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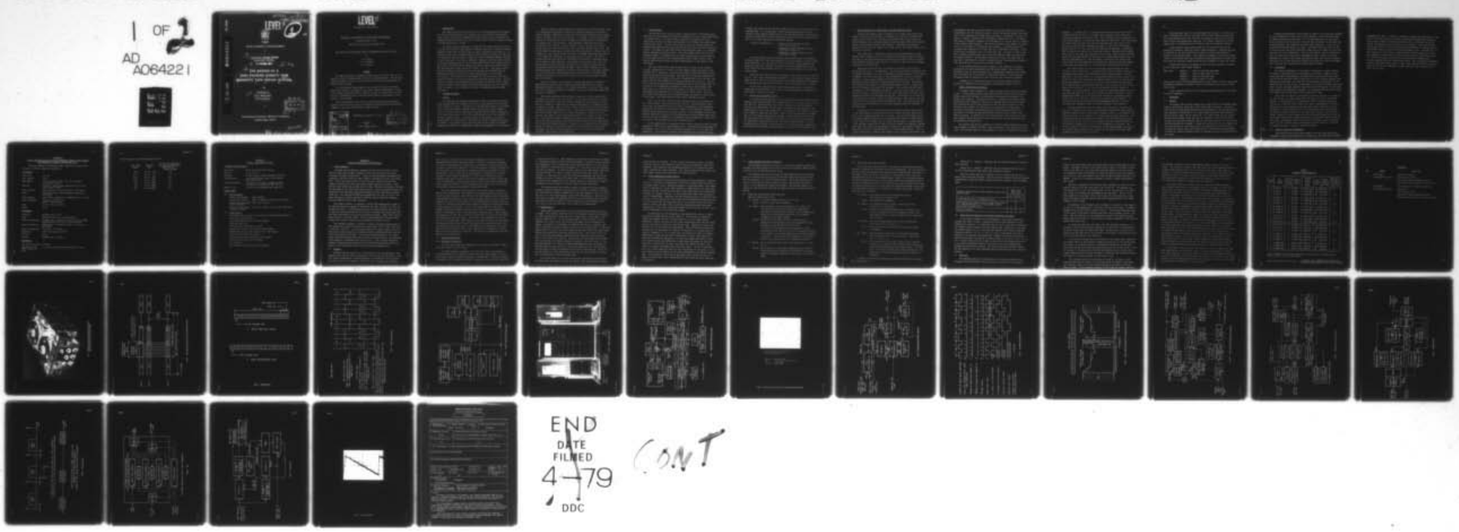

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(6) THE DESIGN OF A HIGH PACKING DENSITY PCM MAGNETIC TAPE REPLAY SYSTEM.

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THE DESIGN OF A HIGH PACKING DENSITY PCM MAGNETIC TAPE REPLAY SYSTEM

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SUMMARY

The Report describes a PCM magnetic tape replay system developed for the replay of airborne recordings made at high bit packing densities. The high data capacity provided is likely to be able to meet all future RAE requirements for aircraft flight testing.

The record/replay systems employ a new multi-track serial word format particularly suited to recording in very severe airborne environments. Design of the replay system places special emphasis on ease of operation and the provision of a comprehensive error correcting system enables a high degree of data security to be obtained.

Brief descriptions of the airborne recording and replay data handling systems are given and the results of performance testing presented with general comments on the choice and handling of magnetic tapes.

Departmental Reference: IT 156

1 INTRODUCTION

This Report describes the principles of a high packing density PCM magnetic tape replay system developed as an integral part of an airborne record/ground replay system, suitable for comprehensive flight testing in the development and acceptance phases of military and civil aircraft and for specific research projects involving experiments in flight.

The ground system is designed to replay and edit flight tapes with the aid of quick look UV records under manual or computer control and to produce computer compatible tapes from the edited tapes for more comprehensive data analysis. As numerous replays may be required during the data analysis provision has been made to produce copy tapes in order to reduce the risk of accidental damage occurring to the flight tape. The system is designed to operate with flight tapes recorded at linear packing densities of either 400 bits/mm (10K bits/in) Bi-phase space or 800 bits/mm (20K bit/in) Delay Modulation on which words are recorded serially on the tape using multi-track formats on 25.4mm (1 in) tape. This system complements the existing PCM parallel word replay systems, at RAE Farnborough and RAE Bedford, which work at the now modest packing density of 40 bits/mm (1K bits/in). The inclusion of a high degree of error correction offers data security comparable to that of the existing low packing density system. Built-in flexibility permits the simultaneous use of multiple acquisition and recording systems in order to obtain higher system data rates and can with minor modifications be adapted to suit 12.7mm wide tape and to accommodate other encoding techniques.

2 AIRBORNE RECORDING

2.1 General

The complexity and advanced technological nature of present-day military weapon systems and civil aircraft give rise to a vast quantity of trials data from a variety of sources. The majority of the data which needs to be recorded is in the form of analogue voltages; however other sources, whose number is likely to increase, are in coded digital form provided by digital transducers whilst some consist merely of two states indicating on-off or the occurrence of an event (bilevel inputs). The total number of data sources, as expected, varies greatly with the nature of the project for which the acquisition system is required. Two extremes may be ventured, about 50 for a specific research experiment and 2000 for a comprehensive flight test programme on a new aircraft.

When the number of input parameters for recording is large the current trend is to arrange the analogue data sources in a number of groups and to provide a separate package, comprising the functions of filtering, amplifying and analogue/digital conversion, for each of the groups. For example, a system with an input capacity of 256 parameters could be arranged in 16 groups each of 16 parameters or 8 groups each of 32 parameters. These packages, termed the remote data acquisition units (RDAUs), are then located as near as possible to the data sources they serve and are controlled from a centrally located control unit. The serial output from each group, together with data presented in a digital form, is transmitted to the central control unit with a consequent reduction, which may be of very significant magnitude, in the weight and cost of cable. This decentralised approach also contributes flexibility by providing a convenient option in the number of RDAUs employed. These inputs to the control unit, after any specialised processing required, are combined via a digital multiplexer, and synchronising and parity information added. They are then converted into the recording format and transmitted in serial or parallel form to the tape transport. The control unit holds the programme required for control of the multiplexing sequence and selection of the recording speed and also provides address information to the RDAUs.

The tape transport must be capable of making high quality recordings at high packing densities in the severest environment experienced in a highly manoeuvrable military aircraft. The leading particulars of a typical tape transport (Fig 1) specially designed for airborne recording in severe environments are presented in Appendix A.

Multi-track recording allows two basic formats for the bit configuration recorded on the tape, serial and parallel. In the serial format the bits associated with a particular sample are recorded sequentially on one track, or alternatively, a number of tracks may be recorded simultaneously, each taking a word or sequence of words. This alternative demands as many sets of write electronics as there are tracks in simultaneous use. In the parallel format the bits associated with the data sample are all recorded simultaneously transversely across the tape, the number of tracks provided being equal to the number of bits in the word. The choice of format is determined by the overall system requirements, record and replay data rates, tape width and speed, packing density requirements and reliability (or data security). The serial format clearly allows the greater degree of flexibility and a multi-track serial record format has been devised and adopted for RAE use that has properties particularly suited to airborne recording. This format is described below.

140

2.2 Record formats

The airborne record circuits accept a single stream of multiplexed serial words from the data acquisition system and distribute it into a multi-track serial word format (Fig 2). The data stream is encoded for recording and 16 bit synchronisation words are added simultaneously to all tracks, interposed between blocks of data words. On replay these words are used as reference points for deskewing and demultiplexing operations and are also used in the error correction process. The number of data words between synchronisation words is a compromise between redundancy and data security. The record format chosen results in an acceptable degree of redundancy for this type of application, and by selecting the same number of bits in the synchronisation word as there are data words between synchronisation words, the logic implementation of the format is made very simple.

The multi-track serial format selected uses 14 tracks of the standard 28 track configurarion on 25.4mm (1 in) wide magnetic tape conforming to IRIG Standard 106-73[1] (using one 14 track in-line head), encoded data being recorded using partial saturation recording. Each data word is recorded longitudinally and is comprised of a number of data bits followed by one edit bit and one 'odd' parity bit, the least significant bit being recorded first, (Fig 3a). The edit bit is obtained by sequentially multiplexing each bit of a 64 bit edit word containing all the housekeeping information, *eg* data syncs, flight number, GMT, frame count, etc, into the serial data stream. On replay the edit bits are demultiplexed and presented at the output as 64 bit serial words. The 16 bit tape frame synchronisation word is inserted between each block of 16 data words on each track. This frame synchronisation word is defined in Fig 3b.

Track 1 is used for recording 'even' transverse parity bits derived from the 13 data tracks. This track, referred to as the 'transverse parity track' in the text, is inhibited for the bit period corresponding to the longitudinal word parity; this period is then used to insert an 'odd' parity bit generated from the serial parity bits of the parity track. This arrangement of serial and parallel parity bits together with the synchronisation words enables data detection and correction techniques to be applied; these are explained in detail later in the text. The recorded tape format is shown in Fig 2.

As the replay system is expected to have a service life of at least 10 years, a degree of flexibility has been provided in it. The system has been designed to accommodate 8, 10, 12 and 14 bit data words recorded in 4, 7 or 14 track configurations. This flexibility permits the simultaneous use of multiple record systems, each using less than the full number of tracks, on one 14 track in line recording head. If a large number of high frequency parameters have to be recorded and the maximum sampling rate for one individual system of 64K words per second is insufficient for this, the effective data rate may be increased by the use of two or more complete data acquisition systems.

Possible combinations are

1 Single 14 track configuration data acquisition system, or

2 Independent 7 track configuration data acquisition systems, or

3 Independent 4 track configuration data acquisition systems.

The ground system can also be used to replay records made on reversible recorders using 4 or 7 track configurations in multiple passes to achieve longer record durations. Also in order to avoid drop-outs due to edge damaged tape which may occur due to airborne recording at very high temperatures a further track variant has been provided; this is a 7 track configuration using only the centre tracks.

The above tape formats result in redundancy levels of 28, 35 and 54 per cent for 14, 7 and 4 track configurations respectively. The relatively higher percentages for the 7 and 4 track configurations are a trade-off against the advantages of increased system data rates which result from using multiple record systems.

All the above combinations of track configuration and data acquisition systems may be increased by a factor two by the simultaneously recording on two interlaced 14 track in-line heads.

2.3 Record code and packing density

At recorded packing densities in the range 200-400 bits/mm (5K-10K bits/in), Bi-phase space encoding (IRIG 106-73 transition for '1' in centre of bit cell) is used (Fig 4). Delay Modulation Mark (Miller encoding) is used for packing densities from 400 bits/mm (10K bits/in) up to 800 bits/mm (20K bits/in). The packing density for a given sampling rate is determined by the number of bits per word, number of tracks and tape speed. Table 1 lists the combinations of these that can be accepted using Bi-phase encoding. Other packing densities within the range 200 to 800 bits/mm can be provided for but require the provision of the appropriate timing oscillators for the ground replay equipment. All the packing densities in Table 1 may be doubled by either doubling the sampling rate or halving the tape speed, and recording the data in the Delay Modulation code.

3 BRIEF DESCRIPTION OF GROUND REPLAY AND DATA HANDLING SYSTEM

Airborne PCM magnetic tapes, recorded in the multiple track serial word format at high packing densities, are processed at a centrally located ground replay facility (Figs 5 and 6) which provides quick-look UV trace records of selected parameters and produces computer compatible tapes (CCTs) under computer control for subsequent automatic data analysis. The present system uses a Honeywell type 516 digital computer for system control, but manual control can be selected if required.

The flight tape is replayed on a high quality instrumentation recorder (primary tape transport) but as the data analysis may require numerous replays, a copy tape at lower packing density is produced using another similar instrumentation recorder (secondary tape transport) in order to reduce the risk of damage occurring to the flight tape.

Replay data from each track is amplified and limited in the recovery electronics and fed to a word processor. In the word processor the encoded data is decoded into NRZ-L, all tracks are deskewed and where possible error correction is applied. The multi-track data is then reformatted by a serial to parallel converter, the word output sequence produced being identical to that of the acquisition system serial word output sequence before recording. The parallel data words are then passed to a hardware demultiplexer at up to a maximum data rate of 262K words/s *via* an edit bit processor. This extracts the edit words containing all the housekeeping information. Sections of the flight record of particular interest are identified with the aid of quick-look UV traces of key parameters produced from the demultiplexed data. The position of the tape sections selected for further analysis are identified by a coded trace on the edge of the UV record controlled by the recorded edit words. The selected data can subsequently be re-recorded on to CCTs under computer control by reference to the edit words.

Transfer of a full length flight tape onto CCTs is rather impracticable, as the large amount of data stored on one full flight tape would require many CCTs for the complete transfer of all the data. Also with the present system the maximum computer input rate for CCT generation is limited to 4092 words/s. A full 203mm (8 in) diameter reel of flight tape recorded at a packing density of 400 bits/mm, replayed at 47.6 mm/s ($1\frac{7}{8}$ in/s) to match the computer's maximum word input rate, would take approximately 16 hours for the complete transfer of data using 35 CCTs at a packing density of 32 bits/mm (800 bits/in). This is clearly impractical in terms of both numbers of CCTs required and transfer time

140

and emphasises the need for severe editing to reduce the amount of data being transformed to CCT for detailed analysis. Also at the present maximum input data rate for CCT generation the flight tapes would have to be replayed at a very low speed (11.9 mm/s), resulting in an unacceptable signal/noise ratio. The replay tape speed is therefore increased by re-recording on to the copy tape at a quarter of the original packing density. This allows a minimum replay speed of 47.6 mm/s ($1\frac{7}{8}$ in/s) to be used on the secondary tape transport. The speed range of the secondary tape transport is 47.6 mm/s ($1\frac{7}{8}$ in/s) to 3048 mm/s (120 in/s), so that the data may be replayed at up to 32 times real time. Provision is made to produce a second low density copy tape in case the original flight tape should not be readily available. During replay the quality of either the flight tape or copy tape is monitored by a series of decimal displays representing the degree of error detection and correction that has been achieved.

To aid system testing and fault diagnoses a test generator to simulate recorded data has been incorporated into the replay system. Data formats are provided to test all operating modes and a comprehensive combination of defined fault conditions can be introduced to simulate the effects of tape drop-outs, providing a means of checking the error detection and correction procedures.

A summary of the leading particulars for the ground replay system is presented in Appendix B and a photograph of the physical hardware in Fig 6.

4 REPLAY SYSTEM DESIGN PRINCIPLES

A schematic block diagram of the complete ground replay system is presented in Fig 7. High packing density flight tapes recorded in the multi-track serial format using either Bi-phase or Delay Modulation encoding are replayed on the primary tape transport. Each head track output is amplified and limited, Delay Modulation encoded signals are decoded into standard NRZ-L form and re-encoded into Bi-phase and the Bi-phase carriers are then fed from the primary to the secondary tape transport for recording at low packing density (copy tape). No data error corrections are applied during the copy process; re-recording is performed by recording the amplitude-limited Bi-phase carriers without intermediate decoding. In parallel with the copying process, data output from either tape transport may be selected for quick-look (Fig 5), and the tape quality may be assessed as discussed below.

For analysis and display purposes the limited Bi-phase waveform from either 140
tape transport is decoded into NRZ-L using a synchronous clock generated for each track. The decoded outputs are then deskewed in order to re-establish track data

alignment. To achieve this, the decoded output from each track is fed first to a frame sync store and then to two deskew stores assigned to that output and operating alternately on each data frame. Each frame sync store is comprised of a serial shift register, and stores one data frame for each track. Two 16 bit parallel output shift registers store the two associated sync words (see Fig 13). Track sync is detected by comparing the outputs of each 16 bit serial shift register with 16 bit fixed sync words for complete bit agreement. Immediately sync is detected the output of the frame sync store is switched from one deskew store input to the other thus ensuring no loss of data. When all the track sync detections have been acquired the data held in the appropriate deskew stores is read out simultaneously at a rate sufficient to allow for tape timing errors. Frame status lines (see Appendix C) indicating the validity of the data frames of each track are generated from their respective sync-recognition circuits.

The deskewed words from all tracks are next passed through the error checking system, where checks on the frame status lines, followed by serial and transverse parity checks, are performed to correct, where possible, erroneous data words. The first check is on the individual frame sync status lines; if all are found to be correct the serial word parity checks for all the parallel word groups are implemented. Two flag bits, A and B, are generated for each word, bit A representing a corrected word, and bit B, a word found to be in error but unable to be corrected. In the latter case the data words are passed on unchanged. It is not possible, with the correction techniques adopted, for the corrected word parity bit to be generated from the parity track data. This is because the relevant bit on the parity track is used for longitudinal parity checking and is not therefore available for transverse parity checking. For these words the parity bit is generated independently with the aid of the corrected flag information after the serial to parallel word conversion.

To speed up editing of the copy tapes, data contained in the edit words have to be examined by the computer in both forward and reverse replay modes to identify sections of data for subsequent transfer to CCTs. It is essential that the correct word and bit sequences are obtained in both replay directions. The track arrangement is therefore switched prior to the serial-to-parallel word conversion to provide the correct word sequence and after conversion data bits are switched to enable the correct word bit weighting to be retained. The serial to parallel converter is essentially a track demultiplexer, the order of the parallel words produced being identical to the order of the serial words produced by the data acquisition system.

These operations result in a discontinuous flow of data. In order to provide a continuous data flow for the quick look UV trace recorders the data and the two multiplexed word status flag bits are passed through a silo to provide output data at the average input word rate. All outputs, together with a word timing clock, are buffered with line drivers to match the computer interface.

A data simulator, generating encoded data in the various multi-track formats is provided to check the overall system performance. Simulated data can be connected to the record head driver circuits of either tape transport or directly to the decoder inputs. Test signals are produced in the form of simple 'cyclic' word patterns which may be encoded in Delay Modulation or Bi-phase code. With these test patterns system testing and fault diagnosis is made very simple.

A visual indication of the degree of data correction achieved is provided by four cumulative count decimal displays.

These are:-

Display 1 - Count of corrected tape frames
Display 2 - Count of tape frames in error
Display 3 - Count of corrected words
Display 4 - Count of words in error.

Sync or word errors occurring simultaneously on two or more tracks are uncorrected. An additional display is provided to give an indication of the tracks on which errors occur.

A more detailed description of the design and implementation of the system is given in Appendix C.

5 DISCUSSION

5.1 General

The present PCM recording systems used in RAE flight test programmes employ parallel word formats operating at about 40 bits/mm (1K bits/in). The multi-track serial word PCM system described has been designed to use the same airborne data acquisition systems which, by a simple change of plug-in data-formatting printed circuit cards, can now provide up to 20 times increase in data capacity. This has been achieved without the need for elaborate or critical day-to-day setting up of the replay equipment, and the operating procedures for the airborne recording systems are unchanged. Although the replay system is more complex than the existing parallel word format system, the performance achieved has fully justified the design, which has followed the well established design philosophy of making the airborne equipment simple and keeping any necessary complication on the ground.

Quoting the performance of PCM systems in terms of error rates may sometimes be very misleading since they give no clear indication of the precautions taken in achieving the quoted error rates or of the operating margins of the system. The real criterion is the word error rate that may be expected in the actual day-to-day operational use, working in less than ideal conditions. It may also be preferable during data analysis to accept a relatively high word error rate and to have each error positively identified, rather than an extremely low word error rate with the errors unidentified. This can save analysis time by avoiding the need for complex data interpolation programmes in order to detect the errors. Comprehensive testing of the system described has shown that working at packing densities of up to about 800 bits/mm (20K bits/in) need not be much more demanding of the user than the present low packing density system.

5.2 Performance

The overall performance of the system is influenced to a great extent by the quality, cleanliness and care in handling of the tapes. Numerous trials using high quality instrumentation PCM tapes (drop-out uncertified) has shown that an overall 'word' error rate of better than 1 in 10^8 is easily achieved, but, perhaps more importantly, has shown that the system must be optimised for the particular type of tape in use. Re-adjustment of the airborne system record head drive currents and replay amplifier equalisation are both necessary if the tape characteristics are appreciably changed; it is therefore essential that all users of a common replay system should use the same type of tape.

Trials with the amplifier equalisation incorrectly set due to a change in the type of tape in use have demonstrated the power of the error correcting system. In one particular test, approximately 19K of corrected words were detected on a 1300m run, with a final error count of approximately 100 words. During this test the system was producing random errors generated by faulty decoding due to poor equalisation of the replay signal, this condition being attributed to incorrect setting of the record head currents in the airborne system. However it clearly demonstrates the large safety margin built into the system which should prove valuable in making for easier day-to-day operation of the system. The average 'word' error rate for the present parallel system is about 2 in 10^6, thus the expected operational word error rate of 1 in 10^8 for the system described is clearly a marked improvement.

5.3 Choice of tape and housekeeping

Tape selection tests have been confined to two tape types specifically designed for high packing density PCM recording and a few well known wide-band instrumentation tapes. On balance at present it appears that Ampex type 797 tape would be the best choice as this tape is specifically designed for PCM applications (also a drop-out certified version, type 799, is available for use in special circumstances where the extra cost is justified). Tape type 890 manufactured by 3M (UK) Ltd, can give very similar performance to the Ampex type 797 with 3M 8901 being the drop-out certified equivalent of 799. Cleanliness is of equal importance to the choice of tape; tape and transport hygiene are always given emphasis in manufacturer's operating instructions but are seldom adhered to. In PCM recording it matters and it is particularly recommended that airborne recorded tapes are cleaned before replay. This can make more difference than the differences between types of tape. Only tapes with antistatic backing should be used as this considerably reduces pick-up of dust particles due to static on the tapes.

Appendix A

TYPICAL SPECIFICATION FOR A HIGH ENVIRONMENTAL MAGNETIC TAPE RECORDER (EMI ELECTRONICS LIMITED, TYPE HER 800) FIG 1

(This tape transport was developed under a Ministry of Defence (PE) contract for TGW6 as common user equipment.)

PARTICULARS

Tape width	25.4 mm
Tape capacity	720 m
Tape speeds	23.8, 47.6, 95.2, 190.5, 381, 762, 1524 mm/s electrically selected
Spooling	Forward or reverse under capstan control at 3m/s. Time to spool $\ngtr 4$ min.
Local controls	Forward/reverse, start/stop, spool, tape speed.
Heads	Head construction, track spacing and mounting to IRIG 106-73
Power supplies	200V, 400 Hz, 3-phase ac (to BS3G100, Part 3, Cat B)
Power consumption	Transport - 90 watts max Heater - 300 watts max
Size	531 mm × 355 mm × 246 mm
Weight	35 kg

ENVIRONMENT

Vibration	BS3G100, Part 2, Cat 5
Shock	MIL-E-5400 (30 g for 11 ms each axis)
Linear acceleration	BS3G100, Part 2, Section 3, Class 1A(1), for highly manoeuvrable aircraft (17 g in any direction)
Crash acceleration	BS3G100, Part 2, Section 3, Class 11 (25½ g) and MIL-E-5400
Angular acceleration	>50 rad/s^2, 5 to 100 Hz
Temperature	-65°C (with heater) to $+70^{\circ}$C
Altitude	21 km
Climatic	BS3G100, Part 2, Section 3

PERFORMANCE

Tape mean speed error	±0.2% max
Tape dynamic skew (with 3 M type 951 tape)	6.5 μm max, peak-to-peak between edges of tape

Flutter measured as per IRIG Standard 118-73[2]

Tape speed (mm/s)	Bandwidth (Hz)	Flutter (in laboratory and under BS3G100 random vibration Cat 5 (% peak-to-peak)
23.8	0.5 to 156	1.5
47.6	0.5 to 313	1.0
95.2	0.5 to 625	0.7
190.5	0.5 to 1250	0.5
381	0.5 to 2500	0.4
762	0.5 to 5000	0.3
1524	0.5 to 10000	0.3

Appendix B

LEADING PARTICULARS OF SYSTEM

AIRBORNE RECORDING FORMAT

Record format	Multi-track serial word (Fig 2)
Bits/word	8, 10, 12 or 14
Encoding	Bi-phase space or Delay Modulation (Miller)
Packing density	435 bits/mm Bi-phase space of 870 bits/mm Delay Modulation
Track configuration	14 track in line head (½ standard 28 track configuration conforming to IRIG 106-73)
Magnetic tape	25.4 mm wide (recommended type Ampex 797)

GROUND REPLAY

(a) Tape transports

Primary and secondary	Ampex FR 2000
Maximum tape capacity	3800 m on NAB hub of 406.4mm (16 in) reel
Operational tape speeds primary transport	190.5, 381, 762 mm/s
Operational tape speeds secondary transport	47.6, 95.2, 190.5, 381, 762, 1524, 3048 mm/s

(b) Replay system

Copy flight tape (facility to re-record with reduced packing density)

Re-record 2nd copy facility

Track deskewing and error correction applied

Parallel word output

Word error rate better than 1 in 10^8

Maximum data rate for CCT production 4092 words/s

Maximum data rate for copy tape editing: 262K words/s

System control, manual or computer

Word and frame error cumulative count displays

Individual track word error indicators

Data simulator

Oscilloscope and system monitor switch panel

Appendix C
DETAILED DESCRIPTION OF SYSTEM DESIGN

C.1 Tape transports

Two Ampex type FR 2000 tape transports are used for the replay of high density flight tapes (primary transport) and of the low density copy tapes (secondary transport) respectively. These are high performance instrumentation transports, with facilities for remote control, yielding low flutter and dynamic skew. A zero loop capstan drive is used with servo controlled vacuum tape chambers isolating the tape in the capstan region from each tape reel. Seven bi-directional speeds are provided from 47.6 mm/s ($1\frac{7}{8}$ in/s) to 3048 mm/s (120 in/s), the tape being at all times under capstan control. Specially designed record and replay heads are used which have been optimised for their respective operating conditions. The standard FR 2000 head pre-amplifiers are used, but due to the large difference in packing densities, different replay amplifier techniques have been adopted for each tape transport.

The primary transport is required to replay high packing density tapes, in the forward direction at speeds of 190.5 mm/s ($7\frac{1}{2}$ in/s), 381 mm/s (15 in/s) and 762 mm/s (30 in/s). At high packing densities the replay signals tend to be of a sinusoidal nature favouring the use of direct recording type replay amplifiers with phase equalisation and cross-over limiting technique. Ampex Miller decoder cards are used (1 card per track). Typical replay waveforms of Bi-phase space encoded data obtained using the above techniques are shown in Fig 8.

The secondary transport is required to replay low packing density tapes in both forward and reverse directions at all tape speeds from 47.6 mm/s ($1\frac{7}{8}$ in/s) to 3048 mm/s (120 in/s). At low packing densities the replay signals tend to be comprised of discrete positive and negative pulses favouring amplifiers working on the peak detection principle. This involves differentiation of the replay signal followed by amplification and low-level threshold detection, the threshold being necessary to eliminate errors due to noise. A set of replay amplifiers applying the peak detection principle with switchable equalisation suitable for replay in both forward and reverse directions has been purpose built.

C.2 Decoders

Defining each bit interval is a vital process in the read operation. The Bi-phase space code used has a transition at the start of each bit period, a data 'one' being represented by a second transition at the middle of the bit period and a data 'zero' by its absence. This code is self-clocking, the transition that occurs at the start of each bit period enabling a bit rate clock to be reconstructed from the encoded data stream. The data is decoded by examining the code for the presence of a transition at the middle of the bit period, but, in order to perform this operation, it is first necessary to define the start of the bit period. As in this code no transition occurs at the middle of the bit period when a 'zero' is written, by checking that no transition has occurred during $\frac{3}{4}$ of a bit period the presence of 'zeros' can be detected, the next transition must mark the start of the next bit period and the phase of the data clock is established. The reconstructed data clock is then used to compare the levels present in each half of the encoded data bit using an exclusive-or gate, the resultant being the desired NRZ-L decoded data output.

The block diagram and timing diagram of the decode circuit are shown in Figs 9 and 10 respectively. The timing of the reconstructed data clock is controlled by shift registers A and B driven by a high frequency crystal controlled clock automatically selected to be 32 times the replay data bit rate. The shift registers are reset at each transition of the encoded data by the pulse train B in Fig 10. Following each reset pulse, register A produces an output pulse after 8 high frequency clock pulses, *ie* $\frac{1}{4}$ of a bit period after the reset pulse, register B similarly produces an output pulse D after 24 high frequency clock pulses, corresponding to $\frac{3}{4}$ of a bit delay after the reset pulse. These outputs are combined in an 'OR' gate C to form the pulse train E driving the flip-flop D and producing the bit rate clock F. The clock is thus generated with a $\frac{1}{4}$ bit delay on the encoded data. Shift register B can only reach count 24 and produce an output pulse when encoded 'zeros' are present; this output pulse must, from the properties of the code, occur at the middle of the reconstructed clock bit period and can therefore be used to reset flip-flop D to establish the correct phase of the clock relative to the data. This process is repeated as each 'zero' appears in the encoded data.

C.3 Frame synchronisation

C.3.1 Principle of operation

For each track, frame sync recognition is achieved in two modes of operation, the 'search' and 'run' modes.

In normal operation the detector is in the 'run' mode, this giving an enhanced probability of recognising a sync word with a small number of bits in error using a reduced recognition threshold. Recognition is achieved by summing the number of bit coincidences obtained by comparing the sync word off tape with a fixed sync word, Fig 11. Sync recognition is accepted as valid when the number of coincidences reaches a preset detection threshold. In order to avoid spurious sync recognition due to the presence of data patterns similar to the sync word, sync detection is inhibited after recognition of a sync word until the following sync word is imminent. To allow for small errors in the frame length, resulting from misclocking of the data, a window is generated about the correct sync position. In the event of the sync word not being recognised, and also during standby, the detector selects the 'search' mode. In this mode the probability of spurious sync recognition is still further reduced by searching for complete agreement with the reference for two sync words one data frame apart.

The synchronisation word should be chosen to produce the widest possible window of minimum coincidence on either side of the point of complete coincidence with the fixed word pattern, assuming worst case data adjacent to the sync word. The 16 bit sync word complying most closely with this property is shown in Fig 11. This allows a recognition threshold level of 14 bit coincidences (sync reference level ≥ 14) and using a window of 5 bits, allows sync to be recognised with a 2 bit error in the sync word and a ± 2 bit error in the frame length.

C.3.2 Implementation

Decoded data from each track is fed to a serial shift register one frame in length. This register consists of two 16 bit parallel output shift registers (A and B) separated by a serial register of length equal to the number of data bits per frame (Fig 12). In the run mode outputs of shift register 'B' are compared with a fixed 16 bit sync word and the number of bit coincidences are summed. The number of coincidences are compared with the sync reference level and if the former is greater a pulse is fed to the 'run' enable gate. If the sync appears within ± 2 bits of the correct position this pulse resets the frame length counter and switches the track sync recognition store. The counter starts the count of the next frame length, enabling the sync recognition circuits 2 bits prior to the correct sync location. Provided the next sync pulse arrives within the ± 2 bit window, the circuit continues to operate in the 'run' mode. A 'sync position generator' is included for checking purposes and gives two outputs; it indicates when the sync pulse is in the correct position and it indicates when the sync pulse is within the window but not in the correct position. These outputs are passed on to the frame status store (Fig 13) which provides an indication of the validity of the stored data frame.

If the sync pulse fails to arrive before the frame length counter reaches its final count the window is closed, the 'search' mode initiated and the frame length counter is inhibited. In this 'search' mode a sync output is obtained only when exact bit coincidence is found in both A and B parallel output shift registers. This signifies the simultaneous detection of two frame sync words with a complete data frame interposed. The 'search' mode sync pulse resets the frame length counter and re-initiates 'run' mode operation.

C.4 Track deskewing and deskew control

A block diagram illustrating the principle of track deskewing is presented in Fig 13. Each track of decoded data is fed via the frame length sync store to two deskew stores A and B, operated alternately on each data frame. Each deskew store is comprised of a serial shift register of length equal to the data frame. As each track sync is detected the output of the frame sync store is immediately switched, for example, from the A to the B deskew store input thus ensuring no loss of incoming data. Immediately the sync detections from all tracks have been acquired, all the deskew store output lines are simultaneously switched from the B to the A stores and the stored data held in the A stores clocked out simultaneously at double the input rate to allow for tape skew and mean tape speed timing errors. This cycle continuously repeats with the function of the A and B stores interchanged for successive data frames.

Sync detection and the initiation of the deskew store read-out is implemented by the deskew control circuit (Fig 14). As each sync is recognised (within the window) the event is stored and fed to a 14 bit adder network. Comparator 1 detects the first of the 14 sync recognitions and starts the deskew delay counter which is driven at twice the bit rate. Comparator 2 detects the presence of 3 or more track sync recognitions. When the skew delay counter has reached count 20, equivalent to a delay of 10 data bits, it is gated with the output of comparator 2. If 3 or more syncs are present the count is allowed to proceed but if there are less than 3 the counter is reset. Thus detection of frame sync requires the presence of 3 or more sync recognitions within 10 data bits thereby reducing the probability of data being interpreted as frame sync. Comparator 3 detects that all syncs are present and enables the master sync control to initiate the deskew store shift-out process. If, due to tape drop-outs, one or more frame sync words are lost, the duration of the search for 'all syncs present' must be limited to that period determined by the expected maximum skew. This duration is controlled by the deskew delay counter and is set to enable the master sync control approximately 53 bits after the first frame sync is recognised.

C.5 Parity checking and error correction

The deskewing operation of section C.4 restores the original recorded word alignment and enables words found to be in error to be corrected, where possible, with the aid of the transverse parity track.

The deskewed words from all tracks are passed through the error checking system to establish the error status of both data frames and individual words. The first priority is a check of the sync status. If all the track syncs are correct then serial word parity checks for each of the parallel word groups (Fig 2) in the complete data frame are performed. The following checks, are carried out and the results determine the degree of error correction that can be applied:

(i) Frame sync checking and track correction.
Check all frame status stores.

(a) Status: All correct (word status bit A and B = 0).
Action: Proceed to word error correction.

(b) Status: One frame sync error (word status bit A = 1 and B = 0).
This may be due to drop-outs during the frame period resulting in misplaced sync position, or bit reading errors during the sync word which prevent the sync threshold recognition level being reached.
Action: The output of the track in error is inhibited and is replaced with reconstructed data words generated from the transverse parity and the other data tracks.
As a result of this operation the serial parity of the reconstructed words may be in error as the transverse parity is not applied to the serial parity bits as already explained in section 4. The correct serial word parity is generated from the reconstructed words as a subsequent operation.

(c) Status: Two or more frame syncs errors (word status bit A = 0 and B = 1).
Action: The limitations of the simple transverse parity check preclude multiple error correction, and the error correcting system is therefore inhibited for the duration of the data frame.

(ii) Word parity and word correction.

If all the frame syncs are found to be correct, then checking and, where possible, correction of individual words can be implemented. The error detection process employs longitudinal parity checking, thus allowing words containing an odd number of bits in error to be detected. Words found to be in error are corrected with the aid of the transverse parity track. As the parallel stream of words is passed into the word serial parity store the longitudinal parity is checked and temporarily stored. Error correction is again limited by the single bit transverse parity check, so that correction cannot be performed if more than one longitudinal parity error is detected in a parallel word group. The procedures here are as follows:

(a) Status: All longitudinal parity in word group correct (word status bits A and B = 0).

Action: Words passed on unchanged.

(b) Status: One longitudinal parity error in word group (word status bit A = 1 and B = 0).

Action: If only one longitudinal parity error is detected, the word is reconstructed from the transverse parity as the next parallel group of words is passed into the word serial parity stores.

(c) Status: Two or more longitudinal parity errors in word group (word status bit A = 0 and B = 1).

Action: No error correction is possible, and words are passed on unchanged.

(d) Status: One longitudinal parity error in word group coincident with a frame sync error on another track. (Word status bit A = 0 and B = 1).

Action: The reconstruction of the lost track of words following detection of a frame sync error inhibits the correction of individual word errors detected on other tracks. If a word error is detected on another track during this period, the whole group of words containing this error is passed on unchanged.

A summary of the possible output data conditions indicated by the status bits is given below:

Status bit A. Logical 1, indicates that the associated parallel word has been corrected.

Status bit B. Logical 1, indicates that the associated parallel word is in error (failed parity check and/or sync recognition errors).

When both status bits are at logical 0 it will indicate that no sync or parity errors have been detected. The word status bit logical levels for possible combinations of frame sync and/or word parity errors are shown in the following table.

Possible combinations of track frame sync and/or word parity errors	Word status logic level	
	Bit 'A'	Bit 'B'
1 word parity error or 1 frame sync error	1	0
Simultaneous word parity errors or frame sync errors or 1 word parity error on 1 track during a frame sync error on another track	0	1
No error detected	0	0

C.6 Track and word orientation and serial-to-parallel conversion

As the control computer will be programmed to continuously examine the replayed edit words in order to identify sections of data required for more comprehensive analysis, it is important that the correct word and bit sequences are obtained in both forward and reverse replay modes. Referring to the group word number sequence in Fig 2, the resultant sequence after serial-to-parallel conversion would be 1 to 13, 14 to 26, 27 to 39, etc this being the correct sequence for the forward tape replay mode. However an incorrect word and bit sequence would result from replay in reverse, namely 27 to 39, 14 to 26, 1 to 13, etc. To avoid this, provision is made to switch the track configuration prior to the serial-to-parallel conversion to ensure correct word sequence when replaying in the reverse direction. The serial-to-parallel converter outputs are then passed on to a word orientation section which produces the correct bit sequence.

C.7 Data silo 140

The deskewing operation followed later by the serial-to-parallel word conversion forms each frame of data into groups of words which are output in bursts at twice the replay rate, each group being further sub-divided into minor groups. The number of words in each minor group is equal to the number of data tracks in use (Fig 15). The large discontinuities present in the data stream are incompatible with the production of quick-look chart records since presentation of data in this form requires equal time increments between successive data samples. A data silo is therefore provided to produce a smooth uninterrupted data stream.

The silo is comprised of three serial shift registers for each bit of the parallel word plus the word status bits A and B (Fig 16). The registers are used sequentially to store the incoming data, and to clock out data in a continuous stream at an average rate determined by the tape speed. The use of the three registers in this mode allows a time margin of $\pm\frac{1}{2}$ frame period to accommodate tape speed variations and any short term averaging errors of the output frequency control system.

The purpose of the frequency control system is to provide a clock signal to the silo at a rate appropriate to the output of data from the tape. A schematic diagram of the control system is given in Fig 17. The reference frequency input to this control is derived by dividing down from a high frequency crystal oscillator. The division ratio is set automatically from the tape speed and track format selection controls at a value giving a reference frequency of 100 times the nominal word output rate.

To obtain the required clock signal from this reference frequency it is necessary to divide the reference frequency by a factor which is proportional to the actual rather than the nominal word rate. The division is carried out in divider A and the rest of the circuit shown in the figure is concerned with working out what the division ratio should be.

To do this the average word rate delivered by the replay tape is measured by counting cycles of the reference frequency over periods of one complete tape data frame. The counting periods are controlled by master sync pulses which occur each time the sync pulses have been detected on all the tape tracks in use. At the input to the data silo words have been combined from all tracks into a single stream of parallel words, the number of words per tape frame being therefore equal to 16 times the number of data tracks in use.

140 This counting operation is performed in counter D, the input to this counter being scaled by counter C in accordance with the number of data words per frame and control of the count being performed by the master sync pulse input as shown. As the reference frequency is 100 times the nominal word rate,

the contents of counter D will be approximately 100 at the end of one frame period. The contents of counter D are then loaded into the programmable divider A so setting the division ratio of A at each master sync pulse. The output of divider A is then used to clock the data words out of the data silo serial shift registers in Fig 16. Divider B counts the number of data words passed out of each serial shift register of the data silo and selects the output of each of the three shift registers in sequence as each is emptied.

As an exact match of the output word rate cannot be selected digitally, long term drift would produce a progressive error in the number of words held in the data silo resulting in the silo either overflowing or becoming empty. To prevent this the count reached in divider B is compared with fixed reference points at each master sync pulse and a correction is generated to add to the output of counter D. This modifies the division ratio of divider A so adjusting the silo output clock rate to counteract the drift. To simplify the logic design of the correction circuit and to make the reference levels for checking the word contents of the silo independent of the data frame length, digital comparators are used to check the contents of divider B relative to $\frac{1}{4}$, $\frac{1}{2}$ and $\frac{3}{4}$ of the full divider count. One of two levels of correction is used depending on the result of this check. If when the master frame sync arrives the count in divider B is found to be within the $\frac{1}{4}$ to $\frac{3}{4}$ full range, a correction of approximately 2% is added to the output of counter D, the correction being negative if the contents of the divider exceed $\frac{1}{2}$ of the full count. This slowly adjusts the output pulse of divider B and hence the sequential selection of the outputs of the serial shift registers so that it occurs midway between master sync pulses. If the count is found to be less than $\frac{1}{4}$ or more than $\frac{3}{4}$ of the full count a correction of approximately 26% of the nominal output rate is applied. This rapidly corrects the contents of counter B and the correction reverts to ±2% when the count is again within the $\frac{1}{4}$ to $\frac{3}{4}$ full range. Thus in normal operation the data output rate will slowly cycle by approximately ±2% about the mean rate with occasional larger excursions immediately following disturbances caused by drop-outs etc.

Fig 18 shows a typical analogue ramp waveform at the silo output, the ramp being approximately four data frames long. A time exposure shows the average time jitter amplitude. In practice only a few samples of any parameter will occur in each tape frame and when demultiplexed the effective time jitter of each sample relative to its own time period will tend to be reduced to a very small value and will be barely discernible on a UV chart print-out.

Table 1

RECORDING PACKING DENSITIES

Bits/ word	CPU output bits/s	Tracks (excl parity track)	Sampling rate (word/s)	Recorded rate (bits/s) (each track)	Tape speed (mm/s)	Linear packing density (bits/mm)	Recording duration for 203 mm dia (8 in) reel (h)
14	458752	13	32768	37809.230	95.2	396.947	2
14	458752	6	32768	81920.000	190.5	430.026	1
14	458752	3	32768	163840.000	381	430.026	0.5
12	393216.0	13	32768	32768.000	95.2	344.021	2
12	393216.0	6	32768	70997.333	190.5	372.689	1
12	393216.0	3	32768	141994.666	381	372.689	0.5
10	327680.01	13	32768	27726.769	95.2	291.095	2
10	327680.01	6	32768	60074.666	190.5	315.353	1
10	327680.01	3	32768	120149.333	381	315.353	0.5
8	262144.01	13	32768	22685.538	95.2	240.089	2
8	262144.01	6	32768	49152.000	190.5	258.016	1
8	262144.01	3	32768	98304.000	381	258.016	0.5
12	453710.76	13	37809.23	37809.23	95.2	396.947	2
12	453710.76	6	37809.23	81920.00	190.5	430.026	1
12	453710.76	3	37809.23	163840.00	381	430.026	0.5
10	446836.35	13	44683.635	37809.23	95.2	396.947	2
10	446836.35	6	44683.635	81920.00	190.5	430.026	1
10	446836.35	3	44683.635	163840.00	381	430.026	0.5
8	436906.666	13	54613.332	37809.23	95.2	396.947	2
8	436906.666	6	54613.332	81920.00	190.5	430.026	1
8	436906.666	3	54613.332	163840.00	381	430.026	0.5

Other sampling rates and tape speeds may be used provided the linear packing density complies with the above table.

$$\text{Linear packing density (bits/mm)} = \frac{[\text{Bits/w} + 1] \times [\text{Sampling rate (words/s)}]}{[\text{Recording speed (mm/s)}] \times [\text{No. of data tracks}]}$$

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No.	Author	Title, etc
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2	Inter-Range Instrumentation Group	Test Methods for Telemetry Systems and Sub-systems. IRIG Document 118-73 Secretariat, Range Commanders Council, White Sands Missile Range, New Mexico, USA

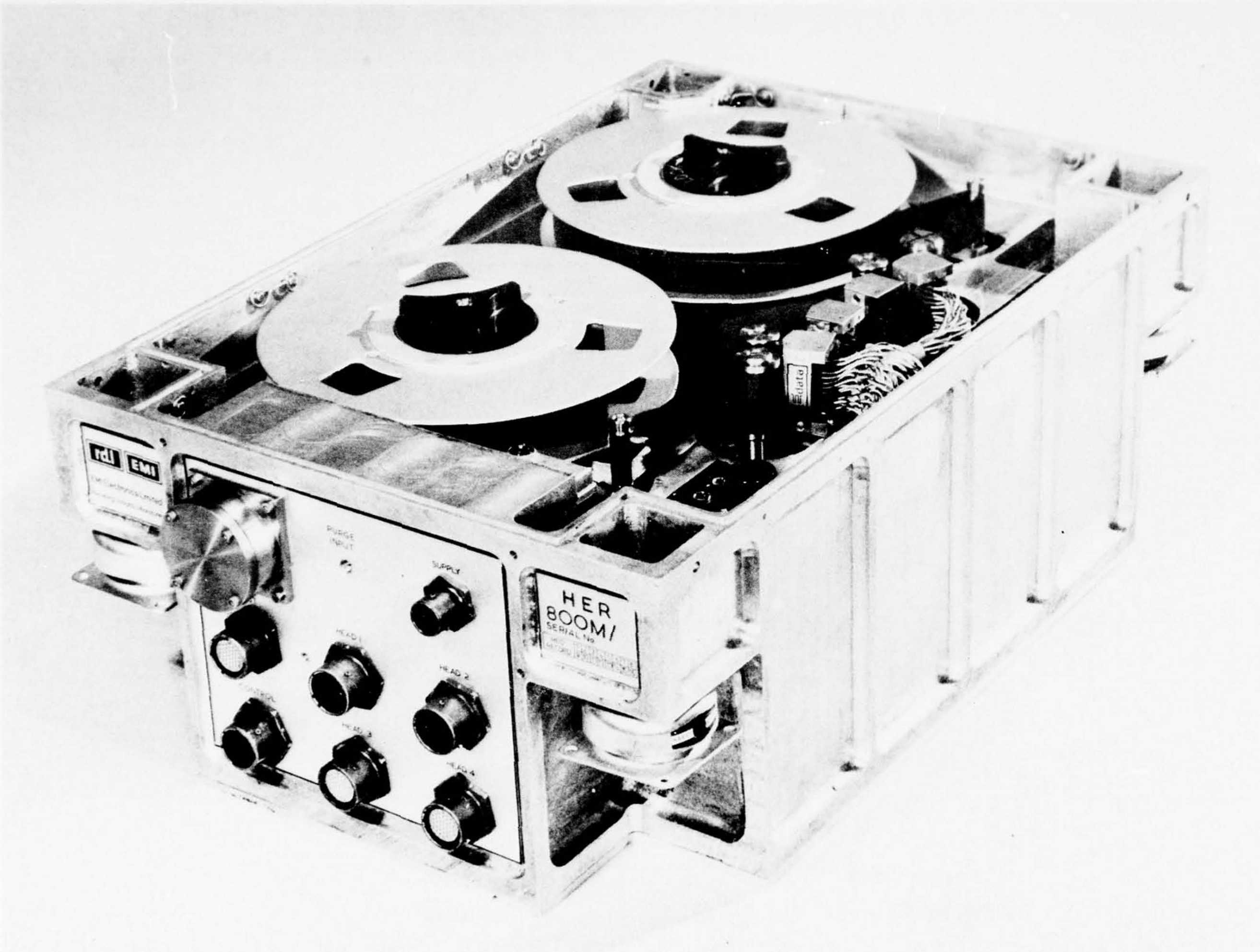


Fig 1 High environmental magnetic tape recorder
EMI (Electronics) Ltd, Type HER 800

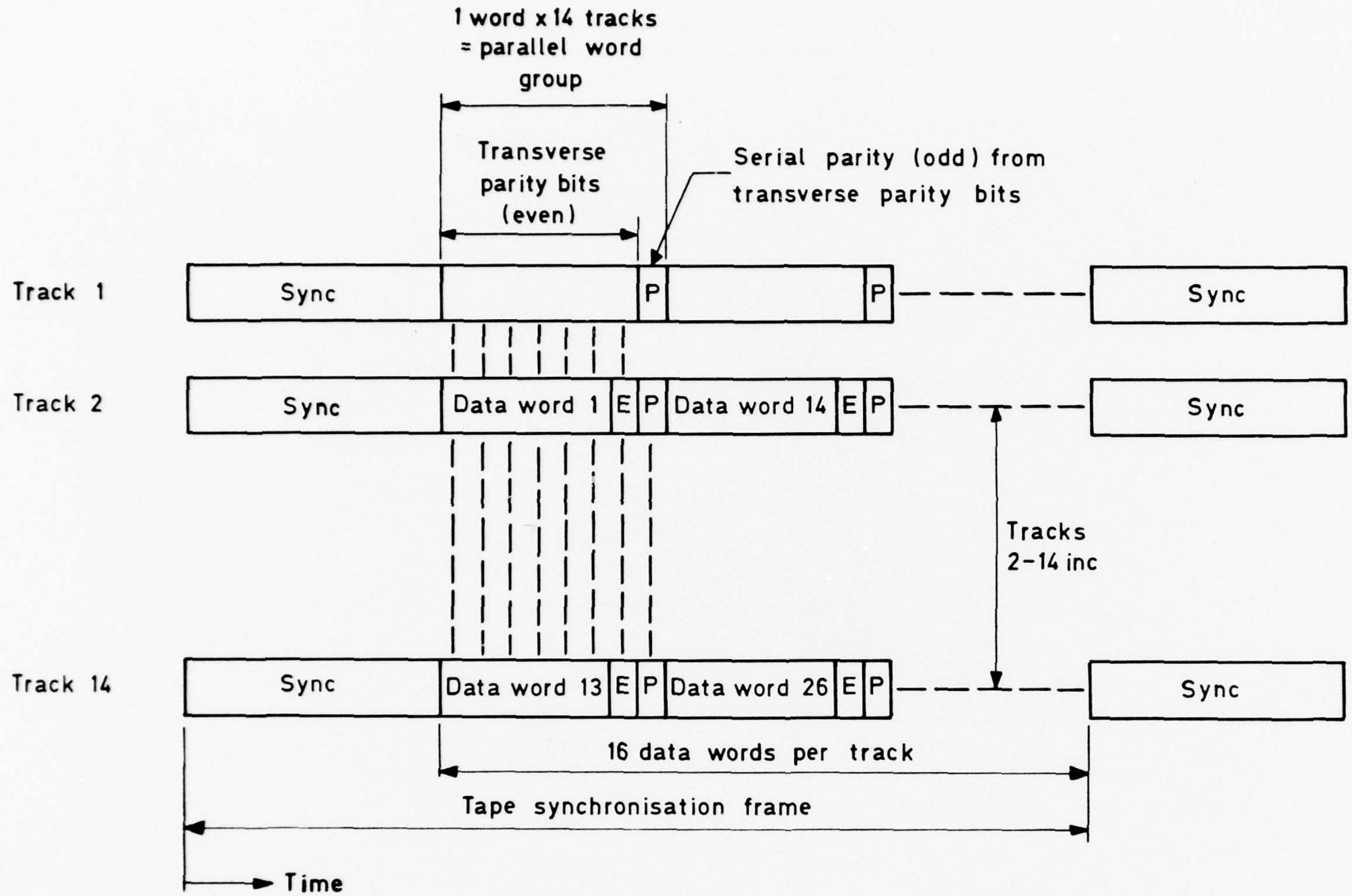
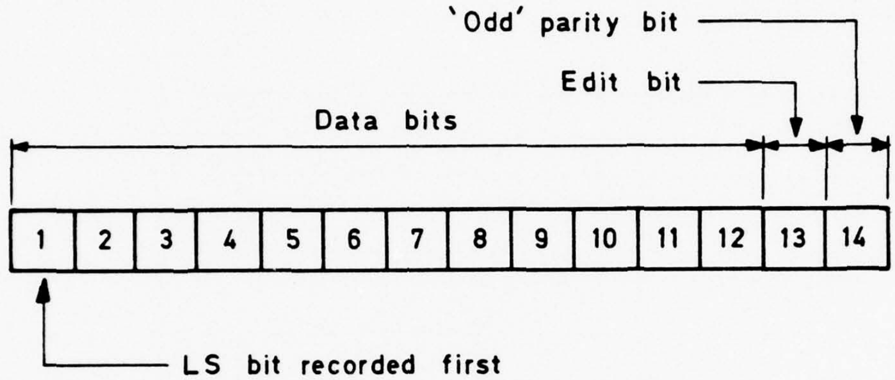
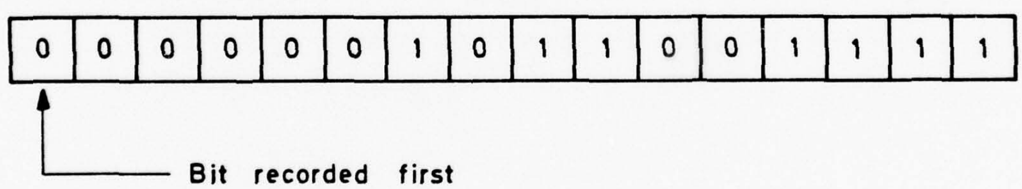


Fig 2 Recording tape format 14 track system/8 bit word



a Record data word format



b Frame synchronisation word

Fig 3 Word formats

Code definitions

Non return to zero level

'One' is represented by one level
'Zero' is represented by the other level
(IRIG 106-73)

Bi-Phase space

Level change occurs at the beginning of every bit period
'One' is represented by a midbit level change
'Zero' is represented by no midbit level change
(IRIG 106-73)

Delay modulation-mark (Miller code)

'One' is represented by a level change midbit time
'Zero' followed by a 'zero' is represented by a level change at the end of the first 'zero' bit
No level change occurs when a 'zero' is presented by a 'one'
(IRIG 106-73 revised Nov 75)

Code waveforms

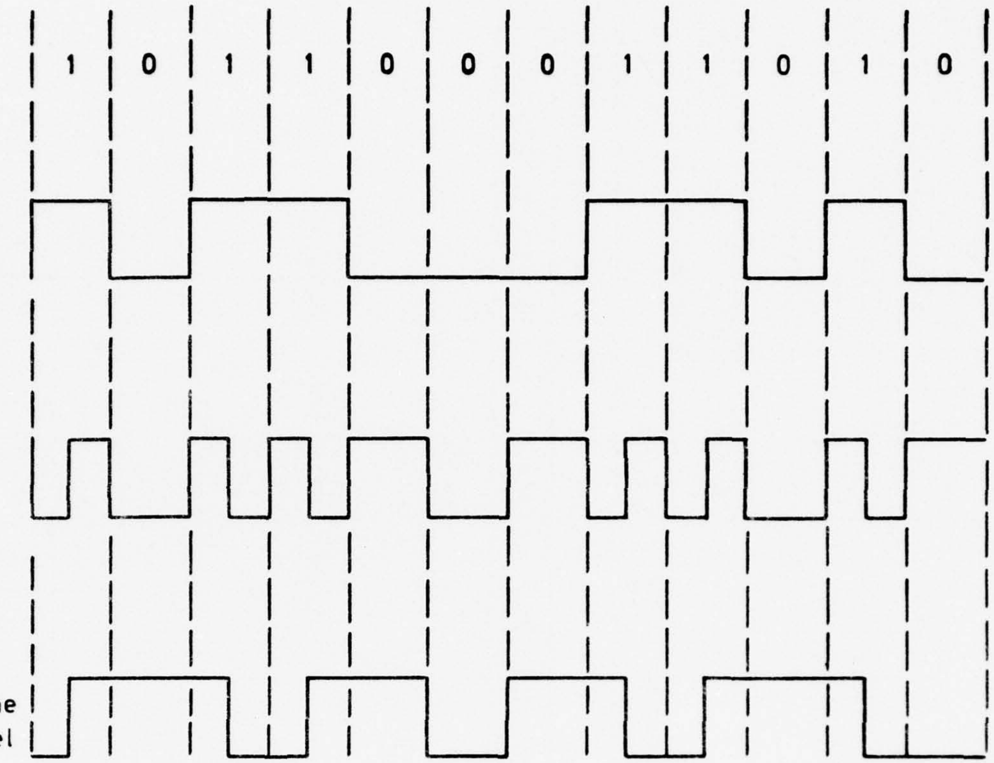


Fig 4 *PCM recording codes*

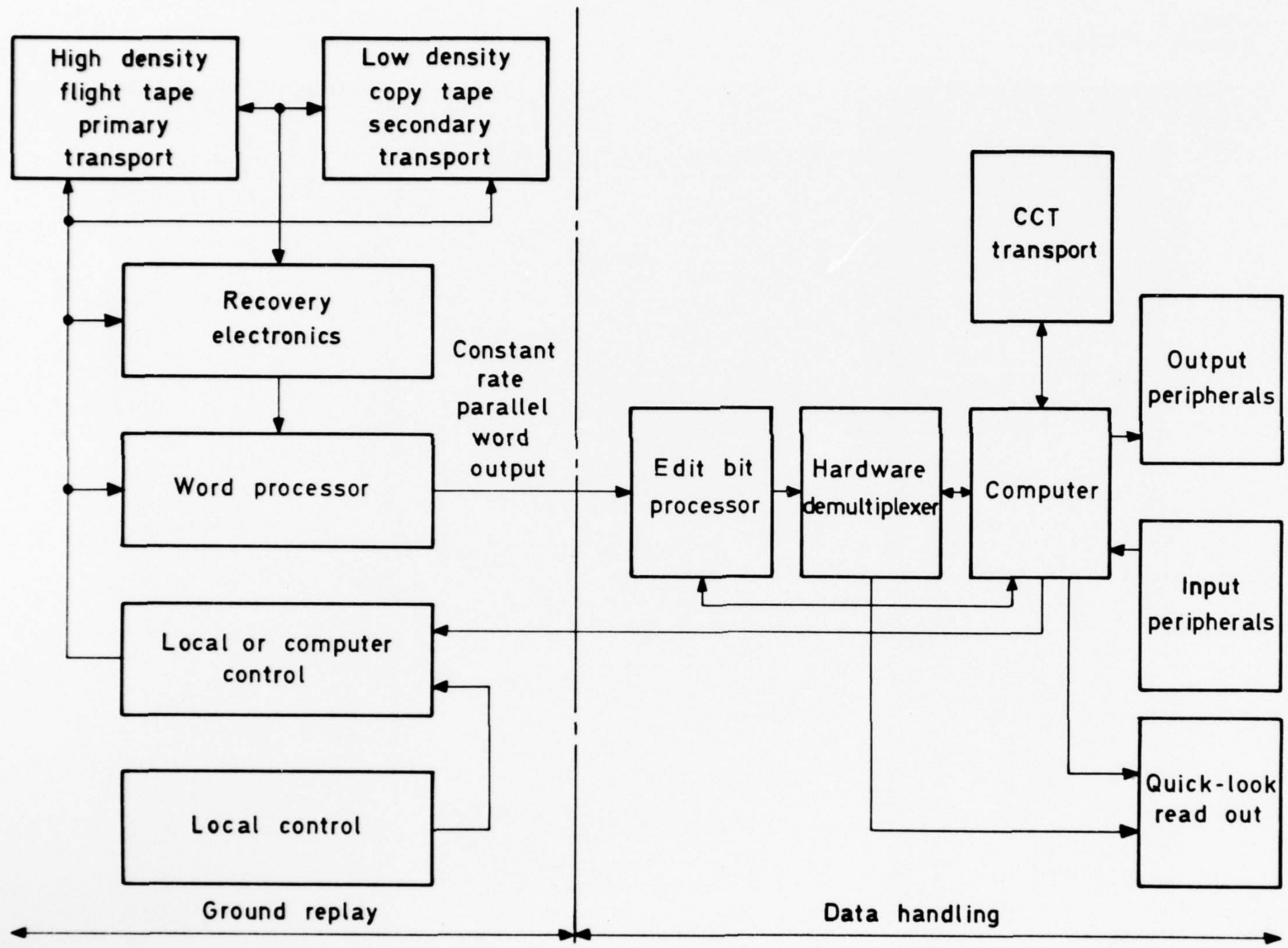


Fig 5 Ground replay/data handling system

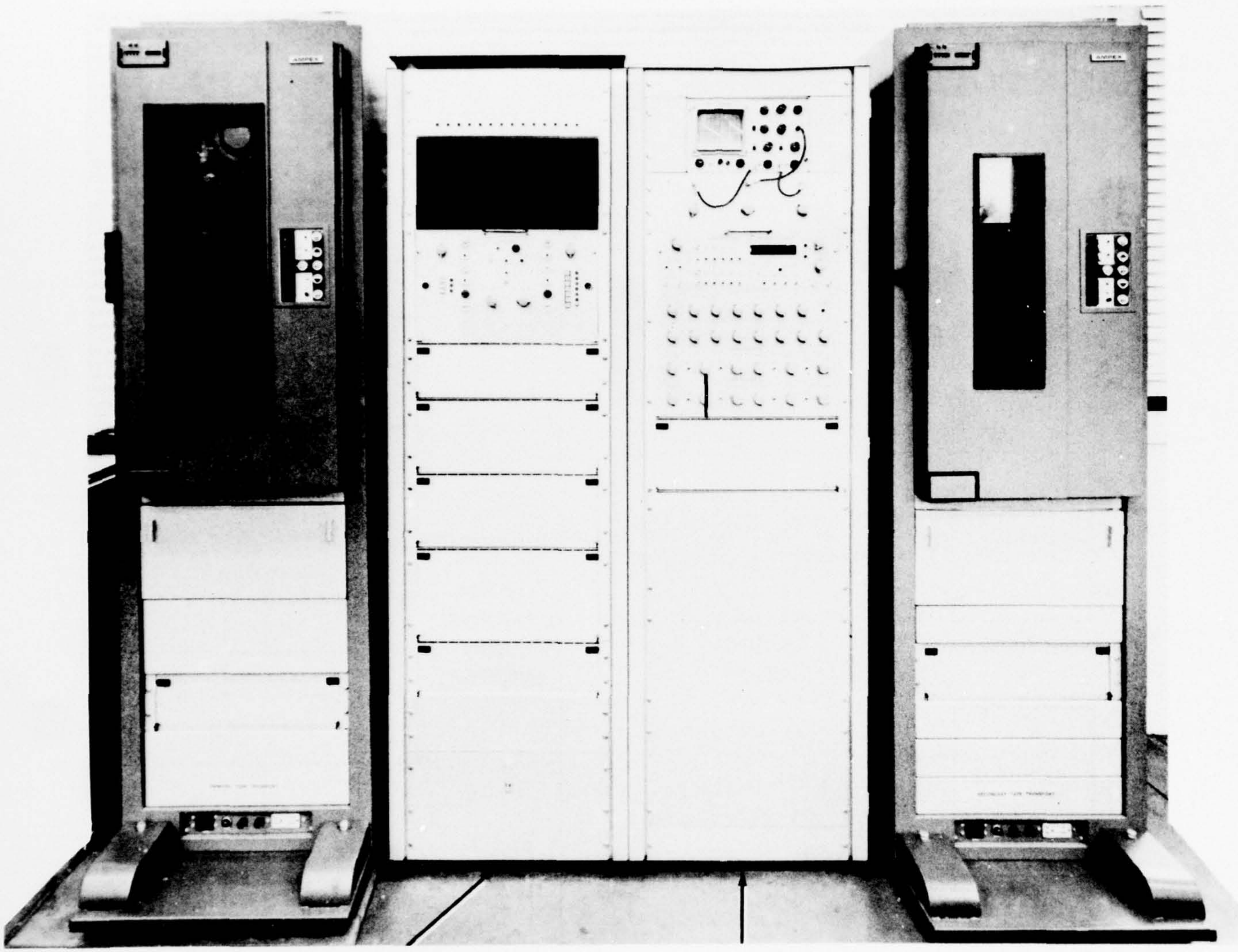


Fig 6 Ground replay system

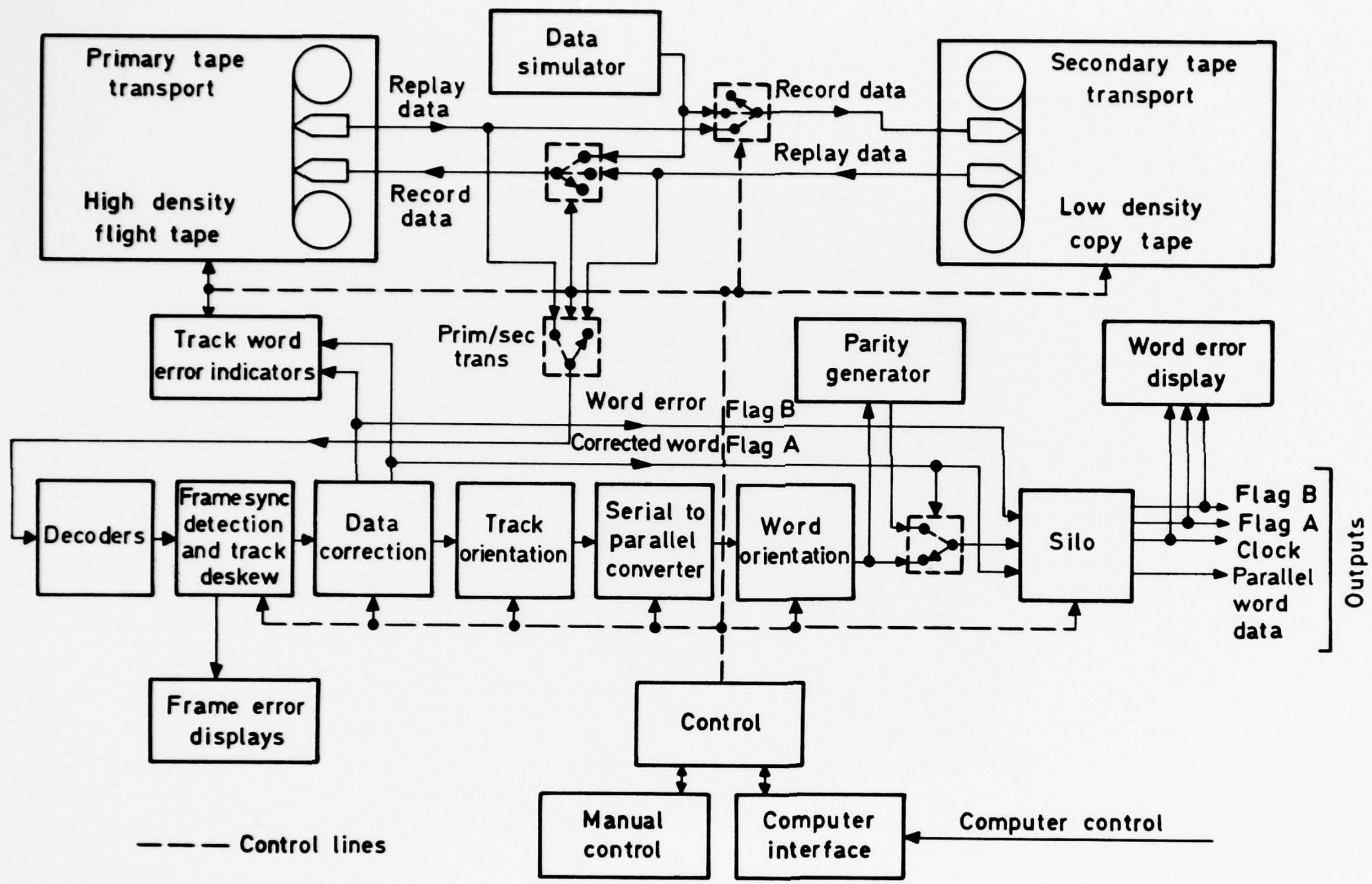
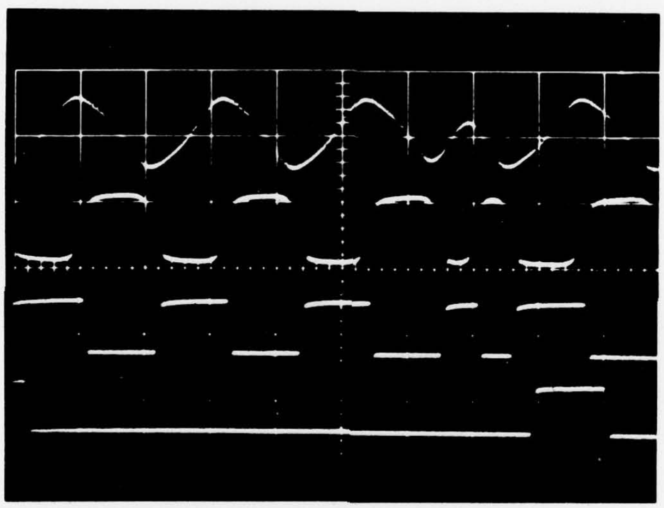


Fig 7 High density PCM replay system



Recorded packing density, 400 bits/mm
Replay speed, 762 mm/s

Upper trace	Pre-amplifier output
Trace 2	Amplified and phase equalised output
Trace 3	Limited output
Lower trace	Decoded output

Fig 8 Typical replay waveforms of bi-phase space encoded data

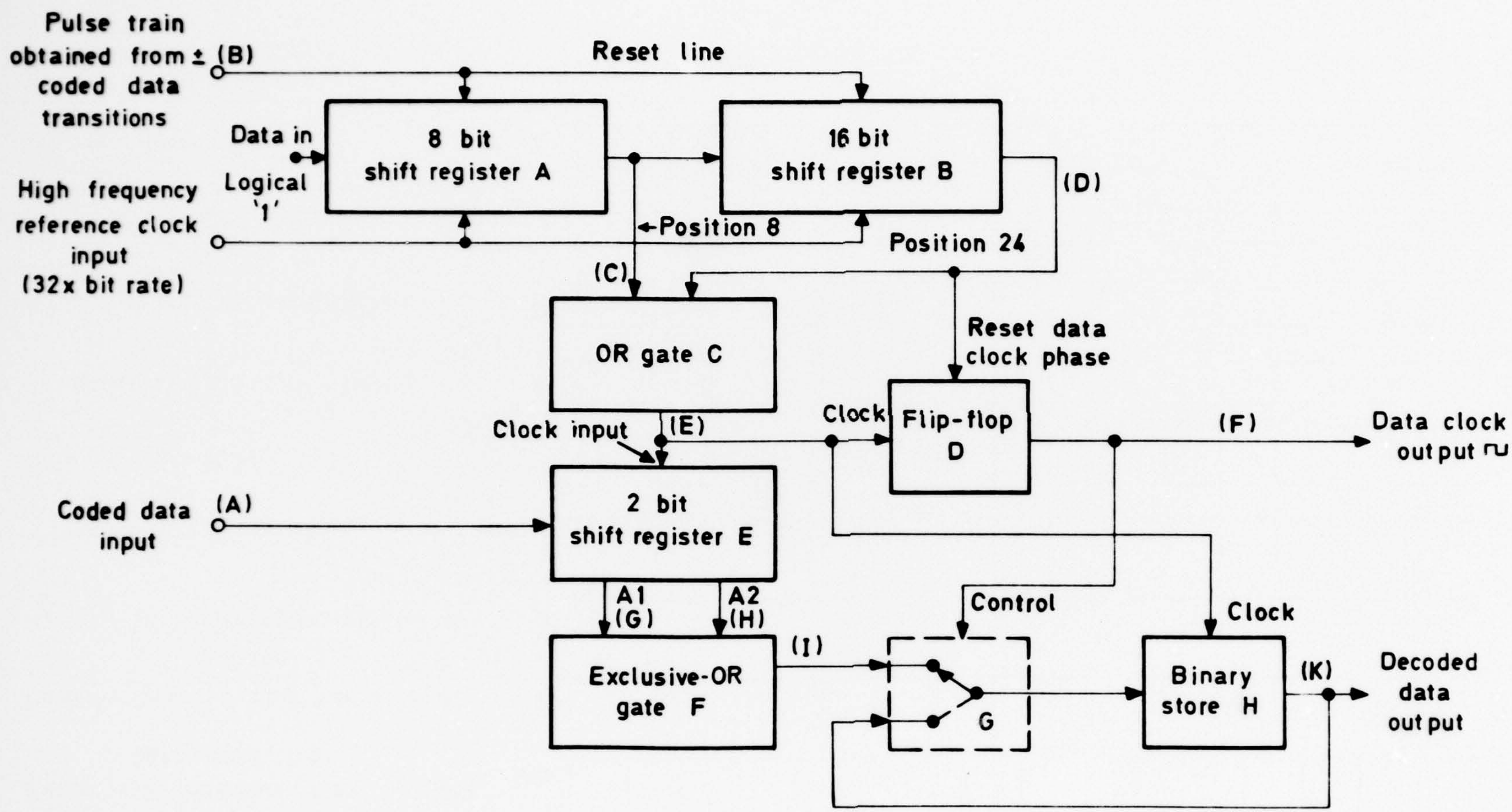


Fig 9 Bi-phase space to NRZ-L decoder

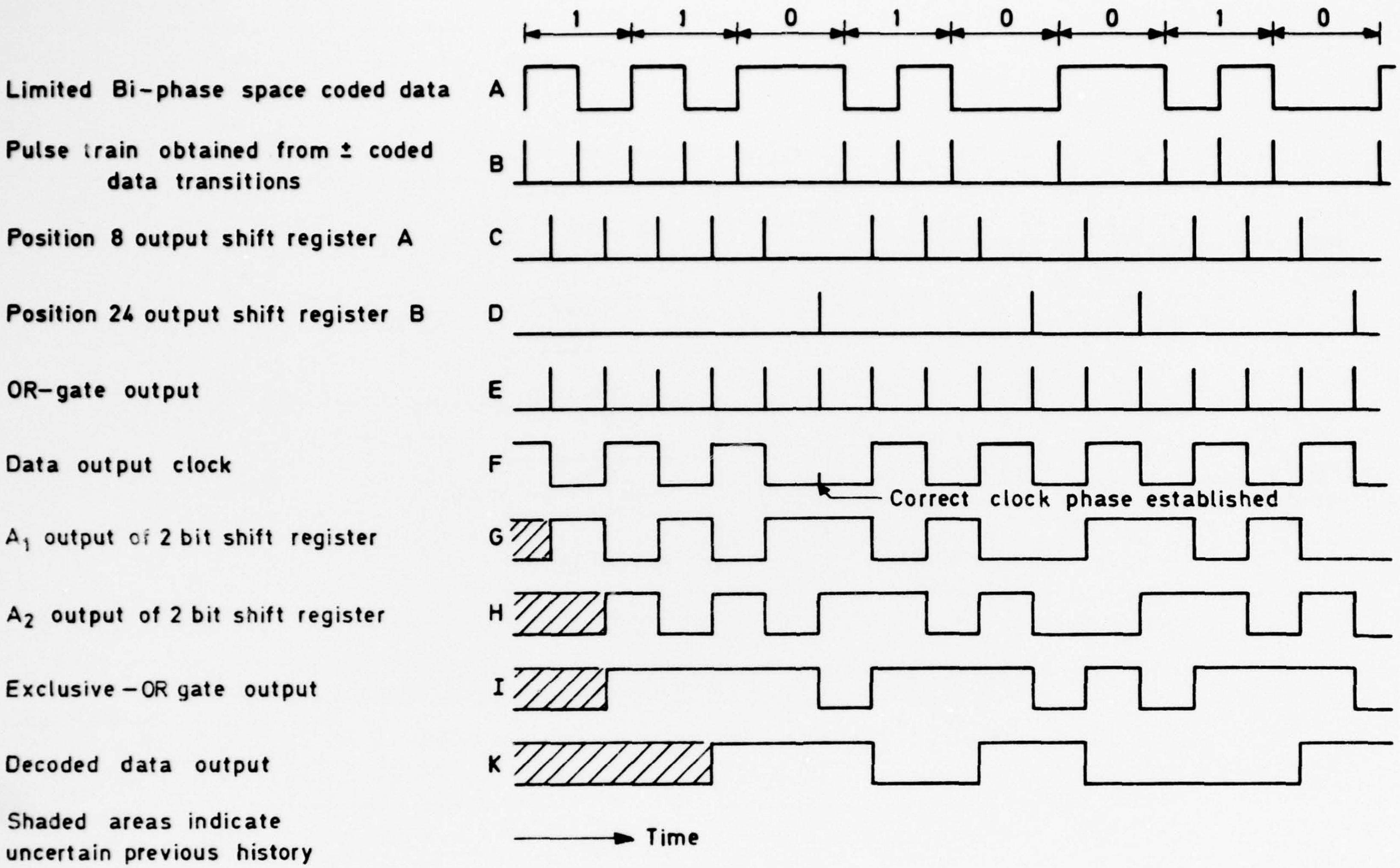


Fig 10 Decoder timing diagram

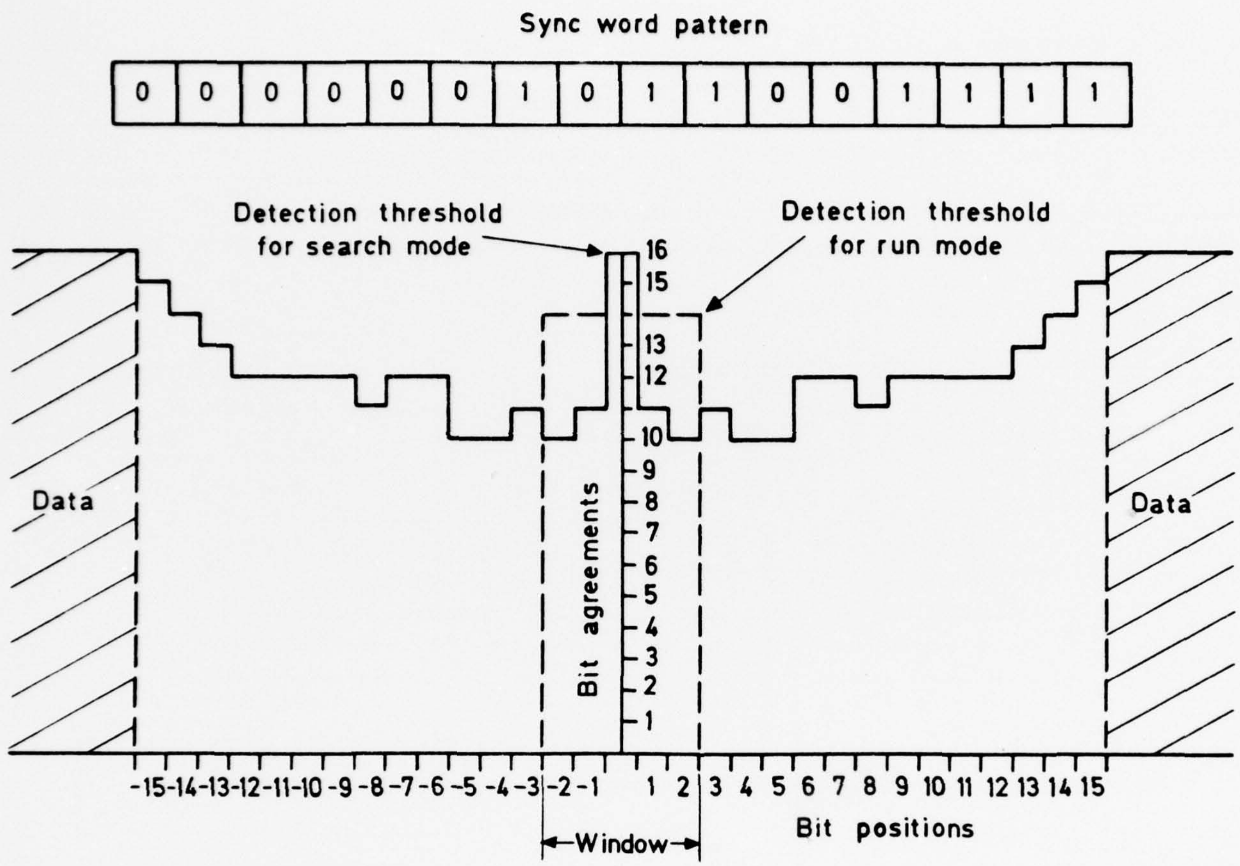


Fig.11 Worst case bit agreements for synchronisation word

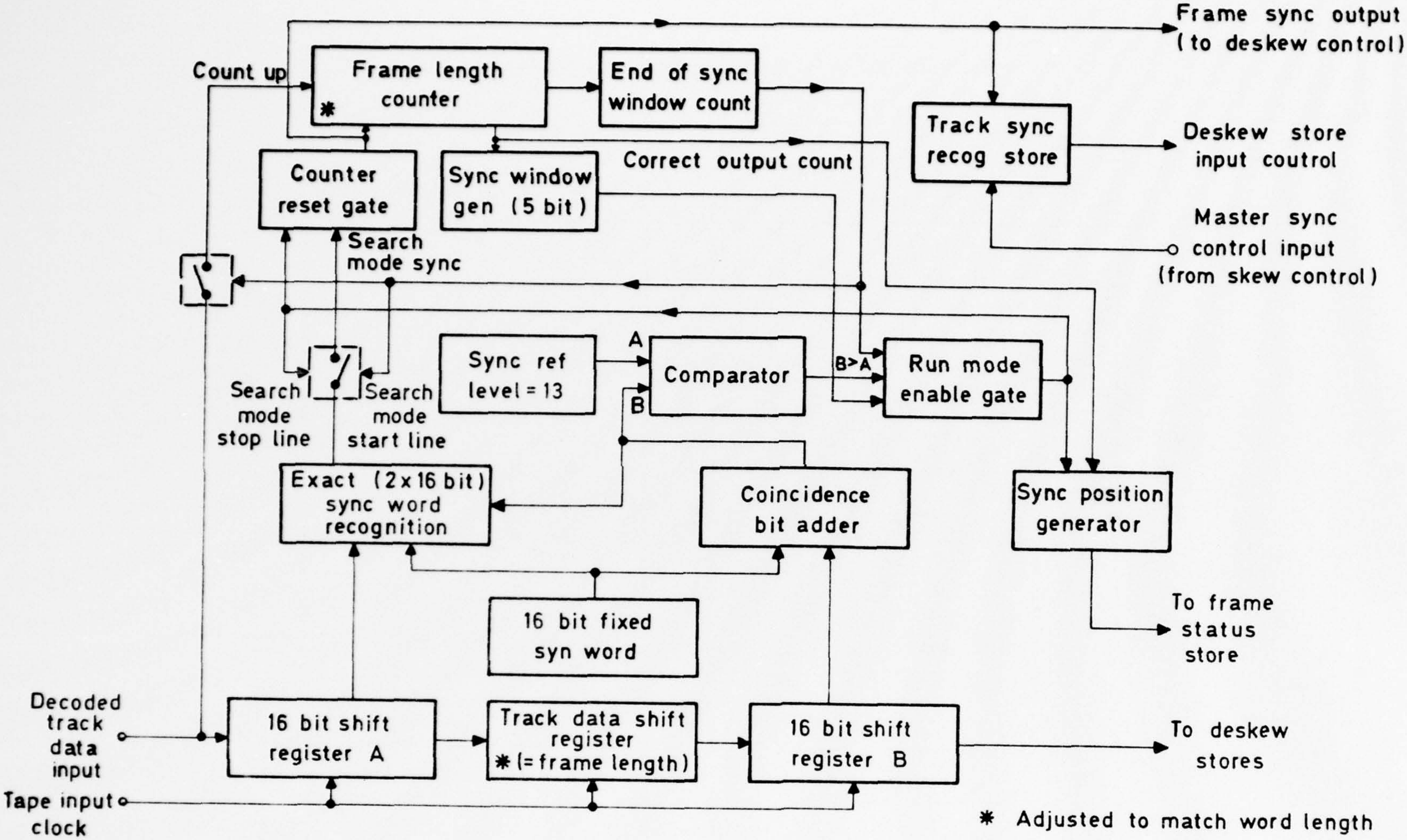


Fig 12 Track frame synchronisation recognition

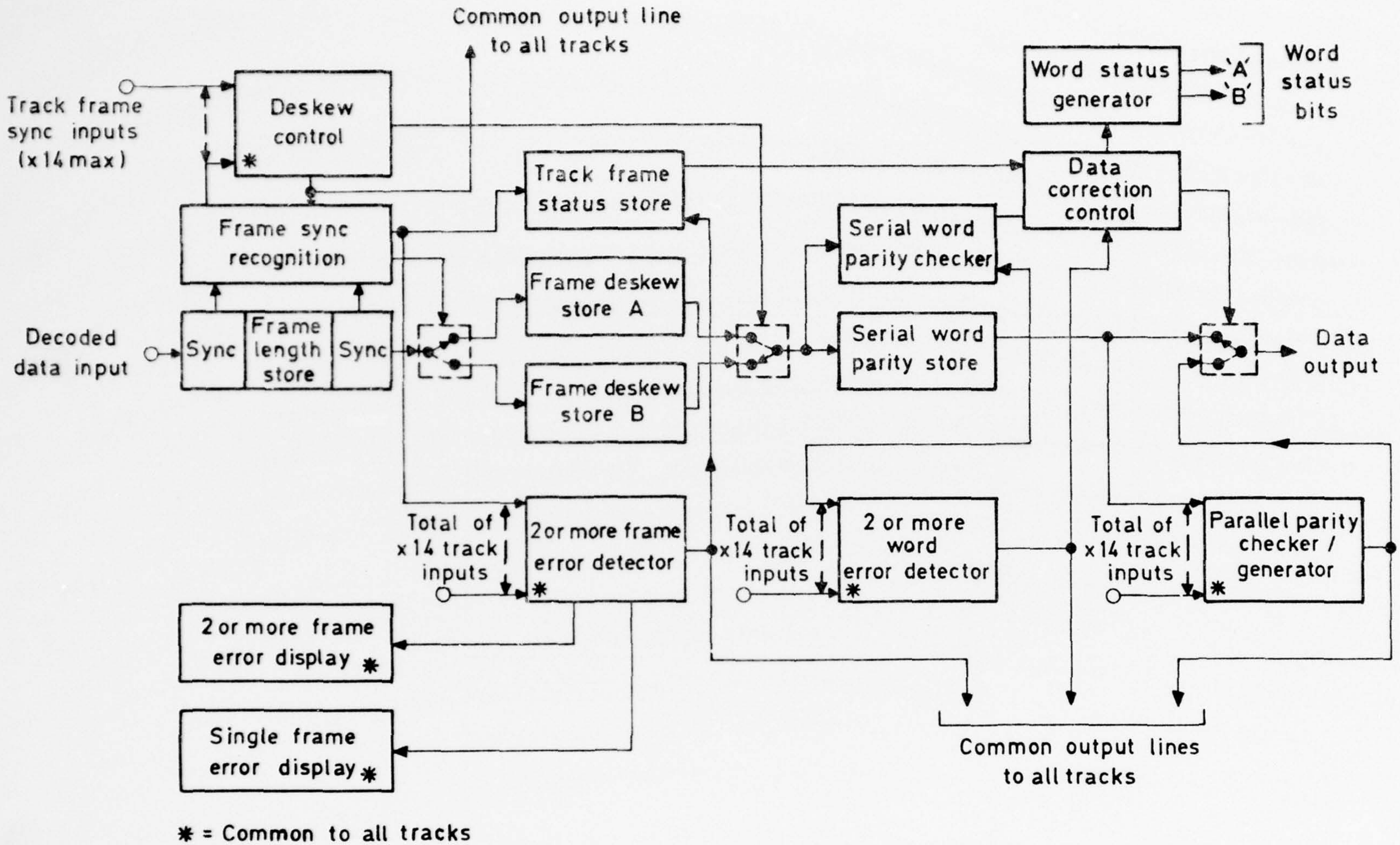


Fig 13 Deskew/error word correction

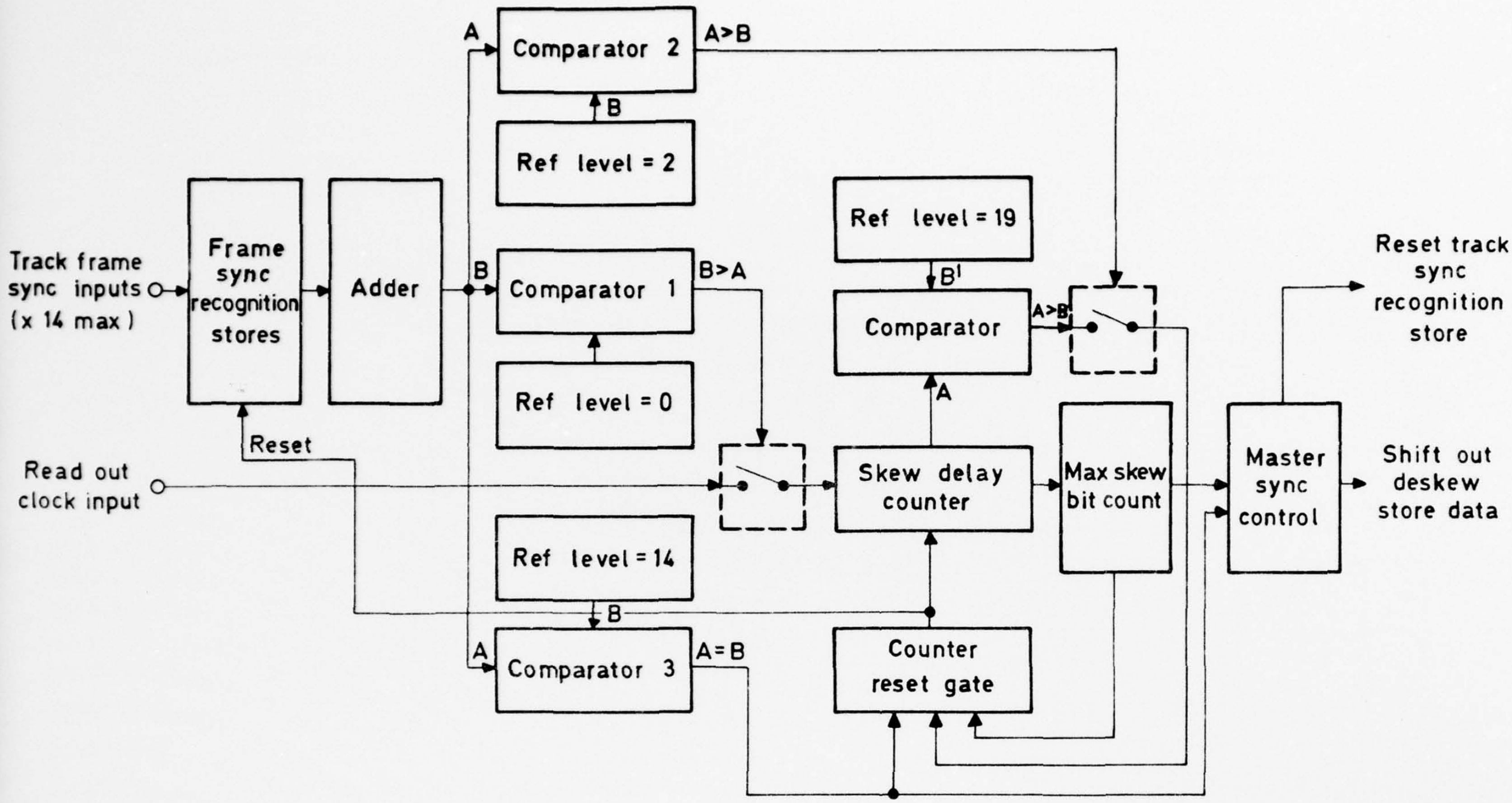
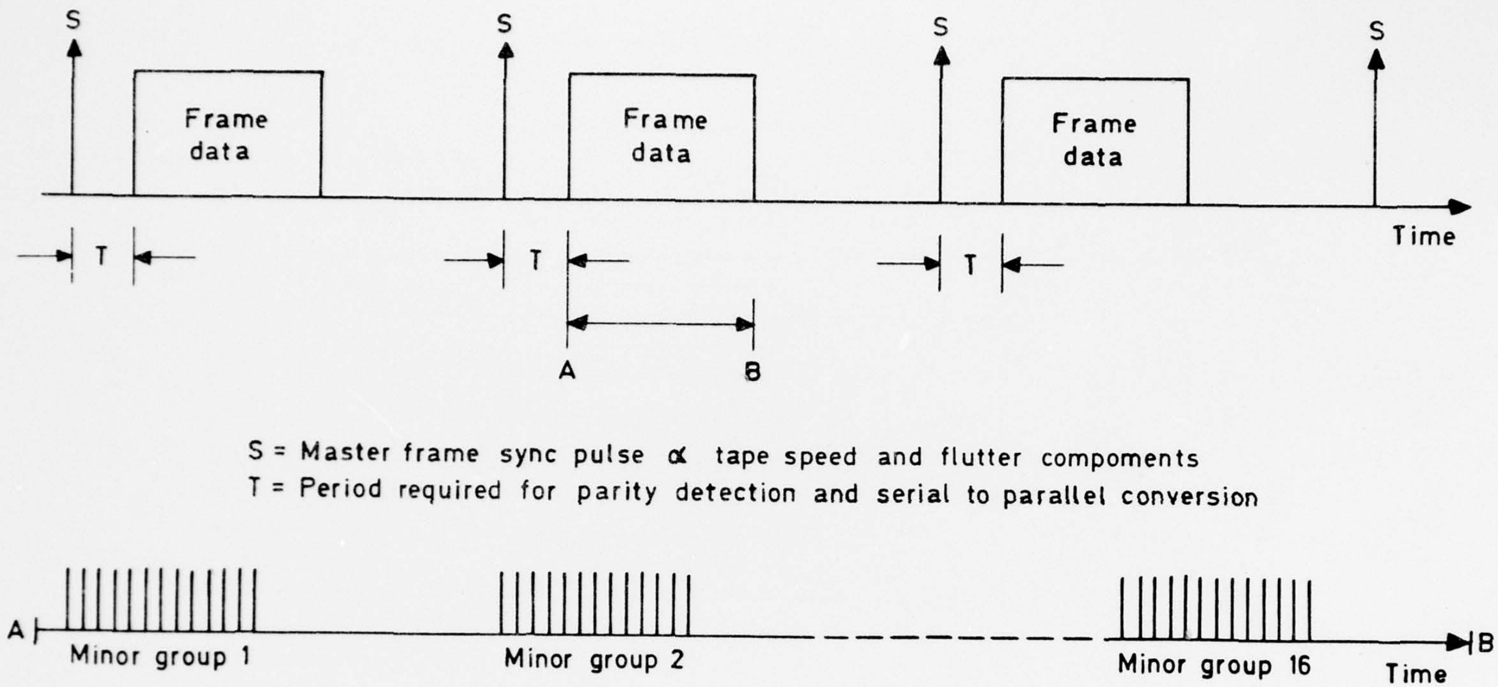
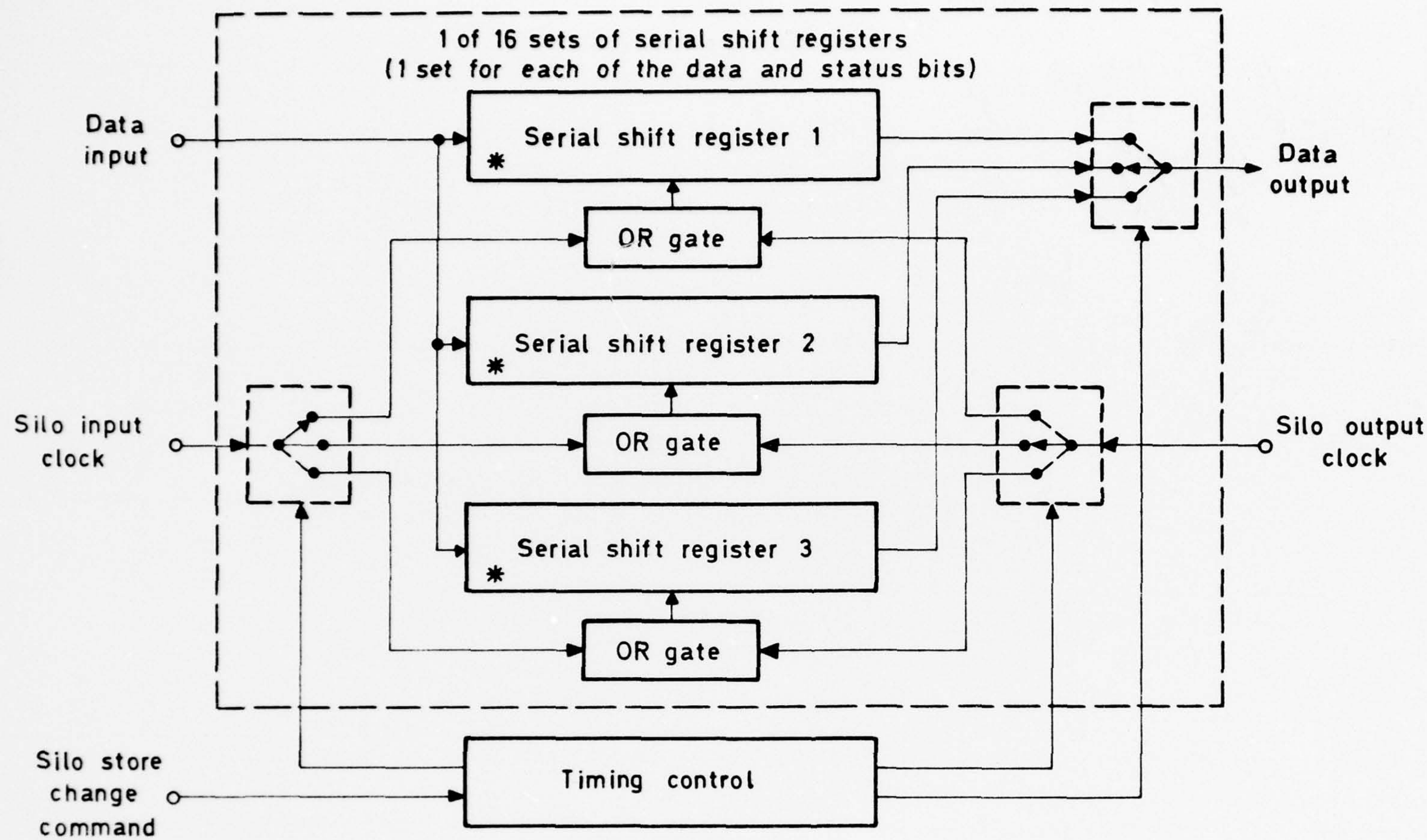


Fig 14 Deskew control



Data bits/minor group = number of tracks in use
(diagram for 13 data track operation)
Number of minor groups / data frame = 16 (constant)

Fig 15 Silo input data



* Length adjusted to match track configuration.

Fig 16 Silo

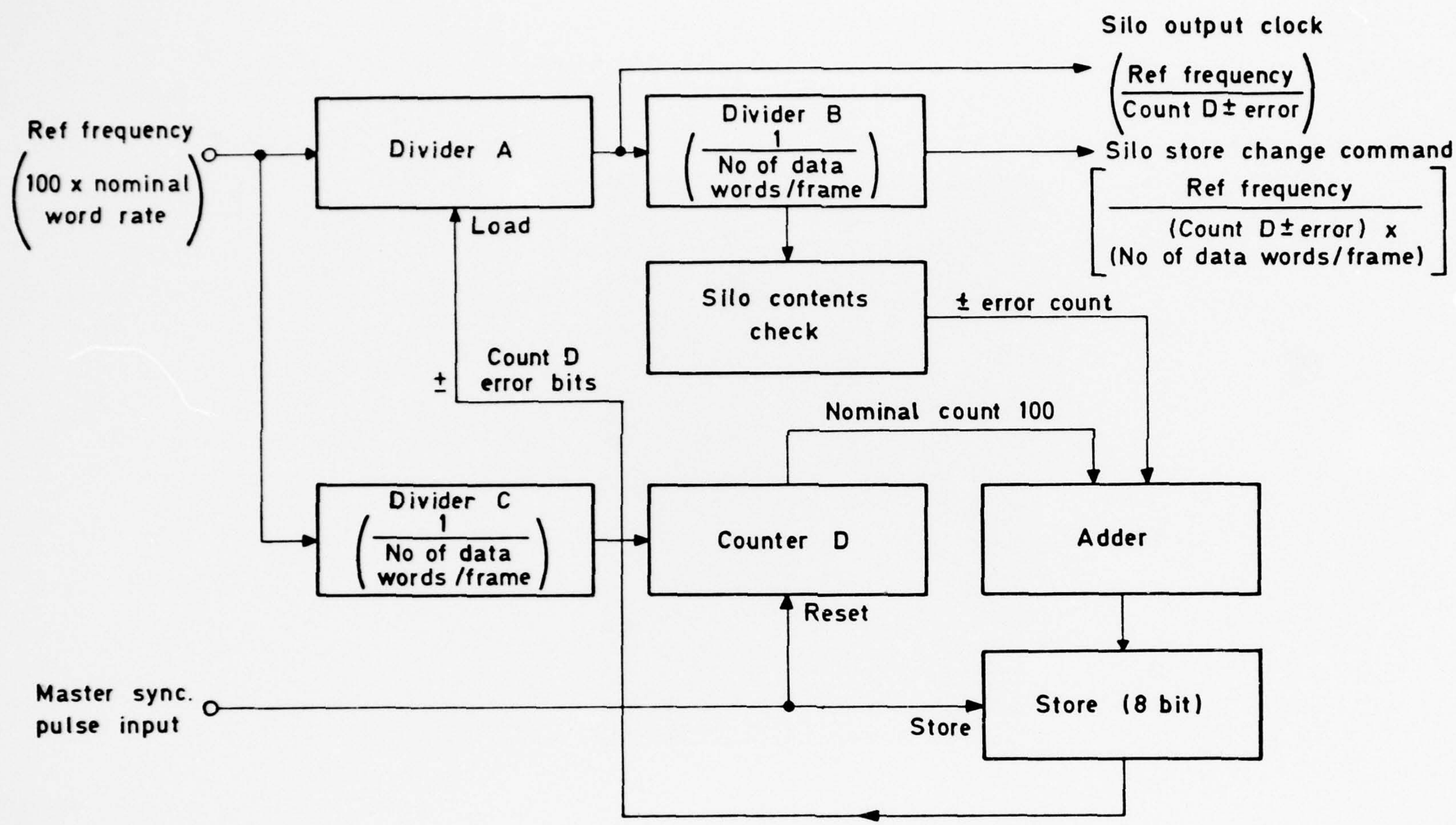


Fig 17 Silo control

Fig 18

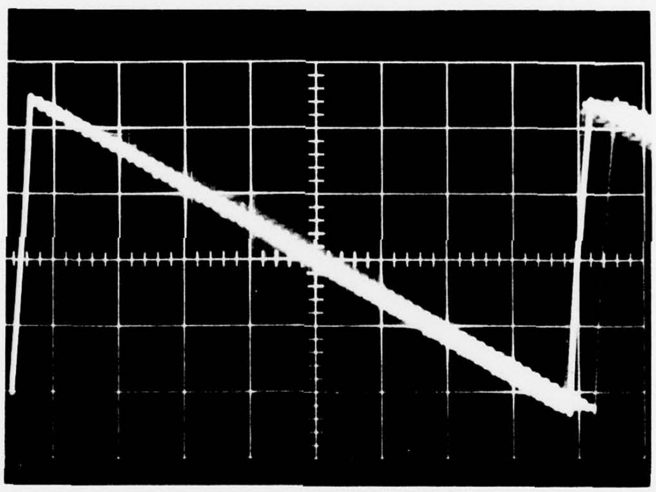


Fig 18 Silo output jitter

TR 77140 C14489

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNLIMITED

As far as possible this page should contain only unclassified information. If it is necessary to enter classified information, the box above must be marked to indicate the classification, e.g. Restricted, Confidential or Secret.

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7a. (For Translations) Title in Foreign Language

7b. (For Conference Papers) Title, Place and Date of Conference

8. Author 1. Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	Pages	Refs.
Labrum, G.R.	Alexander, D.C.	Jackson, C.W.	September 1977	44	2

11. Contract Number	12. Period	13. Project	14. Other Reference Nos.
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Airborne PCM recording. PCM error correction.

17. Abstract

The Report describes a PCM magnetic tape replay system developed for the replay of airborne recordings made at high bit packing densities. The high data capacity provided is likely to be able to meet all future RAE requirements for aircraft flight testing.

The record/replay systems employ a new multi-track serial word format particularly suited to recording in very severe airborne environments. Design of the replay system places special emphasis on ease of operation and the provision of a comprehensive error correcting system enables a high degree of data security to be obtained.

Brief descriptions of the airborne recording and replay data handling systems are given and the results of performance testing presented with general comments on the choice and handling of magnetic tapes.

AD-A064 221 ROYAL AIRCRAFT ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 14/3
THE DESIGN OF A HIGH PACKING DENSITY PCM MAGNETIC TAPE REPLAY S--ETC(U)
SEP 77 G R LABRUM, D C ALEXANDER, C W JACKSON
UNCLASSIFIED RAE-TR-77140-REV DRIC-BR-65971 NL

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Addendum to Technical Report 77140
Received for printing 14 November 1979

THE DESIGN OF HIGH PACKING DENSITY PCM MAGNETIC TAPE REPLAY SYSTEM

by

G. R. Labrum
D.C. Alexander
C.W. Jackson

Addendum to page 12

6 CONCLUSIONS

Testing completed so far shows that the multi-track serial word format provides reliable operation while offering 10 to 20 times the data capacity of the existing parallel word record systems. This has been achieved without lengthy or critical setting-up procedures and the error correcting system has been shown to provide a large operating safety margin. The comprehensive error displays enable the operators to immediately identify those parts of the system needing adjustment and to check overall system performance. Word error rates of 1 in 10^8 are being consistently achieved and should provide adequate performance for any foreseen flight test programme.

Departmental Reference: IT 156