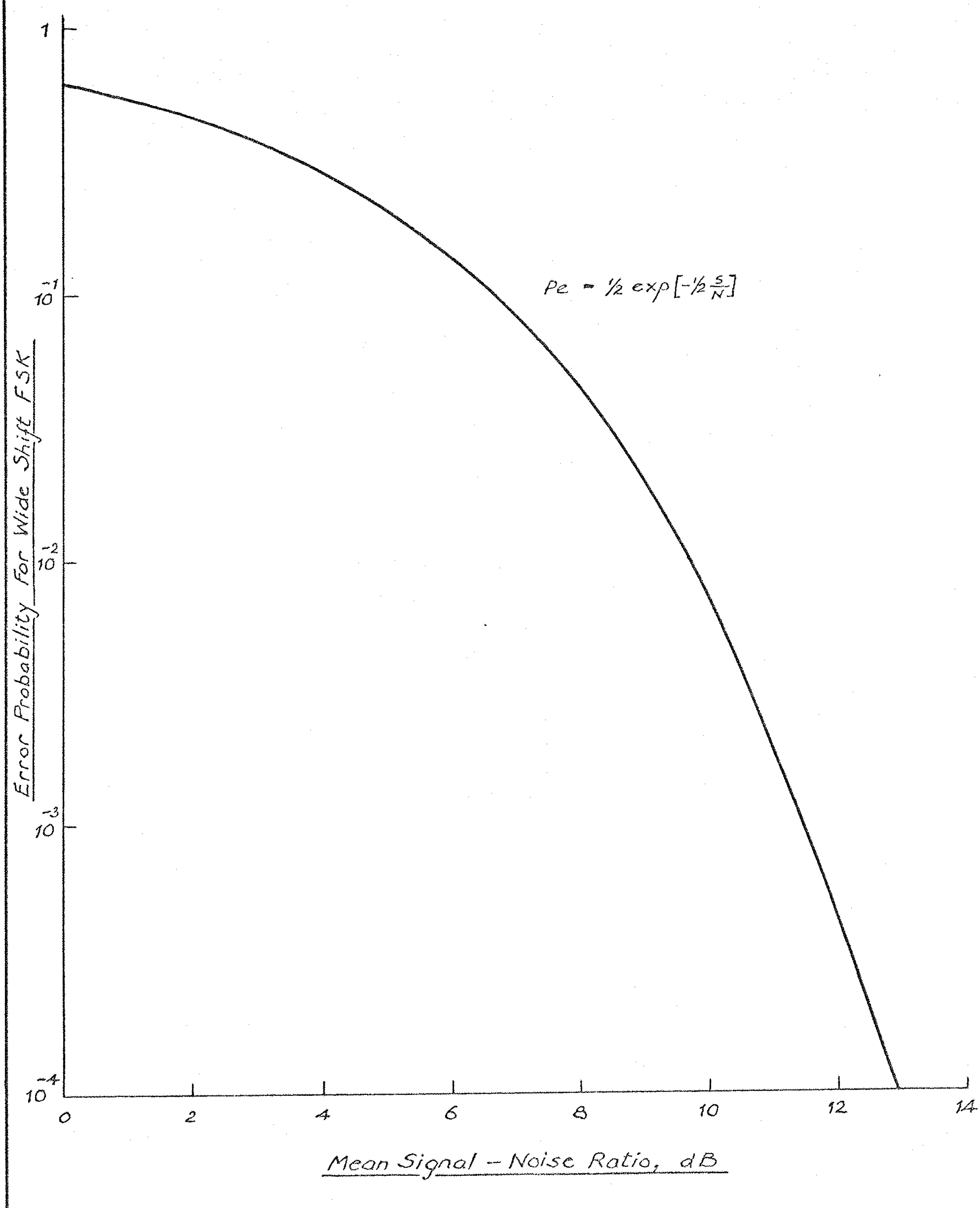
$$P_e\Big|_{\text{flat fading}} = \frac{1}{2+\left(\frac{S}{N}\right)}$$

These error rate/SNR relationships are shown in Figures 2.3.1-5 and 2.3.1-6.

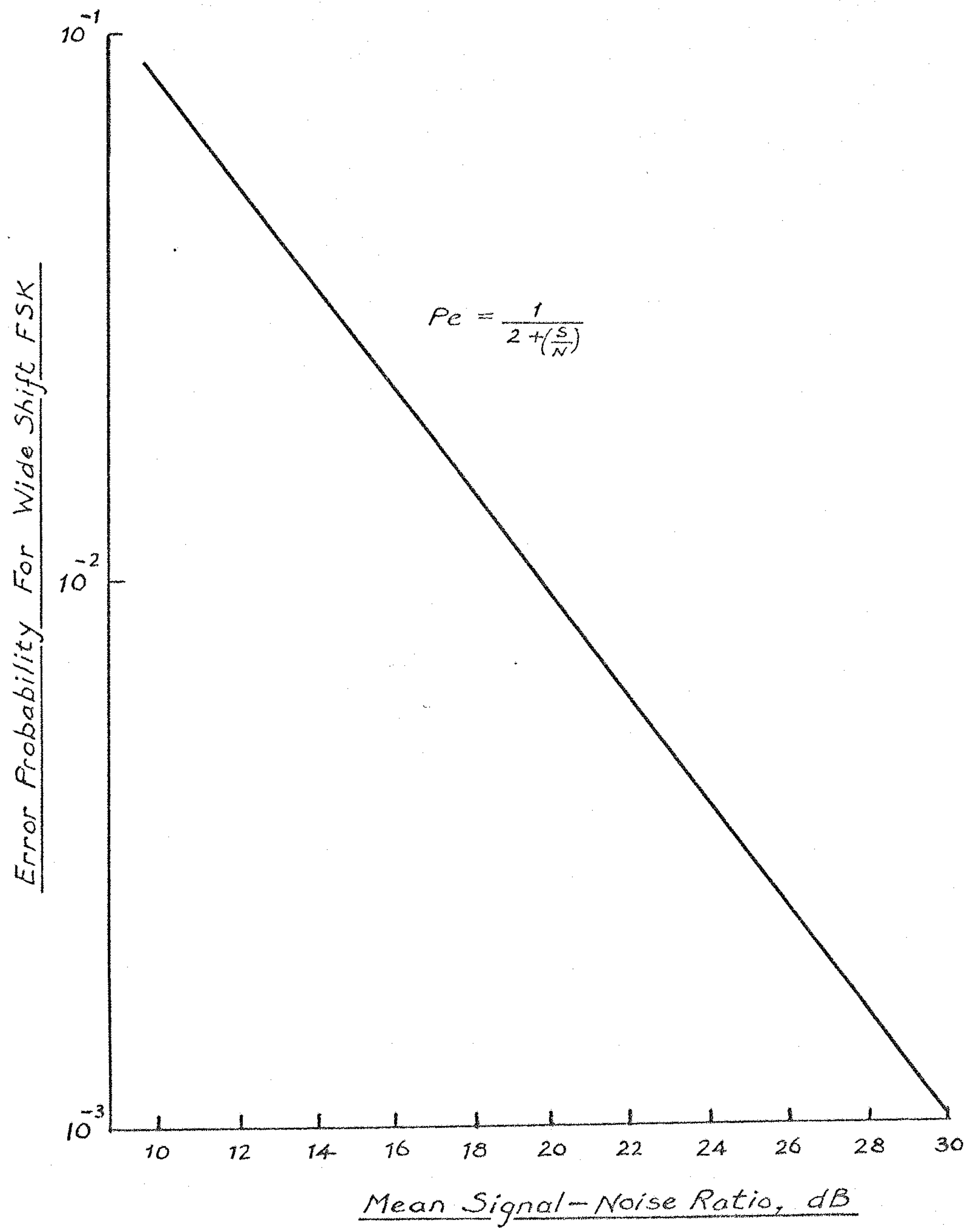
It has been shown (2) that the relationship between the error rates for the FSK data channel and the pilot tone phase error rate will be dependent upon the following parameters

$S_{FSK} : S_{\text{pilot tone}}$ - the power ratio

$N_{FSK} : N_{\text{pilot tone}}$ - the noise power ratio which is equivalent to the ratio of the equivalent noise bandwidths associated with the two signals.

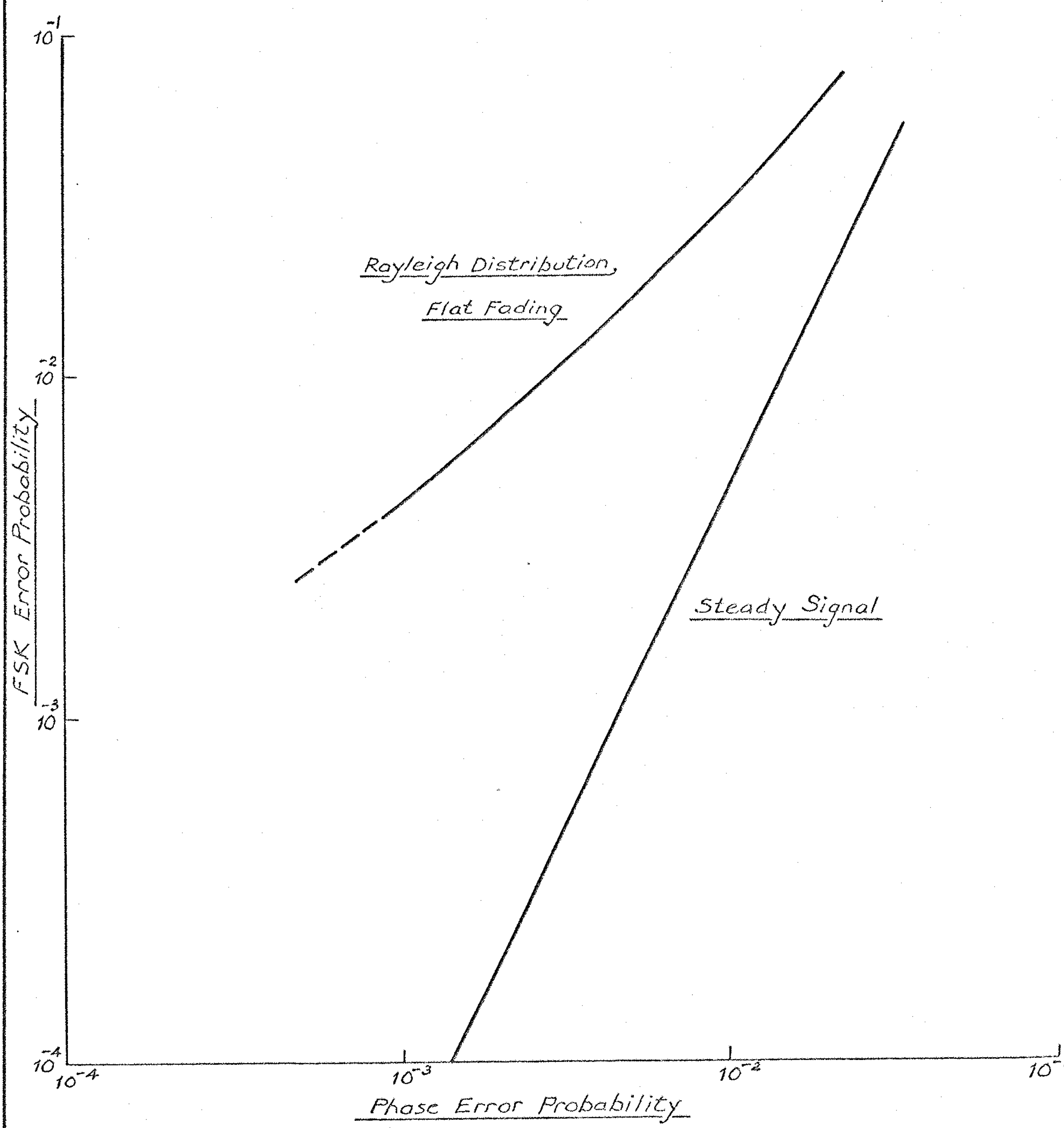


ERROR–RATE PERFORMANCE FOR FSK, STEADY SIGNAL | FIG 2.3.1–5



ERROR-RATE PERFORMANCE FOR FSK
— RAYLEIGH FLAT FADING

FIG 2.3.1-6



THEORETICAL ERROR-RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE PILOT TONE

FIG 2.3.1 — 7

Hence knowing the relationship between the two signal-to-noise ratios it is possible by a mapping of the error rates to establish the relationship between them. The ideal error rate relationship is displayed as a single line at 45^{o} representing a 1 : 1 correspondence of error rate to error rate for a given signal-to-noise ratio. However, whereas the aim is to obtain this ideal relationship at 45^{o}, all of the system parameters influence the positions and slopes of the curves (see Figure 2.3.1-7 for steady signal and Rayleigh conditions cases) and the proper choice for θ_{Th} and τ is therefore critical. Ideally these two parameters should be chosen such that the error rate/SNR curves for the FSK data and the phase of the pilot tone are of identical shape and correspond exactly; e.g. an error probability of 10^{-3} for the FSK channel corresponds to a 10^{-3} figure for the pilot tone phase. While this can be achieved reasonably well for a given propagation condition, say steady signal, it cannot be obtained, given a fixed set of the parameters mentioned above, for all propagation conditions likely to be encountered.

A discussion on choice of system parameters and their optimisation is given in Chapter 4. For the field trials to date optimisation of the parameters has been based upon a compromise between best fits for steady signal and flat fading Rayleigh conditions. The field trial results were obtained and the subsequent analysis carried out with the following parameters

$$S_{FSK} : S_{pilot\ tone} = 16\ \text{dB}$$

$$B_{FSK} : B_{pilot\ tone} = 220 : 10\ (13.5\ \text{dB})$$

(the ratio of equivalent noise bandwidths)

$$\left.\frac{S}{N}\right|_{pilot\ tone} = \left.\frac{S}{N}\right|_{FSK} - 2.5\ \text{dB}$$

(the value -2.5dB has been optimised to Rayleigh rather than steady signal conditio[ns] and also contrasts with -8dB given in (6).)

The bandwidth of 220 Hz for the FSK data signal, bit rate 50 bits/second, is wider than would normally be employed but was dictated by the specification of the available data channel filters.

Figure 2.2.1-7 shows FSK/pilot tone error rate relationship for the values of parameters stated above and with $\theta_{Th} = {}^{\pi}/8$ and $\tau = 10$ ms. Data obtained from the field trial is displayed for analysis as plots on these error rate relationship graphs, each graph having the steady signal condition and Rayleigh flat fading curves as references (Chapter 4, Figures 4.1-1 to 4.1-12).

2.3.2 Equipment Precis

Development of equipment for field trials began after the laboratory simulation was completed (7) and progress through several specifications with changes in field trial proposals. Two main items of equipment were needed:

(a) a modulator generating a baseband signal appropriate for the investigation

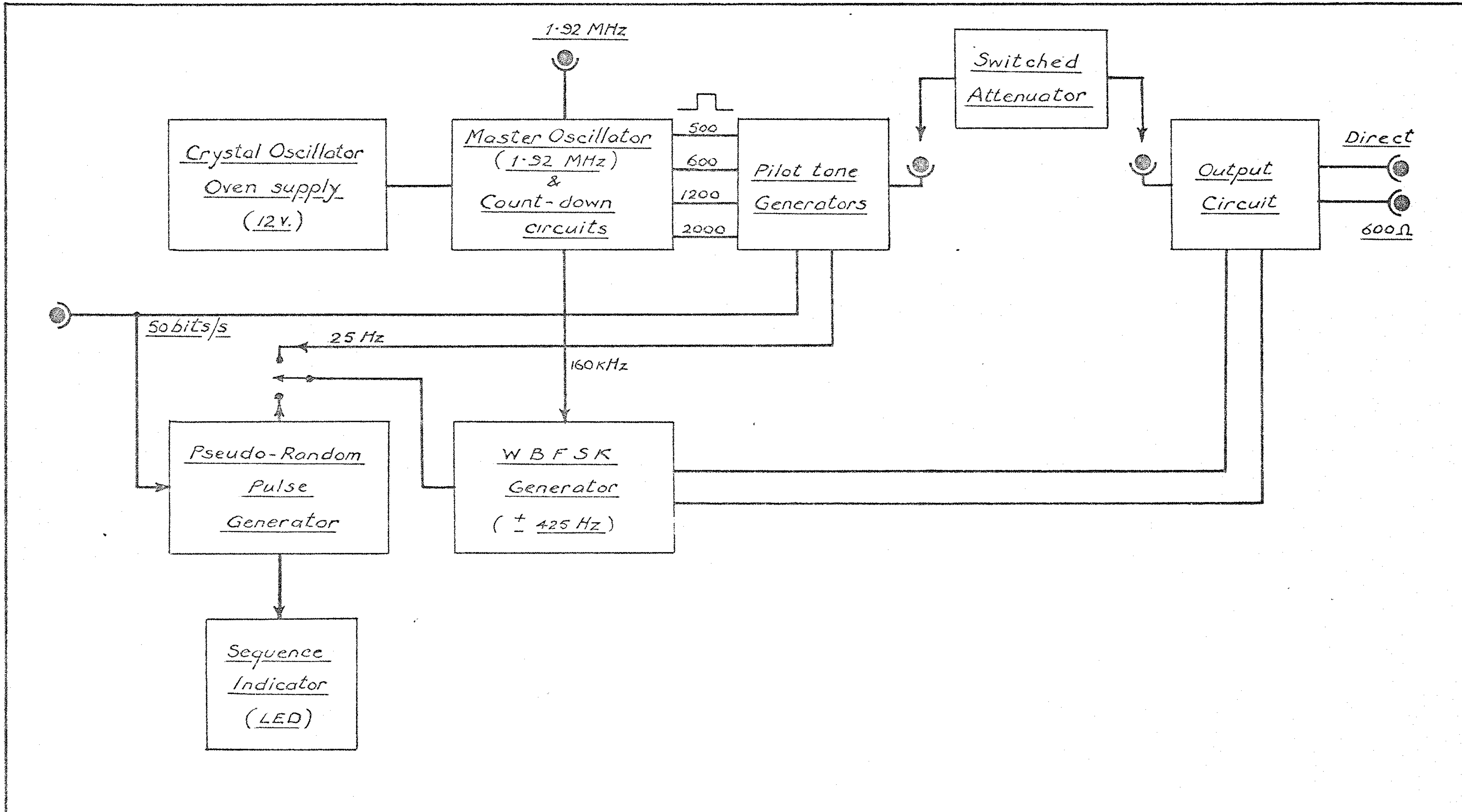
(b) a pilot tone phase analyser and data demodulator to process the information obtained from field trials.

The equipment designed for the initial field trials is described in (4). For the results analysed in Chapter 4 the modulator specification was altered to that given in Chapter 3, but the pilot tone phase analyser and data demodulator unit described in (7) was also subject to the modifications described in (4).

Detail on the equipment used for the United Kingdom/Gibraltar trial is provided in Chapter 3 and the following precis surveys its operation in outline as an introduction to Chapter 3.

2.3.2.1 The Modulator

A block diagram of the modulator is shown in Figure 2.3.2.1-1. Output from the modulator was connected to the low level modulation input



OUTLINE BLOCK DIAGRAM — MODULATOR

FIG 2.3.2.1-1

of a standard 1 kW HF transmitter and provided SSB drive for the simultaneous transmission of 4 pilot tones (500, 600, 1200 and 2000 Hz) and a wide band (± 425 Hz) FSK data signal. These modulation signals are derived from a master oscillator and a FSK generator respectively.

A master oscillator output at 1.92 MHz is applied to TTL digital circuitry to obtain a series of square wave trains by count-down. These square wave trains drive the pilot tone generators and supply the control signals for data signal generation.

An external switched attenuator was used with the modulator to adjust the power ratio of $S_{FSK}: S_{pilot\ tone}$.

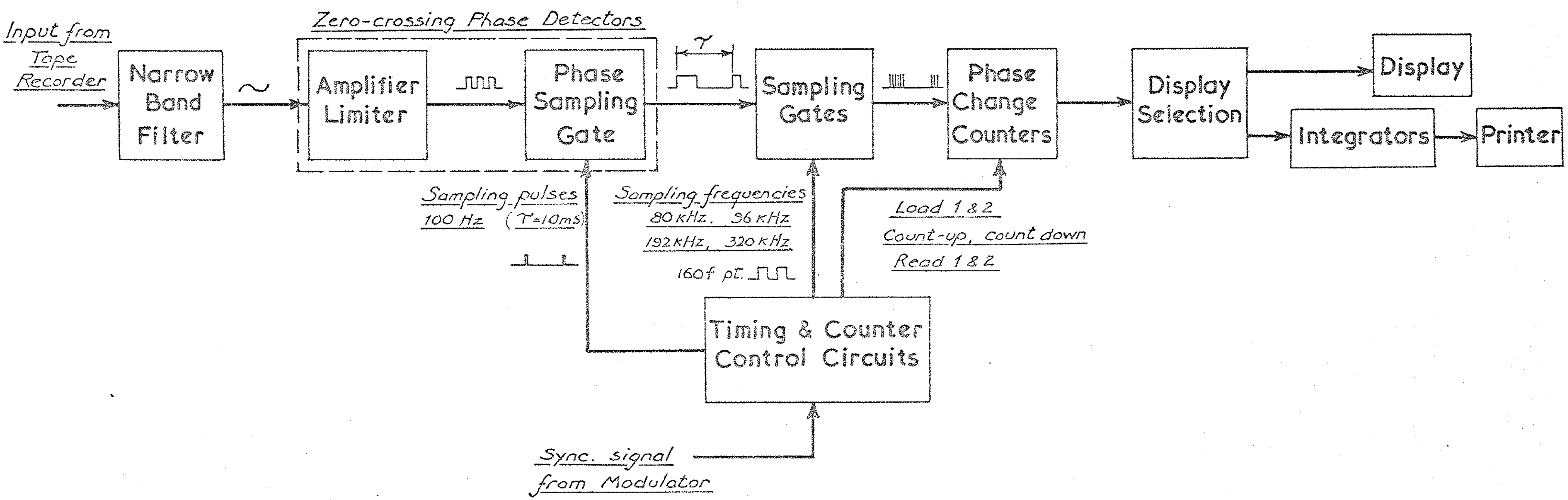
The sinusoidal outputs from the pilot tone generators are passed via the switched attenuator to the output circuit which functions as a mixer for the pilot tones and data signal, the combined baseband information being available at a 'Direct' (low impedance) and a '600 Ω' outlet.

Separate mark and space signals are generated at 800 Hz and 1650 Hz from a 160 kHz control signal. This FSK modulation is keyed by a pseudo-random pulse generator or a 25 Hz signal from the pilot tone generator module. The pseudo-random pulse generator itself is clocked at 50 bits/s, also derived from the pilot tone generator module.

2.3.2.2 The Pilot Tone Phase Analyser

A block diagram of the pilot tone phase analyser is shown in Figure 2.3.2.2.-1. Information recorded during the field trial is replayed and the tape recorder output is passed to the pilot tone and data signal sections of the laboratory analyser unit.

The pilot tones are separated from the data signals by means of narrow band filters (10 Hz bandwidth) fully described in (2)(7). A zero-crossing phase detector follows each filter and the sinusoidal inputs to the detectors are reshaped into square waves with the same zero-crossings as the sine waves. At sampling intervals τ seconds apart the width of a pulse is measured as the period between the instant of sampling and the next



OUTLINE BLOCK DIAGRAM - PILOT TONE PHASE ANALYSER

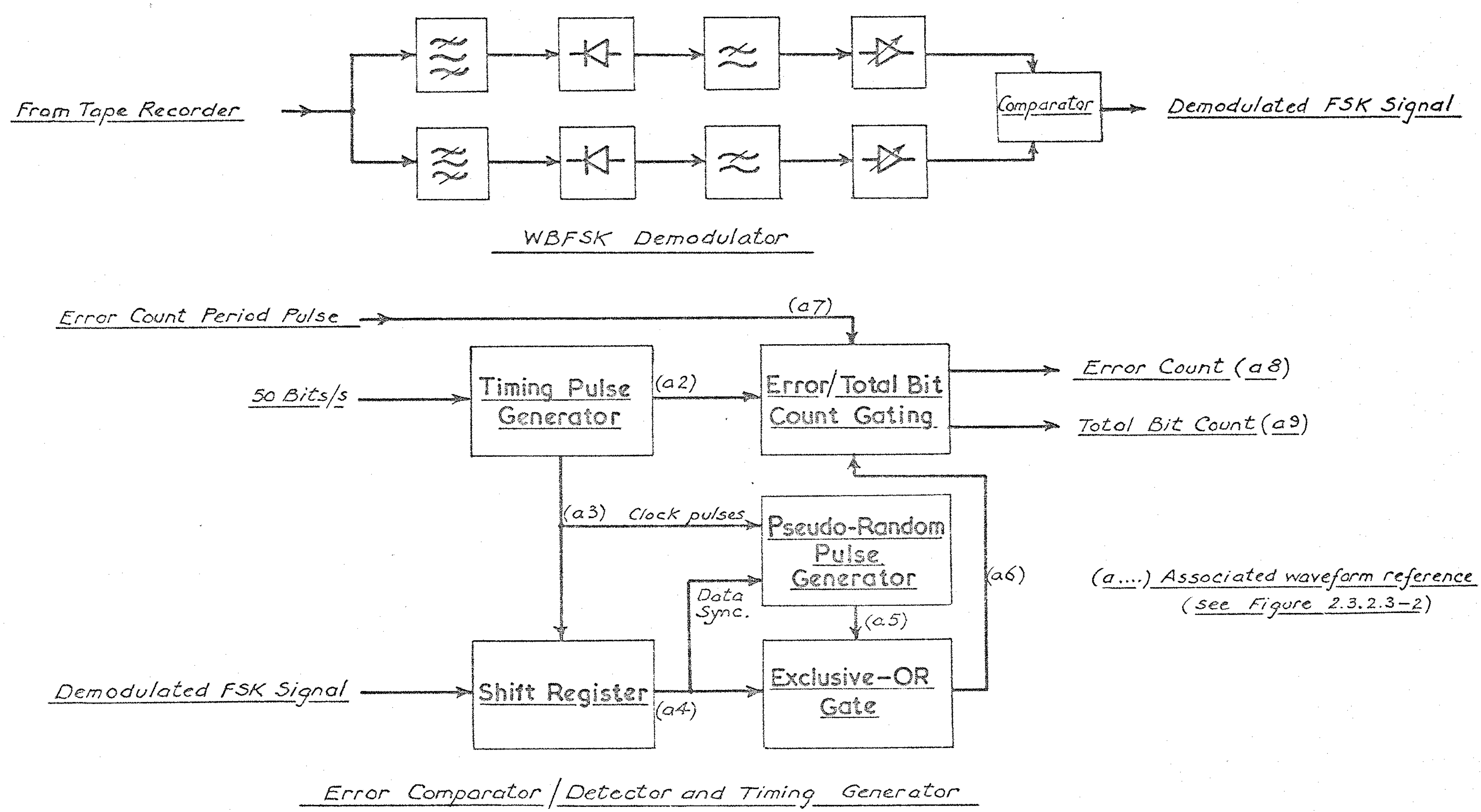
FIG 2.3.2.2-1

zero-crossing of the square wave pilot tone. As this square wave train will be modulated by any pilot tone phase shifts, and the sampling process is designed to interpret these shifts as a pulse width modulated pulse train with individual pulses, τ seconds apart, each individual output pulse from the zero-crossing phase detectors will have a duration proportional to the instantaneous phase θ of the pilot tone relative to the locally generated reference. This pulse train is then gated with a square wave of repetition frequency 160f, where f is the pilot tone frequency, to produce sampled groups of pulses with the number of pulses in any one group proportional to the current value of θ. The phase change θ_{τ} between measurement times is subsequently determined with a counting technique using bidirectional counters in an arrangement giving a count proportional to the change θ_{τ} occuring within each phase sampling interval τ. If, as previously explained in the outline of pilot tone phase measurement (p. 10), θ_{τ} exceeds the threshold value θ_{Th}, an 'error' pulse is transferred to the display unit which is a bank of BCD counters with Numicator-tube read-out showing the errors for each pilot tone for the chosen period of error count, for example, 200 seconds. Error pulses are also applied to a printer via integrators which are again BCD counters but making a count over much shorter periods. For the analysis presented in Chapter 4 information was printed out at 10 second intervals.

2.3.2.3 The Data Signal Analyser (Figure 2.3.2.3-1)

The data demodulator for WBFSK uses the filter-assessor method in which separate filters select the mark and space signals. Both signals are then envelope detected and passed to a variable gain amplifier via a low pass filter. These amplifiers are used to equalise the outputs from the mark and space signal paths before the comparator provides the demodulated FSK signals for error detection processing.

Following the explanation of what is meant by a data signal error on page 10 , the operation of the timing for error detection and gating is best



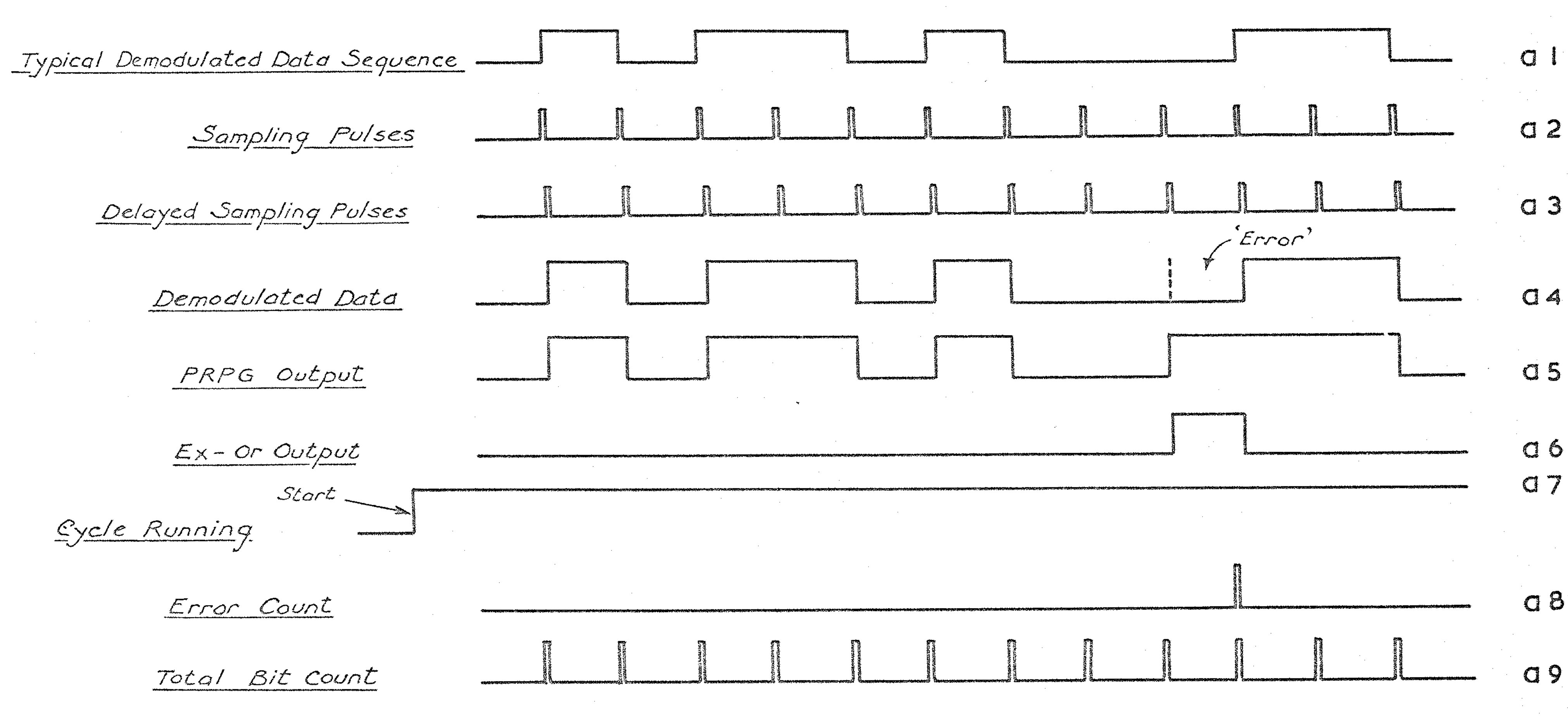
OUTLINE BLOCK DIAGRAM – THE DATA SIGNAL ANALYSER

FIG 2.3.2.3-1

described using the working waveforms (Figure 2.3.2.3-2).

Under the control of the timing pulse generator (a3) the demodulated FSK signal is clocked at bit rate through a shift register and applied as one of the inputs of an exclusive -OR gate (a4). The pseudo-random pulse generator output (a5) is the other input for the exclusive-OR gate. As waveform a3 also clocks the pseudo-random pulse generator, the outputs of the shift register and the pseudo-random pulse generator change at the same time, hence, as long as the waveform of the incoming demodulated data signal (a4) is the same as that of the pseudo-random pulse generator, output of the exclusive -OR gate is held at '0'. When there is an error in the demodulated signal the exclusive -OR gate outputs a '1' and in this way it functions as an error detector. All this assumes effective data synchronisation as the normal condition, obtained in this case by applying the shift register output (a4) to the pseudo-random pulse generator for sectioned insertion by manual push button until locked signals are realised.

An error count is obtained by feeding the exclusive-OR gate output (a6) to the error gating, which consists of a number of NAND gates. The required error count period (e.g. 200 seconds) is used as timing control for error gating by means of the pulse designated T_L (a7) which thus restricts error count to the desired length of data recording run. At the onset of pulse T_L the sampling pulse stream (a2) from the timing generator is gated to the display to give the total bit count (a9) and to a succeeding gate which also receives the error pulses from the exclusive-OR gate. In this way the output from the error detector is sampled at bit rate and passed out to the display for the data signal error count.



WAVE FORMS FOR WBFSK COMPARATOR

FIG 2.3.2.3-2

3. THE FIELD TRIALS EQUIPMENT

3.1 General

The specific circuit information given in this chapter provides the detail to supplement the system operation described in Chapter 2. Some preliminary general comment is appropriate to cover items not apposite for inclusion in circuit detail sections.

Although the modulator was the direct concern of the Author, the laboratory analyser represents the work of Ellington and Betts and circuit information on the latter is briefly repeated here only to complete the presentation.

Dealing first with the modulator, comments in Chapter 1 have referred to earlier, more sophisticated, modulator units than the one described in this chapter, but much of the design effort involved in these earlier developments has been utilised in producing this fourth generation unit hence the detail remains representative of the general engineering task to be met in providing production versions for use with existing HF communications equipment.

The precis of Section 2.3.2.1 and the block diagram of Figure 2.3.2.1-1 will have served to explain the overall operation of the modulator, while its specification given in Section 3.1.1 completes the introductory information. Subsequent sections cover the circuit details of each of the main assemblies making up the unit. These circuit details include examples of functions being achieved by straightforward interconnection of readily available sub-circuits, some instances of direct application of well known circuits with minor modifications and some arrangements developed to satisfy particular needs of the investigation. Collectively these procedures resulted in a prototype modulator unit which met the system performance requirements for the United Kingdom/Gibraltar field trial.

The 'main assemblies' referred to above are convenient sub-sections of the modulator produced on printed circuit boards each one closely corresponding to the block diagram sequence shown in Figure 2.3.2.1-1. A standard nineteen inch rack houses all the printed circuit boards and the modulator power supplies within one instrument case.

As one of the aims of this research is to provide equipment units representing a near-approach to pre-production models, the production engineering aspect received careful attention during the development of all the modulators. In terms of hardware this fourth generation unit benefited from earlier work on assembly, racking and casing requirements, but was not remodelled into the more compact form made feasible by its reduced performance demands. This modification, which awaits further field trials in the present series, will take critical account of printed circuit board stacking potential alongside other possible size reduction features in the unit. At the same time an extensive reconsideration of environmental conditions, reliability, ease of installation and operation will be required.

For a number of continuous running periods of about one week duration, both in the laboratory and on field trial sites, the unit has proved to be reliable for purposes of this research. It has also proved to be durable in transit, and thus gives some measure of confidence for the development of a more fully engineered version including an appropriate reliability study.

The laboratory analyser, like the modulators, developed from the equipment used for the laboratory simulation (7) and most of the circuit detail of the unit used to analyse results from the United Kingdom/Gibraltar field trial has already been published. However, for the purpose of enlarging upon the description of laboratory analyser operation given in Sections 2.3.2.2 and 2.3.2.3, supported by the block diagrams of Figure 2.3.2.2-1 and 2.3.2.3-1, and to provide the technical background for the results discussed in Chapter 4, edited circuit notes have been included at the end of this chapter. Updating modifications to the laboratory analyser were carried out by Betts prior to the United Kingdom/Gibraltar field trial and these are explained in ((4) Appendices 1 and 2). All other relevant references are contained in the circuit notes mentioned above.

3.1.1 Specification of the Modulator

Function

Generate:

(a) four pilot tones for channel estimation by phase perturbation measurement

(b) one wideband FSK data signal for the information stream establishing channel quality in terms of error rate

Baseband Signals

(a) Pilot tones at 500, 600, 1200 and 2000 Hz

(b) WBFSK, ± 425 Hz, mark and space signals at 800 and 1650 Hz

Sideband Distribution

All modulation signals lie within a nominal 3 kHz baseband for location on either USB or LSB of a standard SSB transmitter.

Main Circuit Modules

(a) Crystal-controlled oscillator at 1.92 kHz

(b) Count-down chain from (a) above using standard TTL logic and providing:

(i) generation of four pilot tone pulse trains

(ii) clock pulses at 50 bits/s for the keying signal generator

(iii) a 25 Hz pulse train as a direct keying signal

(iv) a 160 kHz pulse train for count-down to drive the FSK mark and space signal generators at 800 and 1650 Hz.

(v) pulse trains at 80, 96, 192 and 320 kHz for pilot tone phase analyser control signals.

(c) Sinusoidal pilot tone generators

(d) Pseudo-random pulse generator for a keying signal

(e) WBFSK mark and space signal generator

(f) Output mixing/matching circuits

Nominal Load

1 mW into 600 ohms (for 1 kW p.e.p)

Power Supplies

Modular Units by Coutant Electronics:

(a) 1 x GP200/2 providing +5V logic supplies (2A maximum) with external over-voltage protection units

(b) 1 x OA3 providing ± 15V supplies (250mA each rail) with internal overload protection.

Assembly

Printed circuit boards and power supply units mounted in a Vero Card Frame System, the frame contained a Vero D Series Case.

Dimensions

Instrument Case, outside dimensions $19^1/2"$ x 6" x $12^1/2"$.

3.1.2 Specification of the Laboratory Analyser

Function

To facilitate the analysis of signals received over the field trials link and recorded on analogue tape.

Main Circuit Modules

(a) Narrow band filters (10 Hz wide) to select pilot tones from data signals. These filters are separately cased from the main analyser rack in order to apply close temperature control at 40° C.

(b) Pilot tone phase analyser to determine pilot tone phase 'errors' via a pulse technique in which a sampled pulse count indicates phase shifts significant to channel quality estimation as a display on numicator tubes.

(c) Demodulator for wide band FSK data signal.

(d) Pseudo-random pulse generator providing local generation of the random sequence which keys the data signal, for purposes of error detection by comparison with the received keyed signal.

(e) Display system for printer for:

pilot tone phase errors

data signal errors

total bit count

Power Supplies

(a) 1 x 67-10L providing +5V logic supplies (5A maximum) by Roband

(b) 2 x Farnell ± 15V (500 mA maximum)

Assembly

Two separate units are involved:-

(a) Demodulation Unit

3 x 19" racks stacked in a main frame and instrument case incorporating Vero Card Frame System

(b) The Narrow Band Filters

These exist as a separate unit assembled in a Vero Card Frame System 3c and contained in a Vero D Series Case.

Dimensions

Outside dimensions, Demodulation Unit (main rack)

$19^1/2$" x 17" x $14^1/2$"

Outside dimensions, Narrow Band Filters

$19^1/2$" x 6" x $12^1/2$"

3.2 The Modulator

3.2.1 Master Oscillator and Count-Down Chain (Figure 3.2.1-1)

The four pilot tones and various control signals are derived from a 1.92 MHz crystal oscillator; this is a commercially available unit housed in a temperature controlled oven. For the specification and frequency/temperature characteristic of this unit see Appendix 1.

In addition to functioning as the transmitter modulator during field trials, the modulator unit was designed to fulfil a role in the laboratory arrangement for analysis of recorded results and the overall count-down process makes control signal pulse trains available for both these purposes.

The TTL system readily provided the required count-down sequence as shown in Figure 3.2.1-1. Grouping of these integrated circuits was optimised as far as possible to meet the specification with the minimum number of circuit chips in this series. Digital outputs from this circuit module are:

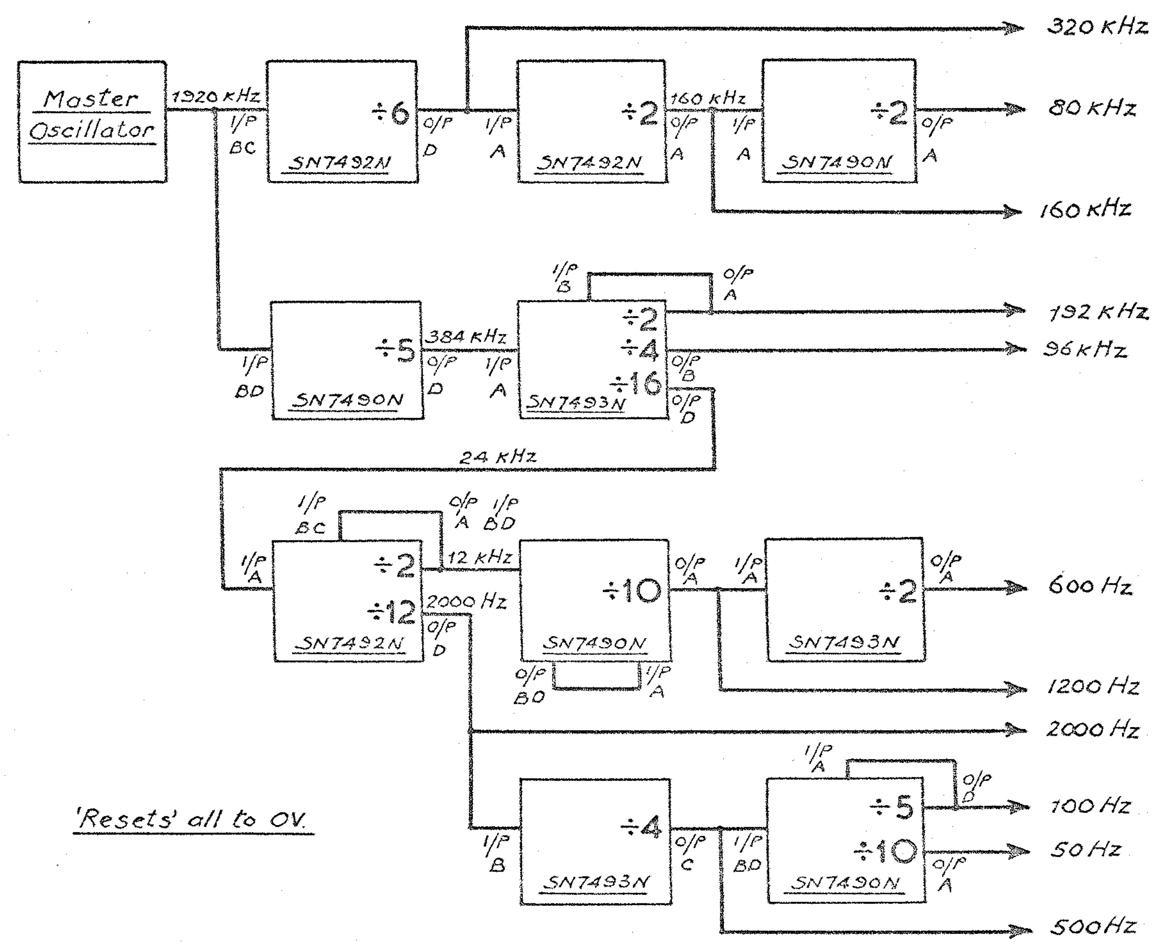
(a) four pulse trains at 500, 600, 1200 and 2000 Hz for the pilot tone generator board. The 500 Hz signal to this latter board is also counted down further to give clock pulses for the pseudo-random pulse generator and the 25 Hz alternative direct keying signal for the WBFSK generator.

(b) a 160 kHz pulse train for the WBFSK board

(c) 80, 96, 192 and 320 kHz pulse trains for the laboratory analyser when the modulator is employed as part of the results analysis equipment and these pulse trains may be used as processing signals for the pilot tone phase analyser.

(d) 50 Hz and 100 Hz clocking signals.

While the above arrangement is most convenient for field trials and the subsequent analysis of results, it is appropriate to comment here that a first consideration of the demands of implementing a practical system have



MODULATOR – MASTER OSCILLATOR AND COUNT-DOWN CHAIN

FIG 3.2.1–1

not revealed any significant problems in the requirement to re-engineer the laboratory analyser into an equipment unit for use at the receiver terminal.

As no special requirement is needed for synchronisation at switch-on, all resets of the integrated circuits on this board are returned to 'OV' and the count-down is free running.

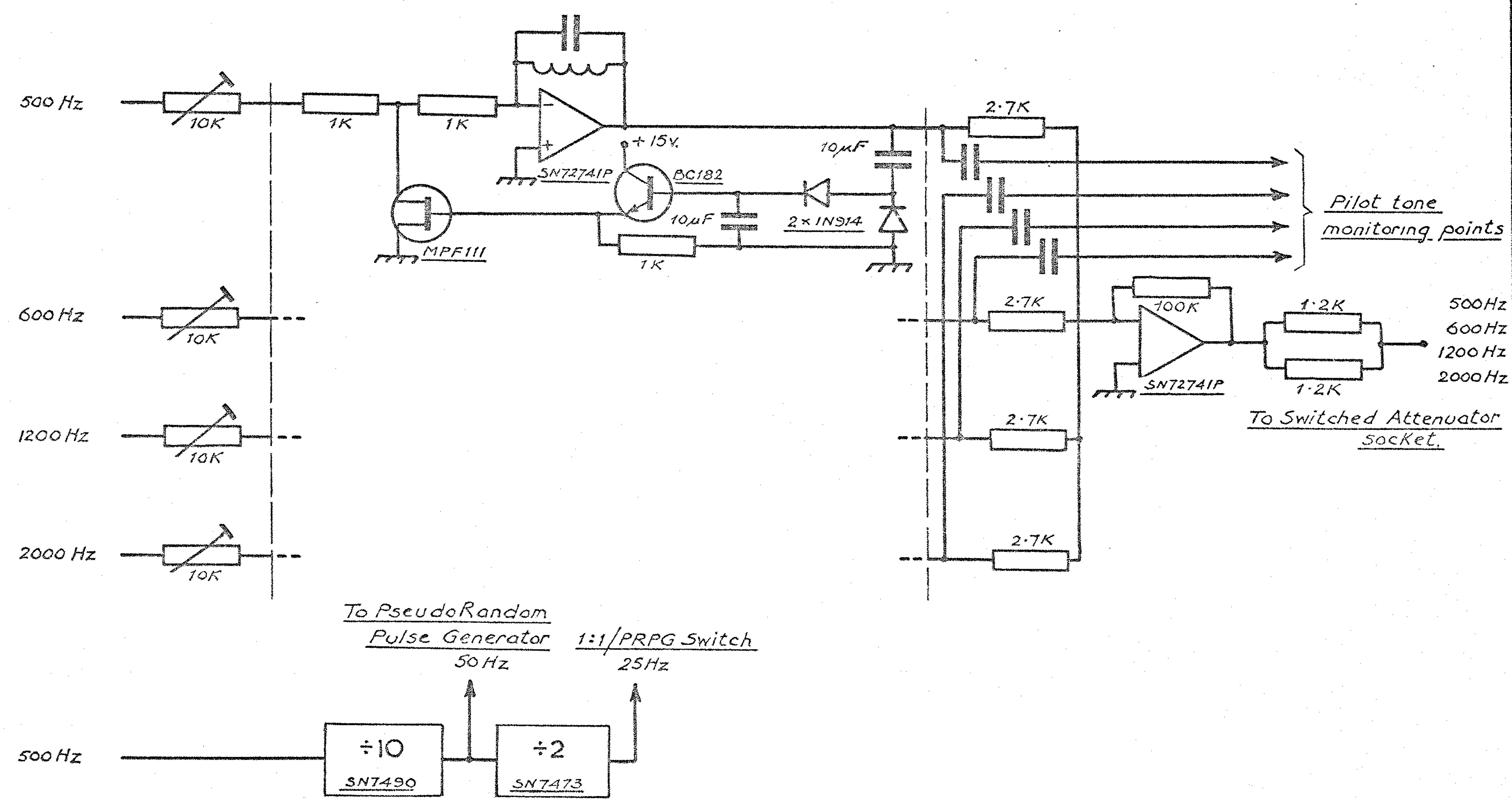
3.2.2 Pilot Tone Generators (Figure 3.2.2-1)

Square wave pulse trains at pilot tone frequencies are converted to sinusoidal waveshape using four operational amplifiers with resonant loads. Inputs to these amplifiers are equalised by pre-set adjustments. The same resonant circuit configurations as used by Ellington in the original laboratory simulation equipment proved suitable for this new design of pilot tone generator. Although the L/C values for these loads do not meet the optimum specification possible for individual circuits wound on this particular pot-core, they have been adjusted experimentally to obtain the more important parameter of stable Q values for all four resonant networks. Table 1 below gives the final selected values

Table 1

Frequency (Hz)	C (μF)	L mH	Turns (Wound on Pot-Core) Type LA2316
500	0.47	218	502
600	0.47	120	372
1200	0.10	144	408
2000	0.10	63.3	271

Additional amplitude stabilisation for the operational amplifiers is provided by a gain control arrangement consisting of a diode pump, emitter



MODULATOR – PILOT TONE GENERATORS

FIG 3.2.2-1

follower and a field effect transistor in a loop applying a control voltage to the inverting input of the operational amplifiers. In the course of developing this circuit a number of alternative arrangements were tried, all with the aim of obtaining a linear control function. It was soon apparent that achieving this aim involved critical values for the field effect transistor potentials and the circuit of Figure 3.2.2-1 is the one that resolved the difficulty of obtaining linear control under conditions of a critical bias range. Decision to use a diode pump instead of the simpler rectifier circuit arose from the fact that the requisite long time constant was more easily obtained by using a diode pump as the control voltage source for the selected emitter follower with its comparatively low input impedance. Output of the emitter follower is bias for the field effect transistor working as the control element.

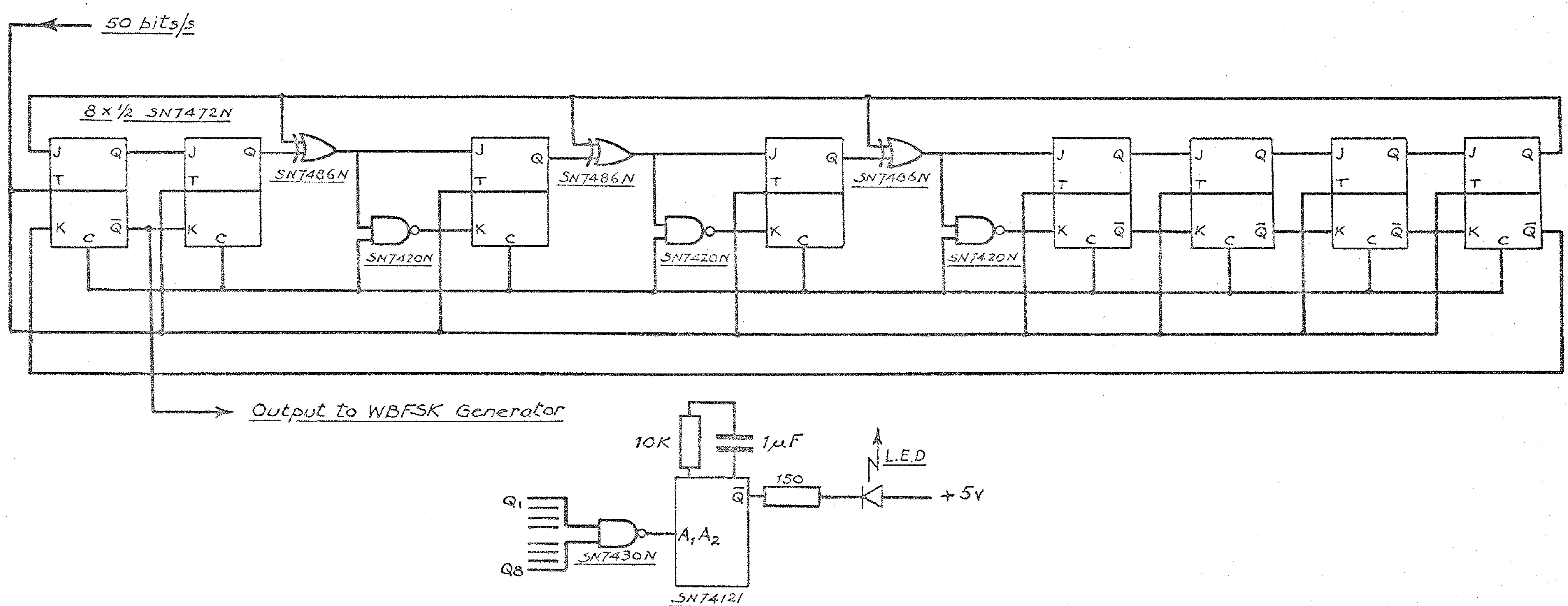
Outputs from all four pilot tone generators are fed to the operational amplifier functioning as a linear mixer, and whose output is loaded for a 600 ohm match to the switched attenuator used externally to the modulator unit to set up the system parameters as described in Chapter 2.

This board also carries the integrated circuits counting down the 500 Hz pulse train for PRPG and direct keying control signals.

3.2.3 <u>Pseudo-Random Pulse Generator</u> (Figure 3.2.3-1)

A large number of references cover the theory and application of binary sequence generating shift registers. Four of these references (15)(16)(17)(18) in particular were used in this work since the requirement was the generation of a maximum length sequence. Figure 3.2.3-1 thus shows well established circuitry employed to produce a keying signal for the WBFSK generator which is random to a degree but has the necessary well defined statistical properties outlined in Section 2.2.

The references show that the sequence obtained depends primarily upon the feedback connexions, and for a given number of stages (n) in the



MODULATOR — PSEUDO-RANDOM PULSE GENERATOR

FIG 3.2.3-1

register there is a maximum to the number of digits which occurs before the sequence repeats itself. This is the maximum length sequence needed, given by (2^n-1) digits. An eight stage shift register has been used hence the period of the keying signal sequence is 255 bits. During development 511 and 255 bit sequences were considered, the former being the internationally agreed length as defined by C.C.I.R. for testing communications systems. It was decided for convenience of equipment design to use the 255 bit sequence.

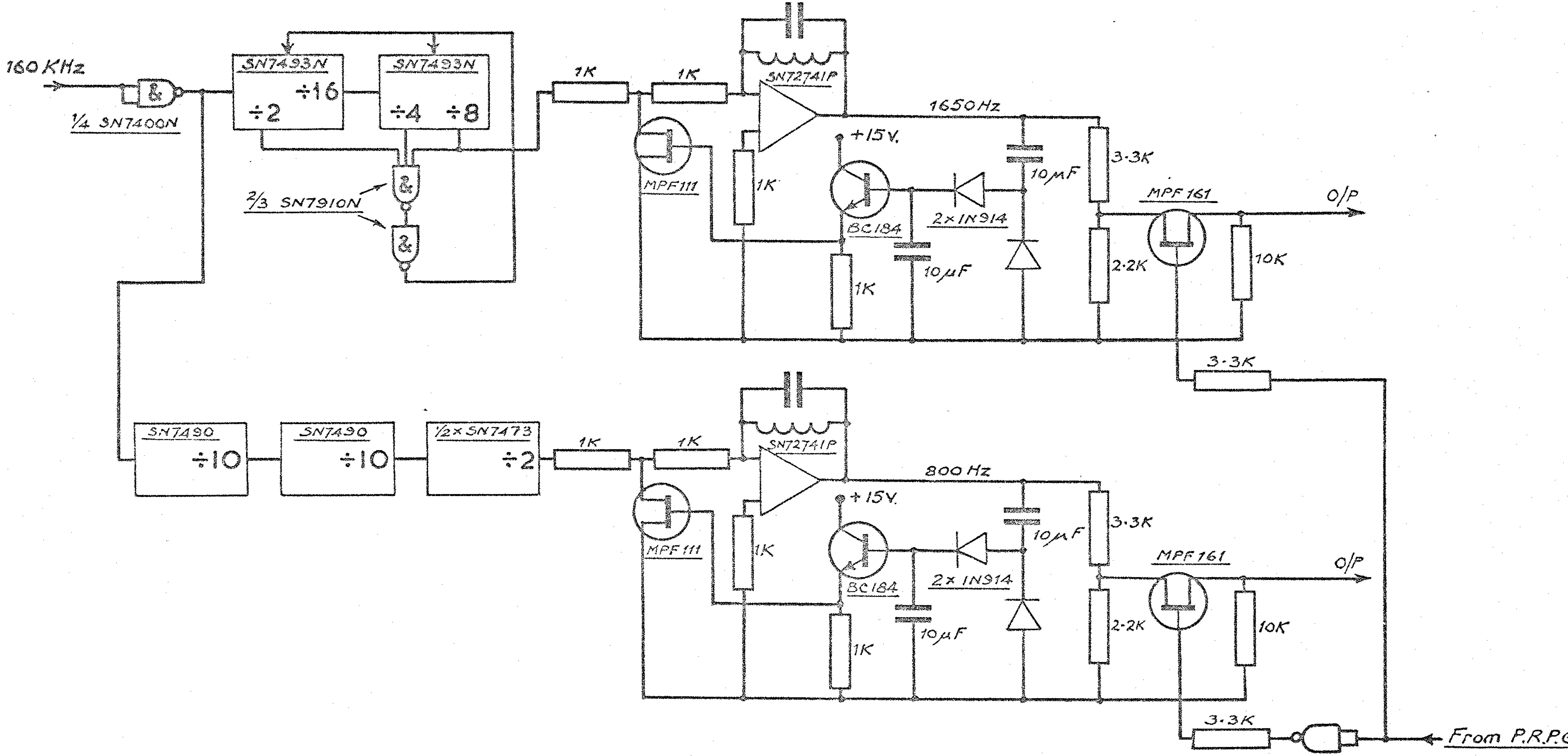
A data rate of 50 bits/s was chosen to accommodate the pilot tones at the nulls in the baseband spectrum (Chapter 4 and Figure 4-1) hence the normal simultaneous consideration of shift register length and clock rate as the initial design step to obtain a desired random sequence was not followed. In the event, the choice of an eight stage shift register proved to be a more difficult arrangement than some others and the three taps shown in Figure 3.2.3-1 meet the requirement of the minimum number that can be used to get a maximal length sequence of 255 bits. In transforming such well established theory into practical circuitry, however, it was also discovered that small design details could have a profound effect on the sequence generated.

Output for the WBFSK generator is taken from $\overline{Q}$ of the first stage of the register.

3.2.4 Wide Band Frequency Shift Keying Generator (Figure 3.2.4-1)

The mark and space tones of the FSK modulation are generated by operational amplifiers loaded with circuits resonant at 800 Hz and 1650 Hz. These sinusoids are amplitude stabilised using the same circuitry performing this function for the pilot tones and described in Section 3.2.2.

A 160 kHz 1:1 square waveform is processed by TTL to pulse the operational amplifiers at keying tone frequency. For the 1650 Hz channel the required control pulse period is obtained as follows. An input of 160 kHz to two cascaded chips, dividing as shown in Figure 3.2.4-1, opens the first NAND gate after a count-down of 97. The truth table is:



MODULATOR – WIDE BAND FREQUENCY SHIFT KEYING GENERATOR

FIG 3.2.4-1

1	2	4	8	16	32	64	128
0	1	0	0	0	0	1	1

At this time a reset '1' is applied to both chips to establish the tone oscillator control pulse with a period of 1650 Hz. A direct count-down from 160 kHz is used for the 800 Hz channel.

The keying signal from the pseudo-random pulse generator controls two series acting switching transistors in the outputs of the mark and space tone oscillators; it is applied directly to one of these field effect transistors and through an inverter to the other. A potentiometer sets the mean bias for the transistor switches and a positive going voltage at TTL logic level from the keying signal determines the 'ON' state. Hence the switching transistors operate continuously under the control of the random sequence keying waveform providing, via the output circuitry, data modulation for the transmitter.

If the keying signal is cut off ('OV' level) the 800 Hz modulation continues.

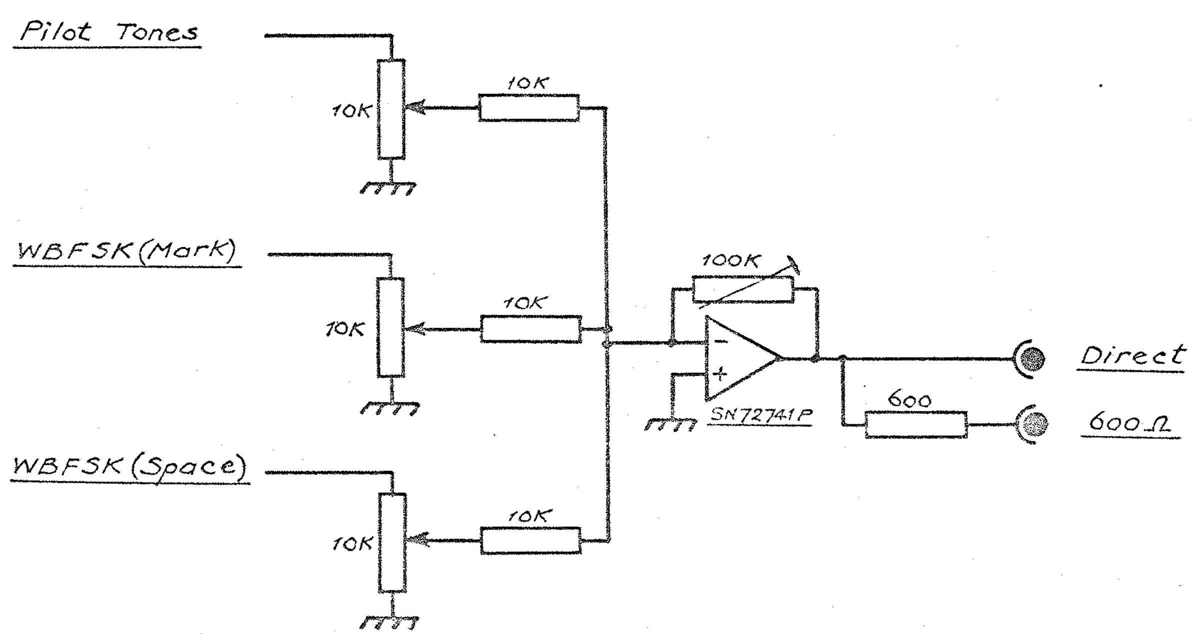
3.2.5 Output Circuit (Figure 3.2.5-1)

Reference to the circuit diagram shows this arrangement as a straightforward linear mixer. The three inputs are equalised prior to summation and preset gain on the mixer allows for setting up the modulation output level to the transmitter. Two matching impedances are available.

3.3 The Laboratory Analyser

3.3.1 The Narrow Band Filters

Four active filters are employed in the current equipment, one for each pilot tone to be extracted from the baseband signal under analysis. The original design for the first practical investigation was evolved by Jones (11) and was developed from work by Kundert (19). However, the



MODULATOR — OUTPUT CIRCUIT

FIG 3.2.5-1

response of a 20 Hz bandwidth at 3 dB proved inadequate when the pilot tones were interspersed with data signals and the filtering problem became one of separating the pilot tones from the information transmitted so that the pilot tones were not corrupted by the information sidebands.

To minimise interference to pilot tones by information signals Ellington verified a requirement for a filter with a near rectangular response and having a bandwidth not greater than 10 Hz (7). An analogue filter design was adopted in the interest of future equipment economics.

The final choice of Bessel filters with maximally-flat time-delays was influenced by the early field trial proposals to include a number of modulation methods for simultaneous investigation. An investigation with pilot tones accompanied by one data signal using a simple modulation technique does not require constant-time-delay filters, nevertheless this type of filter has been retained.

Development of these narrow band filters was based on work by Russell (20) and a circuit section applies the suggested 'Bandpass A' arrangement of this reference. A discussion in (7), Section 3.2.4.6, covers this development and is supported with a summary of Bessel filter theory in Section 3.3 where Figure 3.17 shows the 'Bandpass A' filter section and Figure 3.18 shows the complete bandpass filter section which was the practical outcome of the design effort. Some modification of passive component values was carried out by Betts for the United Kingdom/Gibraltar field trial. Tabular data recording these changes is given in ((4) Appendix 1).

3.3.2 Pilot Tone Phase Analyser

With the work already published on the equipment developed for the differential phase measurement of the system pilot tones (4) (7) only a limited discussion is required here to supplement the description of the pilot tone phase analyser given in Section 2.3.2.2.

Sections 3.2.4.1 to 3.2.4.11 of reference (7) provide the circuit information of the pilot tone phase analyser designed for the laboratory simulation equipment which facilitated the original evaluation of the system. For the United Kingdom/Gibraltar field trial Betts modified a number of the units of this first design by Ellington and the changes are recorded in ((4) Appendix 1 and 2). These modifications are mainly concerned with improvements and specification changes to the narrow band (10 Hz bandwidth) filters selecting the pilot tones from the baseband signals and to the up-down counters performing the differential phase measurement. Another modification applied to the limiter of the zero-crossing phase detector increased the dynamic range of the system to accommodate variations of input level of up to 40 dB. These references, taken together, cover the field trial version of the pilot tone phase analyser, however, the following brief details extend the explanation of Section 2.3.2.2 so that the block diagram of Figure 2.3.2.2-1 may be used to obtain an up-dated performance picture of this unit.

Figures 3.21 to 3.26 of (7) give incorrect response curves for the narrow band filters due to a computational error. Work by Betts ((4) Appendix 1 shows the correct theoretical curves for simple and cascaded Bessel filters, and demonstrates that three cascaded Bessel filters of orders 2,3,3 respectively may be arranged to give a close approximation to a 10 Hz bandwidth rectangular filter with a centre frequency of 500 Hz. Similar responses are obtainable for the other centre frequencies of interest in this project. The construction of filters with the revised characteristics showed close agreement between the theoretical and practical responses and these filters were used in the unit drawn at the input of the analyser channel of Figure 2.3.2.2-1.

The 'amplitude limiter' of the zero-crossing phase detector (Figure 2.3.2.2-1) referred originally to three stages of limiting and 20 dB amplification, the input of the amplifiers being shunted by two diodes restricting the input voltage to 0.6V peak-to-peak. This arrangement was redesigned by Betts and an increased system dynamic range was achieved using a single stage amplifier with similar input protection. A monostable buffers this amplifier from the phase sampling gate, in the interest of cleaner waveforms. Supplementing the explanation of Section 2.3.2.2 at this point, these phase sampling gates are basically J-K bistables functioning as pulse width modulators. They are clocked by the square wave from the limiter (which has the same zero-crossings as the pilot tone sine wave) and sampled at intervals of τ seconds, hence a pulse width modulated pulse train is produced where the width of a given pulse is determined by the period between a sampling pulse and the next zero-crossing of the square wave pilot tone. Individual pulses, τ seconds apart, will thus have a duration proportional to the instantaneous phase θ of the pilot tone relative to the locally generated reference.

The sampling gates which receive the pulse width modulated output from the zero-crossing phase detectors are three-input NAND gates, the other two inputs being the sampling pulses at 160f and the count-up/count-down pulses from the timing and counter control circuits. (In the equipment the sampling gates and the up-down counters are part of the same assembly).

The phase change counters themselves are arranged as 2 x a TTL SN 74192 and SN74193 in cascade. These integrated circuits are synchronous 4 bit reversible (up/down) counters, dual clock with clear. Outputs for the display circuits are taken from the SN 74193 components. For the United Kingdom/Gibraltar field trial Betts modified the counter control and the up-down counter arrangements in order to clear the counters prior to loading, and to carry out loading at a time before the onset of the count period measuring the change θ_{τ} occurring within each phase sampling interval τ.

The amended circuit diagrams and operating waveforms are shown in Figures A2.1, A2.2, A2.3 and A2.5 of ((4) Appendix 2).

Information on the display/printing arrangements is given in (7) as referenced at the beginning of this Section.

3.3.3 Pseudo-Random Pulse Generator (Figure 3.3.3-1)

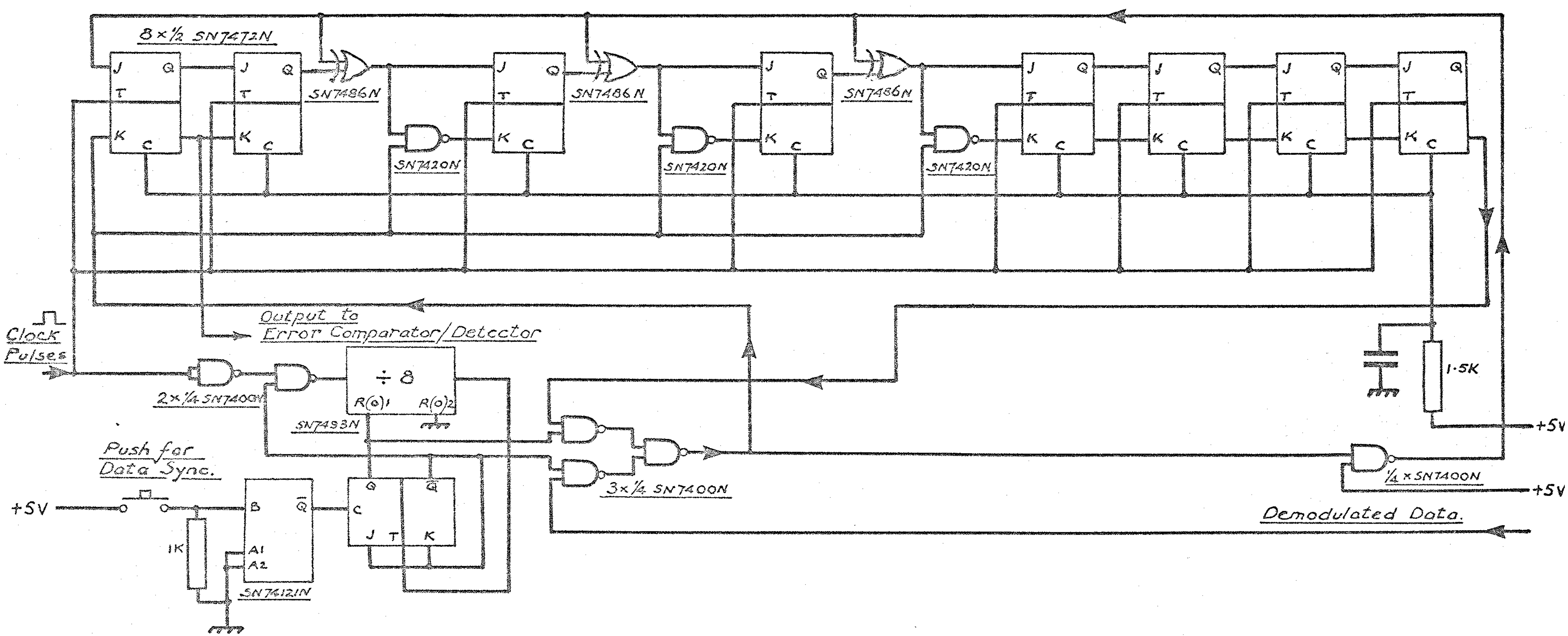
The pseudo-random pulse generator is basically the same as that used in the modulator (Figure 3.2.3-1), the one significant difference being the provision of a circuit to obtain data synchronisation.

Data synchronisation is obtained by breaking the feed-back loop with an exclusive -OR gate and allowing insertion of eight bits from the demodulated data stream at will by depressing a manual push button, thus if the selected eight bits contain no errors the eight bistables in the shift register will, after the insertion of the eight bits, be set to states corresponding to the states they would be in if they had been in the transmitting pseudo-random pulse generator at the time that the data under analysis was transmitted. Clearly the consecutive states of the shift register will be the same as the consecutive states of the transmitted data, i.e. data synchronisation is obtained if eight error free bits are inserted into the shift register.

The exclusive -OR gate receives the pseudo-random pulse generator output from the last stage of the shift register and the demodulated data from the WBFSK error comparator circuitry, and is enabled to insert eight bits of demodulated data by the Q and $\overline{Q}$ outputs of a bistable. This bistable is clocked by the manual push button via a monostable and is triggered from a divide-by-eight count-down of the pseudo-random pulse generator clock pulses.

3.3.4 Data Demodulator (Figure 3.3.4-1)

An introductory description of data signal demodulation using a block diagram (Figure 2.3.2.3-1) was given in Section 2.3.2.3. The filters centred



DEMODULATION UNIT. PSEUDO-RANDOM PULSE GENERATOR.

FIG 3.3.3-1

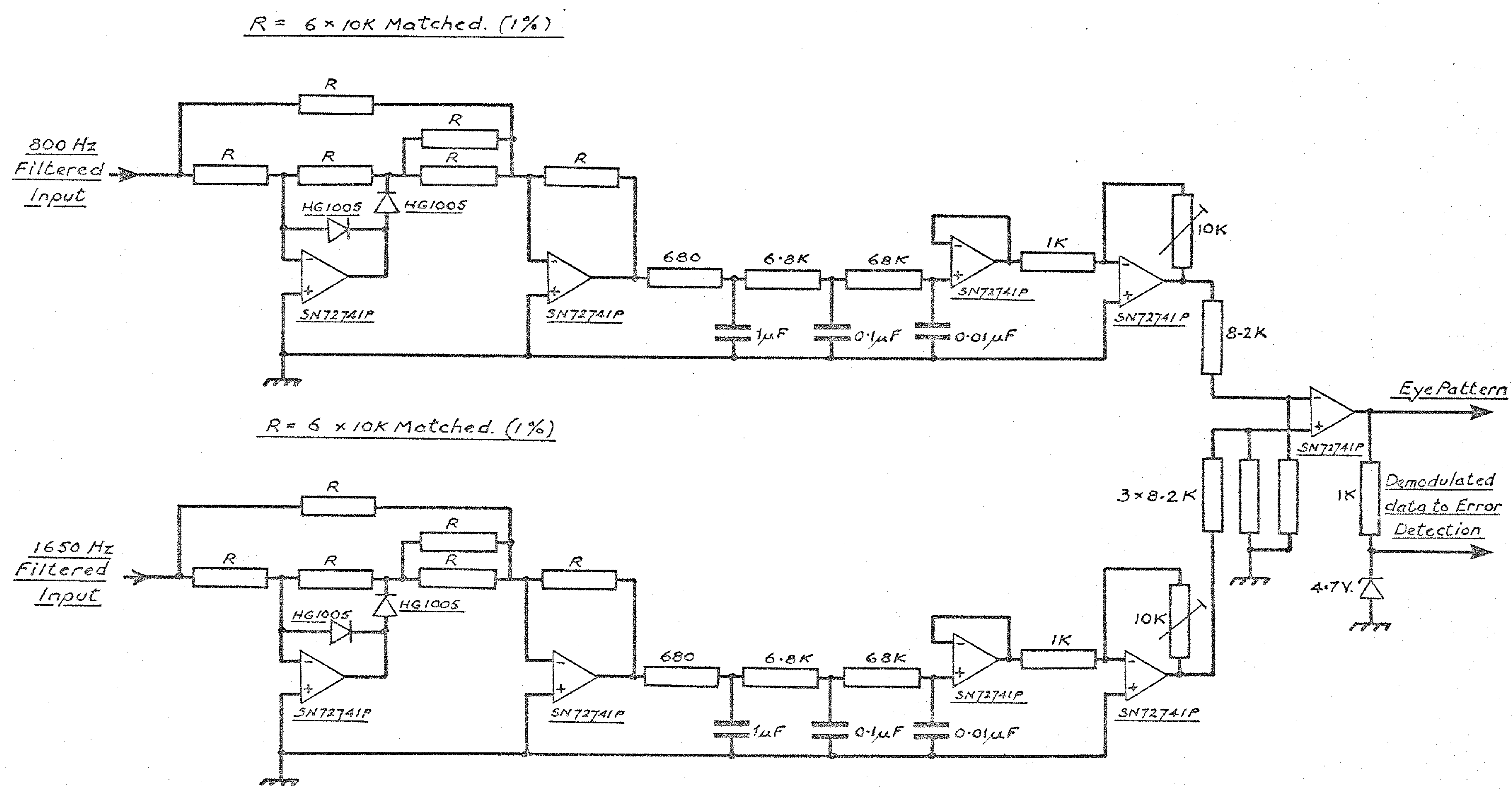
on the mark and space frequencies (800 Hz, 1650 Hz) were developed by Ellington from active filter designs using operational amplifiers, based largely on the work of Russell (20). The basic sections of these filters are the same as those discussed in Section 3.3.1 and a revision of passive component values served to adjust the bandwidth. The practical filters were set up to have a bandwidth of 220 Hz.

Demodulation commences with the filtered mark/space signals applied to envelope detectors (Figure 3.3.4-1). Pre-detector gain, residing in the filters, allows for a useful full wave rectified output over a dynamic signal range in excess of 30 dB. The following three section low pass filter has a corner frequency of 250 Hz and a voltage follower buffers the filter from the variable gain amplifier used for equalising the outputs from the mark and space signal paths. Both outputs are handled by a difference amplifier on open loop gain and are subsequently clamped to TTL logic level before being applied to the WBFSK error detection circuit. The CRO presenting the eye pattern used to obtain bit synchronisation receives its Y deflection input from the data stream taken at the output of the difference amplifier. (Timing information pulses to trigger this CRO are obtained from the timing generator section shown in Figure 3.3.5-1.)

(Overcoming the problems of bit synchronisation also involved strict control of the tape recorder speed. Achieving this meant recording a reference tone on the second track of the tape and devising a tape speed control system with positive adjustment for close synchronisation using CRO monitoring. Work on this arrangement was directed by Betts.)

3.3.5 Data Error Comparator/Detector and Timing Circuits (Figure 3.3.5.-1)

For convenience Figure 3.3.5-1 shows the data error analysis and timing circuits together. Timing control is centred on the two monostables (SN74121N) triggered at 50 bits/s, and the processing due to their outputs has been described in full in Section 2.3.2.3 using the waveforms of Figure 2.3.2.3-2.



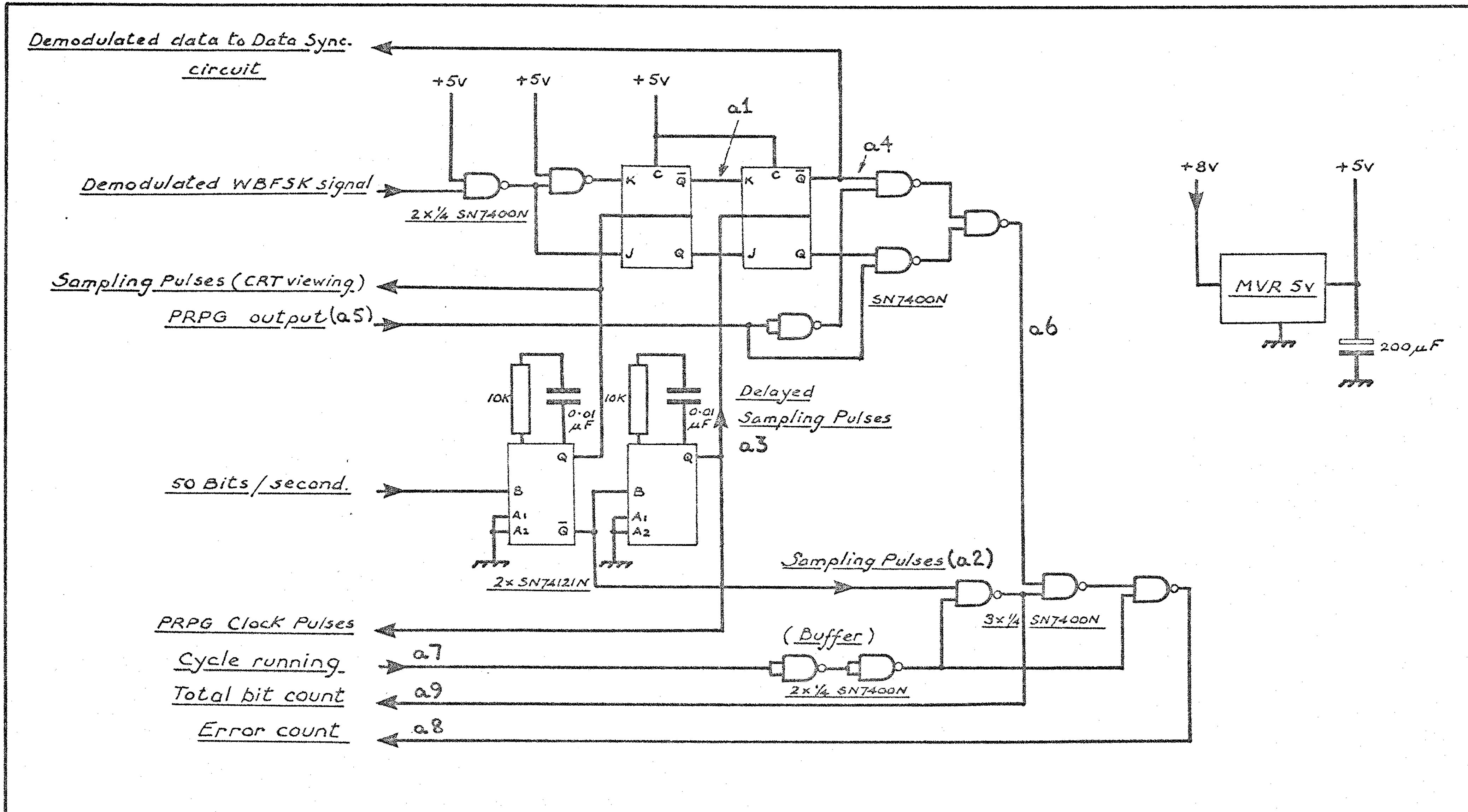
DEMODULATION UNIT. W B F S K DEMODULATOR.

FIG 3.3.4-1

It will now be seen that the timing pulse generator of Figure 2.3.2.3-1 provides sampling pulses and delayed sampling pulses by cascading the two monostables.

Data signal error detection by means of exclusive -OR gate action commences with the demodulated WBFSK signal being gated into a single stage shift register clocked by sampling pulses at bit rate to obtain a decision on the state of the bit once per bit. This signal is then fed to a second single stage shift register clocked by the same clock pulses as the pseudo-random pulse generator whence the outputs of the second shift register and the pseudo-random pulse generator change at the same time. These pseudo-random pulse generator clock pulses are delayed relative to the sampling pulses in order to eliminate the possibility of a 'time race'. Demodulated data at Q and $\overline{Q}$ of this shift register is fed to the exclusive-OR gate, and to the pseudo-random pulse generator to align the transmitted and locally generated (random) sequences, i.e. to provide data synchronisation.

Obtaining an error count first involves a count of the total number of bits occuring during a data recording run. This total count is produced by gating the sampling pulses with the timing pulse which controls the length of a given data recording run, called the 'Cycle Running' (T_L)(a7) pulse and derived from the timing and counter control circuits of the laboratory analyser. These total count pulses (a9) are then used to sample the output from the error detector (a6) to produce a pulse train with each pulse corresponding to an error in the demodulated data compared to the known transmitted data (a4). The error counter output (a8) is provided via another gate passing the error pulses when enabled with the 'Cycle Running' pulse. Two channels of the Digital Display Unit are fed with the above outputs, the total count pulses register on the 'BITS' channel while the error counter output is indicated on the 'ERRORS' channel. These displays facilitate one method of calculation of the error rate on the demodulated data signal.



DEMODULATION UNIT. WBFSK ERROR COMPARATOR/DETECTOR & TIMING GENERATOR

FIG 3.3.5-1

4. THE FIELD TRIAL ANALYSIS

Results from the laboratory simulation of the system showed encouraging close agreement with the predictions from the theoretical analysis and field trials were proposed (7). The first field trials, however, gave disappointing results and it was the third trial that yielded material for a meaningful analysis. In December 1972, during a trial of one week duration over a link from Portsdown to Gibraltar, the received data was recorded on magnetic tapes ready for processing by the laboratory Demodulator/Pilot Tone Analyser. The following discussion, tabular data (Tables 4.1-1 to 4.1-12) and graphical results (Figures 4.1-1 to 4.1-12) is the outcome of work on these tapes.

The aim of the analysis was to establish how much time is needed for an adequate estimation of channel quality.

Specification of the baseband signal is repeated below for convenience:

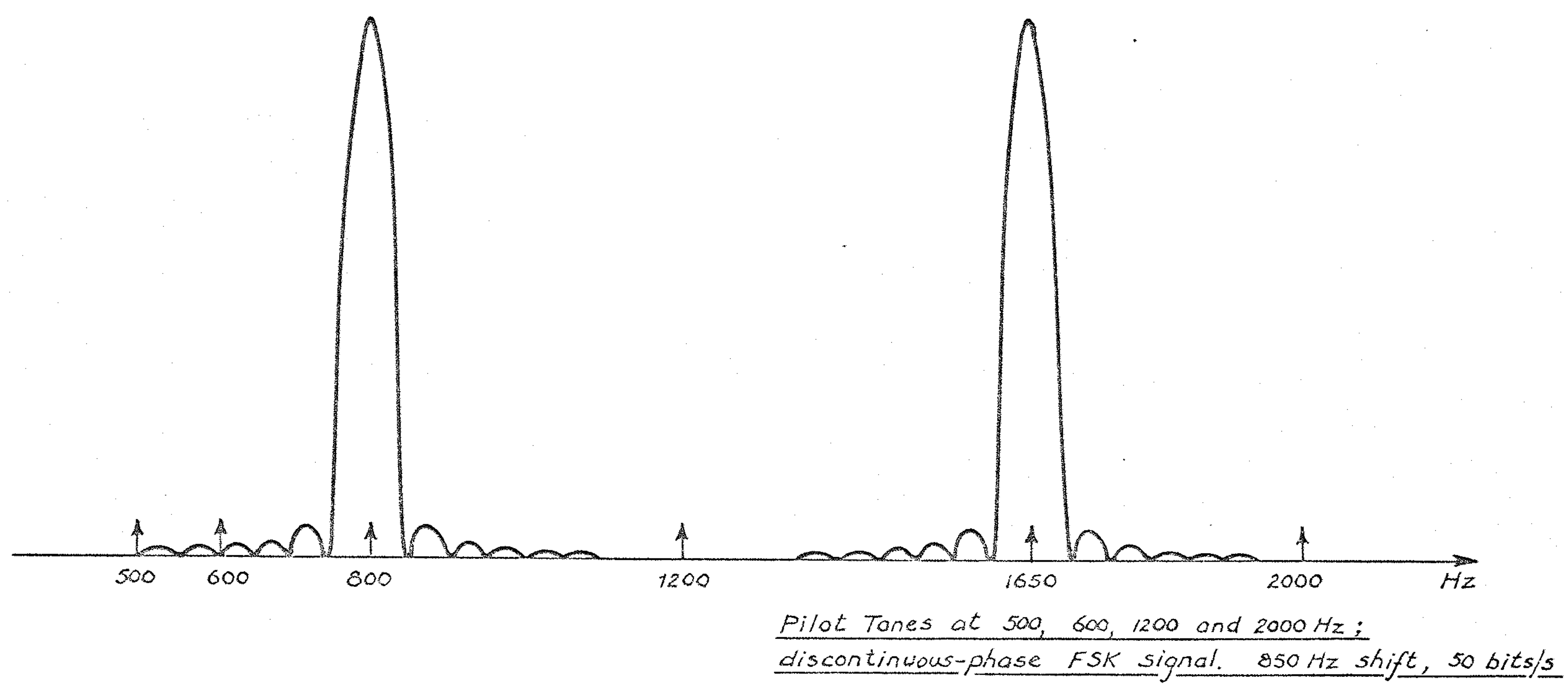
Data Signal - FSK, 850 Hz shift with discontinuous phase and mark and space signals at 800 and 1650 Hz. The data rate of 50 bits/s was chosen for the pilot tones to be accommodated at nulls in the data signal spectrum (See Figure 4-1).

Pilot Tones - at 500, 600, 1200 and 2000 Hz.

This baseband signal provided the SSB drive for a standard 1 kW HF transmitter. Each pilot tone was -16 dB relative to the FSK data.

The frequencies allocated for the trial were:

4736 kHz	12277.5 kHz
5875	13213
6805	15085
8160	16065
9251.5	21840
11229.5	23200
	23345



SKETCH OF THE SPECTRUM OF PILOT TONES AND DATA SIGNAL

FIG 4-1

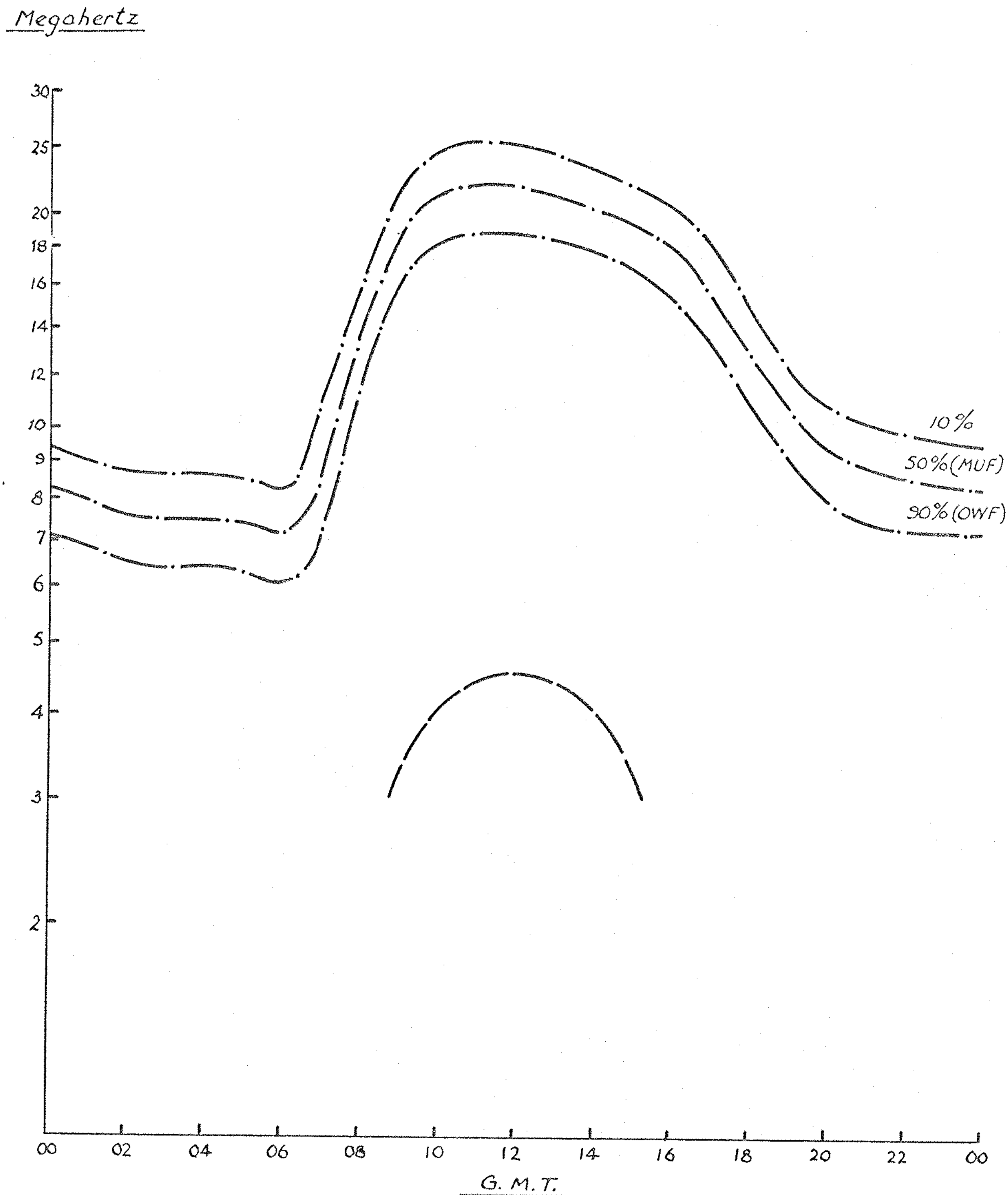
The frequency prediction for the link is shown in Figure 4.2 It was found that 4736, 11229.5 and 12277.5 were relatively free from interference whilst 21840, 23200 and 23345 were for most of the time above the MUF.

It was not possible to obtain the supplementary information of ionograms during the trial.

Information available from the processed tapes would have allowed for examination of the behaviour of the 4 pilot tones (500, 600, 1200 and 2000 Hz) in addition to the single FSK data channel, but the filter for the 2000 Hz pilot tone in the laboratory analyser proved to be unreliable and no importance could be attached to these results. Further consideration of the comparatively small difference between 500, 600 and 1200 Hz and of the fact that the 1200 Hz pilot tone lay midway between the mark and space frequencies of the FSK channel (800 and 1650 Hz) led to the decision to base the phase perturbation analysis entirely on the 1200 Hz pilot tone.

The initial requirement to meet the aim of the analysis was selection of several periods for the error count used to determine channel quality. These periods had to lie within a minimum spread whilst allowing for a purposeful comparison in the drawing of conclusions from the results. The choice of 200, 300, 500 and 1000 seconds for the periods, designated T_L, was reasoned as follows.

For error rates less than 10^{-3} or 10^{-4} (under these conditions deemed to be a satisfactory channel quality) at least 200 seconds is needed to get a valid sample; this gave the lower limit for T_L. The upper limit was less easy to assess and was first considered against the relationship between a 'long' period of channel estimation and a typical figure for the number of times per day the operating frequency of an HF system under human control is changed, for example, 3 or 4 times a day. Clearly, a 'long' period of channel estimation would be very short compared with the time between



FREQUENCY PREDICTIONS
FROM PORTSMOUTH TO GIBRALTAR, FOR DEC 1972

FIG 4-2

system operating frequency changes and, largely from earlier work, it was judged that a period for T_L much inexcess of 15 minutes would contribute little to the significance of information obtained for decision making from successive periods of this order. This judgement considered the period in terms of sample size for pilot tone phase comparisons and FSK total bits and endeavoured to account for propagation conditions and interference. As a result a figure of 1000 seconds was chosen for the upper limit of T_L. One feature of further field trials will be the evaluation of this estimation for the upper limit of T_L. The value 300 seconds was chosen as one close enough to the lower limit of T_L to monitor for any advantages in near values and 500 seconds was chosen as the mean of the range for T_L.

A sample of the print-out used to obtain the tabular data of Tables 4.1-1 to 4.1-12 is given in Appendix 2. Data from the laboratory analyser was printed out at 10 second intervals and summations for the four selected values of T_L were converted into error rates. These error rates are presented graphically in Figures 4.1-1 to 4.1-12.

The focus of this analysis is the examination of how closely the FSK/pilot tone error rate relationship follows the ideal single line referred to in Chapter 2. Figures 4.1-1 to 4.1-12 give the graphical answer for the system parameters chosen for this field trial and it can be seen that, for as much as a one week trial can show, the correspondence is close and encouraging for further field trial investigations embracing different times of the year and conditions more closely oriented to the requirements of frequency management.

Before discussing features important in supplementing the results given in Figures 4.1-1 to 4.1-12 it is possible to summarise the findings of the analysis by one statement - for purposes of real-time channel estimation the same conclusions will be reached after 200 seconds as those reached by waiting 1000 seconds. The first important supplementary feature, however, must preface the analysis detail given in the next section and refers to the fact that the trial operated with unprotected transmissions. Use of a fixed format with no change of bit rate or type of modulation and absence of the benefits of diversity and special coding techniques justifies an enhanced interpretation of the results. While the validity of applying this to a consideration of the results is clear, a meaningful factor of improvement cannot be suggested on this one set of data. Nevertheless, allowing for the trial specification defining an error rate of 10^{-3} as indicating satisfactory channel quality*, this trial represents an 'adverse situation' compared with conditions available for applying the proposed channel estimation technique to existing practical HF communications systems. It will be appreciated that the majority of such practical systems offer a performance improvement over unprotected conditions only in terms of diversity and coding techniques since present HF networks are mainly operated with fixed bit rates and types of modulation. This latter feature turns out to be an advantage for the suggested method of frequency management since it allows the simple concepts of the peripheral equipment to be incorporated with ease into existing networks.

4.1 Analysis Detail

Tables 4.1-1 to 4.1-12 show the data collected from twelve tapes, the average recording run for these tapes being about 70 minutes. The information displayed is largely self-explanatory and, where necessary, significant comments from the trial log have been inserted to distinguish between the various categories of events influencing the data.

As it happened, the trial produced tapes containing examples of channel quality from corrupt to excellent and they demonstrate most situations of

* It will be seen from the tabular data that whenever the FSK error rate is better than 10^{-3} the channel is free of QRM.

interest to this field trial plan, such as, the consequences of various types of fading on a good channel, the cyclic long period appearance and disappearance of good readable signals (about 15 minute periods), the effect of most classes of interference, some tapes recording signals aflicted by all these influences and, finally, long reception periods with strong signals.

There were twenty-one frequency changes during the trial, corresponding in time distribution to the frequency prediction graph of Figure 4.2. These times have not been included in the tabular data, but are shown for greater convenience on the error rate relationship graphs of Figures 4.1-1 to 4.1-12. Among these frequency changes, thirteen are in the region 11-13 MHz and give a reasonable spread of information, three at the low frequency end of the band (4.7 MHz) yeilded two excellent strong signal runs and two at the high frequency end of the band provided one good and one indifferent set of data. The remaining three transmissions in the region of 15-16 MHz were not very fruitful.

A reminder of the sampling quanta for Tables 4.1-1 to 4.1-12 is given below:

T_L	Pilot Tone Differential Phase Comparisons = 10 mS	FSK Signalling at 50 bits/S
200	2×10^4	10^4
300	3×10^4	15×10^3
500	5×10^4	25×10^3
1000	10^5	5×10^4

The translation of the tabular data into the graphical presentation of Figures 4.1-1 to 4.1-12 has been explained in Chapter 2. A legend at the head of each graph identifies the plots with operating frequency and time of recording. Results for T_L = 200 seconds are shown plotted on a base graph and overlays allow for the examination and comparison of the results for T_L = 300, 500 and 1000 seconds. The theoretical curves for steady signal and Rayleigh flat fading conditions are shown on each graph. This plotted data displays a common trend of $P_{e/FSK}$ against $P_{e/\text{pilot tone}}$ for all the frequencies used, i.e. from 4736 to 23345 kHz. Two examples of interpreting these graphs can be used to illustrate all the information presented and to show the predominating effects of QRM (previously considered in Chapter 1).

The data of Figure 4.1-5 (with Table 4.1-5) illustrates a frequency which became unusable due to QRM. On the abscissa a transition threshold in terms of the pilot tone phase error rate can be considered to be at 10^{-3}. All phase error rates greater than this figure are indicative of QRM and examination of all the graphs shows that the usable/unusuable state of a frequency could be based on a 10^{-3} pilot tone error rate as the threshold.

Figure 4.1-7 provides example two from the data of Table 4.1-7; a poor quality channel at first because the frequency of 23345 kHz was above the MUF (1038 GMT) and the error rates were due solely to noise (4.28×10^{-1} error rate being recorded for the FSK channel). In the region of 1100 GMT the regained signal underwent a very rapid improvement in signal-to-noise ratio and a strong signal was readable until a classic fade removed the signal about 1120 GMT. Table 4.1-7 shows why so few points can be plotted and, in fact, the calibration of the graph masks some points that show the complete corruption of the channel.

Other examples such as Figures 4.1-4, 4.1-9, 4.1-11 and 4.1-12 clearly illustrate another important feature of these results - that whenever the FSK error rate is better than 10^{-3} the channel is free of QRM. Taken together with the transition threshold for pilot tone error rate discussed earlier this defines the satisfactory channel quality area on the graphs as bounded by the abscissa and ordinate for 10^{-3}. It also follows that if errors are consistently to the right of the threshold on the abscissa there is a high probability of the need for a change of frequency.

Recalling the contents of Chapter 2, an overall examination of these tabular and graphical results confirms a close correspondence between the theoretical work, the laboratory simulation and the field trial. The FSK/pilot tone error rate relationship follows closely to a single line in every case, with due allowance for the spread of points when an insufficient number of samples were available. This outcome merits the further investigations proposed in Section 4.2, which will establish conditions for tendencies disclosed by all the past work and provide information on aspects yet to be covered.

Ascertaining the maximum period required for making a reasonable estimate of channel performance still needs to be proved despite the indicated solution from this trial for T_L = 1000 seconds. Only further field work can confirm if a longer time is needed to wait for the degradation of a channel to be well established. This point again raises the issue of the most effective minimum number of samples for a specified acceptable error rate, but it is not a matter of the simple arithmetic involving total bit count etc., it is a matter of operational conditions, especially the effects of QRM and finding a threshold in terms of this afliction of HF communication channels.

The object of this and future work is to indicate to an operator, in good time, that a change of frequency is required. The graphical results from this analysis are adequate to confirm that a few plots to the right of the pilot tone error rate threshold do not indicate the need for a change of frequency, so it is necessary to find out how control by the proposed system behaves in relation to typical periods for change with existing installations, and to check that the effects of QRM do not initiate unnecessary shifts in operating frequency unless it is persistent enough to give a significant error rate. This correlation of the system behaviour to the usual three or four frequency changes per day for a system under operator control using frequency prediction will resolve the issues awaiting investigation.

Implicit in the comments of the following Section 4.2 will be the optimisation of the system parameters for other propagation conditions. It has been pointed out that θ_{Th} and τ should be chosen to get error rate/SNR curves of identical shape and exact correspondence and Figures 2.3.1-1 to 2.3.1-4 show how variation in these parameters alters the position and slopes of the relevant curves. Appreciating these tendencies, the routine of obtaining a best fit by experimenting with values must be carried out for other propagation conditions of interest. Assistance with this task should now be available by using the information on pilot tone phase perturbation/signal-to-noise ratio behaviour obtained from field trials. This latter issue has the greatest effect on deriving the error rate relationship curves such as those shown in Figure 2.3.1-7.

As a further lead into Section 4.2 the present analysis must be expanded next time to obtain sets of results for other pilot tones and then, for example, find average conditions for any two or more pilot tones in order to search for conditions that may have been concealed by basing the present analysis on a single pilot tone at 1200 Hz.

4.2 Proposals for Future Work

Since the United Kingdom/Gibraltar field trial analysis has been completed there has been another trial over a Scotland/Portsdown link and a preliminary analysis of the recorded data indicates the same conclusions with the results making a favourable comparison to those contained in this chapter.

This Scotland/Portsdown trial represents the second of a group of three which will allow for an investigation covering a short, medium and long range link at different seasonal times of the year. It is hoped that the third field trial will be over a United Kingdom/Mauritius link, but at the time of writing this trial is in its early planning stage.

Such a group of trials will facilitate a more detailed search to seek correlation between all the results and to examine other aspects not yet considered, though some of these will also call for the implementation of an open loop system under operator supervision and running for much longer periods than those of field trials. Some preliminary discussion of such operational trials has taken place since results to date justify fitting field trials equipment (of pre-production standard) to an HF link to provide a digital read-out functioning as a decision prompter to an operator. This kind of assessment of the system under operational conditions is the next important requirement, to make a start on a full evaluation programme obtaining, for example, information on such aspects as the correlation between decisions by frequency prediction/experience and decisions by measured channel estimation technique, and the number of frequency changes per day prescribed by both methods. An initial investigation of this nature can also include managing separate channels by the two different methods to obtain data covering most of the remaining aspects yet to be considered. Information gathered from this exercise should give a well defined set of requirements for subsequent, more sophisticated, operational trials and help to keep the complete evaluation, with its obvious need for a long term investigation, inside a reasonable time limit. The essential issue of the next step is to prove the system via the suggested hybrid analysis method and get a measure of the feasible signalling improvement if controlled frequency management is offered to an operator. Development from this could be an automatic system with supervising operator having overide control.

The simplicity of the system extends an economy advantage which also invites early validation. All circuitryused employs a minimal quota of logic confined to a few operations and such assemblies lend themselves to ease of production with modern components, are repeatable for defined performance from manufacturers supplies and final units can become very compact 'add-ons'. In fact, further equipment development work is in progress and has taken the peripheral items for an HF communications system sufficiently close to pre-production units to be able to suggest (at current prices) a figure of around £1000 to manufacture both the modulator and the receiver terminal equipment. While this is undoubtedly a rough (probably short lived) estimate, the additional cost of the system will be small compared with that of a complete HF communications system and in terms of making a cost-effective contribution to system performance should prove a very worthwhile investment.

4.3 A Special Conclusion

Reference (21) describes the design and construction of a full duplex adaptive data modem utilising digital synthesis/analysis techniques. This modem has the capability of operating at various data rates in a number of modulation formats over appropriate channels, either radio or line, and is compatible with many varieties of existing communications equipment. It is a very sophisticated example of current modem design and, as such, serves well to make a special conclusion with respect to this present investigation of channel estimation technique. A quote from the chapter of the reference headed 'Conclusions' is all that is required to emphasize the point that commercially available modems of all degrees of baseband processing sophistication cannot make viable contributions to system efficiency if there is no way of interrogating the spectrum.

The relevant quote is:

'b. The versatility of the unit in providing a large library of various modulation techniques and data rates offers the possibility of a powerful adaptive modem technique that, WITH A DEVICE TO SOUND A MEDIUM, could automatically configure itself to provide an optimum system . . . '

(The block capitals have been inserted by the Author).

4.4 Conclusions

4.4.1 HF Communications systems developed to date are dependent upon the frequency prediction method to establish operational parameters. Work on this project has reached a stage of promise to attain a much improved method of determining operational conditions by means of real-time channel estimation applied as a frequency management tool in either hybrid (man/machine) or automatic form.

4.4.2 The hybrid form of this version of real-time channel estimation will provide a clear indication of channel degradation, suggesting the time to change frequency and the next suitable location in the spectrum to use. It will have an initial advantage in the acceptance or rejection of the proferred data being subject to human judgement/experience.

4.4.3 In the long term development of present work and the study of the system behaviour under operational conditions lies the feasibility of incorporating extra logic circuitry capable of taking the decisions involved automatically.

4.4.4 The cost/benefit to the user will depend on the category of user, but the 'add-on' peripheral equipment will represent only a small fraction of the cost of a complete HF communications system.

For the military user category a different set of cost/benefit factors exist compared with those, for example, of the mobile maritime commercial user. In the latter case international legislation is involved in system operating conditions, however, the possibility of an automatic system improving error rate and reducing manning problems with attractive economics could well reduce the normal period for amending existing international rules.

4.4.5 Further development must include thorough trials with operational systems.

Tabulated Results of Data from Tape No. 16

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 4.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	1	19	0.5	19													
	5	10	2.5	10	2	19	0.7	13									
	0	2	0	2	4	12	1.3	8	6	30	1.2	12					
	7	5	3.5	5													QRM
	4	6	2	6	10	8	3.3	5.3	11	12	2.2	4.8	17	42	1.7	8.4	
	13	3	6.5	3	13	6	4.3	4									
	51	35	26	35													Fade out
13213 kHz	155	42	78	42													
	29	94	15	94	176	64	59	43									
	14	38	7	38	22	110	7.3	7.3	193	153	39	61					
	2	4	1	4													
	1	5	0.5	5	2	8	0.7	5.3	8	30	1.6	12	201	183	20	37	

Table 4.1-1

Tabulated Results of Data from Tape No. 16

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 4.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
13213 kHz	3	2	1.5	2	4	3	1.3	2									
	37	48	19	48													QRM/fading
	63	152	31	150	73	191	24	130	76	193	15	77					
	65	134	32	130	92	143	31	95									Speech QRM
	14	27	7	27					106	170	21	68	182	363	18	73	
	37	65	19	65	33	53	11	35									
	168	204	84	200	191	243	64	170									Speech QRM
	47	56	23	56					242	301	48	120					FSK QRM
	8	10	4	10	53	65	18	43									
	15	12	7.5	12	17	13	5.6	8.7	33	46	6.6	18	275	347	28	70	
	21	13	10	13													
	7	6	3.5	6	26	16	8.6	11									
	43	54	21	54	45	57	15	38	46	26	15	10					Speech QRM
	95	156	48	160													Deep fade and QRM
	386	303	193	300	293	293	98	200	506	506	100	200	552	532	55	106	

Table 4.1-1

Tabulated Results of Data from Tape No. 17

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
15085 kHz	2053	275	1020	260													
	2011	353	1000	350	3066	440	1020	290									
	2112	725	1050	730	3110	913	1040	610	5175	927	1040	370					Speech QRM
	1840	692	920	690													Broadcast channel interference
	1919	125	960	130	3100	741	1030	490	3760	1243	750	500	9935	2170	1000	440	
	697	106	350	110	1356	182	450	121									
	288	110	150	110													
	150	46	75	46	316	117	110	78	1013	223	200	90		-			
	829	279	420	280	951	318	320	212									Speech/music QRM
	892	469	450	470					1843	787	370	315	2856	1010	290	200	
	483	233	240	230	1227	664	410	440									
	184	57	92	57	332	95	110	63									
	485	271	240	270					957	395	190	160					
	372	256	190	260	721	418	240	280									
	1090	497	550	500	1232	614	410	410	1647	919	330	370	2614	1314	260	260	

Tabulated Results of Data from Tape No. 17

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
15085 kHz	1040	633	520	630	1200	850	400	570									
	628	557	310	560													
									2090	1609	420	640					
16065 kHz	514	353	260	350													Speech QRM
	259	203	130	200	689	460	230	310									Very weak signal
	159	72	80	72	243	168	80	110	849	610	170	240					
	396	79	200	79													
	269	99	140	100	641	159	210	106	748	196	150	80					QRM
	1138	742	570	740	1162	753	390	500									CW/speech
	1619	1010	810	1010													QRM
						1300			3423	2042	690	820					

Table 4.1-2

Tabulated Results of Data from Tape No.18

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
16065 kHz	1173	546	590	550													Very weak signal
	980	722	490	720	1506	815	500	610									
	738	350	370	350	1385	803	460	600	2599	1505	520	600					CW/Speech QRM
	472	523	240	520													Fading throughout run
12277.5 kHz	76	9	38	9													Strong signal
	7	7	3.5	7	79	13	26	8.7									Slight fading
	45	10	23	10	49	13	16	8.7	101	23	2	9.2					
	34	18	17	18													Some deep fading
	24	31	12	31	48	37	16	25	85	52	17	21	186	75	19	15	
	10	7	5	7	20	19	6.6	13									Strong signal
	15	12	7.5	12													20 dB fades
	8	12	4	12	19	17	6.3	11	29	24	5.8	10					Slight CW QRM
	1	3	0.5	3	5	10	1.6	6.6									
	6	8	3	8					11	18	2.2	7.2	40	42	4	8	

Table 4.1-3

Tabulated Results of Data from Tape No. 18

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	5	32	2.5	32	6	35	2	23									
	10	7	5	7	15	12	5	8									Very strong signal
	5	0	2.5	0					16	39	3.2	16					
23200 kHz	42	17	21	17													
	6	4	3	4	47	21	16	14									Strong signal
	5	2	2.5	2	6	2	2	1.3	52	21	10	8.4					Fading
	5	8	2.5	8													
	8	4	4	4	7	10	2.3	6.6	14	14	2.8	5.6	66	35	6.6	7	
	16	9	8	9	24	11	8	7.3									Signal lost

Table 4.1-3

Tabulated Results of Data from Tape No. 19

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	16	2	8	2													Strong signal
					21	4	7	2.7									
	11	11	5.5	11													CW QRM
	19	19	10	19	25	28	8.3	19	46	32	9.2	13					Deep fade
	8	3	4	3													
	29	18	15	18	37	21	12	14	37	21	7.4	8.4	83	53	8.3	11	
	2	0	1	0	2	0	0.6	0									
	40	17	20	17													20 dB fading
	20	18	10	18	46	21	15	14	48	21	9.6	8.4					10 fades/minute
	9	2	4.5	2	23	16	7.6	11									
	18	0	9	0									89	37	8.9	7.4	
	6	6	3	6	23	0	7.6	0									
	7	6	3.5	6	8	12	2.6	8									
	0	1	0	1					13	12	2.6	4.8					
	9	9	4.5	9	0	7	0	4.7									
	10	22	5	22	19	25	6.3	17	19	32	3.8	13	32	44	3.3	8.8	Slight CW QRM

Table 4.1-4

Tabulated Results of Data from Tape No. 19

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	13	28	6.5	28													Fading
	11	4	5.5	4	13	28	4.3	19									Fading > 20 dB
	16	4	8	4	27	8	9	5.3	36	34	7.2	14					
	9	0	4.5	0													
	3	4	1.5	4	9	0	3	0	16	6	3.2	2.4	52	40	5.2	8	
	3	1	1.5	1	6	5	2	3									Fading
	4	5	2	5													
	28	26	14	26	4	5	1.3	3	7	6	1.4	2.4					Slight CW QRM
	13	10	6.5	10	41	36	14	24									
	3	1	1.5	1					44	37	8.8	15	51	43	5.1	8.6	Very strong signal
	0	1	0	1	3	2	1	1.3									
	0	6	0	6	0	6	0	4									Deep fade

Table 4.1-4

Tabulated Results of Data from Tape No. 20

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	4	96	2	96													
					37	128	12	83									
	74	48	37	48													
	43	31	22	31	84	47	28	31	101	156	20	62					High background noise
	28	3	14	3													
	55	26	28	26	63	27	21	18	103	48	21	19	204	204	20	41	Deep fading
	53	18	27	18	73	20	24	13									
	105	43	53	43													
	25	9	13	9	105	43	35	29	158	61	32	24				-	Slight CW QRM
	23	39	12	39	48	48	16	32									
	6	7	3	7					54	55	11	22	212	116	20	23	Strong signal
	12	2	6	2	11	8	2.6	5.3									Rapid fading 30/40/minute

Table 4.1-5

Tabulated Results of Data from Tape No. 20

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	228	24	114	24													Heavy QRM
					235	27	78	18									
	23	5	12	5													Good signal
									260	38	52	15					
	31	17	16	17	47	19	16	13									Slight QRM
	73	67	37	67													Rapid and deep fading
					87	75	29	50									
	15	8	7.5	8					110	83	22	33	370	121	37	24	
	2	0	1	0	3	0	1	0									Fading
	13	7	6.5	7													
	21	9	11	9	34	16	11	11	36	16	7.2	6.4					Deep fading
	7	4	3.5	4	7	4	2.3	2.7									
	187	171	94	170					194	175	39	70	230	191	23	38	Speech QRM
	370	303	190	300	266	268	89	180									

Table 4.1-5

Tabulated Results of Data from Tape No. 21

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5/6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	803	722	400	720													Weak signal
	1384	1242	690	1240	1484	1353	490	900									Heavy CW QRM
	1029	947	520	940	1732	1558	580	1040	2582	2429	520	970					
	1425	1224	720	1220													Speech QRM
	1331	1307	670	1310	2106	1832	700	1220	3390	3013	680	1210	5972	5442	600	1090	Weak signal
	1408	990	710	990	2058	1689	690	1130									
	1386	1311	700	1310													CW QRM
	1337	922	670	920	2008	1736	660	1160	3416	2726	680	1090					
	1434	1006	720	1010	2149	1503	710	1000									
12277.5 kHz	1954	15	98	15													20 dB fading
	1669	29	640	29	3002	28	1000	19									
	106	15	53	15	727	31	240	21	3695	52	740	21					Good signal
	26	4	13	4													Some QRM
	11	2	5.5	2	34	6	11	4	61	13	12	5.2	3766	65	380	13	

Table 4.1-6

Tabulated Results of Data from Tape No. 21

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 5/6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	1	1	0.5	1	4	1	1.3	0.7									
	0	0	0	0													
	0	2	0	2	0	0	0	0	1	1	0.2	0.4					
	0	6	0	6	0	8	0	5.3									
	2	23	1	23					2	31	0.4	12	3	32	0.3	6.4	
	1	6	1	6	2	23	0.6	13									
	5	8	2.5	8	6	14	2	9.3									
	2	4	1	4					7	16	1.4	6.4					Fading
	14	16	7	16	9	13	3	8.7									QRM
	2	6	1	6	9	13	3	8.7	17	24	3.4	9.6	24	40	2.4	8	
	3	4	1.5	4													

Table 4.1-6

Tabulated Results of Data from Tape No. 22

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
23345 kHz	432	647	220	650													
					1381	2753	460	1830									Weak signal
	1907	4259	970	4250													
									3270	6968	660	2790					
	1895	4212	930	4210	2853	6365	950	4240									
	1987	4286	1000	4280													Signal lost
					3035	6419	1010	4280									
	2082	4193	1040	4190					5023	10629	1000	4250	8303	17597	830	3520	
	1393	2585	700	258	2427	4645	810	3100									Signal regained
	39	18	20	18													Rapid fading
					39	18	13	12	1432	2603	290	1040					
	20	4	10	4													Strong signal
	31	35	16	35	51	39	17	26									
	90	42	45	42					141	81	28	32	1573	2684	160	540	Deep fading
					143	55	48	37									
	72	16	36	16													
	1942	922	970	920	1961	925	650	616									
									2962	2980	590	1190					Signal lost
	1929	4191	960	4190													
					2975	6402	990	4270									
	2077	4399	1000	4390													
	2210	4320	1110	4320	3241	6508	1080	4340	5268	10868	1050	4350	8230	13848	820	2770	

Table 4.1-7

Tabulated Results of Data from Tape No. 23

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
12277.5 kHz	82	9	41	9													Very strong signal
	6	0	3	0	86	9	29	6									Severe fading
	3	1	1.5	1	5	1	1.6	0.7	91	9	18	3.6					
	4	5	2	5													QRM
	8	104	4	100	9	22	3	15	12	110	2.4	44	103	119	10	24	
	5	501	2.5	500	8	588	2.6	392									
11229.5 kHz	33	20	17	20													Fading
	17	16	8.5	16	39	26	13	17									
	10	0	5	0	21	10	7	6.6	56	36	11	44					Strong fading signal
	9	7	4.5	7													
	18	14	9	1.4	16	17	5.3	11	31	21	6.2	8.4	87	57	8.7	11	Speech QRM

Table 4.1-8

Tabulated Results of Data from Tape No. 23

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	17	55	8.5	55	28	59	9.3	40									
12227.5 kHz	2	9	1	9													Strong Signal
	7	12	3.5	12	9	10	3	6.6									
	15	9	7.5	9	15	20	5	13	12	22	2.4	8.8					Deep fading
	0	6	0	6													
	2	4	1	4	0	7	0	4.7	14	18	2.8	7.2	26	40	2.6	8	

Table 4.1-8

Tabulated Results of Data from Tape No. 24

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	Date 6.12.72
12277.5 kHz	18	4	9	4													Strong signal
	0	1	0	1	18	5	6	3.3									
	9	0	4.5	0	9	0	3	0	19	5	3.8	2					
	5	0	2.5	0													
	9	3	4.5	3	7	1	2.3	0.7	22	3	4.4	1.2	41	8	4.1	1.6	
	8	2	4	2	15	4	5	2.7									
4736 kHz	8	13	4	13	24	16	8	11									Strong signal
	24	8	12	8													Fading

Table 4.1-9

Tabulated Results of Data from Tape No. 24

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
4736 kHz	24	22	12	22													Signal lost
	13 16	7 7	6.5 8	7 7	16	10	5.3	6.6	48	24	9.6	10					Signal regained Fading
11229.5 kHz	34 12	228 120	17 6	220 120	35	348	12	232	49	350	9.6	140					Good signal Heavy QRM

Table 4.1-9

Tabulated Results of Data from Tape No. 24

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	4	6	2	6													
	20	2	10	2	9	8	3	5.3									Fading
	24	4	12	4	39	4	13	2.7	36	10	7.2	4					Rapid fading
	21	5	11	5													
	5	3	2.5	3	26	8	8.6	5.3									Good signal
	21	18	11	18	21	18	7	1.2	35	14	7	5.6					
	266	217	140	220													Deep fading
	606	742	310	740	496	382	165	253									Speech QRM
									884	971	180	388	919	985	92	197	Signal lost

Table 4.1-9

Tabulated Results of Data from Tape No. 25

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
4736 kHz	9	9	4.5	9													Good signal
	7	1	3.5	1	14	9	4.6	6									
	2	2	1	2	4	3	1.3	2	16	10	3.2	4					Fading
	11	1	5.5	1													
	6	1	3	1	12	1	4	0.7	19	4	3.8	1.6	35	14	3.5	2.8	
	20	20	10	20	25	21	8.3	14									
	44	21	22	21													Fading
	12	26	6	26	48	38	16	25	68	58	14	23					
	19	13	9.5	13	27	22	9	15									15 dB fading
	5	3	2.5	3					32	25	6.4	10	100	83	10	17	
	17	10	8.5	10	17	13	5.6	8.6									
	13	22	6.5	22	18	22	6	15									Fading
	6	15	3	15					34	38	6.8	15					Slight CW QRM
	9	10	4.5	10	7	19	2.3	13									
	12	11	6	11	20	17	6.6	11	23	30	4.6	12	57	65	5.7	14	Good signal

Table 4.1-10

Tabulated Results of Data from Tape No. 25

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 6.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
4736 kHz	4	3	2	3													
	4	14	2	1.4	7	16	2.3	11									
	1	8	0.5	8	2	9	0.6	6	8	20	1.6	8					Good signal

Table 4.1-10

Tabulated Results of Data from Tape No. 29

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 7.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	27	10	14	10													Strong fading signal
	35	38	18	38	41	25	14	17									
	25	0	13	0	46	23	15	15	74	48	1.5	19					
	32	10	16	10													Fast fading
	60	25	30	25	127	31	42	21	185	35	37	14	179	83	18	17	
	212	60	106	60	257	64	86	43									Speech QRM
	61	3	31	3													
	8	6	4	6	64	6	21	4	276	66	55	26					
	41	28	21	28	46	31	15	21									Good fading
	0	0	0	0					46	31	9.2	12	322	97	32	20	Speech QRM signal
	91	64	46	64	13	7	4.3	4.7									
	25	7	13	7	103	64	34	43									
	8	5	4	5					124	76	25	30					
	4	2	2	2	12	7	4	4.7									
	6	2	3	2	6	2	2	1.3	10	4	2	1.6	134	80	13	16	

Table 4.1-11

Tabulated Results of Data from Tape No. 29

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 7.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
11229.5 kHz	1	0	1	0	1	0	0.3	0									
	9	11	4.5	11	10	11	3	7.3									
	3	0	1.5	0													Speech QRM
	27	0	14	0	29	0	9.6	0	35	11	7	4.4					
	336	274	168	270													
	106	84	53	84	437	356	146	237	446	358	89	143	481	369	48	74	
	29	3	15	3	34	5	11	3.3									
	271	320	136	320													

Table 4.1-11

Tabulated Results of Data from Tape No. 30

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 7.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
4736 kHz	32	10	16	10													Strong signal throughout the run with occasional slight fading.
	31	5	16	5	50	12	17	8									
	22	6	11	6	35	9	12	6	72	21	14	8.5					
	23	5	12	5													
	15	3	7.5	3	32	8	11	5.3	51	8	10	3.2	123	29	12	5.8	
	21	6	11	6	27	6	9	4									
	6	8	3	8													
	18	6	9	6	15	9	5	6	36	15	7.2	6					
	19	2	9.5	2	28	7	9.3	4.7									
	10	1	5	1					38	8	7.6	3.2	74	23	7.4	4.6	
	5	11	2.5	11	13	3	4.3	2									
	20	3	10	3	22	12	7.3	8									
	37	35	19	35					27	17	5.4	6.8					
	16	25	8	25	46	55	15	37									
	11	7	5.5	7	18	12	6	8	62	64	12	26	89	81	8.9	16	

Table 4.1-12

Tabulated Results of Data from Tape No. 30

Pilot Tone = 1200 Hz

Working Frequency	T_L = 200 seconds				T_L = 300 seconds				T_L = 500 seconds				T_L = 1000 seconds				Receiver Log Comments
	$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		$\sum$		$P_e \times 10^{-4}$		Date 7.12.72
	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	P_T	FSK	
4736 kHz	18	14	9	4													
	10	1	5	1	25	15	8.3	10									
	0	6	0	6	3	6	1	4	28	20	5.6	8					
	8	7	4	7													
	10	4	5	4	11	8	3.6	5.3	18	12	3.6	4.8	46	32	4.6	6.4	
	7	3	3.5	3	14	6	4.6	4									
	10	5	5	5													
	8	21	4	21	18	14	6	10	25	17	5	6.8					
	0	11	0	11	0	23	0	15									
	9	1	4.5	1					9	24	1.8	10	34	41	3.4	8.2	
	3	0	1.5	0	11	1	3.6	0.7									
	3	0	1.5	0	4	0	1.3	0									
	13	8	6.5	8					11	7	2.2	2.8					
	4	4	2	4	13	8	4.3	5.3									

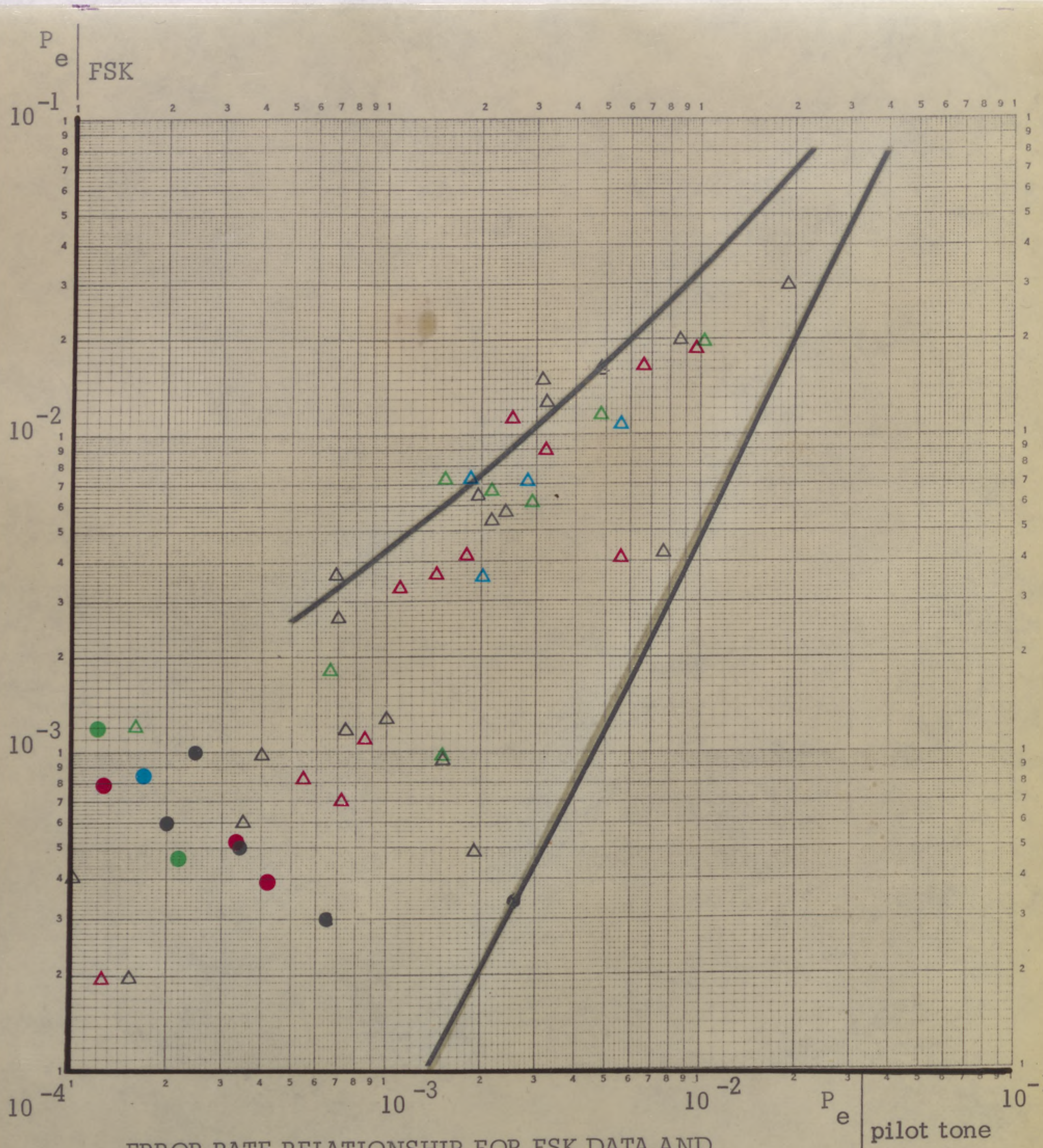
Table 4.1-12

Figure 4.1-1

4 December 1972

● 12277.5 kHz (1535-1600 GMT)
△ 13213 kHz (1604-1711 GMT)

Tape No. 16



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

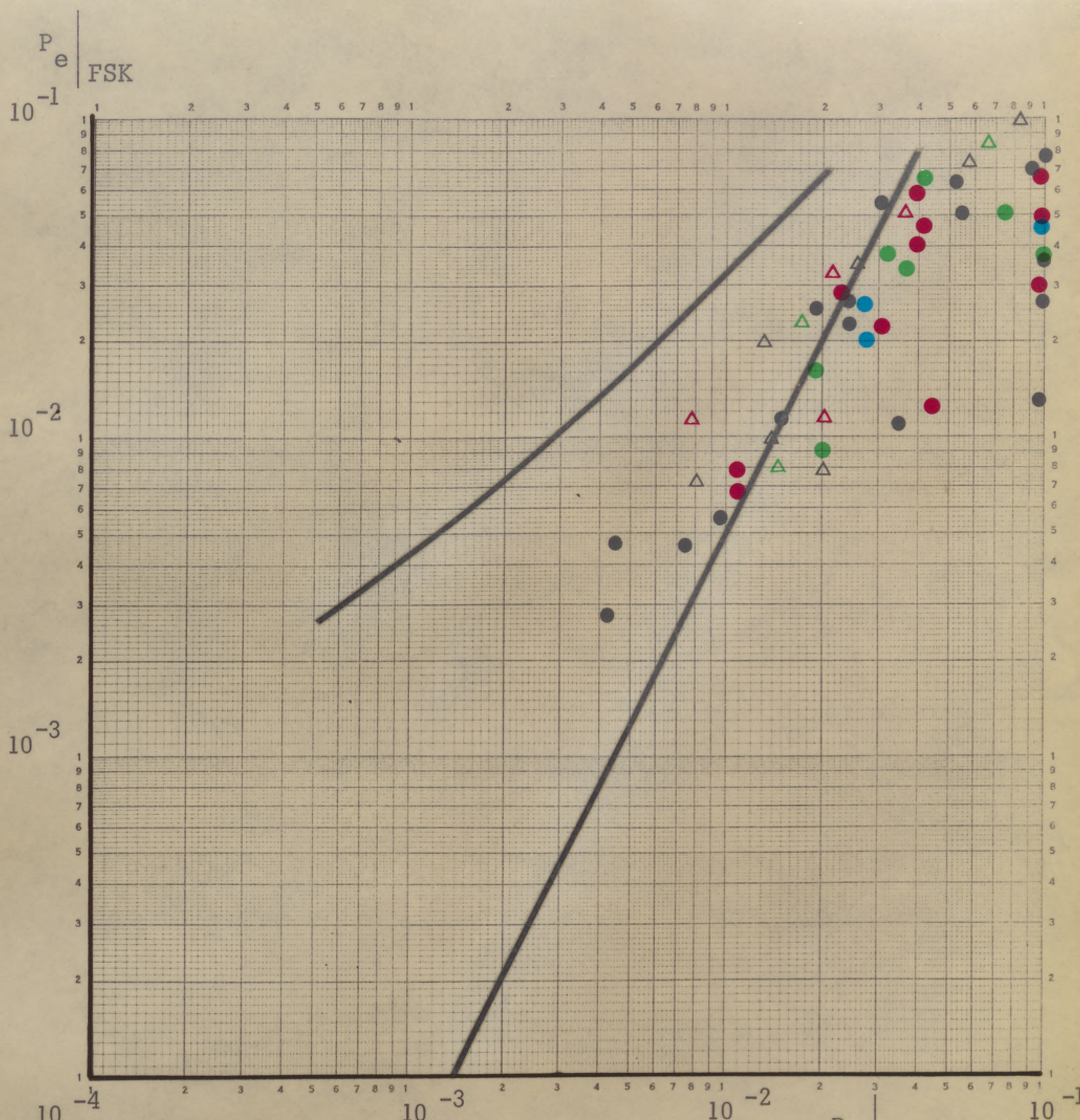
T_L = 1,000 seconds (Blue)

Figure 4.1-2

5 December 1972

● 15085 kHz (0830-0930 GMT)
△ 16065 kHz (0931-0958 GMT)

Tape No. 17



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

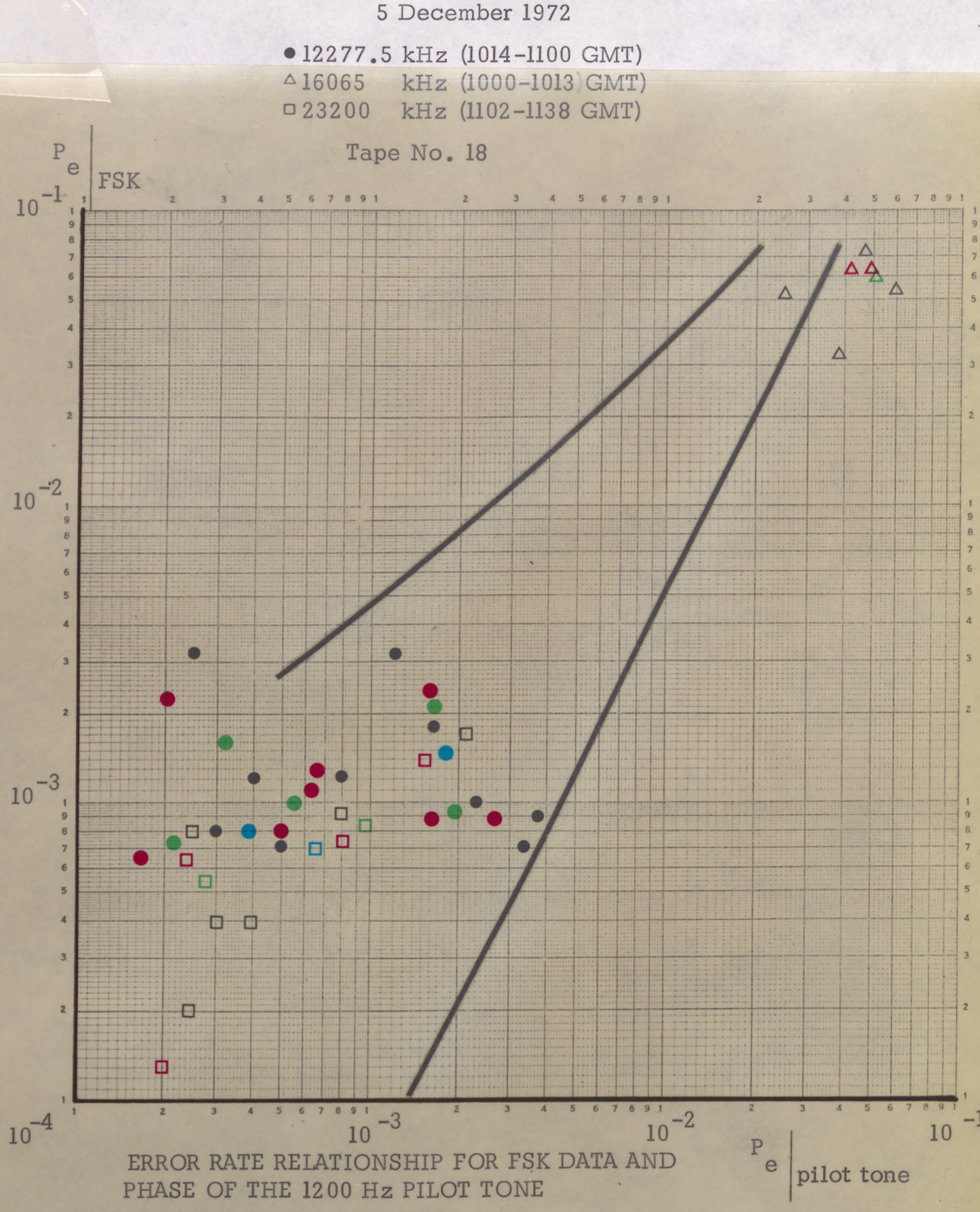
T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

T_L = 1,000 seconds (Blue)

Figure 4.1-3



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

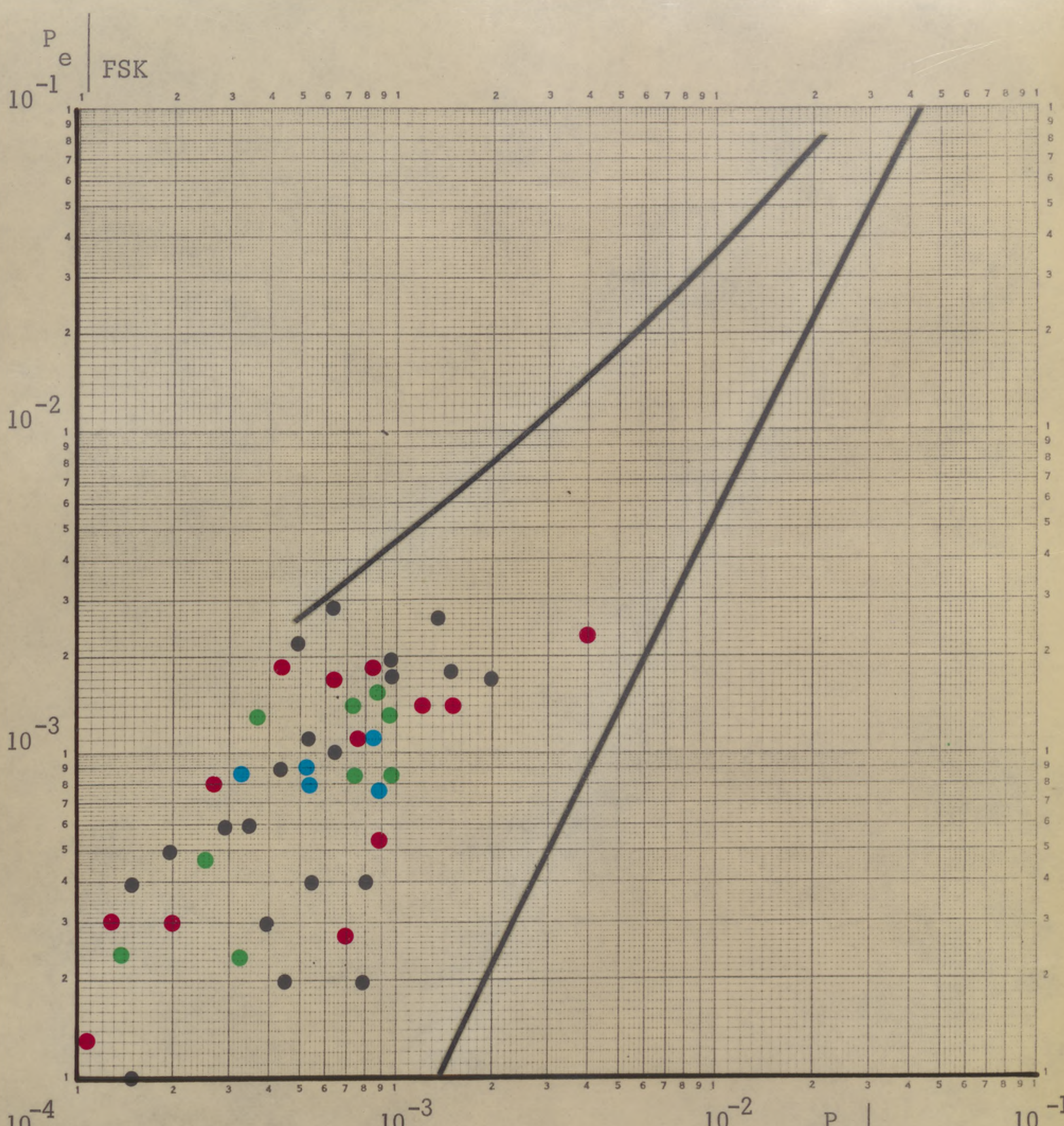
T_L = 1,000 seconds (Blue)

Figure 4.1-4

5 December 1972

● 12275.5 kHz (1346-1523 GMT)

Tape No. 19



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

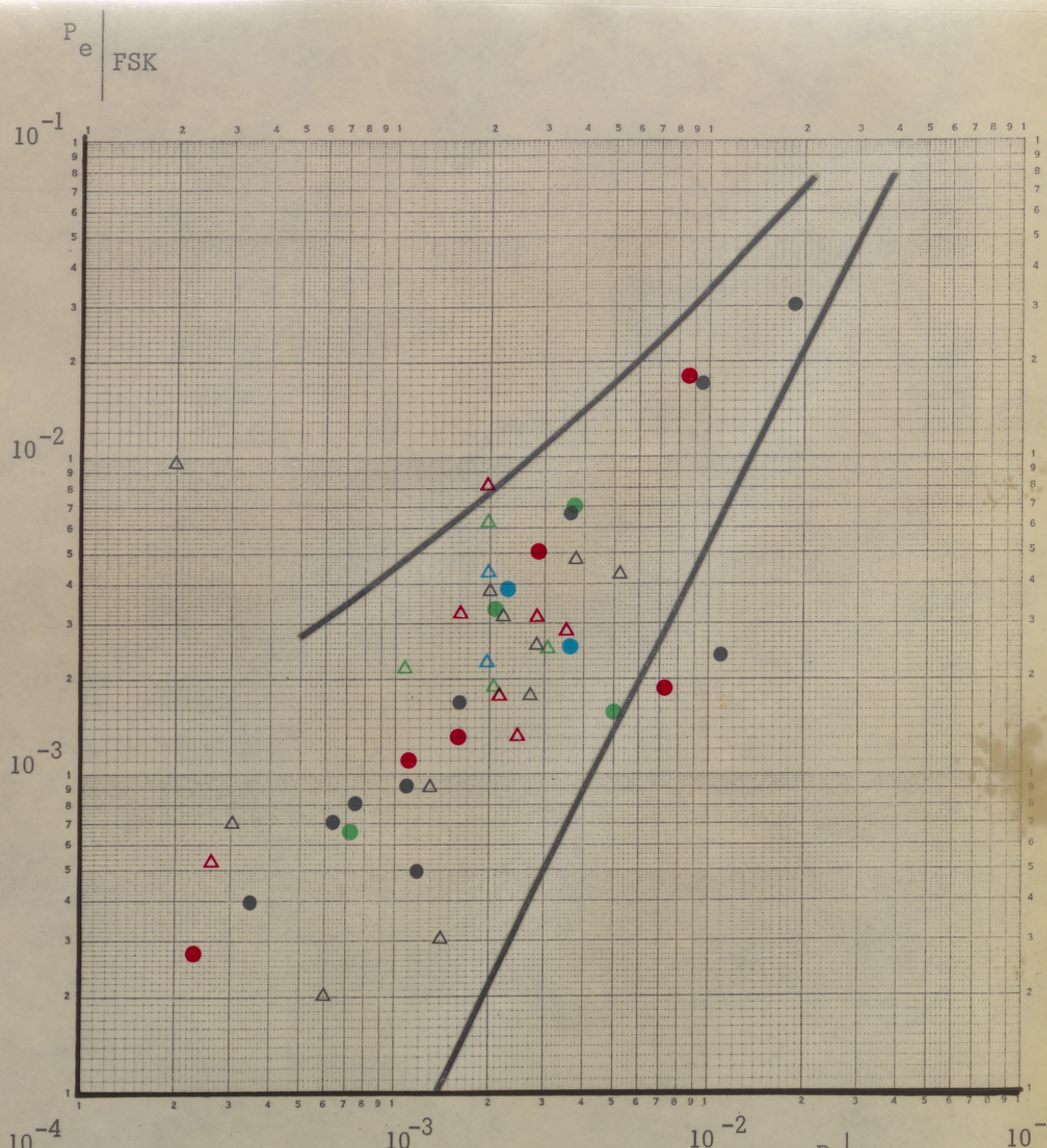
T_L = 1,000 seconds (Blue)

Figure 4.1-5

5 December 1972

● 11229.5 kHz (1645-1723 GMT)
△ 12277.5 kHz (1524-1600 GMT)
(1625-1643 GMT)

Tape No. 20



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

T_L = 1,000 seconds (Blue)

Figure 4.1-6

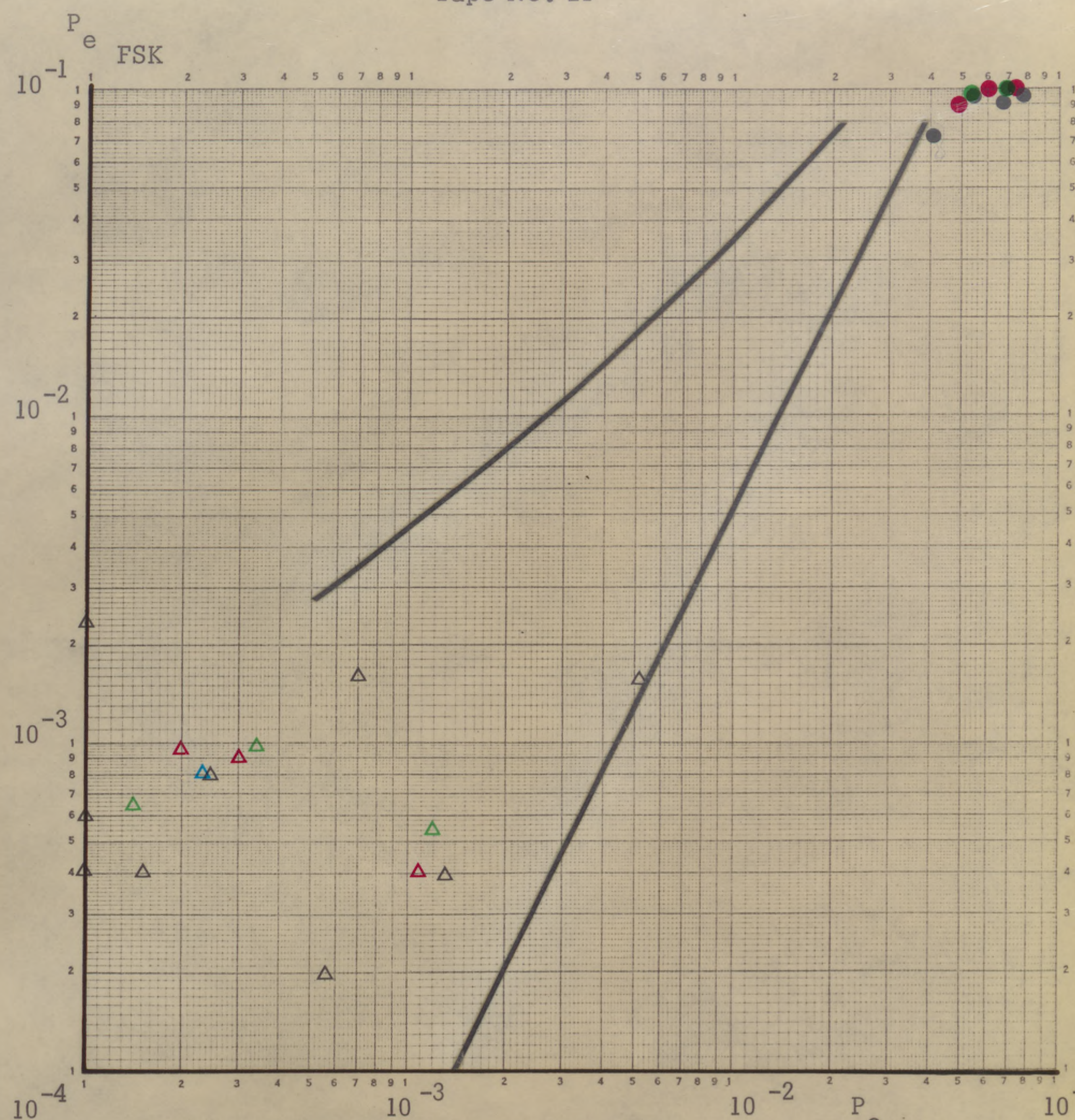
5 December 1972

● 11229.5 kHz (1724-1757 GMT)

6 December 1972

△ 12277.5 kHz (0821-0925 GMT)

Tape No. 21



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

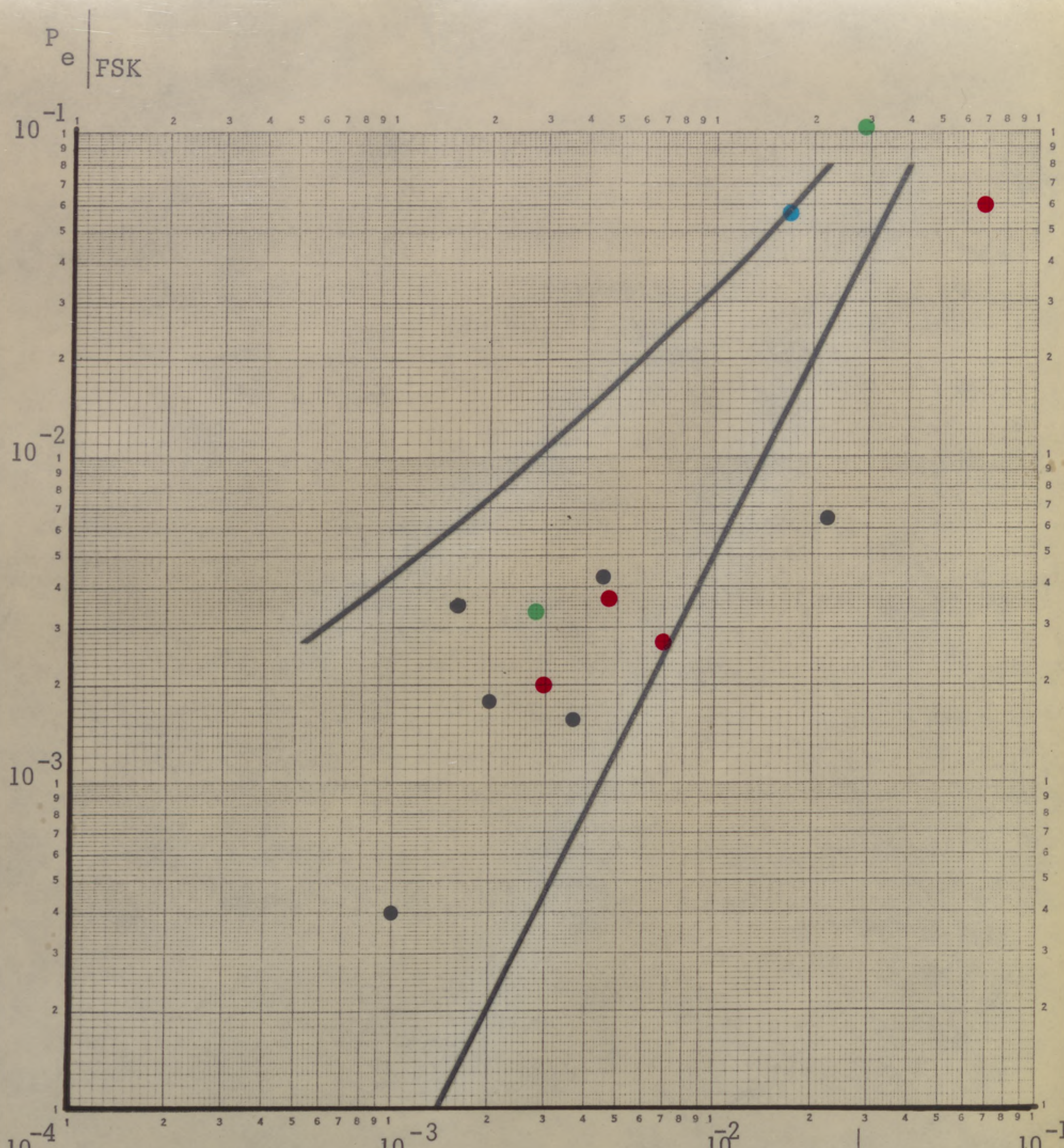
T_L = 1,000 seconds (Blue)

Figure 4.1-7

6 December 1972

● 23345 kHz (1038-1134 GMT)

Tape No. 22



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

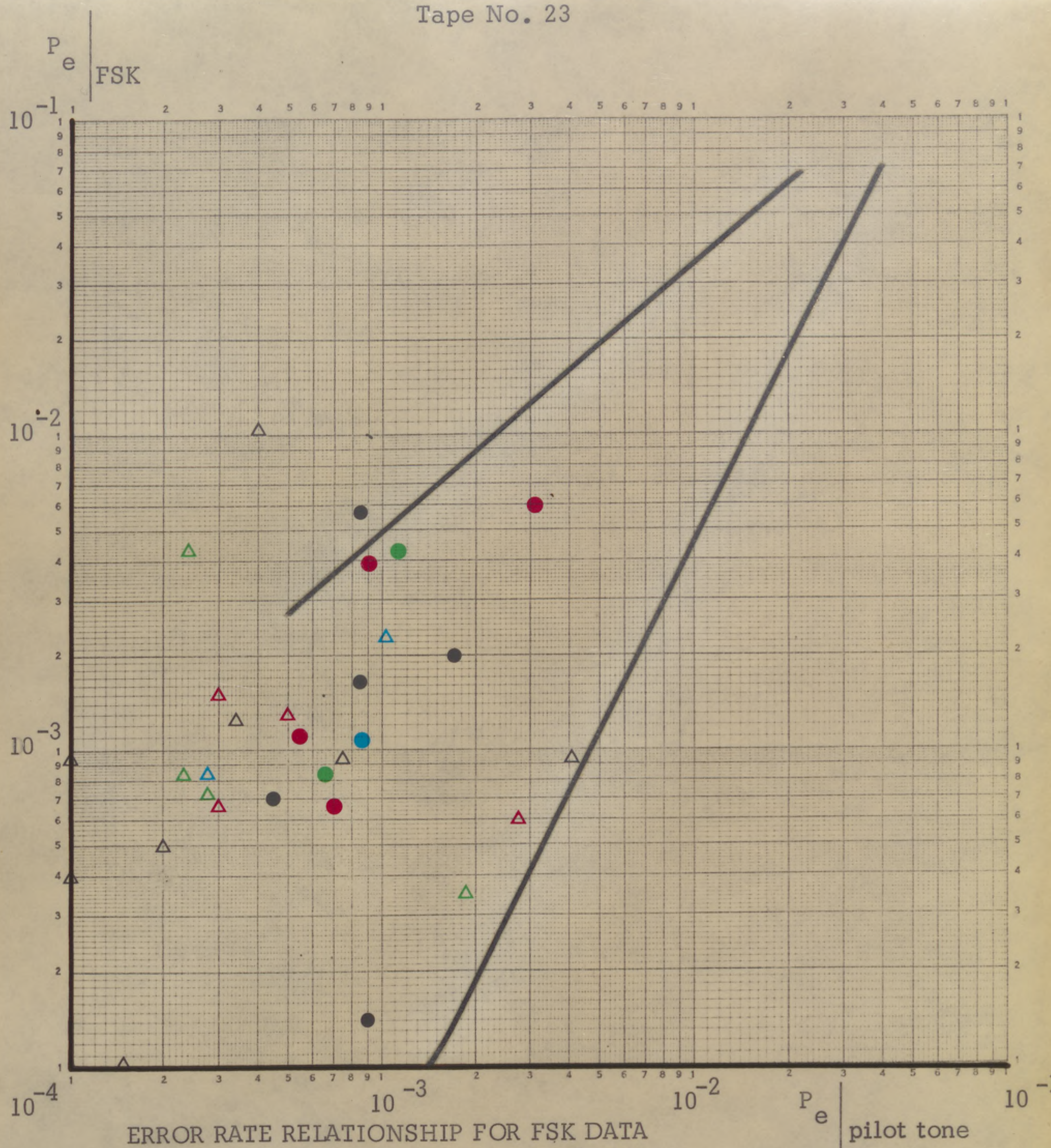
T_L = 1,000 seconds (Blue)

Figure 4.1-8

6 December 1972

● 11229.5 kHz (1431-1455 GMT)
△ 12277.5 kHz (1407-1430 GMT)
(1512-1541 GMT)

Tape No. 23



ERROR RATE RELATIONSHIP FOR FSK DATA
AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

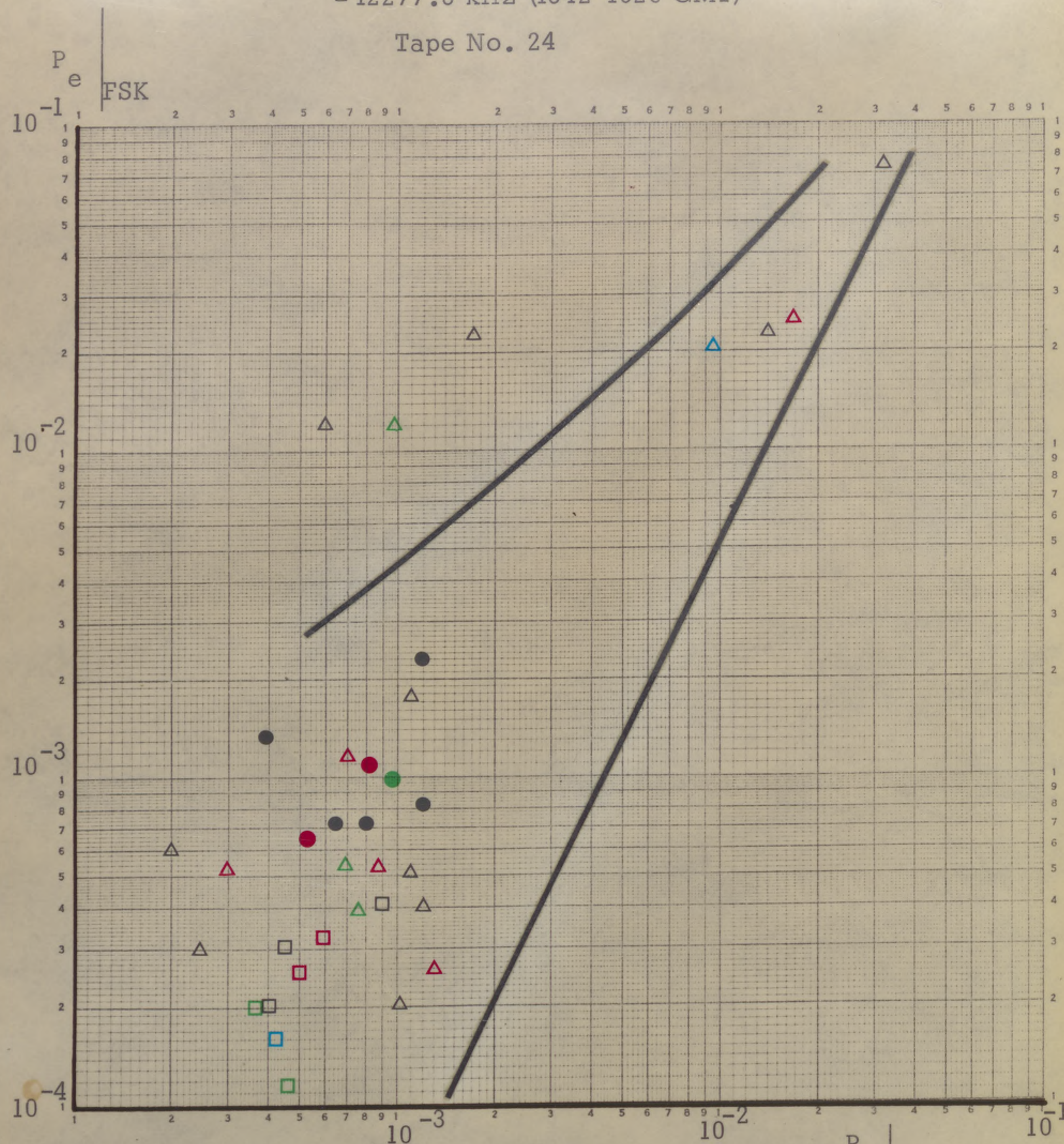
T_L = 1,000 seconds (Blue)

Figure 4.1-9

6 December 1972

● 4736 kHz (1603-1630 GMT)
△ 11229.5 kHz (1631-1718 GMT)
□ 12277.5 kHz (1542-1629 GMT)

Tape No. 24



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

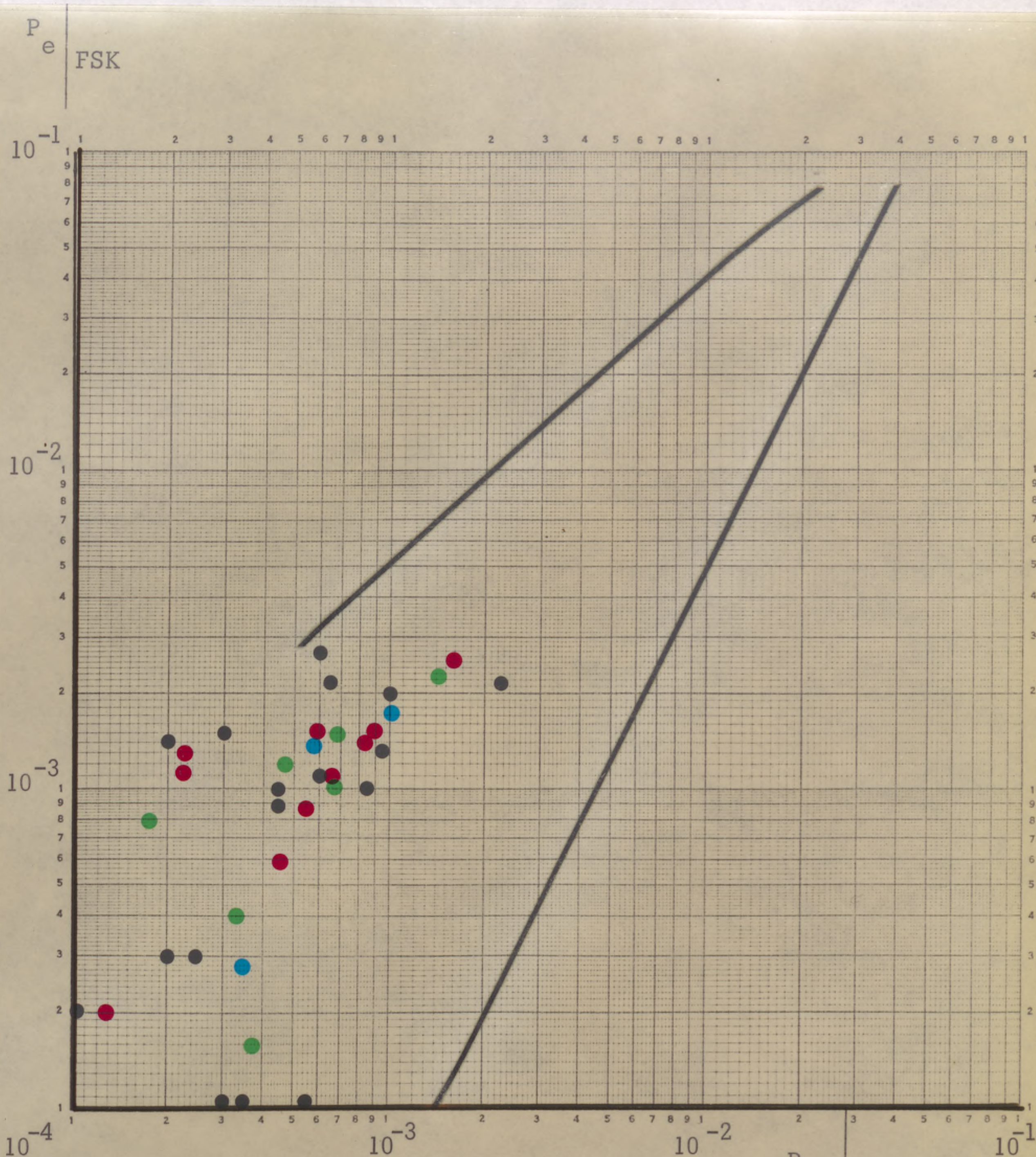
T_L = 500 seconds (Green)

T_L = 1,000 seconds (Blue)

6 December 1972

● 4736 kHz (1825-1932 GMT)

Tape No. 25



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

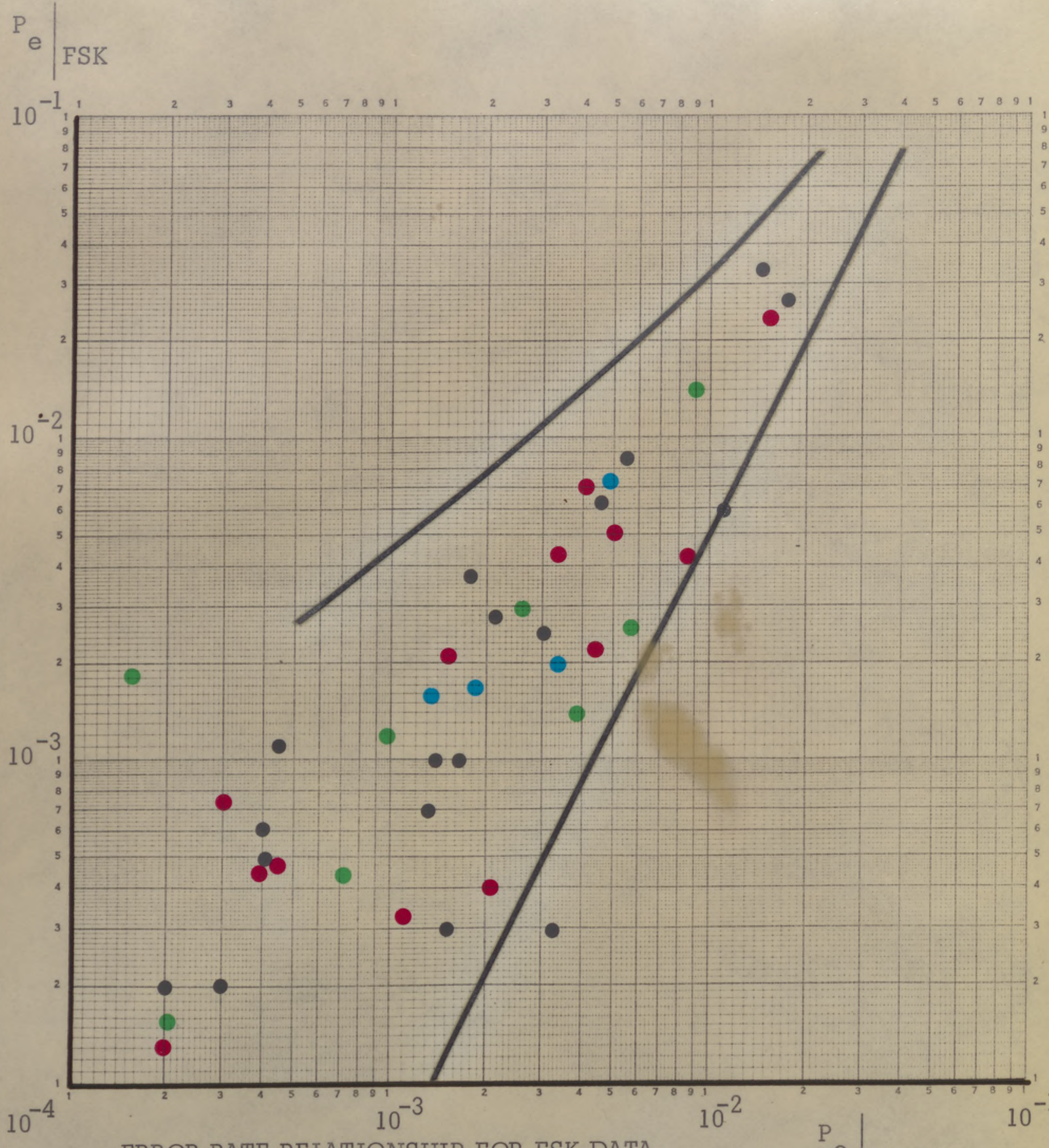
T_L = 1,000 seconds (Blue)

Figure 4.1-11

7 December 1972

● 11229.5 kHz (1526-1650 GMT)

Tape No. 29



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

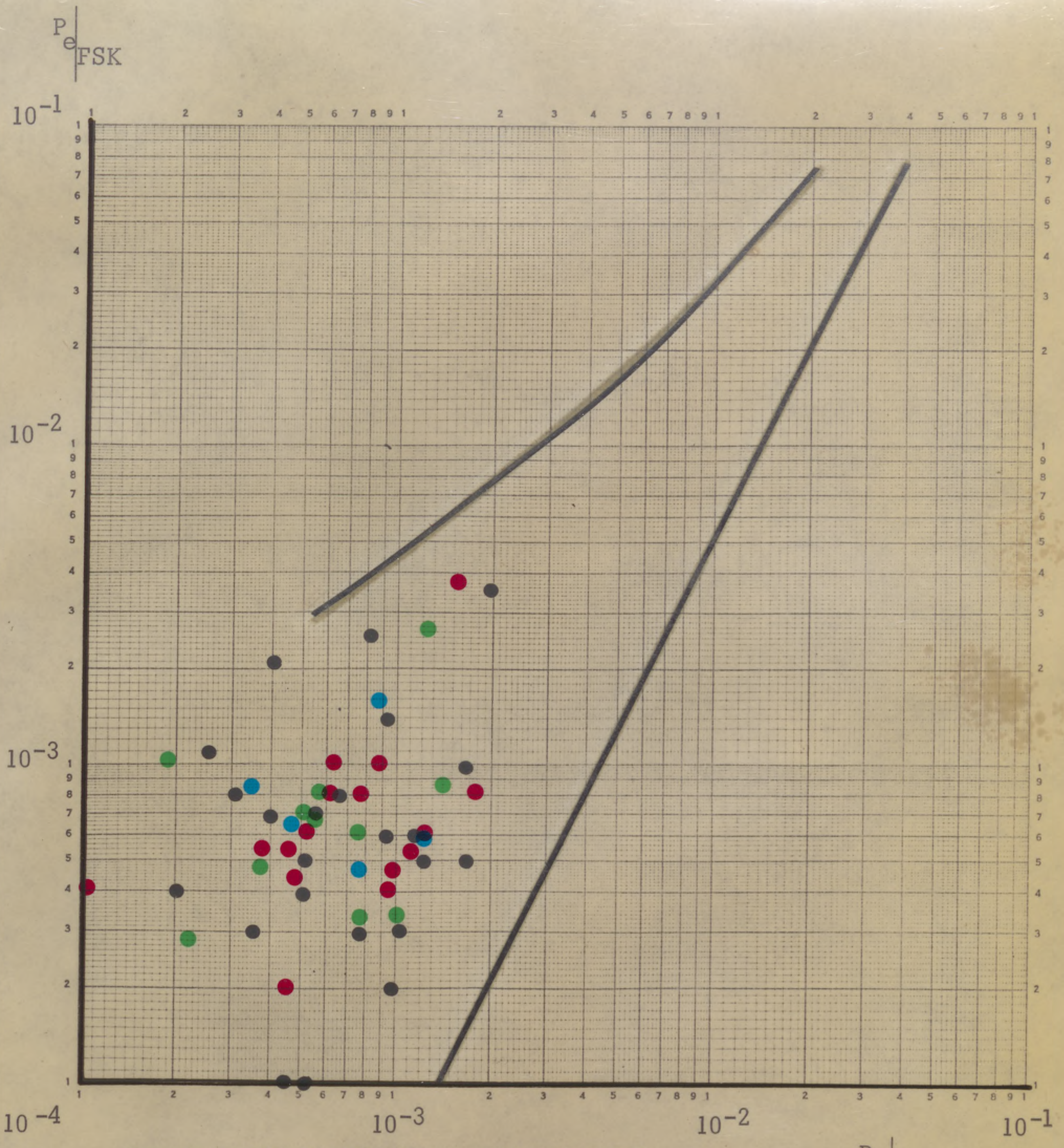
T_L = 1,000 seconds (Blue)

Figure 4.1-12

7 December 1972

● 4736 kHz (1812-1942 GMT)

Tape No. 30



ERROR RATE RELATIONSHIP FOR FSK DATA AND PHASE OF THE 1200 Hz PILOT TONE

T_L = 200 seconds

T_L = 300 seconds

T_L = 500 seconds (Green)

T_L = 1,000 seconds (Blue)

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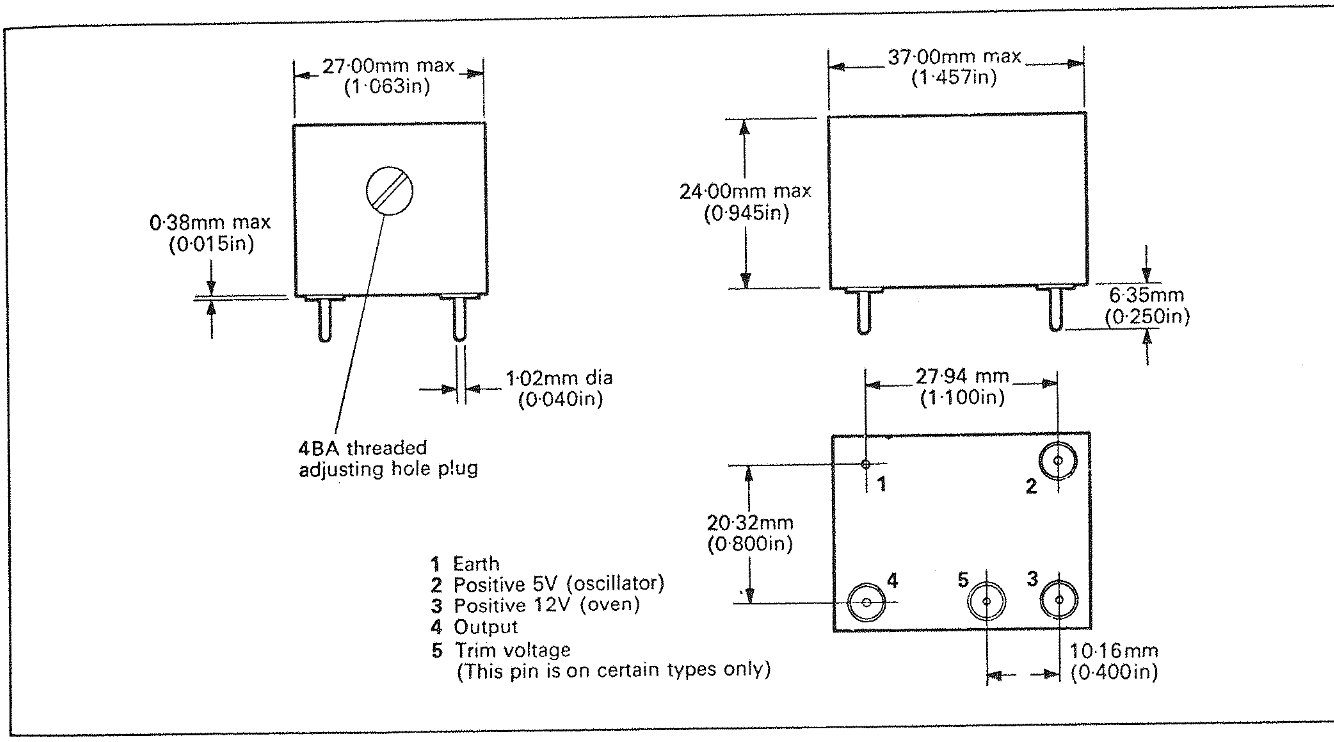
APPENDIX I

CRYSTAL OSCILLATOR UNIT SPECIFICATION

Manufacturer:	Salford Electrical Instruments Limited
Type:	QC 1311
Oven:	Proportional temperature-Controlled

The output of this unit is logic-compatible

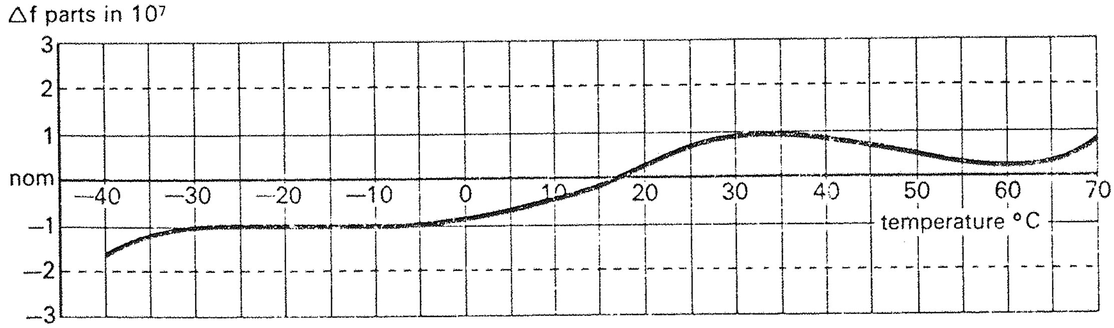


Specification

Output frequency	250kHz—30MHz	Supply voltage to oscillator	+5 volts (±10%) at 60 mA maximum
Frequency stability/ temperature		Supply voltage to oven	+12 volts
−10°C to +60°C	±1 in 10^7	Power consumption of oven	1·2 watts at 25°C; 6 watts maximum at switch on
−40°C to +70°C	±2 in 10^7		
Output voltage high	>2·4 volts		
low	<0·45 volts		

Mechanical trimming is available to compensate for ageing. (1311T)

Typical frequency temperature characteristic



APPENDIX 2

Data Print-Out Examples

Table 4.1-5 (Tape 20)

FSK | Pilot tone (1200 Hz)

0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	1	0	0	1
0	2	7	0	3	4
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	7
0	1	1	0	2	5
0	0	2	0	0	8
0	0	0	0	0	0
0	0	1	0	2	3
0	0	1	0	0	5
0	0	0	0	0	2
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	3

Strong signal; slight CW QRM

Table 4.1-6 (Tape 21)

FSK | Pilot tone (1200 Hz)

1	1	3	0	7	1
0	0	1	0	8	2
1	0	0	0	6	9
0	0	2	0	7	1
1	7	9	1	1	5
0	0	5	1	0	9
1	3	2	0	9	1
0	0	2	0	7	5
1	2	8	1	0	3
0	0	9	0	6	4
1	3	3	0	7	5
0	0	5	0	7	6
1	4	6	0	8	2
0	0	5	0	9	6
0	7	4	0	6	7
0	0	3	0	6	2
0	9	3	0	8	1
0	0	1	0	7	4
1	0	7	0	6	4
0	0	2	0	7	0
0	8	9	0	6	5
0	0	3	0	5	2
1	0	1	0	7	2
0	0	8	0	4	2
0	7	5	0	7	8
0	0	8	0	7	3
1	0	0	0	6	8
0	0	5	0	6	8
0	9	4	0	5	5

Weak signal; heavy speech/CW QRM.

APPENDIX 2

Data Print-Out Examples

Table 4.1-11 (Tape 29)

FSK			Pilot tone (1200 Hz)		
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	1	4
0	0	0	0	2	7
0	0	0	0	0	0
0	0	3	0	2	0
0	0	1	0	1	4
0	0	5	0	5	7
0	1	1	0	4	1
0	0	0	0	0	0
0	1	1	0	1	0
0	0	0	0	2	6
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	1	1

Good but fading signal
with speech QRM

Table 4.1-12 (Tape 30)

FSK			Pilot tone (1200 Hz)		
0	0	4	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	3
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	1
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	3
0	0	0	0	0	0
0	0	1	0	0	1
0	0	0	0	0	2
0	0	0	0	0	0
0	0	0	0	0	2
0	0	0	0	0	0
0	0	0	0	0	0
0	0	0	0	0	1

Strong signal with occasional
slight fading

APPENDIX 3

Example of Ellington Program Read-out for Filter Design

```
10 POLE FILTER
SECTIONS ARE:

CENTRE FREQUENCY=           790.00HZ.,Q=        13.64
-3DB. FREQUENCIES ARE       818.95HZ. AND      761.05HZ.
R1/R2=  .2566503,R*C= 2.849102-04
CENTRE FREQUENCY GAIN=  47.24

CENTRE FREQUENCY=           697.16HZ.,Q=        44.50
-3DB. FREQUENCIES ARE       705.00HZ. AND      689.33HZ.
R1/R2=  .2520022,R*C= 3.228495-04
CENTRE FREQUENCY GAIN= 156.33

CENTRE FREQUENCY=           895.20HZ.,Q=        44.50
-3DB. FREQUENCIES ARE       905.26HZ. AND      885.14HZ.
R1/R2=  .2520022,R*C= 2.514294-04
CENTRE FREQUENCY GAIN= 156.33

CENTRE FREQUENCY=           731.15HZ.,Q=        16.92
-3DB. FREQUENCIES ARE       752.76HZ. AND      709.54HZ.
R1/R2=  .2553366,R*C= 3.078427-04
CENTRE FREQUENCY GAIN=  58.81

CENTRE FREQUENCY=           853.59HZ.,Q=        16.92
-3DB. FREQUENCIES ARE       878.82HZ. AND      828.36HZ.
R1/R2=  .2553366,R*C= 2.636861-04
CENTRE FREQUENCY GAIN=  58.81
```

Solutions for 850 Hz Filter of WBFSK Demodulator