AMPEX CORPORATION
Advertising/Sales Promotion MS 7-14

RO

Fine piece of work WR

April 3, 1968

APR 4 1968
W.E.R.

TO: All Instrumentation Field Sales Offices
cc: Instrumentation Internal

FROM: John Larson
Instrumentation Advertising

SUBJECT: New Sales Aid

Attached is your copy of the revised edition of Erhard Kietz' booklet "Transient-Free and Time-Stable Signal Reproduction From Rotating Head Recorders."

This is the booklet that was offered to respondents in our recent FR-900 mailing.

This booklet is now in stock but bulk quantities have not been mailed to the field. Order additional in the usual way from Marketing Communications, Lit. #D095 "Kietz booklet".

John

JAL:cb

Erhard:
Thought you might like to know that Bill was also impressed - keep up the good work!
Bob Owen

Errata Sheet

for

"TRANSIENT-FREE AND TIME-STABLE SIGNAL REPRODUCTION FROM ROTATING HEAD RECORDERS"

Page 7: In Figure 3, the arrow for f_3 should be extended to have its head pointing at the dashed curve.

Page 13: Replace the first four lines of the second column by the following:

$$\frac{f_c \pm (f_p \pm \Delta f_p)}{2} \quad \text{or} \quad \frac{f_c \pm (f_p \pm \Delta f_p)}{3}$$

where f_c denotes the fm carrier center frequency, f_p the pilot frequency, and $f_p \pm \Delta f_p$ the passband of the pilot filter.

Page 17: Amend formulae as follows:

$$t_2 - t_1 = \ldots\ldots = \frac{TV}{2}\left(\frac{V_1 - V_2}{V_1 V_2}\right)$$

$$t_2 - t_1 \simeq \frac{TS}{2}$$

After the words: "20 decibels," insert an asterisk referring to a footnote as follows:

*) This is equivalent to a signal-to-noise ratio of 35 dB $\frac{\text{p-p}}{\text{rms}}$, or 26 dB $\frac{\text{rms}}{\text{rms}}$, if the 3-sigma value of the noise is considered peak noise, which is true for 99.7% of the time.

Page 25: In the first column, second paragraph, line 14 reads: "and the respective pilot signals are recombined."

Page 26: In the first column, second paragraph of section 1, delete the words: "of the paper on Transient-Free and Time-Stable Signal Reproduction from Rotating Head Recorder."

TRANSIENT-FREE AND TIME-STABLE SIGNAL REPRODUCTION FROM ROTATING HEAD RECORDERS*

by Erhard Kietz

AMPEX CORPORATION
Redwood City, California

REVISED, FEBRUARY, 1968

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*Original Publication in Record of the 1963 National Space Electronics Symposium, IEEE Professional Technical Group on Space Electronics and Telemetry, Miami Beach, Florida, Paper 4.3

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INTRODUCTION

Significant advances in the state of the art of rotary-head recording have been made since the introduction of TV recorders in 1956. The achievements, brought about through continued advanced developments of the TV recording technology, bear directly on the application of rotary recorders to predetection telemetry, post-detected frequency-multiplexed recording, pulse recording, such as radar video, and digital recording (serial PCM).

While longitudinal recorders have been used almost exclusively in the past for the recording of telemetry data, new techniques have been developed on rotary-head wideband recorders which make them attractive for new applications in the field of space electronics.

This paper will treat on those advances emphasizing the technology developed for transient-free and time-base stabilized reproduction of the four classes of data mentioned above.

I. THE GENERAL PROBLEM OF TIME-BASE STABILITY

A. Causes of Time-Base Errors

In magnetic recording, the time function of an electrical signal is transformed into a space function in a way which is similar to the presentation of the signal on the cathode ray tube of an oscilloscope. An important difference between these two methods of information storage is the dependence of magnetic recording on mechanically moved parts at critical places in the system. Therefore, most of the parameters defining the mechanical construction and performance of the recorder enter the transfer function from the time domain to the space domain in the storage process and affect also the reverse process of information retrieval. The end result is that the reproduced information is a time function with spurious variations of the originally recorded signal, which appear as timing, or time-base, errors.

In rotary-head magnetic tape recording, these mechanical system parameters can be divided into two classes. The first class is not time variant, and becomes evident only if the recording is played back on a machine different from the recording machine. If the tape is reproduced on the same machine where it was recorded, these errors will cancel. Factors contributing to this type of timing errors are: the flatness of the base plate which holds the scanning head assembly and its inclination against the tape edge, the tape guide height adjustment, azimuth and quadrature tolerances of the head positions with respect to the drum, differences in pole tip protrusion, and the amount of pole tip engagement with the tape.

The second class of timing errors comprises the time-variable or dynamic errors. Two groups can be distinguished: low-frequency errors usually called "wow and flutter," and errors of higher frequency which may be called "jitter." The first group originates through hunting of the head drum motor, due to non-symmetrical motor fields, variations in the motor load through bearings, and head-tape friction. Other sources of mechanically generated dynamic time-base errors are variations in tape tension, tape guiding, and tape dimensions. Tape jitter originates mainly from irregular changes in head-tape friction.

Beside the many mechanical sources of time-displacement errors, there are others in the electrical system. They can be fixed delays with uniform action on the entire signal (delay lines, flat-response filters), or they can be frequency-dependent, affecting only certain components of the signal spectrum (resonant circuits including the electrical head circuit, etc.). Finally, the system noise will cause, to some degree, a phase- or time-modulation of the signal and give rise to random time errors.

B. Accuracy Requirements

The necessary or desirable degree of time-base stability depends on the specific application under consideration.

Other requirements, such as bandwidth and amplitude stability, are not mentioned here, but it might be noted that spurious transients generated in the recording system are usually of detrimental influence to radar and digital recording. They must be kept below the noise level under all conditions.

1. Television

Monochrome television signals require a stability of approximately ±50 nanoseconds for short time intervals (less than one millisecond), while color television signals require ± four nanoseconds to satisfy the NTSC specifications.

2. Bandsplitting of Coherent Signals

If the bandwidth of a coherent analog information signal exceeds the capabilities of a recorder, the signal can be split into two or more channels and recorded on separate machines, or on a multi-track recorder. The timing stability of the reproduced signals must be such that no serious phase discontinuity occurs in the crossover region of the two channels. A sufficiently smooth transition in the re-combining process will occur if both channels remain within one-tenth of the period of the crossover frequency, relative to each other. This is an empirically-determined upper limit. For an eight-megahertz information band, split at four megahertz (period of 250 nanoseconds), the two channels must remain within 25 nanoseconds of each other. Each channel, if referenced to a stable clock, must therefore remain within ±12.5 ns of the clock.

3. Frequency-Division Multiplexing

The two major areas of applications for multiplexing in the frequency domain are 4-kHz communication channels containing voice signals in single-sideband modulated form (SSB), and telemetry channels containing data of various bandwidths in analog or digital form.

a. Single-Sideband Channels

If a spectrum of several hundred multiplexed SSB signals is recorded and reproduced, each channel and each spectrum component within a channel, contains "flutter," i.e., frequency shifts due to the timing instabilities of the recorder. Flutter (F) is defined as the time derivative of the time-base error (T). For a sinusoidal time-base error of frequency f, the flutter is therefore:

$$F = \frac{dT}{dt} = 2\pi fT.$$

It is known from experience that a flutter of an SSB subcarrier signal of $30 \cdot 10^{-6}$ (i.e., a shift of 120 Hz, if the subcarrier is at 4 MHz) yields very clear demodulated signals, while a ten-times larger flutter renders the voice signal rough and not very intelligible. The highest rate of time-base errors in a rotary-head recorder (which contributes most significantly to the flutter) is approximately at one kilohertz. In order to obtain good SSB reproduction from such a recorder, the time-base error should therefore be limited to:

$$T = \frac{F}{\omega} = \frac{30 \cdot 10^{-6}}{2\pi \cdot 1000} = 5 \text{ ns}$$

If, however, the carrier generator in the demultiplex unit is locked to an off-tape pilot, the effective flutter of all the multiplex channels can be reduced to that of a directly recorded voice channel. For example, a 100-ns time-base error would cause a frequency shift of 2400 Hz on a 4-MHz carrier (i.e., 20 times the above example); yet with a pilot-locked carrier generator, the voice channel output flutter can be reduced at the ratio of 4 MHz to 4 kHz, i.e., to 2.4 Hz frequency shift.

b. Telemetry Channels

From the IRIG standards for telemetry, it can be found that subcarrier deviations as low as ±7.5% are being used. If the noise contribution due to demodulated flutter in a telemetry channel is desired to be kept at 60 dB below the signal level, then the subcarrier deviation due to flutter must be within $\pm 7.5 \cdot 10^{-5}$. For a flutter rate of one kilohertz, the time-base error must therefore be within:

$$T = \frac{F}{\omega} = \frac{7.5 \cdot 10^{-5}}{2\pi \cdot 1000} = 12 \text{ ns}$$

For a SNR of 50 dB, the time-base error would have to be within $3.2 \cdot 12$ or 38 ns.

4. Radar Recording

The requirements differ widely, depending on the type of radar system, the desired range resolution, and the mode of recording. There are two modes of recording radar information: video recording and I.F. recording, i.e., recording after or before the final detector stage in the radar system, respectively. A few examples may illustrate the situation.

For a simple search radar, any time jitter will appear as a range error. It will blur the echo presentation, if its duration is substantially less than the pulse repetition period, and it will produce an echo position error, if the time-base errors occur at a slower rate than the pulses.

For I.F. recording, some systems require very stringent phase stabilities. In an MTI (Moving Target Indicator) radar, for example, any short-term timing or phase instability will modulate the ground clutter and prevent these signals from being canceled out. The spurious signals generated from this effect should not exceed the minimum detectable signal. This means, for example, that for a 30-MHz I.F. carrier, the timing stability must be held within approximately ± one nanosecond.

5. Digital Recording

The rotary-head recorder with its wide bandwidth has opened up an exceptional capability for the recording of digital signals at high bit rates, reliability, and density. At the present state of the art, a 6-MHz analog channel (FR-900) can record 10 to 12 Mbit/s NRZ data. Two such channels are available in a single recorder (FR-950). With the use of an Ampex proprietary method of redundancy recording, a bit-by-bit comparison of the reproduced data yields reliabilities of less than one error in 10^8 bits at a density of approximately 500 kbit/in^2 .

Such a high bit rate requires an accordingly good timing accuracy. At 12 Mbit/s, the bit period is approximately 83 ns. A "window" of about 20 ns must be kept open for all but one bit in 10^8, if this error rate is desired. This leaves 63 ns p-p time-base error allowable for the zero-crossing shifts due to all sources combined. The error function tables show that the "peak" value for a $1 \cdot 10^{-8}$ error density is 5.8 times the rms value. The allowable rms time-base error is therefore 63/11.6 = 5.4 ns rms. Measurements on the FR-900 have demonstrated values of 1.75 to 2 ns rms.

6. Continuous Signal Reproduction

In magnetic recording with rotating heads, at least two heads, and therefore two signal-reproducing channels, are necessary to provide continuous information from the recorder. In the transverse scanning method, four heads are located 90 degrees apart on the periphery of a rotating drum. The tape is wrapped around this drum for approximately 110 degrees, so that some of the information near the edges of the tape is recorded redundantly. During that time of redundancy, when two successive heads carry identical information in playback, an electronic switch performs the transition from one head channel to the following channel, as shown in Figure 1, for the conventional switching technique. If a relative time-base error exists between two successive head channels, a portion of the signal – as much as corresponds to the time difference between the two channels – will either be lost or duplicated in the combined signal at the switcher output, depending on whether the signal in the second channel occurs earlier or later than the signal in the first channel. Another undesirable effect of this switching process is the generation of a transient, if the two signals do not match perfectly in time and amplitude at the instant of channel transition in the switcher.

For these two reasons, it is necessary to implement time-base correction of the reproduced signals individually in the head signal channels, before they are combined in the switcher. The required accuracy of time-base correction for the purpose of avoiding loss or redundancy of information depends entirely on the specifications for a given application.

The requirement for transient-free head signal channel combination is a phase coherence of the channels during the redundant or overlap time of substantially less than 180 degrees. If, for instance, the phase difference is not more than 120 degrees, the timing between two successive head channels for a nine-megahertz carrier is within 37 nanoseconds. The instantaneous peak-to-peak time-base error of each channel with reference to the system clock must therefore be ±18.5 nanoseconds, if transient-free channel combination is to be achieved at all times at this particular carrier frequency. This problem is discussed in detail in Part III.

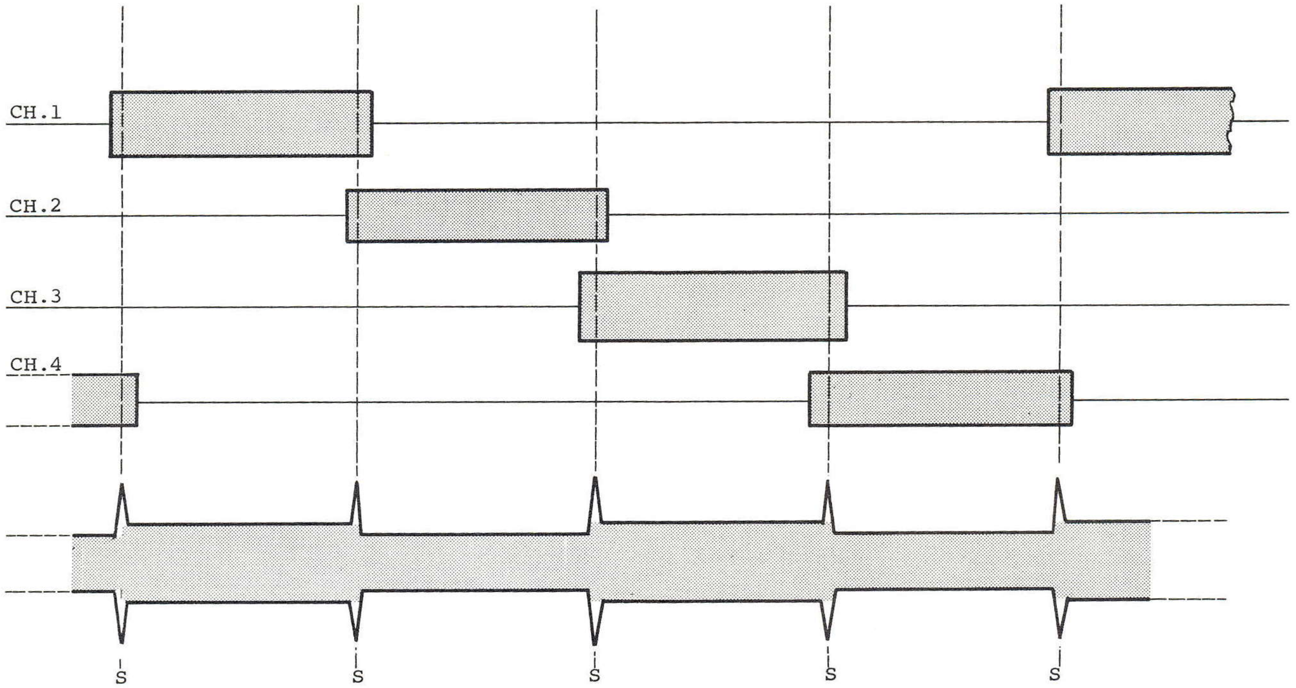


Figure 1. Signal combination in fast switching process (S: Instant of switching)

It is not necessary, in a four-headed machine, to use four separate time-base correction devices in each of the head signal channels. Alternating channels can be combined into two channels, according to Figure 2, and only two time-base correctors are necessary. This method is applicable for any number of heads.

C. Electro-Mechanical Time-Base Correction

The first step toward achieving a time-stable reproduction of a signal recorded with rotating heads is to keep the head-to-tape speed as constant as possible.

In the Ampex rotary-head recorders, a hysteresis synchronous motor is used to drive the head drum. The motor is integrated into two servo loops: a positional loop having a low frequency response and controlling the drum position, and a velocity loop with a larger bandwidth for the suppression of instabilities in the motor (motor hunting). Timing information for the servo is derived from a tachometer signal sensing the drum position This system is capable of holding the reproduced signal within approximately one microsecond for intervals of less than one second. The system can exhibit long-term drift errors of ten to twenty microseconds measured against a stable reference frequency.

An important improvement was achieved with the introduction of the Intersync* system where the recording mode operates in the same way as explained above, and the reproduce mode is a multiple-step locking system which uses, in the first step, the same method as mentioned in the previous paragraph, narrowing the error down to the values quoted there. The system is then switched to the pilot signal reproduced from tape. In this mode of operation, the bandwidth of the electro-mechanical system is extended to approximately 100 Hz by virtue of applying the error signal not only to a voltage-controlled oscillator but, in addition, to a phase shifter. This combination** provides much higher accuracy and speed in positioning the head drum. The result is a reproduced signal which is stable to within 150 nanoseconds peak-to-peak for time intervals greater than approximately 1/100 of a second. Higher error rates cannot be corrected in the drum motor servo, but must be dealt with in an electronic correction system. They do not add more than 50 nanoseconds to

* TM Ampex Corporation

**Ampex Patent No. 3,017,462

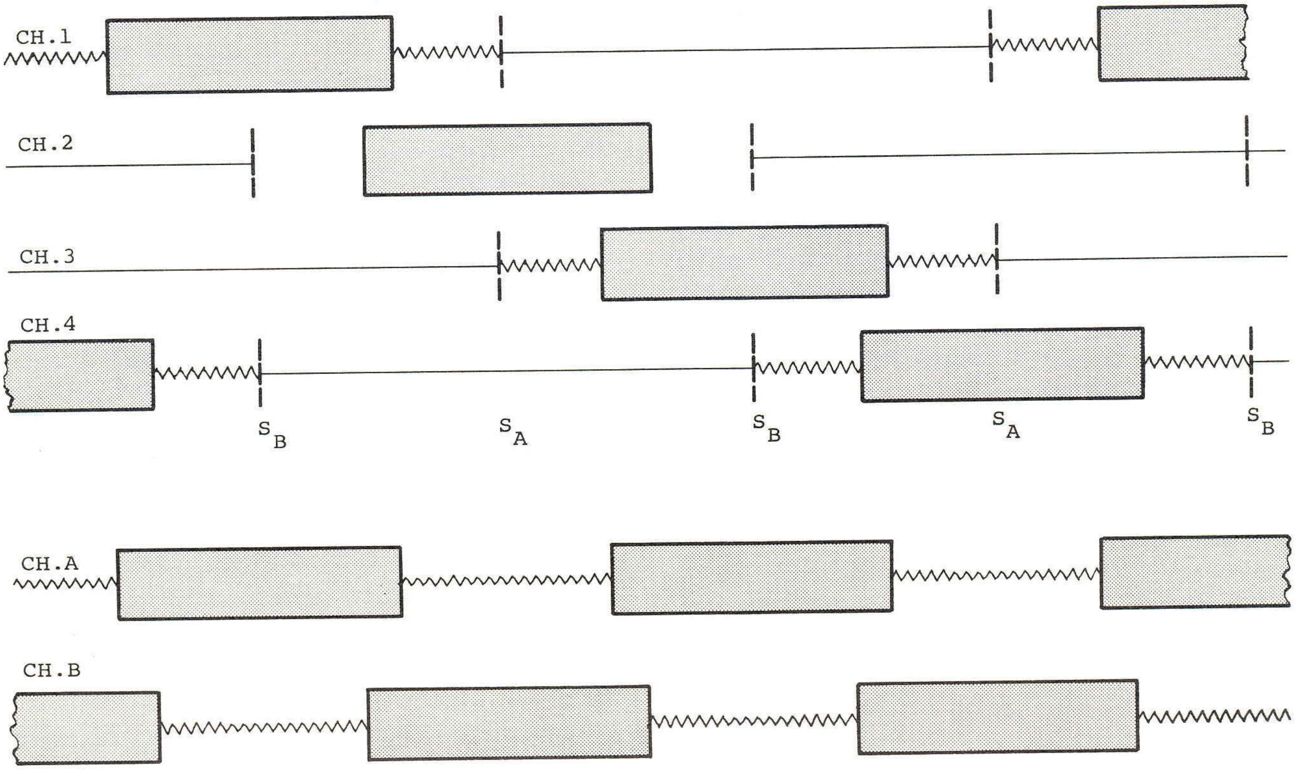


Figure 2. Signal combination into two channels in preparation of time-base correction
S_A: Instant of switching channel 1 and channel 3 to combine into channel A
S_B: Instant of switching channel 2 and channel 4 to combine into channel B

the figure just mentioned, so that the reproduced signal emerges from the tape with a timing stability of less than 200 nanoseconds, or ±100 nanoseconds measured against an external reference.

It should be noted here that in a recorder where the tape is scanned by the heads in a transverse mode relative to the tape motion, variations of the tape velocity have no effect on the time-base error of the reproduced signal, if a perfect azimuth alignment of the heads is assumed. The capstan motor servo, therefore, has no other purpose than to keep the heads on track.

II. ELECTRONIC TIME-BASE CORRECTION

A. The Pilot Signal

1. Necessity of a Pilot Signal

Both the electro-mechanical and the electronic methods of time-base correction are based on a procedure of two elementary steps: measurement of the resultant record-reproduce time-base error, and application of this error, after phase reversal, to the reproduced information or to the process of reproduction. The first of these two steps requires a "yardstick" to measure the error, i.e., a stable timing reference.

In some applications, the recorded information contains an inherent timing reference signal which can be used for this purpose as, for example, the sync pulses and color bursts in television signals. In other cases, the intelligence might be modulated on a carrier which also represents clocking information, as in PCM (Pulse Code Modulation), PAM (Pulse Amplitude Modulation), or even in conventional AM.

But in general, no such information is available and a separate timing signal, a pilot, must be introduced. It is important that such a separate pilot is subjected in the same manner and degree to the various time-base disturbances in the magnetic record-reproduce system as is the intelligence. It might well be desirable that more than one pilot signal is used for reasons discussed in the following paragraphs.

In the subsequent discussions, it is always assumed that the data are recorded in FM modulated form, either as a predetection input signal, or as an analog input signal subjected to frequency-modulation within the recorder prior to the recording process.

2. Methods of Using a Pilot Signal

The method used in applying a pilot signal, before the recording process takes place, must take into account that, after reproduction from the magnetic tape, the pilot must be separated again from the intelligence. Conceivable ways of using a pilot include:

a) Time sharing: The pilot is gated at regular intervals into the information signal (as it is done in television).

b) Space sharing: The pilot is recorded by a separate head on a separate track close to the information track on the tape.

c) Level sharing: If the information is recorded as a frequency-modulated wave, the pilot can be used to amplitude-modulate the FM envelope, and separation is accomplished by different demodulation techniques.

d) Spectrum sharing: The pilot is added to the information at a frequency which is not contained in the recorded information, so that separation is possible by filters.

While method a) can be disregarded here because it does not yield continuous information, method b) has some attractive advantages. The pilot is electrically separated from the signal; its frequency can be selected without regard to the information spectrum and can, in particular, be placed near the center of that spectrum so that circuit delays, especially in the head circuits, have a more uniform effect on the pilot and information signals. Disadvantages are: a more complicated head assembly, a more restricted information packing density on the tape, and variations in tape stretch, as the heads do not pass across the tape exactly on identical paths. Differences of azimuth and quadrature between pilot and information recording heads are of a static nature and could be equalized with fixed delay lines.

As to method c), the amplitude-modulated pilot seems to be very interesting, but has so far proven to be ineffective. With a frequency-modulated intelligence, it is mandatory to drive the magnetic tape into saturation in order to achieve the best possible signal-to-noise ratio. Most of the pilot AM is, therefore, eliminated through the tape saturation, so that the signal-to-noise ratio of the recovered pilot is very poor. The non-linear tape characteristic also produces heavy cross-modulation between pilot and intelligence.

Method d) has been the best compromise with respect to an economical and technically effective solution. This is the method employed in the Ampex line of transient-free, time-stable recorders and will be the only method referred to throughout the remainder of this paper.

3. Selection of Frequency and Amplitude of the Added Pilot

The choice of a suitable frequency for the pilot is limited in both directions by the following considerations and under the assumption that the intelligence is recorded in a frequency-modulated form. The pilot frequency should be low enough to be sufficiently below all significant components of the FM spectrum. It should also be low enough to provide non-ambiguous time-base error information. The pilot frequency must be high enough to be within the passband of the recording system (including head response), and also high enough to provide sufficient error resolution.

Figure 3 shows a scheme of the first, second, and third order lower sidebands under the conditions prevailing in the Ampex FR-900 instrumentation recorder. The graph shows that the second order sidebands are not completely negligible, but they are not useful either, because they extend, in part, below zero frequency. They are, therefore, subject to phase reversal, and would give rise to distortion in the demodulation process, if they would be of appreciable magnitude. All sidebands below 2.0 or 2.5 megahertz may therefore be disregarded and removed by a filter. The pilot frequency can then be selected anywhere below the filter cut-off frequency.

The second requirement quoted above for the pilot frequency was non-ambiguous time-base error information. The amount of timing error that can be measured at a given pilot frequency is limited to the duration of one period of the pilot repetition rate, unless very complicated methods and circuits are used. As mentioned earlier (Chapter C: Electro-Mechanical Time-Base Correction), the total time-base error of the reproduced signal in a transverse-scan rotary-head recorder equipped with Intersync is within ±100 nanoseconds.

With a sufficient margin, a pilot frequency of one megahertz or less is, therefore, appropriate for this purpose. A frequency of 500 kilohertz was chosen.

The error resolution is limited by spurious phase modulation of the reproduced pilot frequency, mainly caused by noise. From the statistical noise theory, an appraisal can be made

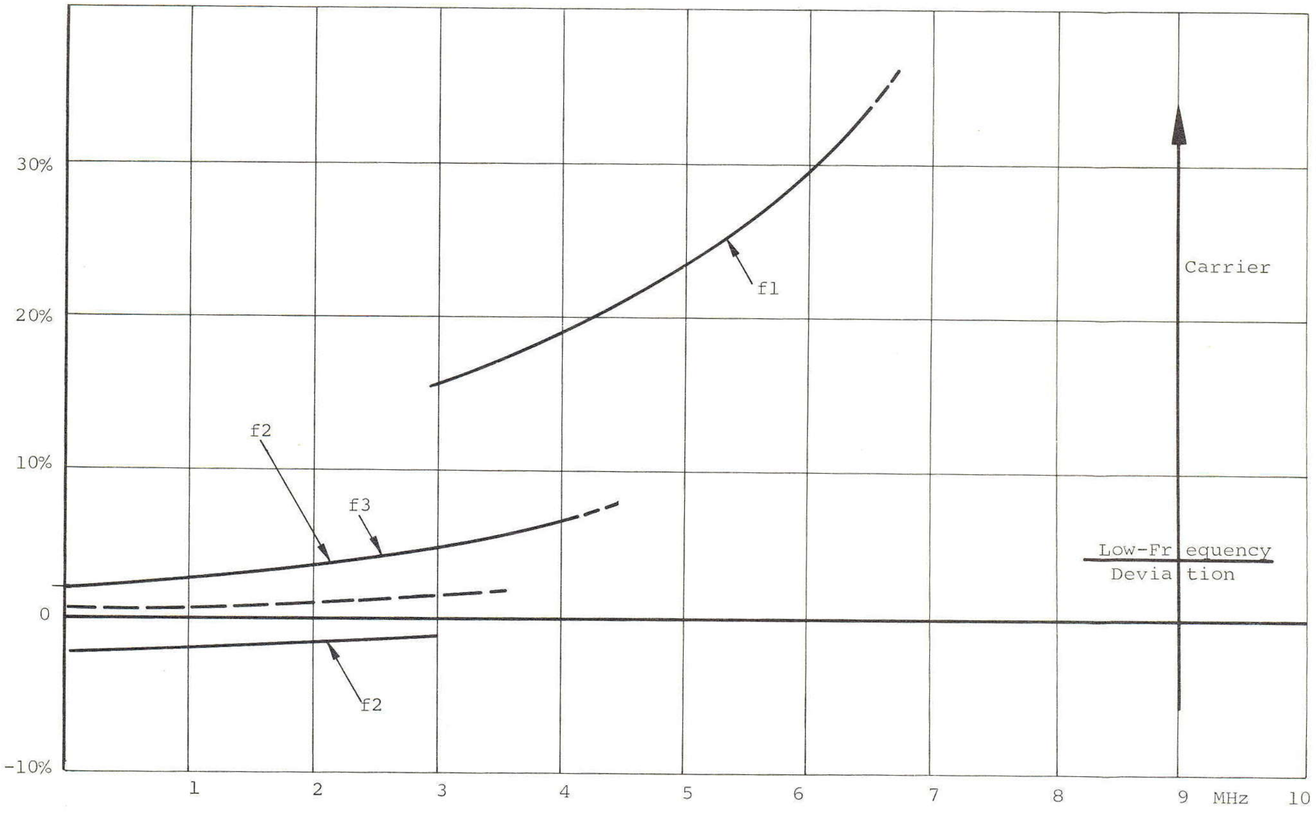


Figure 3. First (f1), second (f2), and third (f3) order lower sidebands in FR-900/950

from which a numerical example with the following figures can be derived: if it is required that a time-base error of ten nanoseconds is exceeded only once in one second, and the pilot frequency is 500 kilohertz, a signal-to-noise ratio of 41 decibels is required. For a pilot frequency of 100 kilohertz, under otherwise identical requirements, the necessary signal-to-noise ratio would be 54 decibels.

The amplitude of the pilot to be added to the FM-modulated intelligence before recording on tape is determined by the following limitations: the pilot amplitude should be high enough to allow the recovery of a sufficiently noise-free pilot off the tape, but the amplitude must not be great enough to generate excessive cross-modulation between the pilot and the FM signal. This cross-modulation results from the fact that the transfer characteristic of the recorder is not linear, especially with respect to the head-tape response. The amount of permissible cross-modulation depends on the particular application and whether or not special measures are taken to compensate for these interference effects. A more detailed discussion of these problems will be given in Part II, Chapter D.

The signal-to-noise ratio of the recovered pilot depends on the overall performance parameters of the recorder and on the bandwidth required for processing the pilot signal. Normally, the 3-dB bandwidth of the pilot-handling circuitry is 70 kHz. This figure represents a compromise between the necessary signal-to-noise ratio and the maximum permissible time delay in the filters involved, rather than a limitation imposed by the highest time-base error rates occurring in the recorder.

The pilot amplitude necessary to obtain the optimum operating conditions, according to the outlined principles, is best determined experimentally. It depends to a large degree on the type and characteristics of the record-playback heads and was found to vary from six to 15 percent of the FM signal to which it was added.

B. Error Measurement

1. Separation of the Pilot from the Intelligence

The pilot signal should undergo as much as possible the same time-base disturbances as the intelligence throughout the whole record-playback process. It should therefore be combined, or at least correlated, with the intelligence during all steps in this process involving time-base distortions, until the final time-base correction is accomplished. Before the correction can be executed, the pilot must be separated from the intelligence and be used for the generation of a corrective signal. From the instant of separation to the instant of correction, pilot and intelligence are subjected to different circuit paths and therefore different time delays. While the information signal suffers only a negligible delay, the filter which extracts the pilot provides a rather large delay. A representative figure, for a filter of 70 kilohertz bandwidth, is approximately ten microseconds. To achieve the best possible time-base correction, it would be necessary to equalize this delay difference by introducing the appropriate amount of delay in the path of the intelligence between the pilot extractor and the time-base corrector. Because the bandwidth of the frequency-modulated information is approximately 15 MHz, such a delay line would be very expensive and bulky.

Fortunately, for slow error rates, this delay difference between pilot and information is not critical, and virtually all important components of the time-base error are in the frequency range below 1000 Hz. If a sinusoidal error of amplitude E and period T is assumed, according to Figure 4, a maximum residual error ΔE (after correction) would exist due to a time delay Δt between the error in the intelligence and the correction of that error. From Figure 4 it can be seen that, if Δt is small compared to T/4,

$$\Delta E = 2\pi \frac{E}{T} \Delta t.$$

If Δt is assumed to be ten microseconds, as mentioned above, a time-base error of 0.5 microsecond peak-to-peak, at a rate of ten hertz, will

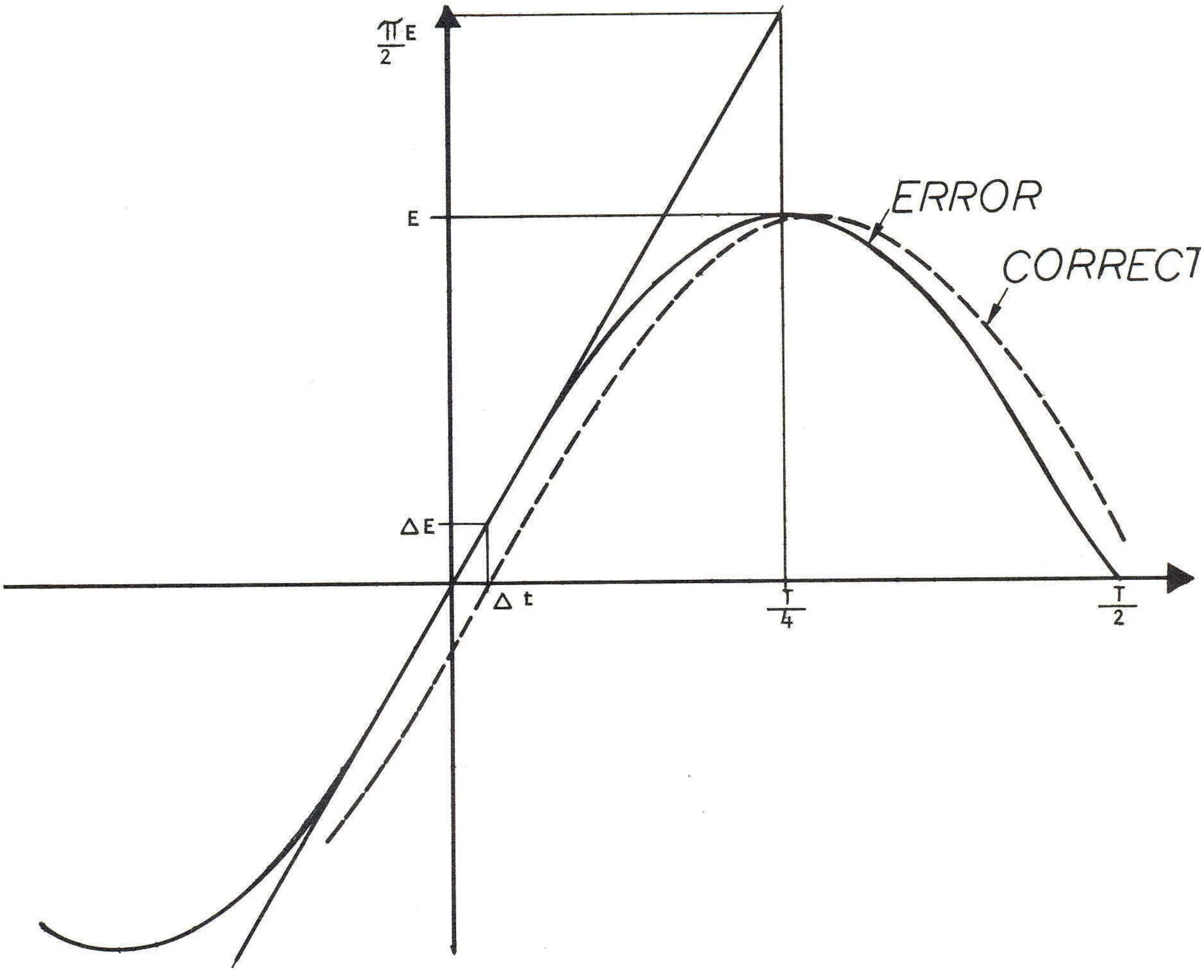


Figure 4. Relation between a sinusoidal timing error and its correction, if a delay Δt exists in error signal path

leave a residual error of 0.3 nanosecond peak-to-peak. An error at 1000 Hz must not exceed 0.16 microsecond peak-to-peak to keep the residual error within ± ten nanoseconds. For an error rate of approximately three kilohertz or more, there is virtually no correction, if the pilot delay is as large as ten microseconds or more.

2. The Error Signal

The pilot, reproduced from tape, contains the timing error in the form of phase modulation. In nearly all applications, the recorder is required to reproduce the recorded information in real time, or in a known ratio or multiple of real time (time compression or time expansion). In all of these cases, the timing error signal must be referred to a stable system clock or frequency standard, the accuracy and long-term stability of it being determined by the particular application requirements. Any phase sensitive detection or demodulation technique could be used to derive the error information from the pilot, if the following conditions are met:

a) Any additional time delay in the circuits should be avoided.

b) The circuits must circumvent phase distortion of the pilot and its error signal sidebands.

c) The phase demodulator must have a very linear characteristic so that the error signal effectively represents the phase or timing information contained in the reproduced pilot signal.

The circuits chosen in the Ampex equipment are shown in the block diagram of Figure 5. After

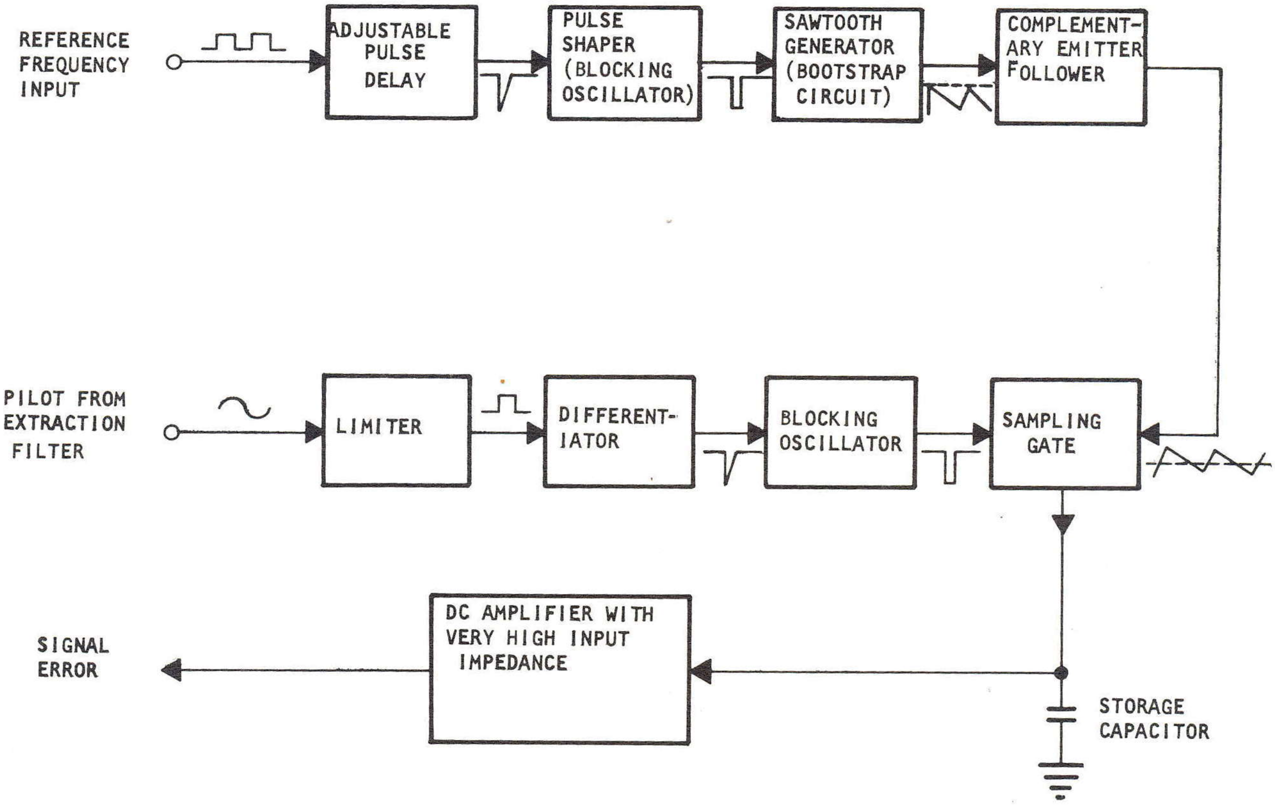


Figure 5. Block diagram of error detector in FR-900

being separated from the intelligence through a band-pass filter, the pilot is subjected to approximately 60 decibels of limiting. The resulting square wave is processed into a sharp pulse of 0.2-microsecond duration which opens a sampling gate. A linear sawtooth waveform, derived from the crystal clock of the recorder, is sampled through the gate into a storage capacitor. The error signal appearing on this capacitor consists of little steps at intervals of two microseconds and is not passed through a filter to avoid further delays. It is integrated only slightly by the time constants of the following circuits.

C. Error Correction

1. General Survey of Delay Devices

Any device capable of presenting a voltage- or current-controlled variable delay to a signal of the bandwidth in question (0.5 to 15 MHz) would be suitable for the correction of time-base errors in the reproduced signals. A great number of such devices has been proposed. Only a few of the more important ones can be listed here, without detail discussions of their merits and shortcomings.

a. Delay Devices Using Special Vacuum Tubes

The transition time of a cathode ray beam can be controlled in two ways: by changing the velocity or changing the beam length. In the latter case, the beam forms a helix with a variable pitch.

A distributed L-C delay line can be scanned by an electron beam which acts as a tap to this line.

The information can be continuously stored on a target by an electron beam which writes a circular path on the target. The scanning velocity along the circle is changed according to the time-base errors during the write-in process, while the read-out process occurs at a constant rate. During read-out or immediately ahead of the writing beam, the previously stored information is erased.

b. Semiconductor Delay

In a transistor, the minority carriers traverse the base region in a finite transit time which may be varied by changing the electrical width of that region. This can be accomplished by changing the width of the depletion layer at the collector as a function of collector voltage.

In switching transistors, several types of storage effects combine to what is called "propagation delay," which can be modified by varying the base current in the turn-on condition. The propagation delay can therefore be useful in delaying digital or FM signals.

c. Sample-Hold Circuits

An analog signal can be delayed by sampling it at a sufficiently high rate, storing the samples on a bank of capacitors, and reading the samples out at a rate which has been modified by the error signal.

d. Magnetically Controlled Delay

A delay line is commercially available which is variable by means of a magnetic or electro-magnetic field. The rate of change of delay can be up to 100 kHz. For good linearity, the relative range of delay variation is rather small (about ten percent).

e. The Voltage-Controlled Diode Delay Line

This is the type of controlled delay used in the Ampex video and instrumentation recorders for the purpose of electronic correction. It will be discussed in more detail in the following paragraphs.

2. The Voltage-Controlled Diode Delay Line

If, in a lumped-constant delay line, the capacitors are replaced by voltage-variable silicon diodes, the delay can be controlled by a voltage signal applied as shown in Figure 6. The push-pull arrangement of the correction signal prevents it from being superimposed to the information signal along the delay line. Because the information being controlled in the delay line is in frequency-modulated form, relatively small by-pass capacitors can be used to complete the signal path. In the instrumentation recorders (FR-900, for example) two such delay lines are used, as explained earlier, before the reproduced signals are finally combined into one continuous wave. Each has a range of delay variation of 0.5 microsecond, the total delay being variable from approximately 1.25 to 1.75 microseconds. The variable-capacitance diodes must be thoroughly graded and matched.

The frequency response and characteristic impedance of this delay line configuration change, of course, with the magnitude of the correction signal applied to the capacitor-diodes. This variation in frequency response is equalized in a special network in the signal output amplifier, as indicated in Figure 7. This equalization is made dependent on the error signal so that the output amplifier tracks the varying response of the delay line in a complementary way. The effect of change in characteristic impedance is minimized by selecting proper source and output terminations so that reflections are kept at a sufficiently low level throughout the entire range of delay variation. An improved performance can be obtained by designing the FM signal amplifier shown in Figure 7 in such a way that its input impedance, which constitutes the output termination of the delay line, varies with the magnitude of the error signal in such a manner that the line is always terminated properly.

The capacitance of the voltage-controlled diodes changes roughly in proportion to the reciprocal of the square root of the bias, and the delay of the line changes with the square root of the capacitance. To obtain a linear relationship

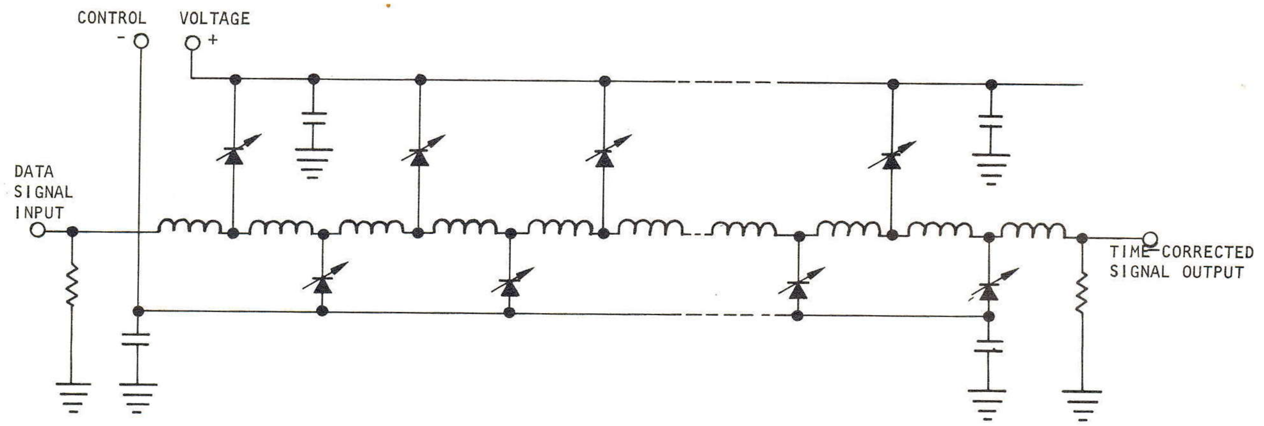


Figure 6. Schematic of voltage-controlled diode delay line

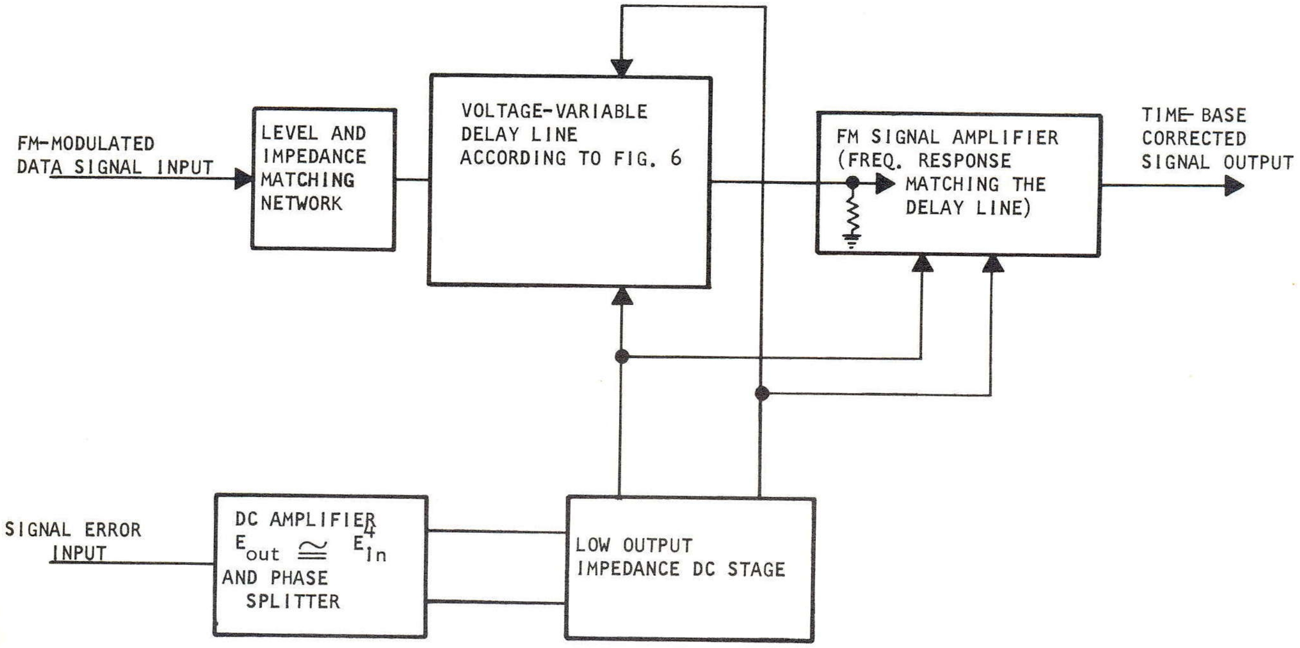


Figure 7. Block diagram of time-base corrector

between error signal and delay, it is, therefore, necessary to include a non-linear network in the error signal path which pre-distorts the error amplitude very closely according to this fourth-power law. It is made up of ten diodes which are biased in properly adjusted increments.

3. Mode of Operation

The electronic time-base corrector can be operated in a closed-loop or open-loop fashion. Both are being used. The latter is shown in Figure 6. In the open-loop operation, the time-base errors which are to be detected are larger and easier to measure, less dc-amplifier gain in the error processing circuits is necessary, no instability problems arise, and less time delay occurs between pilot-signal extraction and error correction. The price to be paid is a higher degree of linearity which must be maintained between the phase of the pilot signal and the corrective delay of the information.

D. Interference Problems

As mentioned earlier, there are many non-linear signal transfer characteristics in the recording/reproducing system. The most important one of these is the head-tape response. If two signals, the frequency-modulated information and the pilot frequency, are recorded simultaneously through the same head, several effects occur. First, the FM signal acts as a bias to the pilot somewhat in the manner as it is known in audio recording. This has the consequence that the pilot amplitude can be held low compared to the FM signal and nevertheless yield a very good signal-to-noise ratio in the reproduced pilot. Also, virtually no harmonic distortion occurs to the pilot. Such harmonics would appear as spurious components in the FM spectrum.

The second important effect of the recording process is the generation of unwanted components originating from the FM spectrum, some of them interfering with the pilot frequency. These interferences occur when certain critical frequencies are contained in the information signal. More details will be given in the next paragraph.

A third consequence of the non-linearities in the recorder is cross-modulation between the FM carrier and the pilot. This will also be discussed below.

1. Critical Signal Frequencies

Under the frequency-modulation conditions applied in wideband instrumentation recorders and outlined in Figure 3, the FM signal contains second order sidebands of approximately three percent and also third order sidebands in the neighborhood of 0.5 percent of the carrier amplitude for maximum input level and in that region of the spectrum where the pilot is located (500 kHz). The pilot level normally used is between six percent and ten percent of the carrier level. The following modulating frequencies will generate second or third order sidebands within the passband of the pilot separation filter:

$$\frac{f_c \pm f_p}{2} \pm \frac{\Delta f_p}{2} \; ; \; \frac{f_c \pm f_p}{3} \pm \frac{\Delta f_p}{2}$$

where f_c denotes the FM carrier center frequency, f_p is the pilot frequency, and Δf_p the passband of the pilot filter.

These sideband frequencies are eliminated by a filter prior to adding the pilot and recording on tape, as mentioned previously. This results in a certain amount of amplitude modulation on the FM carrier envelope. Because the tape is magnetized close to the saturation level by the recorded FM signal, the tape acts as a limiter, the amplitude modulation is, at least partially, removed in the reproduced signal, and the sidebands appear again, to a certain extent. They interfere with the pilot and thus can impair, or even completely upset, the time-base correction, if these critical frequencies are recorded at maximum input level. For decreasing input levels of these critical frequencies, the higher order sidebands diminish rapidly. Therefore, this situation is not critical for radar recording, because the spectrum components of radar signals are normally of sufficiently low levels. In PCM recording the problem is very serious, because certain words or word combinations can contain very high levels of these critical frequencies.

This problem has been solved by extracting the FM sidebands which occur in the neighborhood of the pilot frequency, adding them, after phase inversion, at twice the original level, and subsequent limiting. This renders that area of the spectrum free of sidebands. The pilot signal can now be added and the recording process, which is very similar to a limiting process, will not restore the critical sidebands.

Another critical frequency is the pilot frequency, f_p, itself. If this frequency is recorded as an information signal in frequency-modulated form, any non-flat frequency response in the signal system will produce amplitude modulation. A slightly asymmetrical limiting or distortion of this signal will then produce rectification or detection of the signal and will, consequently, interfere with the pilot. Careful design of all circuits handling the FM signal is necessary to minimize this influence.

2. Pilot Cross-talk and its Cancellation

The principal cross-modulation products between pilot and FM carrier are:

$$f_c \pm f_p \text{ and } f_c \pm 2f_p.$$

They produce spurious signals f_p and $2f_p$ in the output of the FM discriminator, i.e., at the information signal output of the recorder. The magnitude and phase of this signal is not easily predictable, nor under control. It depends not only on the relative amplitudes of the pilot and the FM carrier, and on the absolute amplitude of the combined signal as applied to the heads, but also on subtle details in the recording process which are not fully understood yet.

It is easy to neutralize the effect of this cross-talk to a large extent. Because, at the output of the recorder, the signal is highly time-base stabilized, the spurious signals can be directly canceled by injecting a 500-kilohertz and a one-megahertz sine wave derived from the system clock. The amplitude and phase adjustments of the cancellation signal must be made separately for each reproduced tape and at an instant where no information is recorded in the wideband channel, for instance, by displaying the base line between radar pulses on a monitoring oscilloscope.

E. Differential Delay Between Pilot and Intelligence

It is not possible to comply strictly with the requirement that the pilot be subjected to identical time-base errors throughout the record-reproduce system as is the information signal.

The magnetic head, being essentially a damped resonant circuit with different behavior in the recording and reproducing modes, presents a frequency dependent delay to the signals passing it. But this basic equivalent circuit is greatly, and in a very complex manner, modified by the magnetic properties of the head core and tip materials, their saturation characteristics, skin effect (resistivity), the complex permeability, the gap dimensions, and the fact that different recording currents are used for the individual heads as mentioned later in Section III.C.

Another reason for a differential delay between pilot and FM signal is the fact that in the recording process the point which defines the final tape magnetization, when the tape passes the gap field, depends on the wavelength of the recorded signal relative to the gap length. This means the recording point changes with frequency. It is also dependent on such parameters as signal amplitude, tape coating thickness, field penetration depth, field angle, and head-tape spacing. In general, it can be said that the recording point for the peak of a sine wave signal at low frequencies is located in the center of the gap and moves, for increasing frequencies, toward that edge of the gap where the tape leaves the gap region. With increasing head-tape separation, this effect is enhanced, and the recording point can even move beyond the gap edge. This condition is, for the pilot frequency, modified by the biasing effect of the FM signal.

A third source for differential delays in the recorder is in the equalizing circuits discussed in Section III.C, below. They are used for equalizing the phase response of the four signals reproduced from the individual heads in the FM passband, imparting certain amounts of time delay to the signals, but having no effect on the pilot signal.

The sum of all these delay differences between pilot and information would be of no concern if it were identical in all four head channels. Actually, only the differences between the delay differences in the individual head channels are important. They can amount to as much as 50 nanoseconds and must therefore be compensated. It is obvious that an electronic time-base correction system cannot correct for these errors, because they are not common to both the pilot and the information.

Because of the analytical complexity of these differential delays, the best approach is to determine them by measurement. If a fairly simple repetitive signal (sine wave, square wave, pulse) is recorded, the reproduced signal displayed on an oscilloscope with a sufficiently fast sweep (0.1 microsecond/centimeter) and triggered from a stable external source, synchronous with the recorded signal, appears with four separate traces according to the delay differences in the four head signal channels. The delays can be equalized by separating the pilot from the FM signal and introducing a manually adjustable delay (tapped delay line) in each of the four individual channels. The delay can be applied either to the FM signals or to the pilot signals. It is obvious that this must be done before any of the head channels are combined in order to achieve individual compensation for each separate head channel. After the delay insertion, the pilot and FM signals are combined again so that they are subjected to the same circuits in their further route through the system. This makes possible the alignment of the time-base correctors and the monitoring of the residual time-base error after correction. The latter procedure is discussed below in Section F.

These delay equalizations must be performed separately for each tape reproduction, preferably with a short initial test pulse recording which discloses the characteristics of the particular recorder.

There are good reasons to believe that heads with much more uniform characteristics and consequently closer tolerances can be developed, so that an individual adjustment of delay differences might become unnecessary in the future.

F. Degree of Attainable Time-Base Stability

1. Measurement Methods

There are two possibilities of measuring the timing stability eventually achieved in the system. The first and most direct method requires the recording of a repetitive signal derived from a source of very high frequency stability, for example, a crystal oscillator with very low hum or noise content. If such a signal, reproduced off the tape, is displayed at an appropriate time scale on an oscilloscope which is triggered from the crystal reference, the signal appears spread out to a band which extends over a certain range of time which can be read on the horizontal reticule of the screen (see Figure 8). The time jitter measured in this manner consists of the residual timing error, modified by the wideband noise of the recorder. The method can be refined by applying a bandpass filter of approximately 100-kilohertz width to the reproduced signal. A limiter may be used after that filter to obtain a sharp rise time of the signal to be examined on the oscilloscope.

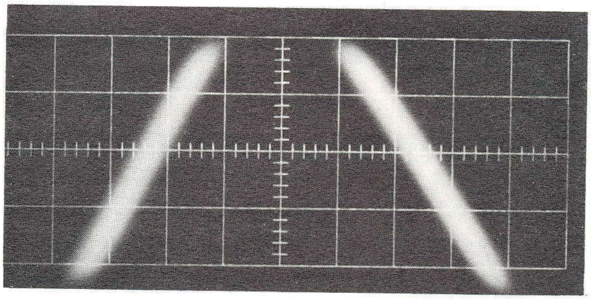


Figure 8. Time-base stability measured as pulse jitter on oscilloscope triggered from frequency standard. Ampex FR-900; horizontal scale: 20 nanoseconds per large division. Exposure time: one second

Another method is based on the fact that the pilot signal has followed the FM information through the electronic time-base correctors and the channel-combining switchers. The pilot is finally separated before the FM signal enters the demodulator. At this point, the continuous, time-base corrected pilot can be phase compared against the crystal clock of the recorder and the residual error can be monitored on an oscilloscope during reproduction of any recorded information signal. The presentation of the residual error on the vertical deflection system of the oscilloscope, if done through dc-coupled amplifiers, can easily be adjusted to any desired sensitivity and calibrated by inserting a small, known delay in the path of one of the signal inputs to the phase comparator. The oscilloscope sweep can be made synchronous with the head drum rotation frequency. Then, the residual error in each of the four head signal channels can be inspected separately.

2. Results

In the application for television recording, where electronic time-base correction first was developed, the timing information contained in the television signal (horizontal sync and color burst) is used as pilot information to derive the timing error of the signal and to correct it. The color signal correction accuracy obtained in this manner is within three degrees of phase angle of the color subcarrier of 3.58 megahertz, or ± four nanoseconds with reference to its long-time average.

The introduction of a separate pilot signal, independent of the recorded data, was connected with some particular problems which have been discussed in the previous chapters. The relatively low pilot frequency which had to be selected for this purpose resulted in larger residual time-base disturbances. The results of measurements on several radar recorders in laboratory and field use can be summarized as follows:

> Residual errors of ±15 nanoseconds peak-to-peak against the reference clock are always achieved, usually by a good margin.
>
> Residual errors of less than ±ten nanoseconds peak-to-peak are frequently observed.

3. Limiting Factors

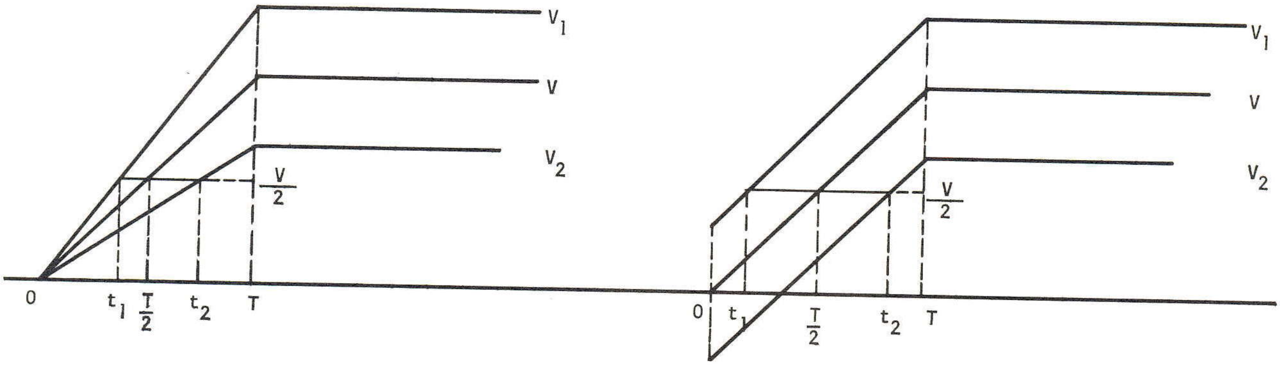
The open-loop mode of electronic correction which has been normally used in the past offers a correction ratio of approximately 10:1. The final residual time-base errors depend not only on the insufficiency (non-linearity, etc.) of the correction system itself, but also on several parameters which limit the end result of the correction process. Only one of these factors will be examined below. The other factors having influence on the time-base stability can be listed as follows:

> Signal-to-noise ratio of the pilot signal. The maximum pilot level is determined by the maximum permissible interference in the reproduced information.
>
> Head-drum motor servo performance during the record and the reproduce process.
>
> Condition of the drum motor bearings.
>
> Field symmetry in the head-drum motor.
>
> Eccentricity of the head drum.
>
> Accuracy of relative angular position of heads (quadrature error for four-head systems).
>
> Azimuth (perpendicularity of head gap with scanning path) and coplanar tolerance (track alignment).

A certain degree of time-base stability is meaningful and useful only if the stabilizing effect on the reproduced data is not appreciably degraded by other qualities of the reproduced signal. The most important of those is the signal-to-noise ratio of the reproduced data. It is irrelevant whether the noise is contained in the input signal to the recorder, or if it is generated within the recorder. There is a relationship between the recorder rise time (bandwidth), the signal-to-noise ratio of the output signal, and the minimum residual time-base error, which is meaningful. This is illustrated in Figure 9. If a series of unit steps is recorded, they will be reproduced with a certain rise time according to the recorder's bandwidth, as shown for the line from zero to V in Figure 9a and b.

Considering first Figure 9a, high-frequency noise components are assumed to be added to the true signal 0-V, which have the same rise time, T, as the signal. Their peak magnitude is given by $V_1 - V$ and $V - V_2$, so that the signal-to-noise ratio, expressed in peak-to-peak (e.g., three-sigma) noise values, is

$$S = \frac{V_1 - V_2}{V}.$$



(a) Noise component with rise time equal to system rise time.

(b) Low-frequency noise component.

Figure 9. Relationship between rise time, signal-to-noise ratio, and time-base stability

The time of occurrence of a step with finite rise time is usually measured at the half-voltage point. If the timing of the average half-voltage level is used as reference, the following can be derived from Figure 9a:

$$\frac{V_2}{T} = \frac{V}{2t_2} \; ; \; \frac{V_1}{T} = \frac{V}{2t_1} \; ;$$

The peak-to-peak time jitter due to noise is, therefore:

$$t_2 - t_1 = \frac{T}{2}\left(\frac{V}{V_2} - \frac{V}{V_1}\right) = \frac{TV}{2}\left(\frac{V \;\; - V}{V_1 V_2}\right)$$

If V^2 is substituted for $V_1 V_2$:

$$t_2 - t_1 = \frac{TS}{2}$$

This means that the noise-simulated time-base error for a peak-to-peak signal-to-noise ratio of 20 decibels or ten percent is five percent of the rise time. If T = 100 nanoseconds (approximately six megahertz bandwidth), this spurious time-base error would amount to five nanoseconds. A time-base correction which is considerably better would be useless.

In Figure 9b, a very low frequency noise component, added to the step signal, illustrates that the situation is even worse in this case, because

$$t_2 - t_1 = TS.$$

III. TRANSIENT-FREE SIGNAL REPRODUCTION

A. General Considerations

It was stated earlier (see I.B.3) that time-base correction must be implemented before the signals from the individual heads can be combined in a switching process, if transients due to switching cannot be tolerated. It was also shown that, for a fast switching process, the two signals to be combined must match perfectly in their timing and amplitudes in order to avoid transients. Because this is not realizable, a different switching method had to be developed.

B. Slow Switcher

1. Functional Description

It can be assumed that the signals in the head channels are very nearly sine waves, because harmonics of the FM carrier are, for the most part, outside the passband of the recorder. Under this condition, the combination of the signals can be made as shown in Figure 10. In Figure 10a, the signals are shown after combination of alternate head signals into two channels, and after time-base correction. The signal envelopes are shaped, according to Figure 10b, so that in the outgoing channel the amplitude decays at a constant rate during a

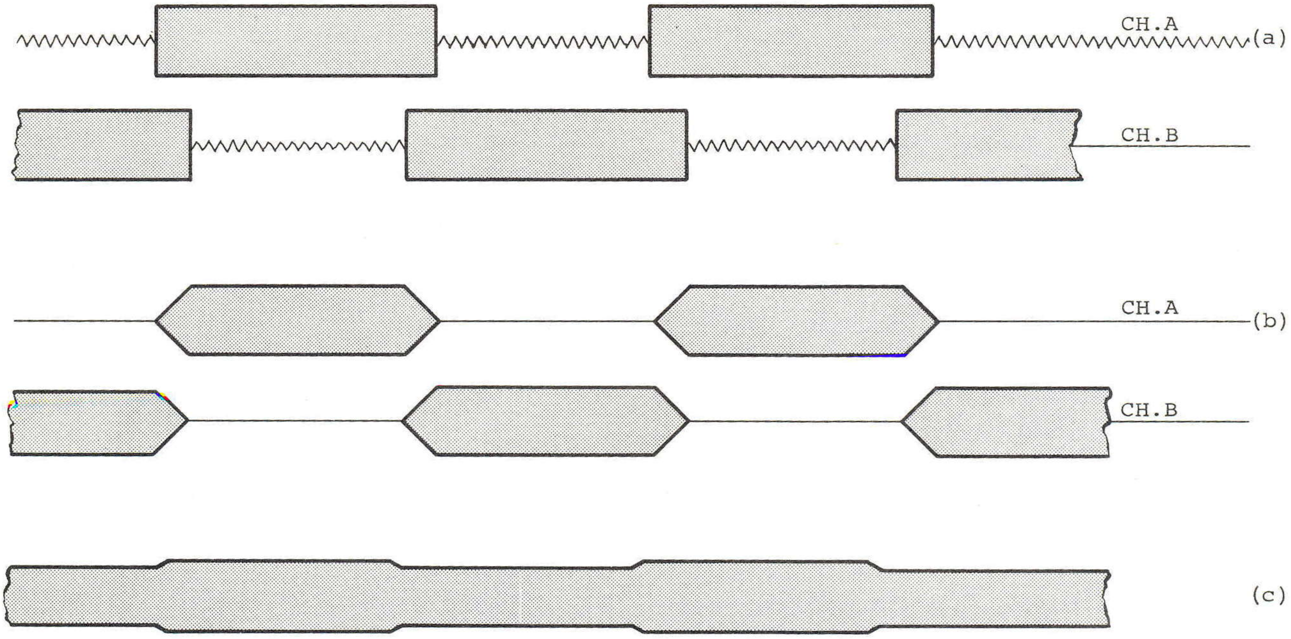


Figure 10. Signal combination process in slow switcher system

(a) Alternate channels combined (Figure 2, lower part) and time-base corrected
(b) Amplitude shaping during overlap period
(c) Final combination (addition)

predetermined time interval, and the amplitude in the following channel increases at the same rate during the same time. If both signals are in phase but have an amplitude difference, an addition of the pre-shaped channels would, then, yield a smooth amplitude transition with no change in phase in the combined signal. If a phase difference of, for example, 90 degrees exists between two channels of equal amplitudes, a smooth phase transition from the condition in the first signal to that prevailing in the succeeding channel occurs, accompanied by a smooth change in amplitude from the original value to approximately 70 percent of it and back to the original value, as it can be seen from the vector diagram in Figure 11.

No transient occurs in the combined signal as long as the phase difference between the two signals is less than 180 degrees, in which case the signals would cancel. The change in amplitude is of no significance, within certain limits, because the FM signal is subjected to limiting later in the system.

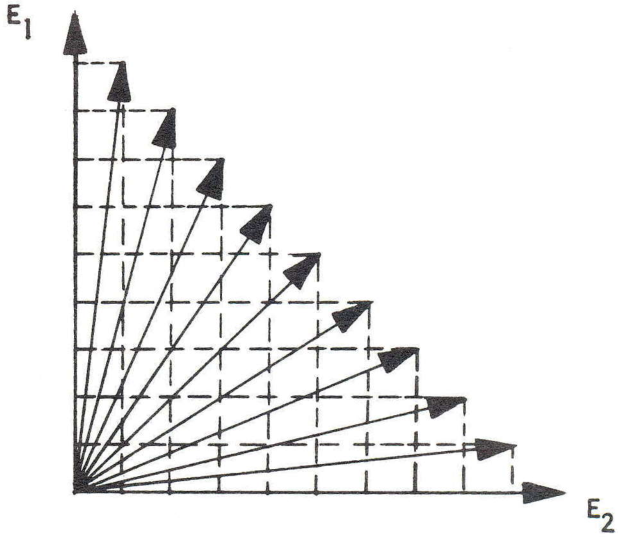


Figure 11. Vector diagram of slow switching process with 90° phase difference between channels

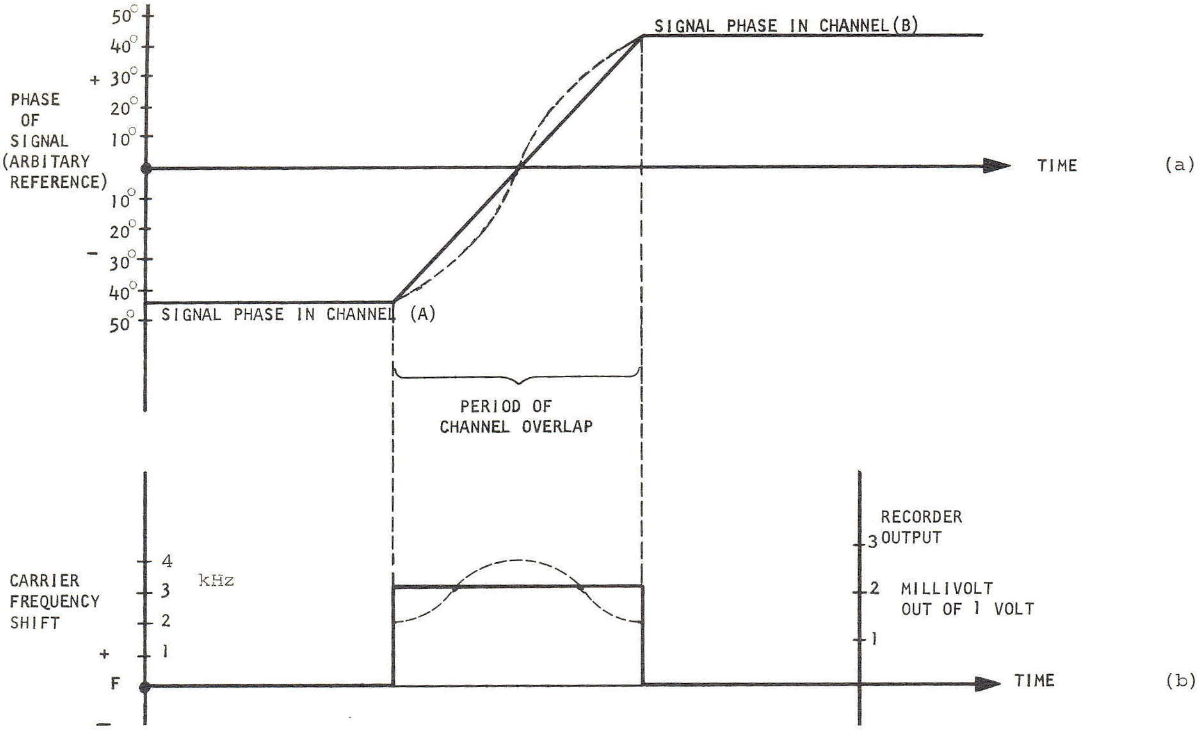


Figure 12. Spurious frequency component during the slow switching process
(a) Phase transition according to a 90° phase difference
(b) Concomitant shift in carrier frequency and spurious component in output signal of the recorder
——— = Linear phase transition
----- = Linear amplitude transition according to Figures 10b and 11

2. Spurious Signal Components due to the Slow Switching Process

The continuous and slow phase transition in the combined signal is shown in Figure 12a as a function of time. This phase shift represents an acceleration or deceleration of the signal and is, therefore, equivalent to a slight frequency shift according to the relation:

$$\Delta\omega = \frac{d}{dt}(\Delta\emptyset),$$

where $\Delta\emptyset$ is the phase difference between the two channels.

If it is assumed, in a first approximation, that the phase changes linearly during the cross-over time (solid line in Figure 12a), the carrier frequency will be subjected to a step in one direction at the beginning of the slow switching process and to the same step in the opposite direction at the end of that process, as shown with the solid line in Figure 12b. This frequency step appears as a spurious voltage step in the output of the FM demodulator. This step is proportional to the carrier frequency, f_c, and the residual time-base error, ΔE, and is inversely proportional to the amount of deviation used in the FM modulation, Δf, and the duration of the cross-over time, t_s:

$$\frac{V_s}{V_i} = \frac{f_c \cdot \Delta E}{\Delta f \cdot t_s}$$

V_s = spurious signal voltage level at recorder output due to slow switching process

V_i = maximum information signal level at recorder output (0-dB level).

A numerical example may illustrate the magnitude of this spurious component. The figures given apply to the conditions in the FR-900. The cross-over time is 80 microseconds. A time difference between two successive channels of 30 nanoseconds, which corresponds to approximately a 90-degree phase difference for a 9-MHz carrier, yields a frequency step during the cross-over time of 30/80,000 out of 9 MHz, i.e., a 3.4-kHz step. The maximum low-frequency deviation in the FM signal is specified to be ±0.75 MHz. The spurious frequency change is, therefore, $3.4 \cdot 10^3 / 0.75 \cdot 10^6 = 4.54 \cdot 10^{-3}$, or -47 decibels. This is approximately seven decibels below the recorder's rms noise level.

For a zero phase difference between the signal channels no spurious signal should be expected, but imperfections in the switching circuits, as for instance non-simultaneous start and slightly unequal rates of the decaying and increasing signal amplitudes, result in a spurious signal of about -50 decibels peak-to-peak with respect to maximum output signal under the conditions assumed in this example.

If, in a better approximation, the amplitude decay and rise in the slow switcher is assumed a linear function according to Figure 10b, the phase transition, derived from Figure 11, will not be exactly linear, but will have the form of the dotted line in Figure 12a. This, in turn, results in a spurious frequency variation, or a spurious recorder output signal, as shown by the dotted line in Figure 12b.

3. Circuit Description

There are different methods to achieve the decay and increase of signal amplitudes for the purpose of the slow transition switcher. An amplifier in which the gain is controlled by a trapezoidal waveform would be the simplest solution. With the use of a beam deflection tube, a very linear shaping of the signal envelope can be achieved. If solid-state circuitry is desired, the six-diode gate is useful, if a push-pull trapezoidal switching signal of properly adjusted amplitude and slope is applied. With a signal of constant amplitude applied to a six-diode gate and the gate being biased by the slope of the trapezoidal wave, somewhere during the slow impedance change of the diodes, the conventional operating condition of such a gate (i.e., the signal amplitude must be less than the bias voltage) becomes invalid. For a high attenuation in the gate, therefore, a sine wave input signal is clipped. This imperfection results in a slight modification of the spurious switching signal mentioned previously.

In another, much simpler, circuit configuration, a large amplitude sine wave is applied to the six-diode gate instead of a trapezoidal waveform. The diodes change their state of conduction during the central, linear portion of the sine waves.

C. Head Signal Equalization and Amplitude Stability

Beside the head channel switching process, there are other system parameters in a rotating-head recorder which would result in a discontinuous signal reproduction if special precautions were not used to prevent this. The main source of these difficulties are the magnetic heads. Variations in the delay characteristics of the individual heads have been discussed earlier (see II.E.). Here, two other qualities are of concern: the tape magnetizing process during signal recording, and the frequency and phase response of the heads in the reproduce condition. In both cases, an amazing multitude of single parameters combine to modify the amplitude and phase of the reproduced FM signal. The modifications are different for the various frequency components of the signal, so that the demodulator produces a distorted signal output.

1. Record Current Optimization

In a recorder designed for signal storage and reproduction of highest possible quality, it is necessary to determine and adjust the record current for each head individually. This results in an equalizing effect over subtle differences in the mechanical construction, the magnetic properties, and the electrical data of the heads, and leads to noticeably more uniform tape magnetization and subsequent signal reproduction.

Record current optimization is also necessary in order to obtain the best possible signal-to-noise ratio. The final settings of the record currents are a compromise between the requirements for the two factors: signal-to-noise ratio and frequency response. The record current requirements do not appreciably differ for either condition.

As the pole tips of the heads wear down during usage, the head efficiency increases and a readjustment of the record currents becomes necessary from time to time. Simple procedures have been worked out to accomplish these adjustments in the field with a minimum amount of time and technical skill, or even automatically. It is anticipated that current developments will eventually provide magnetic heads which are so uniform in performance that individual record current adjustments can be abandoned.

2. Equalization of the Reproduced Signal

In order to keep the influence of the preamplifier input noise as small as possible, it is desirable to obtain the highest possible signal amplitude from the reproduce head, especially at the high-frequency end of the recorded spectrum where the signal amplitude drops sharply because of the gap effect, the increasing influence of head-tape separation, and also because of the decreased tape magnetization in the recording process due to reduced magnetic penetration into the tape and the self-demagnetizing or self-erasure effects. To achieve this, it is necessary to make use of resonance effects of the head inductance together with associated stray and circuit capacitances. Depending on the Q of the resonating head circuit, a more or less severe phase distortion is the consequence. For high quality signal reproduction, an individual equalization of the resonance effects is necessary for each head by special networks connected at the output of each preamplifier.

Another type of equalization is also applied to each head signal separately. The reproduced frequency-modulated signal differs considerably from an ideal FM wave. Most of the upper sideband components are suppressed because of limitations in the head-tape processes involved as mentioned in the previous paragraph. The lower sideband components are also modified in their relative amplitudes, because the FM carrier acts as a bias for its lower sideband frequencies, especially the more remote ones. All these effects produce a frequency response in the demodulated signal which is not flat. Only the amplitude response is affected, not the phase of the FM signal, with the exception of the head resonance mentioned earlier. The amplitude response of an FM spectrum does not need to be flat in order to keep the demodulated signal free of distortion, but the response must be a straight line. The limiter which is used before the demodulation takes place converts any straight-line response into a flat response without modifying the demodulator output. The equalization of the off-tape FM signal must therefore be accomplished by linear-phase networks converting the reproduced signal response into a straight-line response. It has been found advantageous to use a straight-line characteristic which results in zero gain slightly above the highest first-order sidebands (in the FR-900: 9 MHz carrier, plus 6 MHz modulation = 15 MHz). This arrangement rejects all the noise in the unused portions of the spectrum, i.e., above the higher first-order sidebands, and reduces the influence of the noise in the signal components between 9 and 15 MHz by emphasizing the influence of the lower-order sidebands from 3 to 9 MHz which are reproduced with a much better signal-to-noise ratio. The straight-line characteristic is obtained by applying a series of "aperture correction" networks having the characteristic: $1 \pm K \cos 2\omega T$ (where T is the delay of an LC-delay line, K is an adjustable constant), in combination with a linear-phase low-pass filter.

The two equalization methods applied to the reproduced signal as described here require that each recording of actual data is preceded by a short test signal recording which enables the proper adjustments of the equalizing controls to be made in the signal reproduction process. Here also, as mentioned for the recording mode, the advent or more uniformly manufactured heads will reduce the necessary amount and complexity of equalization so that it can be applied equally to all head channels after switching. A step in this direction was the introduction, in some television recorders, of preamplifiers with low-input impedance which suppress head resonance effects and render the FM signals reproduced from the four rotating heads much more uniform. This was made possible by the advent of heads with sufficiently high sensitivity which yielded, without the use of resonance, amplifier input levels high enough above the amplifier equivalent input noise to achieve very good output signal-to-noise ratios.

3. Amplitude Stability

Without using the equalization procedures described in 1 and 2 above, the output signal of the recorder would exhibit severe variations in amplitude and harmonic distortion occurring as a stepwise changing disturbance at the head channel switching rate. This problem would greatly reduce the amplitude stability of the reproduced signal and would have especially objectionable results in such cases of pulse recording where the pulses have a width equal to the reciprocal of the recorder bandwidth or slightly less. Such pulses are extremely susceptible to phase variations in the transmission characteristic. Fortunately, with proper adjustment of the equalizers and record currents, channel-to-channel amplitude variations can be made very small.

There are other sources of amplitude instability which affect the overall signal envelope as, for instance, noise, carrier unbalance and sampling jitter from the FM modulator, variations in the amplitude and the phase response in the voltage-controlled delay lines used for time-base correction, etc.

The most important factor is noise. A representative signal-to-noise figure is 40 decibels peak-to-peak signal versus rms noise. This can be converted into 25 decibels peak-to-peak signal versus peak-to-peak noise (i.e., the peak noise being taken as three times the one-sigma or rms value). Therefore, the instantaneous amplitude of a reproduced signal is undetermined by as much as 25 decibels or ± three percent, due to noise.

D. Transients from Slipring Imperfections

Formerly, the usual method to conduct the recording currents to the rotating heads and the reproduced signals from the heads to the preamplifiers was by way of sliprings and brushes. Such rotating mechanical contacts have many deficiencies which are difficult to overcome, especially at the high velocities involved in rotary-head recording. Some of the causes for contact variations are brush bouncing due to eccentricities, variations in surface finish caused by wear, and development of films on the sliprings due to environmental conditions.

All such contact failures present a source of noise and even large transients might appear in the reproduced signal. The condition is acceptable for television recording; but in cases where pulses are recorded which approach the bandwidth limits of the recorder, the transients caused by sliprings have a shape very similar to the recorded pulses and can present a serious problem.

Because it is difficult to develop rotating mechanical contacts to the perfection needed for this application, other possibilities have been investigated. Experiments with electromagnetic signal couplers (transformers) have resulted in a device practical for use in both television and instrumentation rotary-head recorders. One-half of a ferrite core with one coil is mounted to the head drum while the other half of the transformer is stationary and spaced very closely to the rotating part of the core.

The stationary part is connected to the record or, through a record-playback relay, to the reproduce amplifier. It is, in general, not necessary to use one transformer for each head. Nonadjacent heads can be connected in parallel, or in series, without affecting the signal overlap time which is necessary for head-channel switching after time-base correction.

IV. SYSTEM DESCRIPTION

A. Survey of Equipment

Recording equipment using an independent pilot frequency, electronic time-base correction, and transient-free signal switching was first used for radar pulse recording. Experimental recorders carrying the designation VRX-1006 have been in field use since 1961. They have an information signal bandwidth of four MHz and each system consists of three electronic racks and a VR-1000 type video tape transport.

A fully transistorized system with a rack-mounted transport constitutes the basic unit for a new generation of instrumentation recorders. Known as the FR-900, this basic machine is assembled in a single 19-inch rack and records one information channel of six MHz bandwidth for one hour. This basic recorder is designed with a high degree of flexibility so that a wide range of applications may be accommodated. The applications include the recording of radar and telemetry signals in video or predetection form, and of digital signals in the megabit range. Two or three channels for auxiliary signals can be provided.

The FR-950 is a dual-channel version of the FR-900. A second set of four heads is located on the rotating drum in the same plane as the first set, but at an offset angle of 45°. The tape velocity must be doubled, and the tracks of the two recording channels are interleaved on the tape. Each channel has a capability of handling signals from one Hz (or dc) to six MHz.

The AR-500 and AR-550 are airborne record-only devices which are designed for playback on an FR-900 or FR-950, respectively.

B. Generalized System Block Diagram

Since all recording systems developed along the principles discussed in Sections II (Electronic Time-Base Correction) and III (Transient-Free Signal Reproduction) follow the same general concept with relatively minor variations, it is expedient to describe the synthesis of a general system while mentioning the variations wherever appropriate. No description will be given of the motor and tape reel drive and servo systems, and of the auxiliary circuits. Reference is made to the diagram, Figure 13.

1. The Recording Mode

It is assumed that at the signal input the information signal is available in a form suitable for entering the recording system, i.e., with frequency components and dynamic range according to recorder specifications. In some cases, signal processing takes place before the information is ready to enter the recorder proper, for instance: time or frequency multiplexing, heterodyning, digital-to-analog conversion, or vice versa.

Within the specified limits of frequency and voltage level, the signal may be of arbitrary nature.

Before being subjected to frequency modulation, the signal may pass a pre-emphasis network which emphasizes all components above approximately 500 kHz by 8 to 12 dB. This measure provides a low deviation in the FM modulator, and, therefore, low distortion for the low-frequency components, while providing wide deviation and high signal-to-noise ratio for most of the passband.

The frequency modulation may take place at a high frequency carrier, i.e., in the 50- to 100-MHz range, to keep the relative deviation small so that a modulation characteristic of very good linearity can be obtained. Two oscillators are modulated in push-pull. Their difference frequency, produced in a mixer stage, constitutes the desired carrier frequency for the recording process. In a different method, the frequency of an astable multivibrator is controlled by the information signal.

An interference suppressor (see Section II.D.1.) removes the FM sidebands in the region of the pilot frequency. A linear signal adder (resistive delta network or equivalent) superimposes the pilot frequency to the FM carrier.

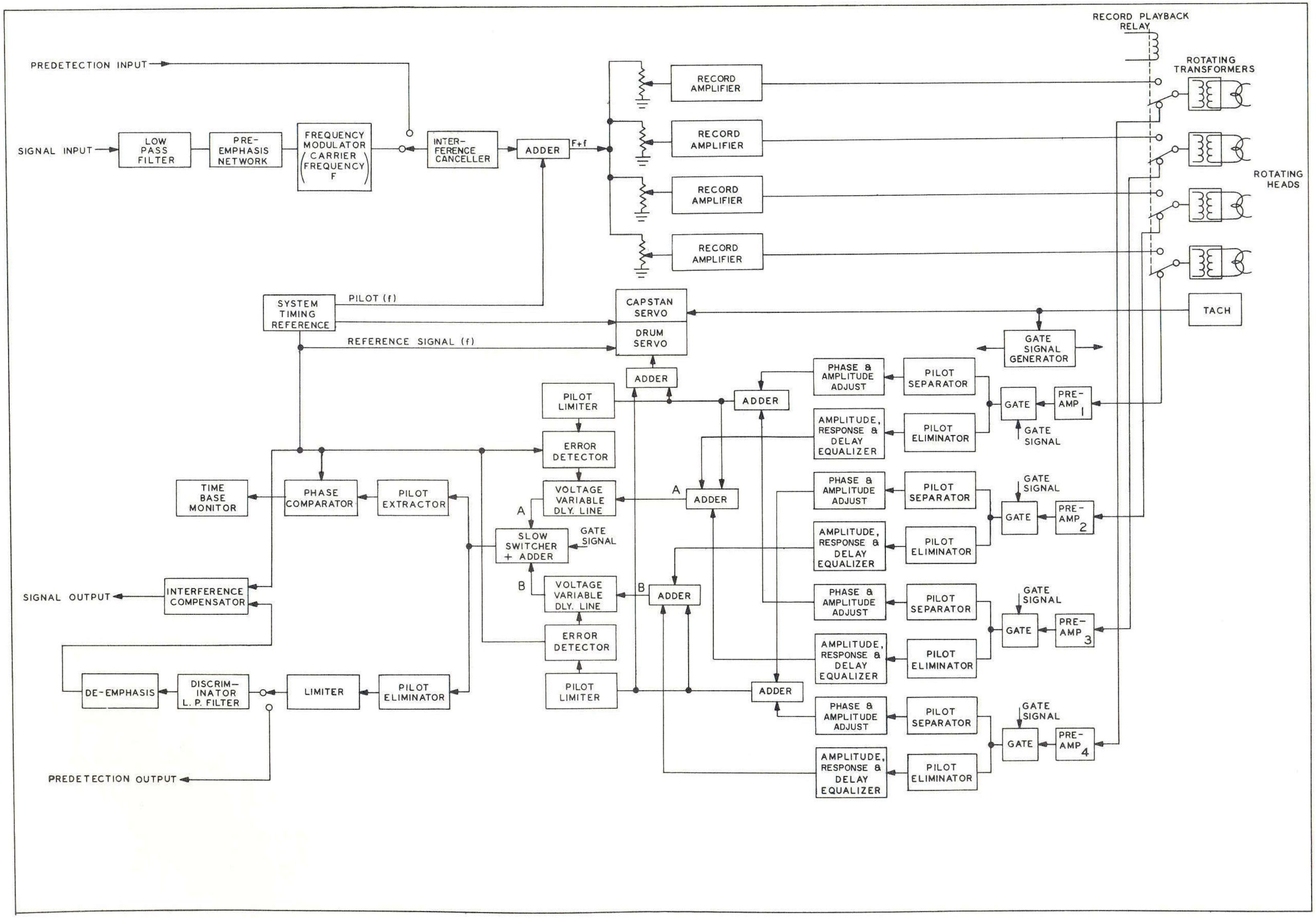


Figure 13. Generalized system block diagram

The pilot is derived from the system timing reference which also synchronizes the head-drum motor and the capstan motor. Through four individual record current adjustment controls, record amplifiers, and rotating transformers, the rotating heads are energized. In some cases, it might be preferable to connect the two heads which are in opposite position on the drum in parallel, or in series. This allows the use of only two rotating transformers, two record amplifiers, and two reproduce preamplifiers instead of four each. It is, however, necessary to provide the possibility of adjusting record currents and equalizing playback signals individually for each head by special switching arrangements.

2. The Reproduce Mode

The reproduce signals from the individual heads and preamplifiers are gated as shown in Figure 2, upper part, in order to remove the noise in the signal channels during the time the alternating channel will later be added, see Figure 2, lower part, so that the overall signal-to-noise ratio will not be deteriorated. After the gating, the pilot signals are extracted and processed separately. The pilot is also removed from the RF signals and the latter are subjected to equalization with respect to amplitude, phase and frequency response, and group delay differences. Alternate channels are then added together and the respective pilot signals recombined. The resulting two channels of composite signals (RF + pilot) undergo the electronic time-base correction according to an error signal derived from phase comparison of the extracted and limited pilot signals with the system timing reference. An open-loop correction system is shown in the block diagram. The extracted pilot signals, summed up from all four channels, are also used for the high-resolution loop of the drum-motor servo.

The time-base corrected signals are shaped in the slow switcher as shown in Figure 10b and added into one continuous channel, as shown in Figure 10c. Here, the pilot is again extracted and used for monitoring the residual time-base error. The RF signal (pilot eliminated) is limited and demodulated. After applying de-emphasis in a network exactly complementary to the pre-emphasis network, and pilot interference cancellation by means of injecting the proper amount of reference signal in phase opposition to the cross-modulated disturbance, the signal is ready to leave the recorder.

CONCLUSION

The improvements achieved during continued development efforts with respect to the timing stability of signals reproduced from magnetic tape have brought the time-base stability of recorders into the focus of attention. It has become a performance parameter as important as dynamic range, bandwidth, storage capacity, etc. Both the stability in real time reproduction and the pulse-to-pulse jitter are of prime significance in the handling of instrumentation, telemetry, and radar information. The values of residual time-base errors which can now be obtained in rotary head recording equipment using a separate, independent pilot signal superimposed to the intelligence are in the region of ± ten to fifteen nanoseconds, measured against a stable clock over any time interval. These low values make rotary-head recorders very attractive for applications where a high fidelity of the reproduced time scale is of major importance.

There is no doubt that the development of recording equipment in the near future will be directed toward an increase of recorded bandwidth, dynamic range, and storage density. These improvements are intimately interrelated with time-base stability. An increased bandwidth requires better time-base performance to obtain a phase discontinuity equal to or less than that achieved at present. An improved signal-to-noise ratio, together with a decreased rise time (or increased bandwidth), makes feasible, and desirable, an improvement in time-base stability. A concurrent improvement in signal-to-noise ratio of the pilot signal will enable this time-base improvement to be implemented.

APPLICATION NOTES

Only a few short remarks will be made to point out the significance this class of recorders has for space electronics and telemetry applications, and the opportunities it offers to the system designer.

1. Predetection Telemetry

Predetection data in FM form are applicable to the recorder in its present form. The FM data can be accepted by the recorder directly, if the center frequency is adjusted to such a value that all significant sidebands are located below 15 MHz. In this case, the modulator and demodulator in the recorder are simply removed or by-passed by a switch.

A separate evaluation for any specific application is necessary with respect to the spurious frequency shifts due to the slow switching process and their effect on the overall system, according to the relation given in Section III.B.2 of the paper on "Transient-Free and Time-Stable Signal Reproduction from Rotating Head Recorders."

2. Post-detection Frequency-Multiplexed Signals

For a post-detected frequency-multiplexed telemetry application, recorders have been built which take simultaneous inputs from 42 channels of IRIG-FM and a 144 kilobit-per-second NRZ signal. The main FM carrier in the recorder is 1.8 megahertz, the writing speed is 625 inches per second, and the recording time is two hours.

Due to the low deviation and narrow spacing of the subcarriers, time-base stability is extremely important in this type of application. For the recording of SSFM data, time-base stability is a dominantly critical factor.

3. Pulse Recording

The described system is ideal for pulse recording applications, such as PCM. Most significant, the time-base stability of the recorder minimizes design requirements for the PCM synchronizer. The overall system performance is enhanced because the phase loop filter can be made narrower, thereby increasing the signal-to-noise ratio.

4. Radar Recording

Range resolution in any radar is based on bandwidth and time stability. A particular advantage of the FM system used in the recorder is the ability to transmit extremely low frequency or even dc components so that, for pulse and radar recording, a baseline shift is either extremely small or completely eliminated.

Of particular interest for radar pulse recording is also the amplitude stability of the reproduced pulses. A separation between head and tape of one wavelength causes an attenuation of 55 decibels. In a wideband longitudinal recorder of 2 MHz bandwidth, for instance, the shortest wavelength is 60 microinches. A fraction of a micron change in head-tape spacing results in a change of signal amplitude of many decibels.

In a 2-MHz FM carrier-type rotating-head recorder not only much longer wavelengths are used, but any change in amplitude produces only second order effects because the signal is limited before demodulation.

5. Diversity Combining

With the time-base stability achievable in this class of recorders, diversity combining of a series of recorded signals into one continuous signal has become possible. This technique applies to all the recording modes mentioned above.