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THE MARK II VLB SYSTEM
Principles and Operating Procedures

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1. Introduction and Principles

It has become obvious that the tape recorder interferometer has become a standard radio astronomy technique, applicable to many problems. This being the case, it was clear we needed a tape recorder system which is logistically lighter than the Mark I system, less prodigal with tape, more convenient to run, with longer recording times, and with greater bandwidth. Work was started on designing such a system in early 1968. It is now complete and has been operating since March 1971.

The critical component of the system is the Ampex VR660 television-type tape recorder. We use the VR660-C, which has enhanced frequency response for use with color TV. In its normal configuration the VR660-C has a bandpass from zero to four megahertz. This is achieved by using FM modulation with a carrier at about 5.5 MHz. The resulting signal is clipped and used to hard-drive the heads. The VR660 has two video heads which are mounted on a drum which spins, in the horizontal plane, at 30 Hz. One head is in contact with the tape at all times. During recording, both heads are always driven, so that the same signal is recorded for a few tens of microseconds at the end of the trace of one head as is being simultaneously recorded by the other, which has just contacted the tape. At playback time, a switching circuit selects signal from the head in contact with the tape.

The effective head-to-tape speed is about 650 inches per second, but the bit density, with 4 megabit data, is still 6000 bits per inch. The head gap is about 40 microinches, so there are only about 4 headgaps per bit. The tape longitudinal motion is 3.7 inches per second, so the video tracks are separated by .06 inches along the length of the tape and 0.010 perpendicular to their length. The overall information content of the tape is about 800 bits per square millimeter, much the same as astronomical photographic plates.

The time stability of the VR660 is about ± 100 microseconds. That is, a recorded picture of a clock would not move smoothly, but would vary by about 100 microseconds from a smooth, linear increase of time.

The interferometer system operates with one bit digitization. We chose to digitize the IF in order to make the recording-playback system as stable and reproduceable as possible. Given that we record digitally, it is easy to show that one bit digitization conveys more information per bit than any multilevel scheme. That is, a two bit digitization produces less increase in signal-to-noise ratio than using the second bit to double the bandwidth of the one bit digitized signal.

In a digital system, the time of a given bit is determined by counting bits from a fiducial mark which occurred at an identified time. Therefore, it is necessary to record the information in a "self-clocking" code, from which it is possible to recover not only the recorded bits, but also a series of clock pulses, one per bit. The code chosen is the digital diphase code. It is illustrated in Figure 1, along with a possible decoding scheme.

The first line, line A, is a representative data pattern with positive representing a binary zero. The next line is the diphase representation of the same data. In the diphase coding, there is always a transition at every 250 nanosecond interval. Where the data are binary ones there are, in addition, transitions in the middle of the bit time.

The process of data recovery is illustrated in the following lines. The data from the recorder is first hard clipped so that it ends up looking closely like line B. The next step is to delay the signal by 250 nanoseconds to get line B prime. Then line B and line B prime are multiplied in a logic exclusive NOR. This logical product is shown in line C. Note that it is identical to line A, the original data, except for a delay. This is the basic technique for recovering diphase data in the processing system. There is, in fact, in addition to the delay line and exclusive NOR circuit, a lot of squaring circuits and filters in between to make the process insensitive to the noise injected from the tape.

The next step is one scheme of recovering clock from the diphase data. Line D is a representation of what you might get by putting both the negative and positive transitions into an edge detector so that each edge of B prime, both positive and negative going, comes out as a narrow spike. You will notice that there is a basic 4 MHz clock running through there, 250 nanosecond period, but there are extra spikes inside some intervals. The only step required the is to eliminate those extra pulses in the middle. The data (on line C) can be used to gate out the extra pulses. If line C is a one, the second clock pulse is ignored. This eliminates the pulses in the middle. This is one of several possible processes of reconstructing data and clock from the diphase coming off the tape. Both of these processes are reasonably insensitive to noise and time jitter.

The recovered clock is used to strobe the bits into an integrated circuit buffer, which is then unloaded by a stable clock driven by an internal crystal oscillator. This process restores the time stability lost in the recording process.

In long baseline interferometry, one frequently encounters very high natural fringe rates, ranging up to about 50 kHz. To reduce these natural rates to a more manageable value, one has two choices: the local oscillator phase at one station may be rotated to follow the differential doppler which causes the fringes, or a phase rotator in the IF at playback time can be used to accomplish the same end. In keeping with a philosophy of minimizing the complexity of the recording equipment, the second approach was chosen. The concept of a phase rotator for a one-bit digitized data stream may seem strange at first, but it is a precise analogue of the usual case. One builds a phase rotator (or single sideband mixer) by constructing two mixers, fed by signals in phase quadrature, and combining the mixer outputs in phase quadrature. In the digital case, a predicted fringe function is produced in square wave form. There is a phase and quadrature output from the fringe function generator. These signals are used to multiply (in the one bit sense, $0 \times 0 = 1 \times 1 = 1$, $0 \times 1 = 1 \times 0 = 0$) one data stream. The outputs, both the sine and cosine components, are multiplied by the other data stream, accumulated, and regarded as the real and imaginary components of the complex fringe coefficient, that is, they are combined in phase quadrature. For optimum signal to noise ratio, the signal should not be multiplied by a square wave, ± 1, which is all the digital equipment can provide. It should be multiplied by a sine wave. It is however, fairly convenient to implement a three level digital logic. The data are added in phase for 3/8 cycle, and in anti-phase for 3/8 cycle. In between, for 1/8 cycle, the data are ignored entirely and correlation is inhibited. The signal to noise loss from this quantization of the sine wave is only 6 percent instead of the 11 percent one gets if the IF is rectified against a simple square wave.

The multiplication and accumulation of the two data streams is done in the standard correlator-counter cards developed for the NRAO Model III correlation spectrometer. The interferometer receiver has 190 correlation channels, that is, 95 channels of cosine components and 95 channels of sine components. These may be fourier transformed to produce 47 independent frequency channels when used as a cross-correlation spectrometer. The shift register clocking may be changed in binary steps to give channel-to-channel lags ranging from 250 ns to 32 μs, giving 8 bandwidths from 2 MHz to 15.625 kHz. In the continuum mode, a range of 31 delay channels, $\pm$ 4 microseconds, is believed to be sufficient for most applications, so only this delay range is brought out of the processor.

The playback unit is controlled (that is, the fringe frequency and delay are controlled) by a Varian 620I computer, acting on line with the processor. This is one of the variety of minicomputers suitable for such applications. The computer also has the task of recording the data for further reduction. This is done on a slow (25 ips) 9 track IBM compatible digital tape transport. In the continuum mode of operation it writes the 64 continuum channels and 16 words of identification data on the tape drive every 0.2 second. In the line mode of operation, it writes half of the 208 word output record at each succeeding 0.1 second interval, so that the complete readout is again done every 0.2 second. The computer reel will hold the output for about 2-1/4 hours of reduction in the continuum case, and slightly more than 1 hour in the line case. Thus, in the continuum case, the processor has taken the initial 3×10^{10} bits from each tape and condensed the correlation function to 5×10^{7} bits. Further reduction programs for the IBM 360 will condense this tape to the few numbers, perhaps totaling 500 bits, which are the eventual output. The processor reduces the data bulk by 10^{3}, but the 360 reduces it by a factor of order 10^{5}.

2. VLB Record Terminal Description

A general block diagram of a VLB system is shown in Figure 2. I will describe the various items in this block diagram.

There is not very much to say about item 1, the front-end. Any good, low noise front-end useful for radio astronomy is good enough for VLB work. Stability is much less important for this application than for most. In fact, the stability is usually determined by the need to be able to point the telescope. We usually try to do this in the total power mode, and the front-end should be stable enough and have low enough noise temperature to be able to do this. The output of the front-end is as shown on the figure; the edge of the passband is always 10, 30, 50, or 150 MHz. The input level requirement is -60 dBm for 2 MHz bandwidth which means that typically you need about 50 or 60 dB gain in the front-end.

2.1 The Local Oscillator System

The local oscillator system consists of two sub-systems, the frequency standards themselves, and the multiplier system which makes up the LO signal from the standard output, usually at 5MHz. Of these two, the standard itself is far the more critical component.

2.1.1 LO System Specification

There are several time scales of interest in comparing frequency standards. Within each realm there are different customary ways of quoting the stability. We shall always refer to time, or phase, stability and we shall limit any discussion to a particular time range. This practice may differ from that of quoting frequency stabilities. For example, if an oscillator has a frequency stability of 10^{-9} on a one millisecond time scale and 10^{-13} on a 100 second time scale, its time stability is 10 ps on a 100 second interval, set by the slow variations.

On the other hand, if an oscillator has a frequency stability of 10^{-7} on a millisecond time scale, and 10^{-13} on a 100 second time scale, its time stability is limited to 100 ps by the short term fluctuations.

For long time scales, greater than a day, the most stable, reproduceable and reliable standards are probably the Cesium beam tubes. This is a matter of only marginal interest to us; it is of interest in time keeping, but, for the most part, the VLB interferometer operator is not interested in long-term time-keeping. For time scales between a few tens of minutes and a day, the hydrogen maser is probably the most stable device going, with the Cesium and Rubidium standards of comparable stability and an order of magnitude worse than the maser. However, this time scale is also of no interest to us.

We are primarily interested in the time scale from a few seconds to a few tens of minutes. Let us look a little more closely at the requirements. The concept of coherence time is useful. Let us consider two clocks, keeping times t_a and t_b. When used in an experiment at frequency f, the coherence of the local oscillators on an interval T is defined as

$$\zeta = \frac{1}{T} \int_{t_o}^{t_o + T} \cos\left[f\,(t_b - t_a) + \emptyset_o + \emptyset_1 t_a\right] dt_a$$

where $\emptyset_o$ and $\emptyset_1$ are adjusted to maximize ζ. The coherence time, T_o, is defined as that interval which reduces the expectation of ζ to a half,

$$1/2 = \left\langle \frac{1}{T_o} \int_{t_o}^{t_o + T_o} \cos\left[f\,(t_b - t_a) + \emptyset_o + \emptyset_1\, t_a\right] dt_a \right\rangle$$

Coherent integration must be broken before the coherence time. While the integration is coherent, the minimum detectable flux decreases as the inverse square root of the integration time; in incoherent integration, the minimum detectable flux decreases as the inverse fourth root of the integration time. Coherence times as a function of frequency for several local oscillator combinations are shown in Figure 3.

Stability on a time scale of a tenth of a second to a few seconds has not, in practice, been a problem. The practical oscillators have sufficient stability in this range that the coherence, at radioastronomy frequencies, is not appreciably reduced by short term variations.

Stability of an oscillator on time scales shorter than a tenth of a second is usually referred to as purity, and considered in the frequency domain rather than the time domain. We have encountered problems with the purity of both our time standards and of our local oscillator chains. The problem is not, however, a fundamental one, and the local oscillators can be made sufficiently pure that coherence is preserved if care is used in the electronic design of the local oscillator chain. However, it should never be assumed without test that a local oscillator chain which works with undetectable loss of coherence at frequency f will preserve appreciable coherence at frequency 2f.

2.1.2 Local Oscillator Stabilities

Figure 3 represents tests made on various frequency standards. All the tests have been made with the same equipment and in the same way. I will say a little about the equipment used for the test after I explain the figure. The Y axis of the figure is the wavelength of a VLB experiment or the RMS time error which will give one radian of phase error at this wavelength; the X axis is the integration interval or coherence time. For example, if you do an experiment at

3 cm and use a Sulzer 2.5C crystal oscillator, you could integrate for about 200 seconds. If you try to integrate longer than that, the RMS time error would be greater than 1 radian. It can also be observed that at 3 cm a rubidium standard would allow integration for about 50 seconds, so for short wavelengths the crystal oscillator is better. In fact, if you unlock the internal crystal in the HP rubidium standard - that crystal is the HP 105 which is marked on one of the curves - you can integrate for longer periods of time at short wavelengths. Of course, at longer wavelengths the reverse is true.

The curves marked "masers" in Figure 2 are for two different sets of masers. The upper curve was a test of a modified Varian H10 compared with the NASA experimental maser. The lower curve is a comparison of another H10 maser compared with the Smithsonian small maser. It is pretty clear that hydrogen masers are a factor of 10 to 30 better than the best crystal oscillator that we have tested. There may be some better crystal oscillators somewhere but I have not seen them. The curve marked "maser electronics" represents the stability of two maser receivers locked to one maser. It was a test to see whether the maser stability was limited by the electronics or by the maser oscillator itself. The results indicate that stability was limited by the maser oscillator itself. You could also draw curves on this figure representing the atmospheric limit and the ionospheric limit to integration time for an experiment. With the hydrogen maser you are limited by the atmosphere.

The very bottom curve in Figure 3 represents the phase stability of the NRAO Frequency Comparator, feeding 5 MHz into both inputs of the Frequency Comparator. The Frequency Comparator is a very handy unit for comparing frequency standards. It consists of a double balanced mixer operating at 5 MHz with a lot of DC gain after the mixer and a very precise phase shifter in one of the 5 MHz paths proceeding the mixer. The phase shifter is adjusted so that the two 5 MHz signals are in quadrature. The Frequency Comparator has enough stability to measure 1 or 2 picoseconds of time error. The usual way of comparing frequency standards is to multiply them up to X-band and compare them there. We started making a setup like that but were having more instability problems with the multipliers than with the phase comparator and finally decided to make the phase comparison at 5 MHz.

2.1.3 LO Multiplier Chain

The LO multiplier Item 6, Figure 2, is not a very critical item since phase stability is usually limited by the primary frequency standards. Possibly with the hydrogen maser frequency standard we may begin to limit phase stability by an unstable multiplier. We have made two useful units for LO generation. The first is a wideband tunable multiplier which takes an input between 1 and 1.25 GHz and provides outputs between 2 and 12 GHz. A YIG tuned filter and a step recovery diode multiplier manufactured by Watkins-Johnson is utilized along with power amplifiers and power leveling circuits. There is also a wideband mixer available from RHG Electronics which operates in the 1-12 GHz range.

A second unit for LO generation is intended for use in the control room. It provides 1.1-2 GHz output in 10 MHz steps, and if you add a synthesizer to it - the synthesizer working in the 100-200 MHz range - it provides continuous coverage from 1.1 to 2 GHz. The frequency standard inputs to the box are at 5 MHz or at 100 MHz and it provides a 1400 MHz output which can be used to phase-lock the frequency standard to a hydrogen maser. This is the most stable way to connect to a hydrogen maser. If you do the phase comparison in that way - by providing the 1400 MHz signal - then the phase instability in the multipliers in the hydrogen maser and in the 1-2 GHz unit will not affect the operation of the LO. However, the multipliers in the 1-2 GHz unit have good stability, and so even when it is driven directly at 5 MHz it is still quite good.

2.2 The IF Converter

The IF converter block diagram is shown in Figure 4 and its front panel is shown in Figure 5. The main function of this unit is to shift a band of data centered at an IF frequency down to the video range. The main signal path is from IF Input No. 1 to the output marked "To Sampler". The unit must shift the data with both variable input center frequency. There are many ways of performing this operation and we have adopted a method which Alan Rogers of MIT/Haystack developed; it is the single-sideband mixer technique using a quadrature hybrid. Figure 6 shows a detailed diagram of the single-sideband mixer. The input signal is applied to two mixers which have local oscillator signals with 90 degree phase difference. At the output of the mixer a 90 degree phase shift is inserted in one signal path and the signals are added. One sideband of the LO is transferred to the output and the other sideband is cancelled to a large degree. Typically, 25 dB rejection of the unwanted sideband is achieved and this is adequate for VLB work.

The development of Rogers' that made this all much more feasible is the wideband phase shift network shown in Figure 6, which covers a video range of 200 cycles to 2 MHz. Sideband cancellations are achieved for bandwidths anywhere in this range. Bandwidths are changed by changing the local oscillator within the 10 to 50 MHz frequency range of the local oscillator quadrature hybrid.

The IF converter contains two inputs. You can either switch at a 1/2 Hz rate between the two inputs or you can lock to one or the other as determined by a front-panel switch. The switched mode can be used for four-antenna VLB experiments (where one antenna at each site is looking at a reference source and the other antenna is looking at an object that you wish to measure) or with dual-frequency or dual polarization front-ends. The 1/2 Hz rate comes from the timing generator so that two terminals will switch in synchronism. The IF switch is a diode switch and the switch driver is driven from 0 to +5 volt logic. An input attenuator is provided so that inputs in the range of -60 dBm to -10 dBm per 2 MHz can be accommodated. We did not provide separate attenuators on the 2 IF inputs; if you use the two input mode you will have to balance the input power levels within ± 2 dB before they come to the IF Converter.

The first amplifier covers the range 10 to 200 MHz with 20 dB gain. Following that amplifier there is either a direct path that is used if the signal is in the 10 to 55 MHz range or a mixer path if the signal is in the 130-170 MHz range. The path is selected by a front-panel switch which also allows selection of various internal oscillator frequencies or an external synthesizer. Following the first mixer there is a 60 MHz low-pass filter which is required to prevent local oscillators and spurious mixer responses from getting into the following amplifier. (The mixers have a strong spurious response at 3 x LO ± IF.) We have kept the IF Converter fairly broadband so that it can accommodate many IF frequencies; however, once you have selected the IF frequency it is desirable to install band-pass filter at the input.

The next component is a 20 dB amplifier in the 5 to 75 MHz range. The signal is then applied to the single-sideband mixer which is shown in detail in Figure 6. The U+ minus U- output of the single sideband mixer is the upper sideband; L+ minus L- is the low sideband as selected by a front-panel switch. I suggest that we stick to upper sideband unless there is some special reason not to.

Following the single sideband mixer there are the six low-pass filters which are switch selectable by the bandwidth switch on the front panel. These are 11-pole filters which have a sharp cut-off to allow efficient use of the bandwidth at a given sampling rate; the 10 dB point is approximately half the sampling rate and the 1 dB frequency is approximately 0.9 the 10 dB frequency. There is also a seventh position on this switch for the external filter through two jacks on the rear panel.

The output of the low-pass filter goes into an amplifier which drives three different outputs. The main output is to a clipper which takes this video signal and clips it into a square wave signal. It provides an output of $\pm$ 0.3 volt which is what the sampler in the timing generator requires. There is a second output from this amplifier which is for a video monitor jack with a level of -20 dBm; this is on the front panel and is for an oscilloscope or spectrum analyzer to see if everything is working correctly. There is a third output which is applied to a square law detector followed by a DC amplifier which gives 1 volt DC output when signal levels are correct. A second DC output is an expansion around 1 volt; it will give plus and minus 1 volt for a variation of 0.9 to 1.1 volts. The expanded output is provided for total-power radiometer use or for observation of a small calibration signal; the output is usually connected to a chart recorder. (In some cases it may be necessary to have a switched radiometer for pointing calibration; this is undesirable because the switch adds to the system temperature.) A meter is provided to monitor the normal total power, the expanded total power, the 5 MHz input level, or a reading which will read mid-scale if all the power supplies are correct.

The remainder of the IF Converter is associated with generation of 10, 30, 50 and 100 MHz LO signals coherent with an input 5 MHz clock signal. A 5 MHz distribution amplifier is provided for generation of other 5 MHz signals which are usually required. The LO generation is performed by dividing a 50 MHz voltage-control crystal-oscillator (VCXO) to 5 MHz where it is phase compared with the input 5 MHz; the output of that phase detector is then used to control the VCXO. A light on the front panel will be on when this phase lock loop is locked. The frequency divider is tapped at 10 MHz which is also multiplied in a tripler to 30 MHz. The 100 MHz output is derived by doubling the 50 MHz.

The front panel "Input Frequency" switch allows selection of 10, 30, 50, or 150 MHz; this is the edge of the lower or upper sideband. The "EXT LO" position allows an external synthesizer to be used for the single-sideband mixer LO. The relays which are at the 60 MHz low-pass input will be in the direct path position. In the "EXT AND MIXER" position the external LO is also connected but the relays will be in the bottom position so that the signal goes through a first mixer.

The general procedure for using the IF Converter is to set the Meter Switch on "X1" and adjust the IF attenuator so that the meter reads mid-scale. The 5 MHz input level must be externally adjusted so that mid-scale indication is also achieved with the Meter Switch set at "5 MHz Level".

2.3 Digital Processing and Time Keeping

2.3.1 The Timing Generator

There are several frequencies used in the rest of the system which must bear a fixed relationship to the system timing. The timing generator generates them. The timing generator is a wire-wrap card of digital integrated circuits which generates these frequencies in a straightforward way. The frequencies are output as TTL logic level square waves (+0.5 V = 0, +3.5 V = 1). The block diagram is shown in Figure 7. The basic input to the timing generator is the 5 MHz output of a time standard. The sampling rate is 4 MHz, so the very first thing that is done is a conversion from 5 MHz to 4 MHz. This is done with an integrated circuit phase-locked oscillator at 8 MHz. Both the 8 MHz and the 5 MHz are counted down to 1 MHz and phase compared to lock the oscillator. The 8 MHz oscillator is divided by 2 so that we have a 4 MHz signal which drives everything else. All the various frequencies are derived from this 4 MHz, which is also used to sample the data. There is, on the timing generator, a missed clock detector on the 5 MHz input; if there is a momentary interruption of more than about 3 cycles of the 5 MHz signal, then the little light on the front of the timing generator that says "time" goes out and stays out and you must set the time again. The 4 MHz is counted down to provide the signals that are needed elsewhere in the system. It is not a very straightforward set of counters because to generate, for instance, 60 Hz, you should divide 4 MHz by 66,666 2/3. Since bit times should not be subdivided, we divide twice by 66,667 and then once by 66,666, which means that the logic diagram is a little bit more complicated than one would really like. The output of the 60 Hz divider is a tick 0.25 microsecond wide occurring at a 60 Hz mean rate. This tick is brought out on the front panel of the timing generator and is very useful for synchronizing oscilloscopes, etc. There is a further set of gates on this divider that selects one of these ticks once a second and this provides a 1 Hz tick, again a quarter of a microsecond wide. This tick also comes out on the front panel. Since these ticks are narrow and hard to find, there is also a one quarter duty cycle square wave nearly synchronous with the 1 Hz tick - with the tick occurring at the fall of the square wave. This again is provided for syncing oscilloscopes and use in other equipment. The 60 Hz signal is used extensively in the video recorder. Each head stays in contact with the tape for 1/60 of a second and therefore the recorder likes data oriented in 1/60 of a second blocks. The recorder headwheel is phase locked to this 60 Hz reference signal. The 1 Hz signal is used to run the Chrono-Log clock. It is the fundamental system timing pulse and should be compared with a local time reference - a portable clock or a Loran receiver. There are also slightly widened forms of the 1 Hz and 60 Hz signals which are used to drive the Chrono-Log clock. The 60 Hz is used in the Chrono-Log clock for internal gating purposes only. The Chrono-Log clock is driven from the seconds tick from the timing generator and therefore the time that the digit changes in the Chrono-Log is dependent only on the timing generator and does not depend on anything within the clock itself.

There is a fourth frequency which is also needed in the system for recording the timing information on the audio track of the tape. This frequency was chosen to be 3.84 kHz, to record 16 BCD digits every sixtieth of a second. This frequency is derived from 4 MHz by division by 1042. In order that the transitions of this frequency always occur lined up with the 60 Hz ticks, the divider is reset every sixtieth of a second. Every sixtieth of a second there is a slightly short pulse in the 3.84 kHz square wave.

There is another auxiliary output, namely, a 200 kHz signal which may be used to drive a Loran receiving unit. A signal of 200 kHz is provided rather than 100 kHz so that a phase and quadrature 100 kHz can be derived to phase detect the Loran.

In addition, there is a very important test function in this unit. This is the pattern generator which generates a 15 bit pattern. When the button on the front of the panel labeled "pattern" is depressed, the data stream output is replaced by this 15 bit repetitive pattern. This pattern is reset by the 60 Hz tick so that all frames are identical. This pattern makes it very much easier to look at what the recorder is doing on playback since it can be seen on an oscilloscope triggered by beginning of frame sync. We strongly recommend putting two minutes of the pattern at the beginning of each tape. The pattern at the beginning of every tape may not actually be used very much, but if something goes wrongly the pattern is there and is a very handy diagnostic tool.

Also in the same chassis with the timing generator there are the samplers for the data. This is a simple sampler which merely takes the 4 MHz square wave generated directly from the digital logic, uses it to drive a snap diode which differentiates one edge to get a very narrow pulse about a nanosecond wide. This drives a diode bridge which samples the signals coming in from the clipper in the IF converter chassis. This is the same sampler used in the NRAO digital correlation spectometers. There are two samplers. This is to give the capability for experiments in which one wishes to look at two signals from either two antennas or two frequency ranges or what have you. One can either switch the input to the converter, or one could have two converters and bring two clipped video signals into the samplers and then the samplers will sample each one at a 2 Mb rate and interleave the samples so that you will eventually have two two-megabit streams interleaved in the recorder. In practice I do not think many experiments will be made this way, but the samplers are fairly cheap and so we built them into the box just to preserve that possibility.

The data coming in to the sampler has been clipped in the clipper so that it is a square wave with transitions at arbitrary times. The sampler then looks at a very narrow window in the square wave separated at 250 nanosecond intervals and generates a signal which holds the same level during the remainder of the 250 nanoseconds.

There is on the digital output of the sampler a circuit which checks and makes sure that you are getting both zeros and ones. If there are not both zeros and ones appearing on the output of the sampler, then the data light on the front panel goes out. When the sampler is in double sampler mode (switched by a toggle switch inside the timing generator), the light will be out unless both samplers are producing both 1's and 0's. The clipper is so good that if there is no input to the clipper it does still output both zeros and ones, so this light does not indicate that there is signal going to the clipper. It merely indicates that the clipper is connected to the sampler. The function of the light is to indicate that the single/dual switch is in the right position, and the fact that the cable is connected from the clipper to the sampler.

The initial start up of the timing is very important. To start the timing generator, that is to get a one second tick out of the timing generator lined up with UTC or whatever other time you are using, you need some sort of input pulse.

In the Mark I VLB the time could be adjusted by a fast-slow pushbutton, but it now seems that the seconds ticks are such common things that we have predicated the use of this on having a seconds tick, that is, a tick which can be conveniently lined up with UTC. Most time standards have some sort of convenient, movable ticks. Synchronizing the timing generator is very much like synchronizing an oscilloscope. On the front of the timing generator there is a sync slope select switch and level set knob, which correspond with the same switches and knobs on the front of an oscilloscope, and there is also a sync arm pushbutton. When you press the sync arm pushbutton all the counters are reset and stopped. After you release the pushbutton, the next time that the input signal on the sync input jack passes by the level you have selected (with the level knob) with the proper slope, then the counters are started. The first quarter microsecond wide seconds tick will occur within the 250 ns preceding the time the sync input signal crosses the selected sync level, and each integer second thereafter. The time light goes out when the sync arm pushbutton is pressed and at the next second tick the time light comes back on again when all the counters are started. When you press the button and release it there is a pause, on the average of a half a second long, before the light will come on. This pause indicates that the unit has triggered properly; if you are triggering on noise then there will probably be no pause after you release the button. The seconds tick may also be compared on an oscilloscope with the original.

The Chrono-Log clock can be set quite separately from the timing generator. It is usually set after setting the timing generator. The run/stop switch on the front of the Chron-Log clock should always be left in the "run" position. When the inhibit/set switch is in the set position you can add hours, minutes, seconds, or days to the count on the clock so that without disturbing any of the other timing circuitry so that the clock can easily be set. The numbers appearing on the face of the Chrono-Log are written on tape and are used in the reduction of the data. The transition times on the Chrono-Log are governed by the timing generator and not by anything internal to it. We recommend setting UTC just because of the time zone problems on the longer experiments; it is still a good idea even if you are operating entirely within one time zone.

2.3.2 The Format Unit

The format unit block diagram is shown in Figure 8. Let us follow the fate of the signals coming over from the timing generator. The data is organized into 60ths of a second blocks called frames, because if you were recording a television picture this would be one screenful. The placement of data on the tape is given in Figure 9. The frame starts out with a sync word which is a unique pattern of transitions which can never occur in data, and then there is a one zero pattern to mark the beginning of the frame. Next there is a six bit number which gives the number of the frame from the last integer second. This number is zero for the frame which begins on an integral second and counts up to 59 and is reset to zero again. This 6 bit frame count is protected by a parity bit. Then at that time, which is 7 microseconds after the even 1/60th of a second, you begin recording data bits and record either 66,001 or 66,000 data bits, depending on whether this particular frame you are dividing 4 MHz by 66,667 or 66,666, respectively. (The extra bit is stuck in the data rather than in one of the other intervals.) Then the frame ends with a unique sync word. After the end-of-frame sync word there is a string of about 600 ones written. This little chunk of time is left unused because at playback time one head is coming off the edge of the tape and the other head is entering the tape, and we allow this piece of time for switching the following equipment from one head to the other and allowing for settling time and for some uncertainty in the switching time. At record time both heads are driven and so the data is actually recorded from the time that the head physically comes in contact with the tape until it physically leaves the tape.

There is an additional feature going into the multiplexer - at 0.512 millisecond intervals an 8 bit pattern is inserted into the data stream which consists of seven ones followed by a zero. At playback time we can test this pattern to see that we have not missed bits in counting data bits from the time of the sync word at the beginning of a frame. We count bits from the beginning of frame sync to the center of the 8 bit pattern. Then, the next zero that we see in the data stream is presumed to have been an integer number of 512 microsecond intervals from the true beginning of the frame, and the playback clock is reset accordingly. So that if we have missed or inserted one or two or three bits, then the playback time clock will be properly reset. One cause of data recovery errors is that there are bad spots on the tape a few thousandths of an inch in size. During these dropouts, the playback circuits amplify and clip their own noise, and thus playback clocks occur at random times. There is some flywheel action in the playback clock recovery circuitry. If the dropout is short, the flywheel coasts over it nicely by itself. If it is a slightly longer interval, you tend to miss one or two bits or the flywheel gets ahead of itself and inserts one or two extra clock transitions. We do not have any good statistics of how often there are serious dropouts of this sort. Just looking at them on the scope you see chunks of missed bits, of length a few microseconds, occurring once or twice a second or something like that.

The output of the multiplexer is fed to the diphase encoder. Leach calls it a split phase mark encoder. The coding scheme is shown in Figure 1 and described in Section 1. The coding is done by selecting inphase or phase inverted 4 MHz clock according to the data bit.

Also in the formatting unit there is a formatting device for the time code data which is recorded on either audio track, usually on audio one. The audio track information consists of 16 BCD digits recorded every sixtieth of a second. The 16 BCD digits are, first, the nine digits that you see on the front of the Chrono-Log clock; then the 6 bit frame counter is recorded in an 8 bit word occupying the space of two BCD digits, and then there are three special digits which are used to mark which is the beginning and end of this 16 digit set. In each unit there is one digit wired to a unit number 0 through 9 so that post-facto at playback time you can find out what unit the tape was recorded on. This just places slightly less reliance on human reliability in writing the right thing on the label of the tapes. The sixteenth digit is, at the moment, a spare. The audio track is also written in diphase coding and has been extremely reliable.

The second audio track may be used for oral notes.

Also in the format unit is the controllable one-shot shown on Figure 10 which provides the 60 Hz reference used by the recorder. This can be moved back and forth to adjust the phase of the recorder headwheel so that indeed the time that the recorder heads are near the edge of the tape occurs during the data gap so that at playback time the head switch will occur at an appropriate time. Also in the same chassis with the format unit, there is a little amplifier that gives an additional DC boost to the headwheel servo that keeps it in phase with this 60 Hz. Without this DC boost, changes in component values would cause the headwheel phase to vary an unacceptable amount, and having the DC boost in a separate chassis rather than the recorder makes possible the convenient feature that we can put on the front of it a phase meter that gives the phase relationship between the headwheel itself and the blanking allocated at the ends of the tracks.

2.4 The Ampex VR660 Recorder

Figure 9 is a tape layout. This figure is taken from the Ampex manual. There are 4 discrete areas of the tape--two audio tracks along the top of the tape, a control track along the bottom, and the video itself is on the helical track occupying most of the tape. Each of these diagonal tracks represents 66,666 bits of data. The tape moves in a wrap around the cylindrical drum, and the heads spin in a horizontal plane. The vertical component of the tape motion and the circular motion of the heads combine to make the apparent path of the heads relative to the wrap of tape be a tightly wound helix. The audio tracks and control tracks are put on after it leaves the helican scan mechanism. The audio tracks are located at the top of the tape and the control tracks are at the bottom. The capstan, which determines the rate of longitudinal motion of the tape, pulls it through the whole system.

There is no great difference in our new or old tape. We do not yet know what the life of the tapes would be. There are obvious cases where something gets jammed and it just chews the tape up, but this has been our only experience in discarding tape. We do not plan to have facilities for splicing these tapes. If we get a gash or stretch in the middle of a tape we just skip over it. There is a video erase head which is on the lower level of the tape recorder, and the audio head is an erase-record-playback combination head. The control track drives the tape to complete saturation so there is no erase requirement on the control track. The audio and control track heads are factory packaged in a single assembly.

Figure 10 is a rather crude block diagram of the Ampex recorder system. The first row across Figure 10 is a summary of the recorder video system. This is actually one of the least complicated subsystems.

The recorder as received from Ampex is basically an FM subcarrier system. That is, it accepts a video signal which is processed as a TV signal, clamping for sync levels and things like that; and it does a sync strip off for controlling the head drum under normal circumstances. Basically, however, the video signal modulates a narrow band FM carrier in the order of 5-1/2 MHz. That carrier output is then driven in to heavily saturated amplifiers which drive the head. Normal video signals have something like 18 octaves of signal frequency from 30 Hz up to 4.5 MHz. The best possible performance from a recorder head system is about 10 octaves. That is the reason they use this FM modulation scheme for video. Even though television video might have 18 octaves spectrum, the signal we are using has maybe 1 or 2 octaves spectrum that we really need to get on tape, so we decided to bypass the FM system entirely.

The video input comes from the coder as a single ended TTL logic level terminated in the recorder at 75 ohms. Then there is an amplifier with a gain control. There is a meter indication--one meter called video. When you are in record that will monitor the level coming into the machine. As in the unmodified Ampex there are two capabilities of controlling this. The signal is processed on what they call the mod/demod board in the back of the recorder. There is a top surface switch on the mod/demod board which says Unity/Variable. This switch selects whether you use the top surface/input level control or one that is a screwdriver adjustment on the board. We will set that pot for the proper levels with the usual connection. If there is some problem with signal level, for example long cables between the coder and recorder, then you can switch to the variable control and use the top surface knob; but at the proper drive the video meter will read 100.

The video coming in after some amplification and metering drives the same amplifiers that the subcarrier oscillator used to drive. The record head is driven directly with diphase square waves. It is approximately current driven--

they put a fair amount of resistance in series with the amplifiers which produce about a 30 volt square wave. The head is in essence driven with a current source. After processing, the signal is sent up to the head preamp board, routed through a relay and a current step up transformer on the head preamp board. It then goes through what they call a rotary transformer to couple from the stationary head preamp to the rotary heads. The signal from the rotary transformer drives the heads. The optimum head driving currents depend slightly on the type of tape. The drive currents should be set up, as described in the Ampex manual, to produce a maximum signal on playback.

On these recorders there is no read-while-you-write provision. They have what is called an EE (electronics to electronics) signal. The EE signal is a direct patch of diphase across from the record drives into the playback system.

The same head is used for both read and record. At playback, the received signal goes through four stages of equalization up in the head preamp board, the circular plug-in card up at the top of the recorder. The equalization is to some extent adjustable by controls on this board. These are needed only in reproducing but must be set correctly also in verifying that you are getting a reasonable recording on tape. If these are mis-set, even if you have a perfect recording, the output will still look bad. Then from the head preamp the signal goes to a multistage limiter. We then bypass the original Ampex discriminator and equalization. We connect to the output amplifiers and finally come out the video output jack with a squared up diphase signal.

Now we will consider the head drum servo system. In the recorder there are two heads mounted on a rotating aluminum drum. Also, on the same drum, inserted at the factory, there are some metallic slugs. As the drum rotates there is a magnetic pick up which picks up the presence of these inserts in this drum. This is called the tac pick up. The idea is to maintain phase of the tac pick up relative to the incoming sync signal wave form. In the case of the record terminal this incoming signal is very close to 60 Hz. In the reproduce terminal it may cover a range from approximately 55 to 65 cycles. If it cannot maintain phase lock, it will attempt to maintain a frequency lock.

The tac pick up is converted to a 30 cycle square wave and then it is converted back into 60 cycle spikes coming in. The negative edge of the sync signal is used to generate a similar set of pulses. Located on the control panel, front right, there is a switch called servo sync external/normal. "Normal" uses the line voltage. It takes a square wave off the line voltage and uses it for a sync signal. For our application we use "external" which derives the sync from the signal supplied at the external sync jack on the end of the recorder.

The frequency and phase comparator, a set of integrated circuit devices, acts as a phase comparator if the two frequencies are about equal; but if it sees two pulses from one source before a pulse from the other, then the frequency comparator takes over. The detector output locks up in either the high state or the low state, as appropriate, until the lagging signal catches up. When the two frequencies become equal, the detector switches from the frequency mode to a phase mode, and it puts out a variable duty cycle square wave, setting on one reference and resetting on the other. The duty cycle represents the phase difference between the two signals. This wave is smoothed, sampled (to eliminate excessive 60 Hz components) by a FET sampler and used to drive the V-to-F converter. The VF converter output drives an induction motor. The slippage in the motor does not affect the servo loop. The tack pick up is also connected to the coder. There is a small circuit in the coder which, triggered by the data gap signal, generates a trapezoid ramp. The head switch edges trigger a sample and hold sampling on this ramp voltage. That DC voltage is used for the DC boost on the phase of the head drum motor servo loop.

Also during record the square wave from the flip flop triggered by the tac pick up is being recorded on the control track. Now we enter the capstan control subsystem. During record the capstan motor drive current is just servoed to 60 Hz. This sets a nominal tape rate of 3.7 inches per second. That is the rate the tape is pulled past the capstan.

In playback the same head is used for reading that control track. The capstan servo loop drives the capstan motor to keep a fixed phase relationship between the tac pick up flip flop and the control track impulses from tape. This phase is varied by the tracking knob on the front of the recorder. You adjust the tracking delay to place the heads on the center of the video band. There is enough varation in this tracking delay to go from the center of one track to the gap between the two tracks, where you see just noise or "spatter" from between the adjacent tracks, and then peak up on the second one. There is slightly more than one track width adjustment available. At reproduce time the tape is speeded up indirectly by first speeding up the head drum, and then the capstan follows the head drum and pulls more tape through so one tape recorder advances relative to the other.

There are three modes of control for the tape tension. On Figure 10 there is one pot for playback and one for record. Whichever is active operates a solenoid setting a reference tension. A lever system compares this reference tension with the tape tension sensed by the tension arm and applies the tension difference to a brake band on the supply reel to servo the tension. There is also a detent at one end of the tension knob. During playback, that is supposed to generate an automatic tape tension control by insuring the proper timing of horizontal syncs. Since we have no horizontal sync pulses, this is no longer usable.

We will now describe the adjustment of the head drum servo. Figure 11 is the schematic. The best operation point for this op amp is about -2.7 volts on the output. It actually swings from about 0 to -5. We put 60 cycles into the external sync of the recorder. We adjust R7 on the head drum board of the operational amplifier for -2.7 volts output at test point E4. That centers the operating point for our op amp at its optimum. The next step is to look at test point E1, which is a variable duty cycle square wave. The duty cycle represents the phase between the input and output. Again, for a 60 cycle input this should have a 50% duty cycle, that is, to have an equal amount of duty cycle pull either way. We adjust the pot on pin 4 of the op amp of the piggyback board for a 50-50 duty cycle square wave, again with 60 cycle input. The head drum servo typically then maintains frequency lock from 56 to 64 Hz, if a variable frequency input is used. The capstan servo should follow this same range. Typically, we find its slewing range is somewhat greater, so that when the head drum is falling out of sync the capstan still has some margin.

The test point on the head preamp card is the waveform as it leaves the head preamp, before the limiter. There is a signal of approximately 100 millivolts peak to peak at this test point. This is a function of the preamp card equalization. The level should be reasonably flat for the length of the track, if the mechanical adjustment is correct. Figure 12 shows the data stream after going through the limiters on the output of the recorder. It presumes a scope synced on the positive slope. There will be a transition every 125 ns. There are no lines which rise at the left of the screen and remain up across the first transition, at 250 ns.

The data information may be thought of as residing in the positions of the zero crossing points. Good data will have crisp transitions, which do not vary from one bit to another. The recorder should be adjusted for a minimum width of the zero crossing lines. If they are smeared out to a width more than about ± 25 nanoseconds, then you probably begin to lose data. There are two controls which you adjust for this. One is called chroma--it is located on the back platform. The other is R24 up on the head preamp board. Chroma is low frequency boost, oddly enough. Between this R24 and chroma we try to get the best set of zero crossings.

You may also sync the scope in such a fashion that the recorded test pattern is stationary on the screen. Its reliability is perhaps a more satisfactory indication of the state of the system if you are using a low frequency (slower than 10 or 15 ns rise time) oscilliscope to check out the system.

2.5 Adjustments and Tests

The playback time equipment is far more sensitive to adjustments than the record time equipment. However, things do get out of adjustment. The equipment should be thoroughly checked before being used in an experiment. In addition, a log should be kept to help determine the status of head wear, etc.

2.5.1 Adjustments

The adjustments we have found to be occasionally necessary are given below.

The recorders have been mechanically aligned for approximate compatibility before leaving Green Bank. It is unwise to modify this adjustment without being prepared to devote several days to the process, and without having on hand a standard tape to align the machine to. The only excuses for mechanical realignment are if the guides become so misaligned that data is being lost off the edges of the tape, or if the alignment is beyond the capability of the reproduce machines to duplicate. On the other hand, if the two halves of the helical scan assembly become misaligned, so that the tape is not stretched smoothly and tautly across the gap, this should be corrected immediately.

The rubber pinch roller should be aligned as described in the Ampex manual. It is possible for tape to "creep" past the capstan if this is not done regularly, resulting in non-standard and irregular tape motion.

When heads are changed, the head positions should be set as described in the Ampex manual. If the dihedral adjustment is left undisturbed, it will usually require no adjustment. The head drive currents should be set as described in the Ampex manual. Note that two different drive levels are required, one for low coercivity tape, like Ampex type 142, and one for high coersivity tape, like 3M and the new Ampex 143 back-coated tape. The machine time, measured tip projections, and the recovered signal level (at head preamp TP10) under standard conditions of tension and chroma setting should be logged. The recovered signal is a strong function of tape type and playback head, but a decrease far below the initial value indicates a failed head.

The playback data path may occasionally need adjustment, chiefly R24 on the head preamp board. Other than that, we expect no electronic adjustments to be needed, except after a case of component failure. The most common type of failure, however, is a sticking or non-contacting relay.

2.5.2 Format Unit Test Points

The format unit test point waveforms are shown in Figure 13. A brief description of the signals is given below.

TP1 4 MHz clock

TP2 60 Hz tick, .25 μsecond wide, + going

TP3 1 Hz tick, .25 μsecond wide, - going

TP4 60 Hz reference to Ampex, approximately 50% duty cycle, adjustable by front panel pot.

TP5	3.84 kHz clock for audio track data, exactly 64 cycles in 1/60 second
TP6	Clock interogate, 250 μs + going, 60/second
TP7	Write gap, 156 μsecond, + going, 60/second
TP8	Write sync word - up for 3 μs at beginning of frame, up for 6 μs at end of frame, so a pair of pulses 60 times per second
TP9	Write frame count up for 2.5 μsec 60 times per second
TP10	Write data. Down for 167 μsec every 60th of a second
TP11	Write check Bits, + going, up for 2 μs every 512 μs, up first time 510 μs from beginning of frame.
TP12	Frame count sync, + going, 250 μs wide, 1/second
TP13	NRZ data stream from timing generator
TP14	NRZ data out, with frame count sync word, data gap and check bits inserted
TP15	Output clock
TP16	Diphase to recorder
TP17	Time code NRZ. Refer to Figure 14, audio track format
TP18	Time code diphase to recorder audio track
TP22	Record phase analogue
TP23	+5 power supply
TP24	Signal Ground

2.5.3 Check List

We strongly suggest you read over this list in the course of an experiment, to find what you have been forgetting to do. An abbreviated form is included as Figure 15 for clipping and posting on the wall.

2.5.3.1 In advance.

Observing frequency and sideband agreed

LO's available, both stations

Polarization agreed

Tapes on hand

Spare heads on hand

2.5.3.2 Before experiment

Primary time standard determinded, either by transporting clock or by LORAN C

Feed polarization determined

LO frequency set

Receiver operating

IF brought to converter

- Converter oscillator locked
- Sideband selected
- Input frequency selected
- Switching set to proper mode
- Level set
- Bandwidth set

Check pinch roller alignment

Video recorder cables connected to format unit

- 4 MBit data
- 60 Hz Ref
- Time Code
- Head switch return
- Head drum phase control
- Microphone

Video recorder controls set

Head override	- off
Sync	- external
Audio edit	- off
Record	- $V+A_1+A_2$
Mode	- Normal
Slow motion	- off
Tension	- mid range

2.5.3.3 Once per shift

Clean audio and control track heads

Clean tape path-guides and helical scan mechanism

Clean pinch roller with alcohol - head cleaner will cause it to crack

Run pattern test

On two minutes or more of recorded test pattern, rewind the recorder to the beginning of pattern. Connect scope probe to TP10 on preamp board, adjust tracking control to maximize output. Output should be steady - a rapid fluctuation in level (at a few Hz) probably means the capstan servo is unlocked. A slow fluctuation may mean a loose guide or tension servo oscillation. Note level, compare with value recorded in machine log for this type of tape when heads were new. Connect scope to video output jack. At 2ms per division, sync scope from 60 Hz from line or timing generator. The data gap, a burst of diphase 1's, should be visible as a bright vertical line. This should remain nearly stationary on the screen. At 1 μsec per division, internal sync, verify that pattern has a 7.5 μsec repetition interval. Using both sync level and variable sweeptime controls, synchronize to patter, verify that all transitions are reliable. Watch for flicker, indicating a difference between heads. If present, examine each head individually by adding the headswitch waveform to the data and using a DC sync.

Local oscillator connected to frequency standard

Video recorder cables connected to format unit

Recorder sync on external

VLB seconds tick agrees with primary time standard or LORAN C

2.5.3.4 Each tape

Clean video heads

Mount tape

Record 2 min. of test pattern

VLB clock agrees with WWV or external clock -

check day, hours, minutes, seconds

IF meter approximately centered

Headwheel phase approximately centered

2.5.3.5 Each observation

Telescope on Source

Polarization correct

Front end switching surpressed

LO frequency correct

Bandwidth set

Converter phase lock light

Timing generator phase lock and time lights

Start observation

Log start time

Stop observation

Log stop time

3. The Playback System.

The Mark II playback system is designed as a unit, but the implementation is done partly in hardware, partly in software. There is no very clear separation between the functions, and any given task was assigned to the medium in which it could be done more easily. In the description below we shall first discuss the principles of operation in sections 3.1-3.3, then the practical adjustments an expert operator will on occasion need to make in section 3.4, and finally the normal operating procedures which a novice operator will need to know, and which an observer needs to know to understand the capability of the device, in section 3.5. In all of this, we will switch between discussing hardware and software with bewildering rapidity.

In discussions of software, specific reference will be made to the standard 31 channel continuum programs. Anyone using variants of these programs such as the 95 channel line program, and various pulsar programs, should consult their authors.

3.1 Electronic System, Principles of Operation.

The operation of the VR660 recorder has been described in detail in section 2.4. For instance, the head-drum servo system operates in exactly the same fashion during playback as during record. That is, the mechanical motion of the head drum is phase locked to a 60 Hz external signal, provided, in this case, by dividing down a 4 MHz crystal oscillator. In the playback equipment there is no external DC boost on this signal, so that this phase relationship must be adjusted from time to time.

Provision is made within the playback controller to slide the relative phase of the two signals supplied to the external sync inputs when it is desired to change the relative mechanical position of the two head wheels (and hence the relative time of the data each is picking up).

The capstan servo and tension servo operation during playback are described in section 2.4.

The equalization of the signal from the video head is briefly discussed in section 2.4 and the decoding scheme in section 1.

In addition to the clock recovery discussed in section 1, there is what is known as an "assured clock". The clock recovered from the data is fed into an L-C filter of fairly low Q and is reclipped after the filter.

This provides a flywheel effect, and if a clock transition is missed, or an extra transition inserted, the spurious timing pulse does not have enough energy to accelerate the flywheel, and the assured clock maintains the proper timing. The design of the assured clock is one of the most critical items in the whole system.

The data from the video bit stream goes into an integrated circuit flip-flop buffer. Conceptually you may think of the buffer as being arranged in a large circle. The buffer is a clock-like device with bit addresses going from zero to 2048 around the buffer. There is a half millisecond of data in the buffer. There is a buffer load pointer which is set to zero by the beginning of frame sync word and then is driven around the buffer by the recovered clocks from the tape. The location into which a given bit is stored is determined by counting the clocks from the assured clock. The buffer is a small fraction of a frame; the load pointer thus goes around the buffer about thirty-two and a half times each frame. Every half millisecond, when the buffer load pointer is about to cross zero on the buffer, one of the 8 bit minor check patterns is expected. As soon as the pointer gets nearly to the zero point, a window opens and the device starts looking for a zero in the data. When it is found the buffer load pointer is set exactly to address zero again. If the pointer address had to be changed to do this, the red "Dropout" light is lighted. This minor resyncing is done every buffer cycle, every half a millisecond.

Also, in the buffer there is an unload pointer. This is set to zero initially when the tapes are brought into synchronization. The two unload pointers of the two buffers are set to address zero at the same time exactly, and then from that time forward the unload counter is stepped by a 4 MHz crystal clock and keeps time at a steady rate from thence forward. The unload counter may be thought of as following the load counter around the circle. The load counter is dropping data into the circumference of the circle and the unload is sweeping it up behind it so that as long as the phase of the load counter is within ± 256 microseconds of the phase of unload counter determined by the crystal clock, then the unload pointer will sweep up the data after it has been put down by the load pointer and before it has been over written again by the load pointer. This phasing is maintained by using the unload counter address to generate the 60 Hz sync input sent to the head drum servo of the recorder. The phase angle may be adjusted by the head drum natural rate adjustment, R7 on the head drum servo board.

The relative delay between the two bit streams is controlled by the rate at which the unload pointer is driven, so that the geometric and other relative delays between the bit streams are taken into account by dropping a pulse from the clock that advances the unload pointer. The recorder head drum, of course, continues to follow the unload pointer.

Out of the two buffers we have two bit streams which reproduce the record time bit streams, with a relative delay inserted. These bit streams go from the playback controller to the correlator controller. At this time they have all the essential properties of the IF from a regular interferometer. The first thing done with these IF's is the insertion of a phase rotator in one of the IF's, so that the fringe rate is reduced from its natural quantity, whatever that may be, to a sufficiently low rate to allow you to integrate for long enough to drastically reduce the quantity of data. For the lobe rotator you need to generate artifical fringes which you use as the input to the lobe rotator. This is done by a computer controlled programmable divider. The programmable divider divides the 4 MHz clock rate by a number received from the computer. This number comprises a 19 bit integer part and a 16 bit fractional part. It will accommodate fringe rates from essentially zero, that is, infinite period, to rates of the order of 100 kHz. The least significant bit is a period increment of about 60 ps. The phase of the artifical fringe is reset 10 times a second; there is sufficient precision in the fractional part to allow the divider to coast for a tenth of a second if the fringe rate is less than about 100 kHz. The output of the fractional divider is 2 square waves in phase quadrature - the cosine wave and the sine wave - which are then multiplied by one of the data streams to rectify it. The lobe rotator also produces a blanking signal, as explained in section 1, which inhibits correlation for part of the cycle, making the square waves better approximations to the desired sinewave.

One bit stream has this phase rotator in it. It produces two output bit streams, one of which has been multiplied by the cosine wave approximator, the other by the sine wave. These are presented to the correlator which has a total of 95 complex channels, that is, there are 95 sine component correlators and 95 cosine component correlators. The 96th channel is used to accumulate the total number of attempted correlations, for normalization purposes. The shift clock into the correlator that determines the delay interval between two successive channels of the correlator is not fixed at 4 MHz, but can be divided by 2 to the n^{th}, so that, for spectral line interferometry, a correlation function of various widths may be selected. At the different shift rates, corresponding to different sampling intervals, there must, of course, have been an appropriate filter in the IF at record time. The correlator has bandwidths ranging from 2 MHz to 15 kHz.

The multichannel correlator is useful on two counts -- for line work it is used in the same fashion as the autocorrelation function spectrometers, and for continuum work a range of delays is examined to take into account the uncertainty in the position of the radio sources or in the baseline.

The correlator is wired so that the first word received by the computer is the normalization count for cosines, the second is the cosine channel with a lag of 93 shift clock times, the third the cosine channel with a lag of 92 shift clock times, etc. The first 32 words are cosine channels, the second 32 are sine channels, the third 32 cosine channels again, etc. The sine normalization count is found in the first word of the second block, that is in the thirty-third word read by the online computer. From this we can note that the instrumental delay to the center of the first 31 channels is -20 microseconds at 2 MHz bandwidth (4 MHz sample rate), -40 microseconds at 1 MHz bandwidth, etc. The delay to the center of the 95 channels is -12 microseconds at 2 MHz bandwidth, -24 at 1 MHz, etc.

3.2 The Online Computer.

The online computer is a Varian 620-I, with 4k of memory, hardware multiply/divide, extended addressing, and interrupt options. One interrupt line, accessing location 0, is active. The computer is programmed in Assembler language, using a cross-assembler on the IBM 360. Its peripherals include a single nine-track, 25 IPS magnetic tape drive and an ASR 33 teletype.

3.2.1 Computer Interface Organization.

The computer is connected to the correlator controller in two ways. First is the interrupt line, which is triggered 60 times/second by the beginning-of-frame signal from buffer A.

Second, the computer has four Varian digital I-0 modules, with addresses from octal 60 to 63. Each module contains a 16 bit output buffer, a 16 bit input buffer, 8 sense lines, and 8 output pulse lines. The 8 output-pulse lines are driven from the same one-shot; the true duration of the output pulse is given by the one-shot time setting, or the time the CPU connects a different output pulse line to it, whichever is shorter. In practice, all input lines are buffered in the correlator controller, and the input buffer is not used. Also, we have less need for sense and pulse output lines, and most of them remain unused.

Below is a list of the functions of the I-0 bits. The types are denoted OTB (output bits), BI (binary inputs), SEN (sense lines) and POT (pulse outputs). OTB and BI are numbered by the output address (60-63) and bit number (0 (least significant) to 15 (sign or most significant)). POT and SEN are given the line address, e.g., POT-060 is line 0 of the module whose address is 60.

OTB 61-3 (most significant) to 61-0, OTB 60-15 to 60-0 (understood binary point follows 60-2), and OTB 62-15 to 62-0 give the fringe period in microseconds. It is actually interpreted as ratio to 4 MHz clock times, with the binary point following OTB 60-0.

OTB 61-7 to 61-4 gives the phase to be strobed into the phase register at the next (usually 0.1 second) sync time. This is really a 3 bit number in twisted ring counter format: 0000=0, 0001=1, 0011=2, 0111=3, 1111=4, 1110=5, 1100=6, 1000=7.

OTB 63-15 to 63-8 is the memoscope Y displacement, OTB 63-7 to 63-0 is the memoscope X displacement.

OTB 61-8 is blank correlator multiplication.

OTB 61-9 is select next Beginning of Frame A as sync time.

OTB 61-10 is set interrupt mode.

OTB 61-11 is set correlator recover mode.

(During correlator recover mode, carries between correlator cards are inhibited. This mode should be set for at least 128 microseconds after readout, before unblanking).

OTB 61-12 is erase memoscope.

OTB 61-15 to 61-13 are unused.

BI 60	16 bit binary - correlator output		

BI 61 and BI 62 - Audio track time code. BCD coded.

BI 61 bits	15, 14	day of year, hundreds
	13-10	day of year, tens
	9-6	day of year, days
	5-4	tens of hours
	3-0	units of hours
BI 62 bits	15-13	tens of minutes
	12-9	units of minutes
	8-6	tens of seconds
	5-2	units of seconds
BI 62-	1, 0	display time constant switch
		11 = $^{s}.2$
		10 = 1^{s}
		01 = 5^{s}

BI 63-15 - 63-10 A Helical track frame count.

BI 63-7 to 63-0 2 BCD digits, unit numbers from audio track

BI 63-8, 9 Unused

POT 060	Retard data stream A 1 bit
POT 160	Retard data stream B 1 bit
POT 260	Reset controller
POT 061	Select "A" time code
POT 161	Select "B" time code

POT 261	Fetch word from correlator (the first word is always available, this command fetches subsequent ones. Correlator must be blanked).
POT 062	Reset error indicators and lights
POT 063	Light "COMPUTER" light
POT 163	Light "DELAY TRACKING" light
SEN 060	P4B, data transfer
SEN 061	Controller stopped (tapes may still be moved, of course, under local control).
SEN 062	Sense output frame B
SEN 162	Sense frame count B $\neq 0$
SEN 063	Sense error A
SEN 163	Sense error B

3.2.2 Program Organization

A flow chart of the computer program is shown in Fig. 16. There is a single interrupt entering the computer which interrupts it at the 60 Hz rate at the time of the beginning of frame on "A" tape recorder. At that time, the computer, using a starting value and delay rate, estimates what the delay should be set to, and if it is not, it increments the delay by one bit, stealing a pulse from the appropriate buffer unload counter. Then the computer updates the on-line display. This display is the sine component of the center 12 channels of the correlator plotted as a function of time. If the residual fringe rate is not exactly zero, then a sinusoidal pattern is displayed on the CRT screen in much the same fashion that you see fringes coming out of the analog correlator on a conventional interferometer.

Thereafter the program branches to various tasks, depending on the exact time--specifically on the frame count (count of 60^{ths} of a second within the second) recovered from the helical data of recorder "A". If six divides the frame count with a remainder of 5, the precomputed fringe phase is placed in an output buffer, and a circuit is armed which will strobe it into the fringe phase buffer on the next beginning of frame from buffer A.

If six divides the frame count evenly, i.e., an even tenth of a second, the precomputed fringe period is inserted in its output buffer, where it is used immediately. The computer then calculates the phase, delay and period expected at the next even tenth second. The phase expected is calculated from the days, hours, minutes, seconds of the A recorder audio track, and the sixtieths from the helical track. The following equations are used:

$$\phi = B_1 + B_2 \cos((T + T_o)*1.002737923) + R*T$$

where T is the UT time less the day specified on the input tape,

$$B_1 = B_z \sin \delta$$

$$B_2 = \sqrt{B_x^2 + B_y^2} \cos \delta$$

$$T_0 = (-\arctan \frac{B_y}{B_x} - T_s + \alpha)/1.002737923$$

T_s is the sidereal time at midnight, UT, that day and R is the local oscillator offset. The delay is given by

$$D = (B_1 + B_2 \cos(T+T_o)*1.002737923))/F + D_o$$

where F is the operating frequency, taken to be the signed sum of 60 frequencies. The fringe period ρ is given by

$$\rho = \frac{1}{\dot{\phi}}$$

$$\dot{\phi} = B_2 \sin((T+T_o)*1.002737923)*1.002737923 + R$$

If 12 divides the frame count evenly, the correlator is read before the above calculation is performed. 192 sixteen bit words are extracted for the correlator, in blocks of 32 cosine components followed by 32 sine components as explained in section 3.1. The correlator is blanked during this time, approximately 5 milliseconds. After going through the phase calculation the computer issues a write command to its tape unit, and the first 31 each of the sine and cosine data channels are transferred to the IBM compatible tape. The remainder of the channels are discarded, because they are not useful for most continuum applications, and they would occupy an unnecessarily large space on the output tape.

The constants B_1, B_2, T_o, D_o, R and 1/F are calculated by the program REDPREP and are put at the beginning of the output tape in a format convenient for the on-line computer.

3.2.3 Record Formats.

The formats of the input (parameter record prepared by program REDPREP) and output records is given below.

3.2.3.1. Input Records

The tape is headed by blocks of source data, which are prepared by the program REDPREP, which also prepares the standard tape label for the data set. The format of these records is given below. The locations are given in 16 bit Varian 620 words, which are IBM 360 half words (INTEGER*2). The tapes are nine-track, SL tapes RECFM = V

WORD

1,2 Scan number (up to 30 bits * $0<N<10^9$)

3 Day of year of observation

4-6 Negative of the time (UTC), this day at which the source will cross the great circle determined by the NCP and the interferometer pole (46 bit number*. Divide by 2**44 to express time in fraction of a day). (T_o of section 3.2.2)

7-9	$B_1 \sin\delta$	Interferometer parameters, (46 bit numbers,
10-12	$B_2 \cos\delta$	divide by 2**15 to convert to wavelengths)
13	Start time	(UTC), Divide by 2**14 for
14	Stop time	fraction of a day

15 Code - 0 Tape recorders were not stopped after observation (Code = blank)

1 Tape recorders were stoped after observation (Code = 'S')

2 Last observation this tape, (Code = 'T')

16-18 Reciprocal of the frequency

(Divide by 2**45 to get microseconds)

19,20 Delay center (clock correction) divide by 256 to get microseconds.

21,22 LO OFFSET (divide by 2**28 to get MHz)

23 0 = unswitched LO

1 = Even seconds

2 = Odd seconds

24 Interval between records, in units of 0^{s}2. Either 0 or 1 indicates unaveraged records.

25-28 Source Name (in EBCDIC, 8 characters)

29-32 α(1950) 360 floating double precision

33-36 δ(1950) " " " "

37-40 α(precessed) 360 floating double precision

41-44 δ(precessed) " " " "

45-48	B_x	Baseline parameters. $\underline{x}$ axis points to
49-52	B_y	$\lambda=0, \phi = 0$), $\underline{y}$ axis to ($\lambda = 90^o, \phi = 0$) $\underline{z}$ axis
53-56	B_z	to ($\phi = 90^o$ (NCP)) wavelengths, 360 floating double precision.

$B_1 = B_z$, $B_2 = \sqrt{B_x^2+B_y^2}$

57-60 Sidereal time at 0^hUTC. Sidereal time during observation is extrapolated from this time at the mean rate.

61-62 Latitude station A

63-64 Longitude station A

65-66 Latitude station B

67-68 Longitude station B

360 floating single precision

69-74 Comment (14 EBCDIC characters)

75-80 Prep Date (EBCD16)

Numbers are given in Varian 620 notation. A single precision word consists of a sign and 15 magnitude bits. In higher precisions, the sign bit of the second and third word is set to zero, so they add only 15 bits to the length. In the 360, the resultant value is calculated for double precision as = 32768 word 1+ word 2 and for triple precision = 1073741824*word + 32768*word 2 + word 3.

3.2.3.2 Output Data Format.

One record in the following format is written each 0.2 seconds:

WORD

1,2 Scan numbers (as above)

3,4 Date and Time (30 bits divide by 2**21 to get day of year and time fraction of a day)

5,6 Fringe Frequency Set (divide by 2**28 for MHz) } at start of integration

7,8 Net delay set (divide by 256 for microseconds) } at start of integration

9 (Spare)

10 Number of times assumed frame count was wrong this scan, +256 times number of times units seconds was wrong.

11-12 Number of frames with length checks this 0.2 second, A and B units

13 BCD characters from video tape $X_A Y_A X_B Y_B$

14-16 (Spare)

17 A_0 Total integration time (cosine) (multiply by 8 for microseconds)

18 A_1 Channel 1 cosine

19 A_2 Channel 2 "

20 A_3 Channel 3 "

To convert to correlation coefficient

$C_n = (2*A_n/A_0 - 1) + i\ (2*B_n/B_0 - 1)$

B_0 is word 49

'

'

'

'

47 A_{30} Channel 30 cosine

48 A_{31} Channel 31 "

49 B_0 Total integration time sine

50 B_1 Channel 1 sine

'

'

'

'

79 B_{30} Channel 30 sine

80 B_{31} Channel 31 sine

3.3 The start up sequence

Thus far, we have discussed the operation of the playback controller as it occurs in normal data transfer operation. This operation presumes that the two recovered data streams have been aligned in time. This section covers the alignment procedure. Time alignment occurs in two major phases: first, the controller hardware aligns the two data streams exactly, then, the computer slews the delay to the desired value.

3.3.1 Playback Controller Servo Phases.

P0 - Stopped. Both Servo putputs are 60Hz so that adjustments on the recorder may be made without switching from external sync. "STOP" light is on. Exit from P0 when the START REPRO SEQ pushbutton is pushed.

P1 - Start. Relay closes, initiating play of recorders if they are in remote status. Both Servo outputs remain at 60 Hz for ~10^s while recorder heads are coming up to speed. Exit from P1 after time delay.

P2A - "Course sync" light. A output remains at 60 Hz. B output is controlled by the difference between the audio track outputs for the two recorders, the seconds and tens of seconds digits being observed only. The slew rate is between 5 and 10 percent. It may be limited by either of two Servo VCO's, the one on J10 in the recorder controller which provides the sync signal to recorder B; or the one inside the recorder which supplies the drive to the motor. If the slewing is assymetric (much faster in one direction than the other) adjust R51 on J10 (this resistor is accessible from the top without removing the board) so that the Servo output frequency swings equally in both directions.

That is, set the two tapes about 30 seconds apart; during the half minute when the seconds and tens from B lead A, the output should be about 55 Hz; during the half minute when the seconds and tens from B lag A the output should be about 65 Hz.

If this does not restore symmetry, see the procedure for the headdrum servo adjustment in section 2.4.

The Servo system leaves P2A when the time codes have been equal for 36 consecutive frames.

P2B - The Servo input is the difference between the audio track frame counts from the two recorders. The offset voltage for this input may be in error by a sufficient amount to cause the Servo to seek a difference of 1 rather that zero. This same offset voltage is used in P3A, q.v. The Servo system leaves P2B when the time codes have been equal for 64 consecutive frames.

P3A - "FINE SYNC" light is lighted. The Servo input is the difference between the helical frame counts from the two recorders. The offset voltage may be adjusted by connecting an oscilliscope to test points 7 and 27 (PBFC = 0 A and B resp.), and adjusting the pot on A58 J4 so that the Servo pulls the two into coincidence, and the Servo passes readily to P3B.

During P3A the Servo sometimes "runs away", that is, the frame count is read erroneously, and a large input signal is given to the Servo, which causes the head wheel to speed up or slow down so much that a good frame count cannot be read. The system sometimes recovers itself after one or more seconds of difference are inserted, and proceeds to lock up on the wrong second. If a runaway occurs, press the "RESET" button to return to P2.

The system leaves P3A when the helical frame count from recorder B is equal to 59 in the center of A frame 59.

P3B - The Servo input is the phase difference between the two reference outputs. The frame counts continue to be monitored during P3B, and if they become unequal, the Servo is returned to P3A.

The Servo leaves P3B when the two reference transitions fall within 150 μs of each other for eight consecutive frames.

P4A - "DATA TRANSFER" light comes on. The reproduce controller Servo is disconnected. The two 60 Hz reference wave forms are generated by data buffer control logic, and are controlled, open loop, by the computer.

The system leaves P4A when the two recorders have been within 250 microseconds of each other for 16 frames successively.

Failure to leave P4A, or very rapid passage through P4B to P5, is probably due to misadjustment of either recorder Servo phase. With the controller on "STOP", connect an oscilliscope to sync from playback frame, and look at the recorder reference input waveform. Adjust R7 on the recorder Servo board so that the rise of playback frame precedes the rise of the reference signal by 250 microseconds. The rise of the reference signal coincides with the beginning of frame output from the buffer.

P4B - "DATA TRANSFER" is signaled to the computer.

P5 - "BUFFER FAULT" light on. Time error of one recorder has exceeded the buffer capacity; which buffer and what state (i.e., OVERFLOW or STARVE) is indicated by the buffer status lights. Reference output is unchanged from P4.

During normal operation, the computer presses the "RESET" button immediately upon detecting this condition.

In order to find out what condition is causing a persistent problem, stop the computer so that the buffer error condition lights can light.

In attempts to recover data with large bad spots in it, it may be desirable to stop the controller from entering P5, which may be done by setting the "P4 HOLD" test switch in the playback controller. The data so processed should be regarded as somewhat suspect, and during processing you should watch carefully that the time delay does not become one frame in error.

3.3.2 Computer Phases

C0 - Computer idle. Corresponds to P0. "COMPUTER" light is lighted.

C1 - During servo phases P1-P4A the computer is in C1. In this phase if SS2 is reset, the computer switches the time code display to B if A shows an even second and to A if B shows an odd second. Otherwise, it just waits. The "COMPUTER" light is lighted.

C2 - When the servo first reaches P4B the computer enters C2. The relative delay of A and B is slewed to the value calculated from the geometric delay and the given clock error. The slewing is done very gently so that the recorder servo is not upset. The maximum rate is slightly more than 1 ms/sec. The delay is calculated and is slewed to that value, then recalculated (to allow for the elapsed time from the first calculation) and slewed a second time. During C2 the time code select remains on "A" and the "COMPUTER" light is lighted.

C3 - Delay is tracked, fringe frequency is set, data is input from the correlator, and the CRT display is active. The time code display is switched between A and B at 10 Hz. The computer leaves C3 when a) the start time specified to REDPREP is passed, b) after 1 second, whichever is later.

C4 - In addition to the functions of C3, data is recorded on the output tape.

If the computer detects either of two error conditions: 1) Controller phase other than P4B, or 2) erroneous delay (the computer can detect all cases of 2 frames error, and about half of all single frame errors), it presses the "RESET" pushbutton to return the controller to P2, and returns itself to phase C1. Erroneous delays are usually caused by the capstan servo slipping one cycle at 30 Hz, causing the delay to be in error by exactly two frames. A mechanical slippage of the tape past the capstan can also occur, and in this case any integer number of frames error may accrue.

3.4 Adjustments

There are a number of fairly critical adjustments on the playback equipment. If the playback terminal starts showing strange symptoms of any sort, the odds are high that it is due to incorrect mechanical alignment or incorrect electronic alignment in the video data path.

The various circuit boards may be located by reference to Figure 17.

3.4.1 Mechanical Alignment

The tape alignment is best checked by looking at the output of the head preamp board EB1, test point E10. The video should be on the order of 100 mV peak-peak at this point. Scope sync can be picked up from the 30 Hz headswitch at E11 or E12 on this board. A sweep rate of 5 ms/div will display both head outputs. Good tape alignment produces a display at E10 like Figure 18 a.

As the tracking control is turned through its full range, this pattern will peak in one or two places and will go through a null in one spot. At the null position the heads will pick up "splatter" from the tracks on each side, giving a display like Figure 18 b.

Because of slightly different tape guide settings and tensions, a tape played back on a machine other than the one on which it was recorded will not track perfectly. The tape head path and recorded tracks may look as sketched in Figure 18 g.

These show up at E10 as patterns like Figure 18 c, d, or e.

The amplitude response varies somewhat from tape to tape, but if the response from one head is near zero, there must be a clogged head at either record or playback time. To tell the difference, turn the tracking control to play the same recorded track with the other head.

a. Set tension knob to about two or three o'clock position on its scale.

b. Using upper guide only, move the tape up or down to find the maximum output on "Audio 1" meter. The angle of this guide should be such that the tape is kept taut as it leaves the head drum cylinder.

c. With the scope connected to head preamp output, sync from head-switch. Change the tracking, lower guide vertical position and angle setting until the "most rectangular" envelope is found. Large changes in lower guide vertical position (1/2 turn or greater) may require readjustment of the upper guide angle setting.

d. A pattern like Figure 18 f. results from a difference in tension between the top and bottom edges of the tape. It responds to lower guide angle or sometimes upper guide angle. Small improvements in shape of the pattern may be made by adjusting tape tension. Tension should not have to go too high, i.e., knob position should remain clockwise from an eleven o'clock position.

e. Using delayed/expanded scope trace, examine the headswitch/record gap alignment. Record gap is 160 μs of encoded "1" and the headswitch should fall in the middle, moving back and forth less than 50 μs. This should look like 19 a, but may look like Figure 19 b. or c.

In either case, headswitch causes a marked disturbance of the signal. The data gap shows up as a brightening of the display. In Figure 19 b, the tape is wrapping around the head drum too high and should be lowered. In Figure 19 c., the reverse is true. Turn both vertical adjustments by the same amount, clockwise to lower and CCW to raise the tape. Tracking will subsequently have to be readjusted. This should be done in steps of 1/2 turn or so.

3.4.2 Servo Adjustments

Servo adjustments are discussed in the servo phases descriptions in Section 3.3.1.

3.4.3 Data Path Adjustments

a. Connect oscilloscope to recorder video output. Sync internally at 100 ns/division. A typical pattern is shown in Figure 12.

The fuzziness and occasional double nature of the vertical lines of the pattern is due to the influence of the previous bit upon the current transition, as well as to noise. Alternately adjust R24 (this circuit will oscillate if turned too high, i.e., too counter clockwise) on the head preamplifier board and the chroma control on the video control board until the total zero crossing width is a minumum.

b. Adjust differential chroma, R55 on the head preamplifier board, for a minimum of 30 Hz flicker in the zero crossings.

c. Connect recorder to playback unit and look at the playback frame, test points 12 (for "A" machine) and 32 ("B" machine) on the front panel of the reproduce terminal, and make small adjustments to chroma, R24, and the clipping level (R50 on the decoding board in the reproduce terminal) until the frame signal is reliable (down for 167 μs every 16 ms, missing a 16 ms frame at most 1/second).

d. Play test pattern. Sync oscilloscope from playback frame. Test point 12 ("A" machine) or 32 ("B"), positive going edge and look at recovered data (test points 9 ("A") or 29 ("B") at 1 or 0.5 μs/division. Make small adjustments in R24 and chroma on the tape unit, and on R50 on decoding board in reproduce terminal, until recovered pattern is stable and reliable. (Recovered clock errors may cause a momentary 1-bit shift of the displayed pattern - the pattern should not jump back and forth, as well as being free from unreliable bits.) It is advisable to occasionally look back at playback frame during this adjustment.

If the channel has not been set up for this recorder you may also need to adjust R77 (NRZ data detection clipping level) and R83 (sync word detection clipping level) to compensate for small frequency response differences from recorder to recorder.

e. Check the stability of the pattern farther down the frame, using the delaying sweep. The mechanical smoothness of the recorder head motion limits you to about 0.5 ms of pattern that you may readily examine this way.

3.5 Normal Operation

This section covers the procedures you will need to operate the machine in the absence of abnormal conditions.

3.5.1 Computer operating procedures

A more complete description of the Varian 620 console procedures will be found in the computer manual. To do anything other than the simple procedures described here, or to find out why these procedures work, you are referred to that manual and to the program listings.

3.5.1.1 The computer controls

STEP stops the computer if it is in the run mode, causes it to execute one instruction if it is in STEP mode, or causes it to repeatedly execute the instruction in the U register if it is in STEP mode and REPEAT is set.

RUN causes the computer to enter the RUN mode. The first instruction executed is the one in the U register. Therefore, the U register should be cleared if a transfer is made.

SYSTEM RESET initializes the tape unit, turns out the overflow indicator and inhibits interrupts.

SS1 reset tells the computer to ignore the teletype.

SS2 set places the time code display under manual control during phase C1.

The "OVERFLOW" indicator has no useful significance at any time.

Pressing "LOAD FORWARD" on the computer tape drive causes tension to come onto the servo arms. Pressing it again causes the tape to seek forward to the foil beginning-of-tape indicator. You may then press "ON LINE" to make the drive available to the computer. "WRITE ENABLE" should be lighted. If it is not, either there is no write ring in the tape, or the tape was not mounted firmly.

3.5.1.2 Loading the Key-in Loader

The key-in loader is normally left in the machine, but it is possible for erroneous procedures to damage it. It is reloaded by the following procedure. If the program loading does not function normally, try this procedure.

Set the starting address (Octal 07765) in the P register.

Set a store command (Octal 54000) in the U register, and set the instruction REPEAT switch.

Enter the first instruction of the key-in loader (07766) into the A register (the key-in loader listing is posted on the front of the computer).

Press STEP and RESET, to enter this instruction and clear the A register for the next one.

Continue with following instructions, pressing STEP and RESET for each after entering them into the A register.

When all instructions have been entered, the P register should read 10000 octal.

Clear the U register before doing anything else.

You may examine the key-in loader, to see if it is correct, by setting 07765 in the P register, a load command (octal 14000) in the U register, setting the REPEAT switch, displaying the A register, and pressing STEP to display each command in turn.

3.5.1.3 Loading Program Tapes

It is a good idea to reload the program tape before starting processing to make sure the variant you want is in the machine.

Ready the program tape on the tape transport

Clear the U register

Press SYSTEM RESET

Transfer to 07766 (that is, insert octal 07766 into the P register, press RUN)

The program will then be loaded into core. If the loader detects a tape error, it will type an "E" on the teletype (if the teletype is turned on) and halt, with 077XX in the P register. If the program is loaded correctly, it transfers to an address in the program, approximately 4000 octal, depending on the version, before halting.

3.5.1.4 Loading REDPREP Tapes

Mount Prep-tape on transport, clear U register, transfer to location octal 42.

3.5.1.5 Program Restart

If the program has been stopped, stops spontaneously, or loops, it may be restarted by clearing the U register, and transferring to location octal 40.

3.5.1.6 Source Pointer Control

There are up to 20 blocks of source information on the prep tape from REDPREP. These are taken in sequence, the pointer advancing to the next whenever the stop time is exceeded while the computer is in mode C4. Additional control of this pointer is provided as given below.

The pointer is set to the first prep-tape source by 1) successful reading of the prep-tape data from entry point 42, or 2) transfer to 46_8.

Entry point 40_8 does not affect the source list pointer

Entry point 44 advances the pointer by one.

Entry point 54 backspaces the pointer by one.

Entry point 56 causes the scan number to be written on the teletype, if the teletype is turned on

3.5.1.7 End-of-File

For processing by the IBM 360, an end-of-file and appropriate trailer label must be written on the output tape.

An End-of-File is written if

1. Controller is in delay tracking mode at stop time of source for which "CODE='T'" was specified at REDPREP time.
2. An 'X' is typed while controller is in delay tracking mode.
3. Transfer to 50.

To position output tape to end of existing data, transfer to 52.

3.5.1.8 Delay Control

The delay may be controlled through the IBM 360 with the CLOCK input to REDPREP. It may also be changed through the on-line computer, by teletype input. If sense switch one is set, the teletype accepts a limited range of characters. 1,2,3,A,B, and C control the delay. Return, line feed, and space control the teletype. X causes an end-of-file to be written. All other characters are ignored (not printed). Any printed character has been acted upon.

Typing 1, 2, 3, causes to delay to change by +1, +10, +100 microsec respectively. This is the same sense as the REDPREP 'CLOCK' input. It is as if this corrected number had been specified on the REDPREP tape for this scan only. It remains associated with this scan until the REDPREP tape is reread. A'1' causes fringes to move to higher numbered delay channels. It is required if the Station B clock was slow relative to the Station A clock.

Typing A, B, C causes the delay to change by -1, -10, -100 microsec respectively.

Note that typing numbers on the teletype to change delay affects only the source list entry currently pointed to by the pointer. When the pointer is advanced, the next item still contains the original REDPREP value of clock error.

However, if the pointer is returned to the current item, the changed clock error value still remains in force. Rereading the REDPREP tape, of course, restores all of the original values.

3.5.2 Initial Set-up

First, you must check out 800 BPI digital tapes to be used as parameter input-data output tapes. Then, you must run the program REDPREP (described in Section 4.2.). This can be done well before your time on the processor comes up.

When you're on the processor, your first act must be to go through the mechanical adjustments described in Section 3.4.1. These adjustments are made with the playback controller in STOP mode.

Then you <u>must</u> play back the pattern at the beginning of the tape. This also done with the controller in STOP mode. The scope must be triggered by the rising edge of playback frame (Test point 12 or 32) and look at playback data, making the adjustments of 3.4.3. until the pattern is stable and reliable.

This adjustment must be re-done, or at least checked, if you change tape type in the middle of the experiment. Otherwise, the only adjustment needed is the tracking control, which will need small corrections at the beginning of every tape, and occasionally during it.

3.5.3 Controls and Indicators

3.5.3.1 Recorders

Head over-ride should be left off to avoid cutting the tape and wearing the heads. Sync must be on external so that the recorder headwheel follows the sync signals generated by the recorder controller. The control switch may be switched to "REMOTE" so that both recorders may be started or stopped simultaneously with the "START REPRO SEQ" and "STOP" switches on the recorder controler. On the other hand this is not a necessity, and it is sometimes convenient to use the local controls of one recorder to assist the course sync servo.

3.5.3.2 Recorder Controller (Digital Reproduce Electronics)

STOP - Stops recorders under remote control, sets P0.

START REPRO SEQ - Sets P1, starts recorders under remote control.

RESET FAULT - Lights if a buffer fault occurs (during normal operation the computer turns it off again before the light bulb has a chance to warm up. Pressing the reset button at any time resets the servo phase to P2A, and this, in turn sets the computer phase to C1.

MISSED CLOCK - is lighted by an interval of 750 ns without a clock transition on the recorded data stream. The assured clock can easily coast over this interval without loss of clock information, so it does not necessarily indicate a major fault. However, it does indicate an interval in which no signal sufficient to overcome the hysteresis of the first clipper is being recovered during at least part of the frame.

SYNC ERROR - This light comes on for 0.1 second if two End-of-Frame-Syncs or two Beginning-of-Frame-Syncs occur in a row. Even this light does not necessarily indicate a major fault; a common error is the occurrence of a spurious end-of-frame sync at headswitch time. A flash of this light a few times each minute is entirely normal.

BUFFER OVERFLOW
BUFFER STARVE - Buffer starve occurs if a bit arrives at the buffer after the unload clock pulse meant to unload this bit. Buffer overflow occurs if more than 2048 bits arrive before the unload clock pulse to unload the first. The mean relationship between the load and unload clocks is adjusted by R7 on the recorder head

drum servo board, as described under section 3.4.2.3 above. Unless the P4 hold switch is set, the controller will go directly to P5 if these lights are activated.

3.5.3.3 Correlator Controller

The day and time from the audio track of one tape unit is displayed in the nixie tubes at the top of the unit. Which time code is played is indicated by the light "UNIT A" or "UNIT B". If the computer is stopped or in Phase C0 the unit may be selected by pressing the associated pushbutton, which changes from one to the other (about half the time, due to contact bounce, it changes right back).

The lights 1's and 0's indicate that 1's and 0's respectively are being received from the indicated unit. If one is off while the unit is running it is either burned out or something is drastically wrong.

The "DROPOUTS" lights indicate that the 8 bit resynchronizing pattern has been used to resynchronize the data. The light remains on until the end of the frame, and then is turned off by the computer. These lights are normally on when the computer is not in Phase C4.

The "COUNTER FUNCTION" switch selects whether the monsanto counter shall display delay (in microseconds, every second) or predicted fringe rate (in Hz, every two seconds). In order that the counter fulfill this function, its plug must be connected to the gate signal from P6, its input connected to P7, and its controls set to external gate. (Beware a tendency to double count at slow fringe rates.) The sign of the delay is indicated by the two lights adjacent to this switch (the sign of fringe rate cannot be displayed). A minus sign indicates that the source is nearer Station A than Station B.

The "INVALID DELAY" light has about the same significance as the "OVERRANGE" light on the monsanto counter when it is counting delay. It is normal for it to light once a minute or so as a frame count is mis-read.

The display time constant switch selects the averaging applied before the data is displayed in the memoscope. The AUTOCORRELATION/CROSS CORRELATION switch may be used to select autocorrelation to determine the receiver passband. The bandwidth switch may be used to select sampling rates other than 4 megahertz; an appropriate analogue filter must have been used at record time. If this switch is set to something other than 2 Mhz, or if AUTOCORRELATION is set, the "NARROWBAND" warning light is lighted.

The "COMPUTER" light is lighted in C0, C1, C2; the "DELAY TRACKING" light is lighted in C3, C4. If the computer is operating properly, one of these lights is on. They are never on simultaneously.

3.5.4 Abnormalities

The quality of your data is most accurately accessed by means of the red "DROPOUT" lights on the correlator controller chassis. If these lights remain dark you are getting good data. If they are a constant bright red, start over from square 1.

The correlation coefficient is occasionally reduced by as little as four errors per second. I would be suspicious of exact amplitudes where the error rate was greater than 2/second, and would worry that real fringes would be missed with error rates more than 5/sec.

The computer occasionally spontaneously stops or enters an infinite loop. This is indicated by both the "Computer" and "Delay Tracking" lights on the correlator controller being off. If the computer is in "RUN" mode, press STEP to stop it. Clear the U register and transfer to location 40.

The computer occasionally receives a bad time from the audio track. This can cause it to conclude that the time has passed the stop time, and it skips ahead to the next source. You will then see the computer patiently waiting for the start time of the next scan. You must stop the computer (by pressing STEP), reset the playback controller, and transfer to location 54 to backspace to the present scan.

Whenever the computer is restarted it assumes that there is zero delay between data streams. To insure that this is the case, press "Reset" on the playback controller before restarting the computer. Otherwise you may find that you have put in the delay twice.

4. IBM 360 Software

The programs described below, for the most part, comprise the continuum source processing system. The detailed description of the programs gives their full capability. For most purposes, you may leave many parameters at their default value. For a typical dataflow through the programming system, refer to Section 4.12 below.

Note also, that whenever the term "correlation coefficient" is used below, it means the one-bit correlation coefficient and thus is smaller than the IF correlation by the factor $2/\pi$ (or by the more general arcsine correction if the correlation is near unity.)

4.1 Assembler, Loader

Since the VLB computer has only mag tape and ASR-33 I-O devices, it is practical to assemble in the 360 and load from mag tape, but impractical to assemble long programs in the 620 (requiring two or three passes through the ASR 33). Therefore, an assembler for the 620 has been written to run on the 360. The programming language is PL1.

The assembler operates in the same manner as the DAS assembler, with the following exceptions (for the most part frills which would add as much programmer time to implement as they would save in use):

a. Punching is in EBCDIC

b. Label begins in card column 1. Instruction, variable, and remarks fields are separated from the previous field by one or more blanks. All six characters of labels are processed.

c. * and / (multiplication and division) are not permitted in the variable field. Parentheses may not be used in the variable field.

d. Alphabetic constants are not permitted.

e. Floating point constants are not implemented.

f. Indirect address constants are not permitted; you must add octal 0100000.

g. Literals are not permitted.

h. MERGE, COMPL, INCR, DECR, ZERO are not implemented.

i. SET, MAX, MIN, OPSY, LOC, BEGIN, USE, DUP, IFT, IFF, GOTO, CONT, and NULL assembler pseudo ops are not implemented.

j. PZE generates zeros only; MZE and BES are not implemented.

k. Blocks of storage may be zeroed with BSZ (constant up to 64).

l. Alphameric data (ASCII) is generated by BCI. Variable field contains number of words, followed by comma, then message at 2 characters/word.

m. Scaled decimal data is generated by DEC. Operands consist of FORTRAN-type integer or floating constants, followed by B (single precision) or BB (double precision) and the scaling (i.e., number of places the binary point is located to the right of bit 15). If B or BB does not occur, B+15 is assumed (i.e., integer arithmetic).

n. Extended address instructions may be caused to reference the instruction counter, by referring to it as index register 0.

o. If a single word memory reference instruction may refer to an operand both directly and relative to the instruction counter, it will use the instruction counter reference.

The program to be assembled is punched on a 029 keypunch. The assembler uses temporary storage which must be allocated by a DD card with name GO.TEMP. UNIT=SYSDA and a space allocation are all that are needed. DCB parameters are specified in the program. The output file has DDNAME of GO.ASMOUT, and should specify an unlabeled, 9-track, 800 bpi tape.

A job step to write the bootstrap loader on the output tape may precede the assembler; in which case, the disposition of the output tape should be DISP=MOD and only needs the DSNAME passed from the preceding step. The JCL to execute assembler and write bootstrap loader is shown in Figure 20.

The key-in loader is an 11 word program which must be entered in memory from the keys. It then bootstraps in a more sophisticated loader. The bootstrap loader then is capable of loading the output of the assembler.

The key-in loader is:

LOC		COMMAND	CODE
7765		DATA *+1	07766
7766	L1	EXC 010	100010
7767		SEN 0110,L2	101110
7770			07773
7771		JMP *-2	001000
7772			07767
7773	L2	CIA 010	102510
7774		STAE L1	06057

7775		07766
7776	JMP* L1-1	01000
7777		107765

Its entry is at location 7766. It will be restored after use.

The output of the assembler consists of 132 16-bit words of two characters each. The first word is the load address. The second gives the number of words to be loaded from this record. The third is a checksum (words summed algebraicly, plus carries beyond 16 bits), and the fourth is, for the moment 0. There then follows up to 128 words of assembled programs.

The bootstrap loader forms the words and stores them in the proper location in core, checking the checksum and parity as it goes. If it finds an error, it halts and types an "E" on the teletype.

If the assembler 'END' instruction specified an address other than zero, the loader will transfer to that location; otherwise, it will halt, and will load another tape upon passing start. The entry point for the loader is 07654.

4.2 REDPREP

The program REDPREP accepts a rather general input format and prepares a fixed output tape for the Varian 620 correlator-controller computer, which in turn uses it for its own output tape. The format of the output records is given in Section 3.2.3.1.

The program will, if requested, perform precession, convert baselines from geodetic to rectangular coordinates, and assign scan numbers.

The best way to describe the program is to list the input parameters. A single observation is described by a collection of parameters of the form

NAME =VALUE

Different observations are separated by semicolons. Different parameters are separated by blanks or commas; note that the end of a card is <u>not</u> necessarily a delimiter. Order of parameters is immaterial. Since blanks are used as delimiters, any quantities which contain blanks must be enclosed in single quotes. Quantities not specified are given a default value. Where two default values are listed below, the program takes the first listed if possible. The various parameters which can be specified are listed below.

SCAN - up to a 9 digit number--this scan number will be associated with the observation in all subsequent reduction. Defaults to last value read plus one, or to zero.

YEAR - year of observation, defaults to last value specified or the the present year. (Used only for precession; if you do your own precession this need not be specified.)

DAY - day of year of observation, defaults to last value specified. Must be specified for first observation.

STATIONA - geodetic station coordinates in order latitude (degrees, minutes, seconds), longitude (degrees, minutes, seconds), elevation above MSL (meters), station name (or other comment), which will be printed on output but otherwise ignored. Value must be enclosed in single quotes and must fit on a single card. Need not be specified, but baseline must be specified somehow.

STATIONB - Similar to STATIONA

BX, BY, BZ - Baseline in retangular coordinates, X-axis points to $\lambda = 0$, $\phi = 0$, y-axis to $\lambda = 0$, $\phi = 90^\circ$, z-axis to $\phi = 90^\circ$. Units are wavelengths (NB, the baselines are printed in the output with included commas for legibility. Included commas may <u>not</u> be used on input.) The sense is STATIONB-STATIONA. For default, see below.

BXM, BYM, BZM - Same as BX, BY, BZ, but units are in meters

F - Observing frequency in megahertz. Defaults to last value read.

LO-OFFSET - Difference in frequency of oscillators at observe time, in the sense $LO_B - LO_A$. Defaults to last read value or to zero.

CLOCK - Clock error difference at observe time, $Clock_A$-$Clock_B$- Instrumental Delay (see Section 3.1). Units are microseconds. Defaults to last value read or to zero.

START - Start time (hours, minutes, seconds) UT. Data before start time are not written on Varian output tape. Defaults to stop time of previous observation or to zero. Must be enclosed in single quotes.

STOP - Stop time (hours, minutes, seconds) UT. Must be enclosed in single quotes. When stop time is encountered, the Varian begins to set up for next source. Defaults to last value read (but must be specified for first observation).

TIME - Sidereal time at midnight UTC (hours, minutes, seconds). Must be enclosed in single quotes. Defaults to mean time with UT1-UTC=0. NB, beginning in 1972, the difference UTC-UT2 will be permitted to accumulate up to 1/2 second.

NAME - Source name, 8 characters max, must be enclosed in single quotes. Defaults to last value read. Excess characters cause truncation on the right.

RA, DEC - Source position (hours, minutes, seconds; degrees, minutes, seconds). Must be enclosed in single quotes. Defaults to last value read. Must be specified for first observation.

EPOCH - Source position given is assumed to be mean position of this year (written without decimal point). If EPOCH='DATE' is coded no precession is done. Defaults to last value read or to EPOCH='1950'. Should be enclosed in single quotes.

A,B,C,D - Besselian day numbers. Units of seconds of arc. Defaults to last value read or to values for general precession, the 18 year term of nutation, and aberration expected from a circular orbit. This results in errors of about 5 seconds of arc max.

E,J,JPRIME - Second order Besselian day numbers--E and J in seconds of time, JPRIME in seconds of arc. Default to last value read or to zero.

LOSW - For switched LO observations, this selects whether this set of parameters applies to odd or even seconds. Options are 'OFF', 'ODD', and 'EVEN'. Defaults to 'OFF'.

CODE - Tells what you want done when stop time is reached. Options are

' ' (blank).	Slew delay to value for next source
'S'	Press "Fault/Reset" button and set up for next source
'T'	Write file mark and rewind output tape

Defaults to blank.

COMMENT - up to 14 characters of comment which will be associated with the observation on the output tape. Must be enclosed in single quotes. Defaults to last value read or to blanks.

The default rules for baseline parameters are given below. The computer searches down the list until one is encountered which works.

1. BX, BY, BZ specified for this observation
2. BXM, BYM, BZM specified for this observation
3. Baseline computed from STATIONA, STATIONB vectors if <u>either</u> was specified for this observation
4. BX, BY, BZ specified for some previous observation
5. BXM, BYM, BZM <u>or</u> STATIONA, STATIONB specification, whichever occurred most recently--if they occurred in the same observation the BXM, BYM, BZM specification is accepted.

Up to 20 observations may be placed on a single REDPREP tape, the description of each observation being delimited by semicolons. A single run of REDPREP can prepare up to 16 tapes, the successive tapes being specified in DD cards with names SYSOUT0, SYSOUT1, SYSOUT2...SYSOUTF. A typical REDPREP deck is shown in Figure 23.a.

Note that all tapes must have been previously labeled at 800 bpi.

4.3 INDEX

INDEX is the basic display program. I would expect that this program would be applied, in one form or the other, to all continuum data. It is designed to give you a good feel for what data you have, but it is not intended to be a program from which accurate numerical data is read.

It prints the following information:

1) A listing of the preptape information at the beginning of the tape, with source name, 1950 and precessed positions, the baseline parameters, and the clock parameter from REDPREP time.

2) A listing of the channels from which data has been discarded due to exceeding the 3% correlation level. Correlation coefficients greater than this are usually due to instrumental faults. This level can be changed by including PARM='DISCARD=nn' on the execute card, where nn is the maximum percentage correlation accepted.

INDEX then takes records in groups of 64, and takes a spectrum in the time direction (fringe frequency spectrum) for each lag, and prints those spectra which contain points deviating from zero amplitude by more than three sigma. Note that, if the program is analysing random noise, a spectrum will be printed about every twelth record group. For each group of 64 records analysed, it prints two lines, the first giving the block for channels A and B. The second gives the day, time (of the last record of the group), and estimated clock parameter (including numbers typed on the teletype, also refers to the parameter in force at the time of the last record of the group). For each fringe frequency spectrum printed, INDEX prints a header line giving delay channel, scan number and sigma (for this record group and delay channel).

The 64 point spectrum follows. The frequency window (f_0) covered is the reciprocal of the sample time - for unaveraged data this is 5 Hz. The zero frequency is listed first; each subsequent number is the amplitude at a frequency higher by $f_o/64$, (5/64 Hz for unaveraged data). Since frequencies are aliased on an f_o grating, frequencies near $f_o/2$ cannot be distinguished from frequencies near $-f_o/2$. These frequencies are found near the middle of the printout. The last number printed is the amplitude at $-f_o/64$ fringe rate (-5/64 Hz for unaveraged data). Large values of correlation coefficient (larger than 3 sigma) are flagged by an asterisk.

INDEX requires no input other than the DD card describing the input tape.

INDEX examines the times on the record, and if they do not fall in uniform sequence, recognizes a gap, discards whatever information it has accumulated to this point and immediately begins to accumulate data for a new spectrum.

In its normal (or default) mode, INDEX produces a spectrum at the beginning of each scan, after each gap in the record, and if more than 400 seconds have elapsed since the last spectrum.

At execute time, parameters may be specified to cause all of the data to be processed (PARM=SEARCH), causing INDEX to imitate the program SEARCH. It may also be requested to print all spectra, rather than just the ones containing large amplitudes, by specifying PARM='PRINT=ALL'. 'PRINT=ALL' implies 'SEARCH'.

An output is also provided on FT07F001 giving the largest amplitude for a particular group of spectra. This can be printed for your convenience, or it can be punched, directly ready for input to the program VLBAMP. This output is surpressed for PARM=SEARCH.

A starting scan number may be specified by including 'PARM=START=nnnnnnnnn' on the execute card, where nnnnnnnnn is the scan number.

The JCL needed to execute INDEX is shown in Figure 23 b. with PARM=SEARCH specified. It is automatically executed as the second jobstep of the catalogued proceedure VLBAVG, shown expanded in Figure 24 a.

4.4 SEARCH

SEARCH is the minimum display program. Its behavior is nearly independent of tape format errors, and is therefore useful for those cases when the data has been damaged by erroneous programs or a convoluted sequence of button pushing at playback time. For normal data, a more pleasing printout is produced by the program INDEX, with PARM=SEARCH.

The JCL necessary to execute SEARCH is shown in Figure 21 a. The single parameter card is read with a FORTRAN I10 format; the last digit must be in column 10. This card gives number of records skipped before processing is started. This number must be at least as large as the number of records prepared by REDPREP or the REDPREP parameters will be assumed to be correlator data.

From this point hence, data records are assumed to occur at equal time intervals. Sixty-four records are read, and the 31 complex correlation coefficients are extracted from each record. Correlation coefficients larger than 0.03 are set equal to zero since they are probably due to hardware faults. The fringe frequency spectrum is computed and examined as in INDEX. If the greatest amplitude exceeds the three-sigma level (calculated for this record group and delay channel), the fringe amplitude spectrum is printed on the printer.

For each record group, the program prints the day and time taken from the last record of the group. Each spectrum is identified by the delay channel number. The spectrum is listed in the same order as that printed by INDEX.

4.5 OFFSET

There has been occasional trouble with DC offsets in the correlator channels (traced in hardware to pick-up causing an open pin to occasionally register zero rather than 1). Although the fault has been corrected, the program OFFSET was written to evalutate the effect, and is still kept in the library. It simply adds (vectorially) the amplitudes for all the specified scans.

The JCL to run the program is shown in Figure 21 b. The DCB parameters are specified explicitly in the FT08F001 DD statement because some on-line computer stops cause the block count to be erroneous, which, if standard label processing is specified, causes an ABEND at the end of tape, which prevents the final output.

The results are both printed on the printer, and if significant, punched on cards, through FT07F001.

The records to be processed may be specified by data cards in the file FT05F001. A scan number is specified in columns 2-10 (I9 format). A blank in column 1 indicates start - all scans previous to this one are skipped. An "X" indicates exclude this scan. A "T" indicates print results and terminate when this scan is encountered.

As in INDEX, correlation coefficients greater than 3.5% are discarded, but the limit may be modified by specifying PARM='DISCARD=nn', where nn is the limiting percentage permitted.

Control of the cards punched is through the parameter PARM='LIMIT=nnn', where nnn is the limiting correlation coefficient, below which cards will not be punched. nnn is in units of 10^{-5}.

4.6 LITTER

This program produces a direct, unedited dump of the Varian tape. The JCL to run it is shown in Figure 21.c. The data card(s) (following FT05F001 DD *) have the following format. There are 11 numbers read in an I5 format, each number ending in a column divisible by 5. The function of each parameter is listed below along with the column in which it <u>ends</u>.

5 Number of records to be skipped before start

10 Number of records to be read between printouts. If left blank, all records will be printed.

15 First cosine channel to be printed.

20 Number of cosine channels to be printed.

25 First sine channel to be printed.

30 Number of sine channels to be printed.

35 First amplitude (square root sine squared plus cosine squared) to be printed.

40 Number of amplitudes to be printed.

45 First phase to be printed.

50 Number of phases to be printed.

55 Number of last record to be processed before reading next data card (if left blank, all records will be processed).

The program will print the record number, scan number, date, time and cosine and sine normalization factors in one line. Then it will print the requested cosine channels in 0, 1 or 2 lines, the requested sine channels in 0, 1 or 2 lines, etc.

This program enables you to dump the raw correlation functions in either sine-cosine or amplitude-phase format, printing, if you so specify, every nth record.

4.7 VLBAVG

This program is the key to the processing system. It accepts input in the format of the Varian output tape, performs averaging and, if requested, various correction functions, and produces an output in the same format, so that the output tape can be analyzed by the same programs used to process raw data. This capability gives you a very large flexibility in the way in which you process your data.

The primary function of VLBAVG is to average adjacent data records. The number of records to be averaged may be specified as an execution parameter, PARM='INTVL=n', where n is the number of records to be averaged, or on the "L" card, q.v.

VLBAVG checks for consistency of the two total count normalization parameters. If either is wrong, the record is discarded.

VLBAVG will also separate switched LO or switched IF records into odd numbered seconds and even numbered seconds. If you specify PARM=SEPARATE odd numbered seconds will be written on FT09F001 and even numbered on FT10F001, averaged over the second. If you are interested in only the odd, or only the even, you may specify PARM='SEPARATE=1' for odd seconds only, or PARM='SEPARATE=2' for even seconds only. The output will still be on FT09F001 or FT10F001 respectively, and a DD Dummy Card must be included for the unwanted one, but computing time will be reduced considerably.

The input data cards have the following format: Column 1 contains a code letter, columns 2-10 contain the scan number to which the data card applies and three numerical values are found in the 20 column fields ending in columns 30, 50 and 70. If no scan number is found in columns 2-10, the card is assumed to apply to all the data. The various card types are listed below.

The "B" card specifies the baseline. It has a "B" in column 1, scan number in columns 2-10, and the three baseline parameters, B_x, B_y, B_z, which should have been used in REDPREP in the other three fields. They are read with a FORTRAN F20.0 format. The phase and hence rate of the fringes is corrected for the erroneous baselines. The delay is not corrected. For doing delay-fringe rate positions, you should have either specified good baseline parameters to REDPREP, or work with the raw rates and delays, making the corrections by hand.

The "S" card specifies the source position. (It must have a scan number specified.) The source RA and DEC (of date) are specified in the first two numeric fields, ending in columns 30 and 50 respectively. They are read with FORTRAN formats R20.4 and S20.3. Once more, the delay is not corrected.

The "L" card specifies LO offset, sidereal time at midnight, and an alternate input of INTVL. The formats are F20.10 (Hz), R20.4, I20 respectively.

The "C" card corrects for a D.C. offset in the correlators. The correlator number, the cosine offset, and the sine offset are specified in the three fields, with formats I20, F20.5, respectively. The program OFFSET will punch these cards for you.

The "A" card specifies correction for atmospheric phase path. The total atmospheric path in meters, relative to a vacuum path to the source, for STATIONA and STATIONB is specified in the first two fields, and read with an F20.5 format. In order for this correction to operate, STATIONA and STATIONB must have been specified at REDPREP time. If they were not, unpredictable and erroneous results will occur. The correction assumes an infinite plane stratified atmosphere at each station separately (phase correction proportional to sec z). Again, no delay correction is made. The constants given will be about 2 meters.

A catalogued procedure has been written to execute VLBAVG. An execute card is shown in Figure 23 c, and an expansion of the procedure in Figure 24 a. The procedure executes INDEX on the averaged data. The procedure input parameters are INDSN, the input data set name, INTAPE, the input tape number, OUTTAPE, the output tape number (if OUTTAPE is not specified the output data is written on disk), OUTDSN, the name you wish to give to the output data-set (if not specified, it is assigned a temporary name of &&TEMPNAME), and FILE, the number of the file on a multiple file output tape you want the data to go into.

The procedure assumes you want a one second averaging time; to over-ride this, code PARM.AVG='INTVL=nn' or specify it on a type "L" input card. To get the INDEX card output on the printer instead, code CARDS=A. To transmit the SEARCH parameter to the INDEX jobstep code PARM.INDEX=SEARCH.

4.8 VLBAMP

This program takes an estimate of the fringe delay and rate, and calculates the best fit amplitude, rate and delay, printing answers at specified intervals through the scan.

For fitting purposes the delay pattern is assumed to be that of a 0-2 MHz square bandpass. Errors in this assumption increase the fitting noise but do not, to first order, change the expected fitted values. Three points on the delay pattern are used for the fitting, resulting in an efficiency (i.e., decrease in signal-to-noise ratio relative to that of an infinite integral formulation) of about 90%. Note, however, that substantial errors will be introduced if you have, for instance, processed 1 MHz data with the 1/4 microsecond delay steps appropriate for 2 MHz data.

In order to do the delay pattern fitting, the computer must know whether the IF frequency was positive or negative (i.e., if the RF band center is higher or lower, respectively, than the signed sum of the local oscillators), as this gives the sense of phase rotation with delay. This may be specified in the execution parameters by including 'USB' or 'LSB', respectively. If you include neither, the program will solve for the sideband for you.

A catalogued procedure has been written to execute this program. An execute card is shown in Figure 23 d, and the expansion of the procedure in Figure 24 b. The parameters INTAPE and INDSN are as in VLBAVG, but FILE now refers to the file number on a multiple file input tape. In addition to the 'USB' or 'LSB' parameters mentioned above, a parameter 'TIME=nn' may be included. The program then averages for nn seconds. If this parameter is not included, an average for 75 records (15 seconds for raw data) is taken.

The input card contains in order the scan number, date and time that the card is to first apply (the first card of a scan applies immediately), delay channel, fringe rate (Hz), correlation coefficient, and rms noise (if the correlation coefficient is less than 3.5 σ, the card is ignored; this is so that output from INDEX may occasionally be fed directly to VLBAMP). The card format is I10, I4, R9.0, I7, F10.7, F10.5, F10.5. Note that, except for date and time, all fields end on a column whose number is a multiple of 10. A card of identical format is punched by FT07F001 of INDEX, with the addition of the source name in column 71. The input cards must be ordered in the order in which the data is ordered on the tape.

The range of delay searched by the program is $\pm$ 1.5 channels. The range of fringe rates searched is $\pm$ 1.25 turns per integration interval.

The program printer outputs are 1) the day and time of the integration center, 2) the integration length in seconds, 3) the solved delay in microseconds (this includes the CLOCK parameter from REDPREP, but will be wrong by any digits typed on the teletype at playback time and will be wrong for bandwidths other than 2 MHz), 4) the solved fringe rate, 5) the solved fringe amplitude, 6) the solved (or given) sideband, 7) the resolution vector (u, v) in millions of wavelengths 8) the audio track BCD digits (recorder unit numbers) and 9) error counts. In the error counts, the column headed T gives the number of times time had to be reset due to multiple errors in reading frame counts. This column is usually 0; a non zero number here is a matter of concern.

The other two columns give the number of times the "DROPOUT" lights flashed during the integration.

The program also produces a card output on FT07F001 if desired, which is used as input to the programs PLOT and AMPAV.

4.9 PLOT

This program takes the card output of VLBAMP and performs two functions. First, it averages 2, 4, 8, 16 etc. cards with a vector average and prints the result. With good signal to noise ratio and a short averaging time, this allows you to estimate the coherence time very easily. For each card, the total phase is estimated using the rate from this and the previous card to estimate the number of integral turns. Then, for each integration interval the phase rate is estimated as the phase of the last card less the phase of the first. This phase rate is used to correct the phases in the interval before the vector average is taken. For the first level of averaging, the possible incoherence is taken into account by using the phase rates from the two cards, and connecting by the cosine of the difference between the true phase change and the one estimated from the rates. This is a noisy estimate, in which there are systematic deviations downward, so this column is often a few percent lower than those on either side. At the end of each portion of a scan, the arithmetic average of the various vector averages is printed.

The second function of PLOT is to produce a printer plot of the two card averaged amplitudes and phases. The phases have a mean line removed. Automatic scaling is applied on both quantities. Phases are plotted in turns.

4.10 AMPAV

This program takes the cards from VLBAMP and performs incoherent averages. Each card is weighted by the integration time specified on that card. The program prints 1, 2, 4, 8, 16 and 32 minute averages. Each printout gives the mean time (minutes and second - hours only for 1 minute printouts), the integration time (in seconds) in the time slot, and the arithmetic average amplitude.

4.11 BCA

The path indicated above is suitable and superior (because it lets you see what is happening better) if the signal-to-noise ratio is large within the coherence time. If it is not, the style of analysis done on the MARK I VLB data is more appropriate. The program BCA (Broken Coherence Analysis) is set up to do it.

The data should be preaveraged, with VLBAVG, to a suitable degree. That is, the interval between records should be short compared to the overall uncertainty in frequency, but 64 records should comprise a time greater than or about equal to the coherence time.

Then you should punch a card giving the scan number, ending in column 10. The delay range to be analyzed is given in integer channel numbers (beginning channel number ending in column 20, ending channel number ending in column 30). If these fields are left blank, the whole range of channels, 1-31, are analyzed (the provision to restrict the range is for saving computer time). If it is desired to break the scan into chunks (to look for changes with hour angle), a length of <u>incoherent</u> integration interval may be specified, in seconds, in F10.0 format in columns 31-40. The coherent integration interval is implied by the preaveraging you use and the output bandwidth you choose. If you wish to discard the first part of the scan, a start time can be specified in columns 41-50 (R10.0 format).

If the integration interval is left blank, the scan will be treated as a unit. If the start time is left blank, or specified as zero, the scan will be analyzed from the beginning. The cards must be ordered in the order in which data is found on the tape.

The sideband (that is, whether the band center is above or below the signed sum of LO frequencies) must be specified on the EXEC card, by punching PARM=LSB of PARM=USB. The JCL necessary to operate the program is shown in Figure 23 g.

The program operates in two steps. During the first jobstep the input data is read, the wanted delay range selected, and the amplitudes of adjacent delay channels combined in quadrature (under the assumption of a 2 MHz bandwidth and the sideband specified on the execute card). Then a sixty-four point Fourier transform is taken and the absolute squares of the amplitudes taken. These fringe power spectra are passed to the second jobstep. The first jobstep prints the end times of each 64 record block used.

The second jobstep takes the fringe power spectra computed by the first jobstep, averages over the incoherent integration interval specified on the input card (or the whole scan if none is specified) and examines the resultant data for fringes. If N channels were specified to be searched, the program marks the N largest fringe powers as worth printing. The program then considers the possibility that the fringe spectrum is spread by loss of coherence, or by fringe acceleration effects. It runs a two point running mean down the data, and again marks the N largest values for printing. It repeats the procedure with

4, 8, 16 and 32 point running means, each time marking N values for printing. Finally, for each fringe frequency marked for printing, it prints all 6 of these running means.

For printing, the fringe spectrum power is converted to an amplitude estimate. The power spectrum is corrected for noise by subtracting a mean noise power derived from the remainder of the points in the fringe power spectrum for this delay channel not covered by the running mean. The square root of the absolute value of this residual is taken, and the sign of the residual is transferred to this amplitude estimate. This is not a maximum likelihood amplitude estimate (and indeed the negative amplitude estimates are rather hard to interpret in any formal theory). The maximum likelihood estimate involves inverse modified Bessel functions and is rather difficult to compute. This estimate converges to the maximum likelihood one very rapidly, so that its error is negligible by the time the fringes are strong enough for you to claim a detection.

Note that in this incoherent integration scheme, the noise on the square of the amplitudes goes down with the square root of time, and hence the minimum detectable amplitude goes down as the fourth root of time. Since this minimum detection level, and also the print cutoff levels, are calculated by rather obscure rules, estimates of these levels are printed on the output. These are estimates only, because they assume that the noise is identical on all delay channels, whereas the program internally calculates a separate rms noise for each channel. The minimum detection level printed is made on a fringe which would be a three sigma deviation on the fringe power spectrum. The number printed is a slight underestimate, because the uncertainty in the noise estimate is not taken into account. Note too, that many frequencies and delays are examined and not printed, so a deviation exceeding three sigma, whose inherent probability is only .0027, will be printed fairly frequently.

The first and second columns are not very useful for exact numerical work, because they are so widely spaced in fringe frequency. If a fringe falls half way between two examined frequencies, its amplitude will be only .64 that seen if its frequency had fallen on the frequency examined. The running means reduce this effect as well as allowing for incoherence. The correction is shown in the table below:

Number of Points in Running Mean	Maximum Correction
1	.6366
2	.9003
4	.9246
8	.9375
16	.9439
32	.9472

Incoherence, by causing a similar scattering of power in the exact frequency case, reduces the corrections. It is for this reason we recommend that data be pre-averaged until 64 records exceeds the coherence interval.

A correction must also be applied because the true derived delay is, in general, not at one of the values printed. The correction to be applied to the largest value printed is plotted as a function of the ratio of second largest to largest in Figure 25.

A catalogued procedure has been written to execute BCA; its execute card is shown in Figure 23 g, and its expansion in Figure 24 c. The parameter USB or LSB is passed by specifying, for instance, PARM.BC=LSB.

4.12 A Typical Data Flow

The options of all the individual programs have been described above. It may still be unclear just what one does to reduce the data. A typical data flow is described in this section, which can be taken as a model to be modified to your special circumstances. The data flow is schematically described in Figure 22.

4.12.1 Searching for Fringes

The observer brings his video tapes to the processor and, using the program REDPREP, prepares a data tape for what he expects will be his observation with the strongest fringes. A typical REDPREP deck is shown in Figure 23 a. When his time comes up on the processor, the observer then mounts the video tapes for this observation, and plays it back repetitively until he finds fringes or gives up. He will have inserted an estimate of the clock parameter in REDPREP, and search the region around this value by using the teletype increments. For correlation coefficients greater than .002 or so fringes will be seen on the CRT display, so no effort to make the output tape comprehensible is necessary, and delay stepping can proceed rather rapidly. We recommend you leave a 0.1 Hz residual rate in this tape to make the fringes more conspicuous.

A typical rate of delay stepping is given below as a function of the expected correlation coefficient. The table also shows what programs are necessary to display the outputs.

CORR. COEFF.	DELAY STEP RATE	OUTPUT DISPLAY
>.0040	1 μs every 5 sec	CRT
.0040→.0025	3 μs every 30 sec	CRT or INDEX
.0025→.0015	5 μs every 60 sec	INDEX
.0015→.0007	7 μs every 3 min	VLBAVG and INDEX

As an example, suppose 5 μs were entered on the TTY every minute. Then, some of the recorded delay comb misses being displayed on the CRT, since it is only 3 μs wide. The data could then be processed by the program INDEX. You would specify PARM=SEARCH to produce a fringe spectrum every 12.8 seconds instead of every 400 seconds. The JCL is shown in Figure 23 b.

4.12.2 The Main Reduction

Having found fringes, you set up for a production run. This involves making the REDPREP input cards for all of your scans, dividing them into 2-1/4 hour blocks, and making a REDPREP tape for each block, using the CLOCK parameter found in your delay search. After carefully checking the REDPREP outputs for error indications, you proceed to play back the observations.

As each REDPREP tape is completed, you will want a quick look at its output. If your fringe rates are well known, it is convenient at this time to do an average as well. Typical execute card which does an average and INDEX is shown in Figure 23 c. Note the FILE=n parameter on the execute card. This means the output data is going into the nth file on the output tape. Because of the higher tape density, higher blocking factor, and averaging, an entire experiment can conveniently be stored on one output tape in this fashion, using multiple files (up to about 60 hours).

When the entire playback process has been completed, further evaluation is in order. The first thing you will want to know is an estimate of the coherence time. Use the program VLBAMP, JCL shown in Figure 23 d., on a few of your strongest sources. Then give the output cards to program PLOT. (JCL is shown in Figure 23 e.) PLOT attempts various coherent averaging times - we recommend using the time in which the coherent average is down by about 15%. Putting that time in the PARM='TIME=nn' in the program VLBAMP, you may process the remainder of your data where the sources are sufficiently strong. "Sufficiently strong" is approximately .0050 $T^{-1/2}$ where T is your analysis time.

PLOT gives a nice data display for editing purposes. You may edit your card deck by throwing out all cards you find displeasing. The arithmetic average amplitudes with printout intervals of 1, 2, 4, 8, 16 and 32 minutes, suitable for looking for variations, are produced by the program AMPAV, JCL shown in Figure 23 f.

You then process the weak sources by way of the program BCA. You first preaverage to at least 1/60 of the coherence time found on the strong sources. You may do this by feeding averaged data back through the program VLBAVG. Then you analyze the data through the program BCA; JCL is shown in Figure 23 g. From the output of BCA you should pick the broadest fringe bandwidth in which there is good signal-to-noise ratio (well above the three sigma level). To this number, you must make the correction for discrete delays plotted in Figure 25 and sin x/x corrections for fringe frequency errors, and finally you must normalize by a calibrator source analyzed with the same fringe bandwidth.

5. How the Mark II VLB Should Have Been Built

In any project, after the first is completed, one knows how to build the next better. Here is that advice, recorded for posterity.

5.1 The VR660 Recorders

The VR660 was the best buy for the money at the time it was selected. Since then several companies have introduced one head video recorders, utilizing one inch tape, which appear to be both mechanically and electrically superior to the VR660.

5.2 The Diphase Coding

The diphase coding intrinsically occupies about one octave bandwidth - in our case from 2 to 4 MHz. More economical codes could be used. For instance, one could use NRZI coding (non-return-to-zero-integrated; the absolute value of the derivative of the recorded signal is the data bit) with a mandatory 1 inserted after every fourth bit for clocking purposes. This coding scheme occupies about 2-1/2 octave of spectrum. It would be possible, though difficult, to compensate the video recording apparatus over this bandwidth. One would expect, using this coding scheme, to easily get 8 megabit bandwidth, and possibly 12.

5.3 The Beginning-of-Frame Syncword

Since one wants an assured clock with a flywheel effect, the syncword should have the same frequency properties as data, to avoid disturbing the assured clock. The present syncword does not. A pseudo random pattern repeated a few times could be used as a syncword with a low probability of occurring by chance in the noisy data.

5.4 The Start-Up Sequencing

This part of the machine is implemented in hardware, a very bad choice. It should have been done in software, because one would like to implement a more complex algorithm than the hardware uses. To implement it in software would require the following hardware changes: a) the B helical frame count sent to the computer, (only A is sent now). b) Digital dividers implemented to slew B relative to A at $\pm$ 5% and to scan at $\pm$ 1%. c) A computer command to sync B output address to A output address, to initialize the output alignment once the heads are pointed to the proper frame. d) Computer resets and sensing, on the buffer fault indicators. e) Possibly, even computer control over the slewing functions. This arrangement would have the following advantages: a) one could employ a more efficient algorithm, expecting sync word recovery only when the head rate has been returned to 60 Hz, enabling easier setup on marginal data; b) the syncing process would be rather faster in any case, and c) arbitrary time offsets could be used - the present system scans delays at only about 1.2 ms/sec; d) having only digital components, nothing would drift with time or temperature.

5.5 The Lobe Rotator

Alan Rogers has suggested a lobe rotator consisting of a buffer to which a phase increment is added every half microsecond, in place of the programmed divider used in the present equipment. This not only requires less digital I-O but it eliminates the only triple precision division in the program, a notable saving in space, time and complexity.

6. Acknowledgements

Much of the equipment described in this report was initially designed by Leach Corporation, and described in their manuals.

George Grove, Bill Vrable, Dwayne Schiebel, and Ray Hallman have made significant improvements in the equipment in the course of its construction.

The correlator boards were designed by Art Shalloway, who has assisted in their incorporation in this receiver.

Line interferometry aspects have been considered by Steve Knowles, Jim Moran, and Alan Rogers.

VLB CHECK LIST

Once Per Shift

Clean audio and control heads
Clean tape path
Clean pinch roller with alcohol
Run pattern test
   Pattern reproduces
   Head wheel servo lock
   Capstan servo lock
Local oscillator connected to frequency standard
Video recorder cables connected to format unit
Recorder sync on external
VLB seconds tick agrees with primary time
  standard or LORAN C

Each Tape

Clean video heads
Mount tape
Record 2 min. of test pattern
VLB clock agrees with WWV or external clock -
  check day, hours, minutes, seconds
IF meter approximately centered
Head wheel phase approximately centered

Each Observation

Telescope on Source
Polarization correct
Front end switching suppressed
LO frequency correct
Bandwith set
Converter phase lock light
Timing generator phase lock and time light

Start observation
Log start time

Stop observation
Log stop time

Figure 15

```
//jobname   JOB    (acctg information),MSGLEVEL=1,etc
//BSL       EXEC   PGM=BSL
//STEPLIB   DD     DISP=SHR,DSNAME=CLARK.VLBLIB
//FT06F001  DD     DUMMY
//FT08F001  DD     DISP=(NEW,PASS),DSNAME=&&OBJDECK,LABEL=(,BLP),
//                 UNIT=TAPE,DCB=(RECFM=F,LRECL=164,DEN=2),
//                 VOLUME=SER=number
//ASM       EXEC   PGM=ASM620
//STEPLIB   DD     DISP=SHR,DSNAME=CLARK.VLBLIB
//          DD     DISP=SHR,DSNAME=PL1.LINKLIB
//SYSPRINT  DD     SYSOUT=A,DCB=(RECFM=FBA,LRECL=133,BLKSIZE=1330)
//TEMP      DD     UNIT=DISK,SPACE=(TRK,(20,20))
//ASMOUT    DD     DISP=MOD,DSNAME=&&OBJDECK
//SYSIN     DD     *
assembler source program
```

Figure 20. Assembler

```
//jobname   JOB   (acctng information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB    DD    DISP=SHR,DSN=CLARK.VLBLIB
//GO        EXEC  PGM=SEARCH
//FT06F001  DD    SYSOUT=A
//FT08F001  DD    UNIT=TAPE,VOL=SER=tape#,DSN=name,DISP=OLD
//FT05F001  DD    *
(search input cards)
```

Figure 21 a. Search

```
//jobname   JOB   (acctg information),MSGLEVEL=1,CLASS=C
//JOBLIB    DD    DISP=SHR,DSN=CLARK.VLBLIB
//GO        EXEC  PGM=OFFSET
//FT05F001  DD    *
(Offset control cards, if any)
//FT06F001  DD    SYSOUT=A
//FT07F001  DD    SYSOUT=B
//FT08F001  DD    UNIT=TAPE,VOL=SER=tape#,DSN=name,DISP=OLD,LABEL=(2,BLP),
//          DCB=(RECFM=VS,LRECL=200,BLKSIZE=204)
```

Figure 21 b. Offset

```
//jobname  JOB   (acctg information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB   DD    DISP=SHR,DSN=CLARK.VLBLIB
//GO       EXEC  PGM=LITTER
//FT05F001 DD    *
(one or more control cards)
//FT06F001 DD    SYSOUT=A
//FT08F001 DD    UNIT=TAPE,DISP=OLD,VOL=SER=tape#,DSN=name
```

Figure 21 c. Litter

```
//jobname   JOB    (acctg information),MSGLEVEL=1,CLASS=B
//JOBLIB    DD     DISP=SHR,DSN=CLARK.VLBLIB
//PREP      EXEC   PGM=REDPREP
//SYSPRINT  DD     SYSOUT=A
//SYSIN     DD     *
F=frequency    START='start time'   STOP='stop time'   SCAN=scan#
NAME='source name'    RA='       '   DEC='      '      etc, etc
//SYSOUT0   DD     UNIT=TAPE,DISP=(NEW,KEEP),VOL=SER=tape#,DSN=name,DCB=DEN=2
//SYSOUT1   DD     UNIT=AFF=*.SYSOUT0,DISP=(NEW,KEEP),VOL=SER=tape#,
//                 DSN=name,DCB=DEN=2
etc.
```

Figure 23 a. REDPREP

```
//jobname   JOB    (acctg information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB    DD     DISP=SHR,DSN=CLARK.VLBLIB
//GO        EXEC   PGM=INDEX,PARM=SEARCH
//FT06F001  DD     SYSOUT=A
//FT08F001  DD     DISP=OLD,UNIT=TAPE,VOL=SER=tape#,DSN=name
```

Figure 23 b. INDEX, PARM=SEARCH

```
//jobname   JOB   (acctg information),MSGLEVEL=1,CLASS=jobclass
//          EXEC  VLBAVG,INTAPE=tape#,INDSN=name,OUTTAPE=tape#,OUTDSN=name,
//                FILE=n
//AVG.SYSIN DD    *
(avg. control cards, if any)
```

Figure 23 c. AVERAGE and INDEX, Using Cataloged Procedure

```
//jobname  JOB   (acctg information),MSGLEVEL=1,CLASS=jobclass
//         EXEC  VLBAMP,INTAPE=tape#,INDSN=name,FILE=n
//AMP.SYSIN DD   *
(amp input cards)
```

Figure 23 d. VLBAMP Catalogued Procedure

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=C
//JOBLIB     DD     DISP=SHR,DSN=CLARK.VLBLIB
//GO         EXEC   PGM=PLOT
//FT06F001   DD     SYSOUT=A
//FT08F001   DD     *
(cards from VLBAMP)
```

Figure 23 e. PLOT

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=C
//JOBLIB     DD     DISP=SHR,DSN=CLARK.VLBLIB
//GO         EXEC   PGM=AMPAV
//SYSIN      DD     *
(cards from VLBAMP)
//SYSPRINT   DD     SYSOUT=A
```

Figure 23 f. AMPAV

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=jobclass
//           EXEC   VLBBCA,INTAPE=tape#,INDSN=name,FILE=n,PARM.BC=sideband
//BC.SYSIN   DD     *
(control cards, one per scan)
```

Figure 23 g. BCA Using Cataloged Procedure

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB     DD     DISP=SHR,DSN=CLARK.VLBLIB
//AVG        EXEC   PGM=VLBAVG,PARM='INTVL=5'
//FT01F001   DD     UNIT=DISK,SPACE=(TRK,(2,1)),DCB=(RECFM=F,BLKSIZE=80,
//                  LRECL=80)
//FT02F001   DD     UNIT=DISK,SPACE=(TRK,(2)),DCB=(RECFM=VSB,LRECL=604,
//                  BLKSIZE=3024)
//FT05F001   DD     *
(AVG control cards if any)
//FT06F001   DD     SYSOUT=A
//FT08F001   DD     DISP=OLD,UNIT=TAPE,VOL=SER=tape#,DSN=name
//FT09F001   DD     DISP=(NEW,PASS),DSN=outname,VOL=SER=tape#,UNIT=TAPE,
//                  LABEL=n,DCB=(RECFM=VSB,LRECL=164,BLKSIZE=3448)
//INDEX      EXEC   PGM=INDEX,COND=EVEN
//FT06F001   DD     SYSOUT=A
//FT07F001   DD     SYSOUT=B
//FT08F001   DD     DISP=(OLD,PASS),DSN=outname
```

Figure 24 a. JCL Equivalent to the Catalogued Procedure VLBAVG

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB     DD     DISP=SHR,DSN=CLARK.VLBLIB
//AMP        EXEC   PGM=VLBAMP
//FT01F001   DD     UNIT=DISK,SPACE=(TRK,(2,1)),DCB=(RECFM=F,BLKSIZE=112,
//                  LRECL=112)
//FT02F001   DD     UNIT=DISK,SPACE=(TRK,(2)),DCB=(RECFM=VSB,BLKSIZE=3448,
//                  LRECL=164)
//FT05F001   DD     *
(AMP control cards)
//FT06F001   DD     SYSOUT=A
//FT07F001   DD     SYSOUT=B
//FT08F001   DD     UNIT=TAPE,DISP=OLD,VOL=SER=tape#,DSN=name
```

Figure 24 b. JCL Equivalent to the Catalogued Procedure VLBAMP

```
//jobname    JOB    (acctg information),MSGLEVEL=1,CLASS=jobclass
//JOBLIB     DD     DISP=SHR,DSN=CLARK.VLBLIB
//BC         EXEC   PGM=BCA1,PARM=sideband
//FT01F001   DD     UNIT=DISK,SPACE=(TRK,(1)),DCB=(RECFM=VSB,LRECL=164,
//                  BLKSIZE=3454)
//FT02F001   DD     UNIT=DISK,SPACE=(TRK,(2)),DCB=(RECFM=VSB,LRECL=184,
//                  BLKSIZE=3500),DSN=&&HEADER,DISP=(NEW,PASS)
//FT06F001   DD     SYSOUT=A
//FT08F001   DD     DISP=OLD,UNIT=TAPE,VOL=SER=tape#,DSN=name
//FT09F001   DD     DISP=(NEW,PASS)UNIT=DISK,DCB=(RECFM=VSB,LRECL=280,
//                  BLKSIZE=3364),DSN=&&DATA,SPACE=(CYL,(5,3))
//FT05F001   DD     *
(scan select cards)
//PRINT      EXEC   PGM=BCA2,COND=EVEN
//FT01F001   DD     DISP=(OLD,DELETE),DSN=&&HEADER
//FT06F001   DD     SYSOUT=A
//FT08F001   DD     DISP=(OLD,DELETE),DSN=&&DATA
```

Figure 24 c. JCL Equivalent to Catalogued Procedure VLBBCA

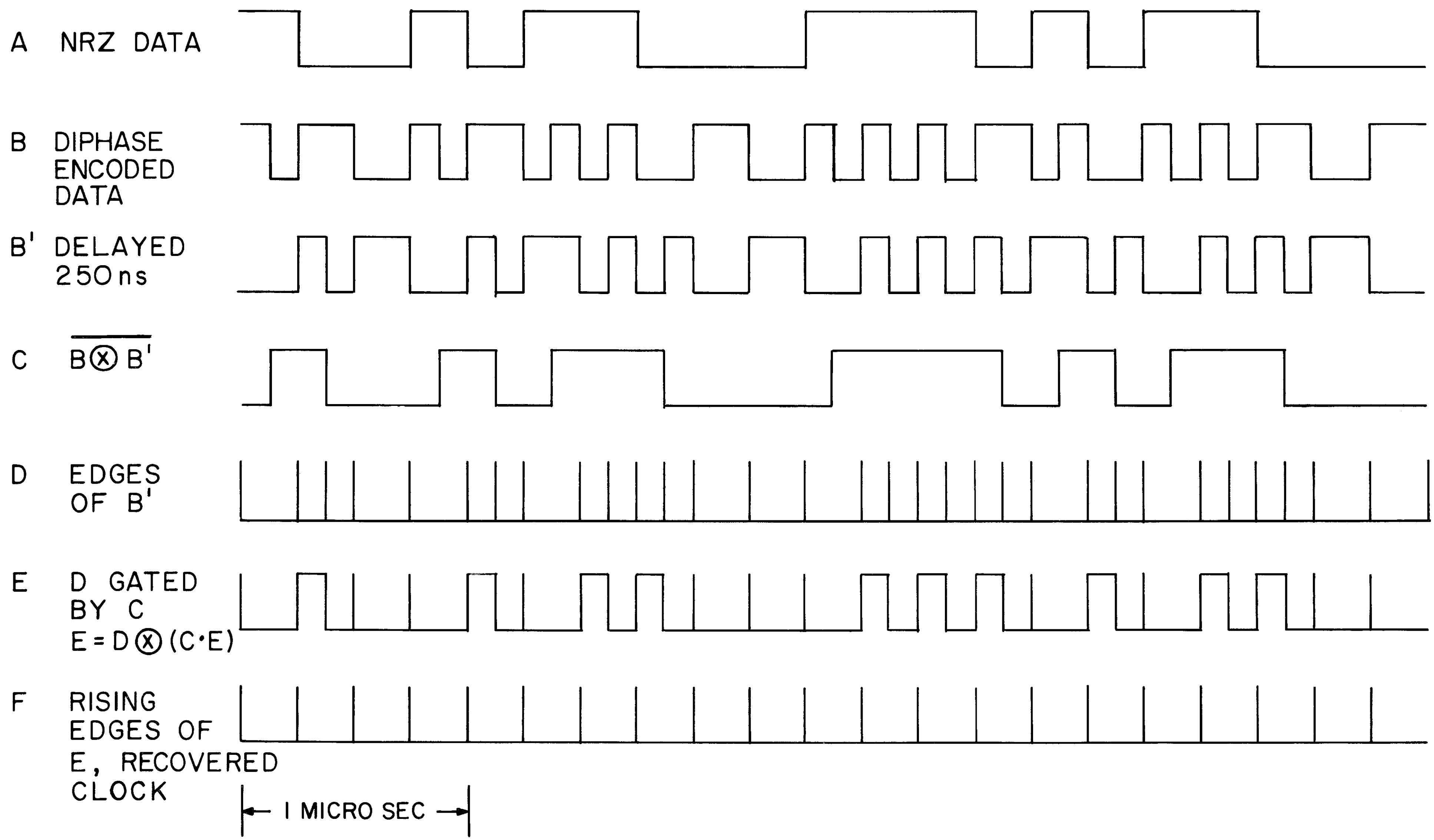

A NRZ DATA
B DIPHASE ENCODED DATA
B' DELAYED 250ns
C $\overline{B \otimes B'}$
D EDGES OF B'
E D GATED BY C
E = D ⊗ (C·E)
F RISING EDGES OF E, RECOVERED CLOCK
1 MICRO SEC

FIG. 1

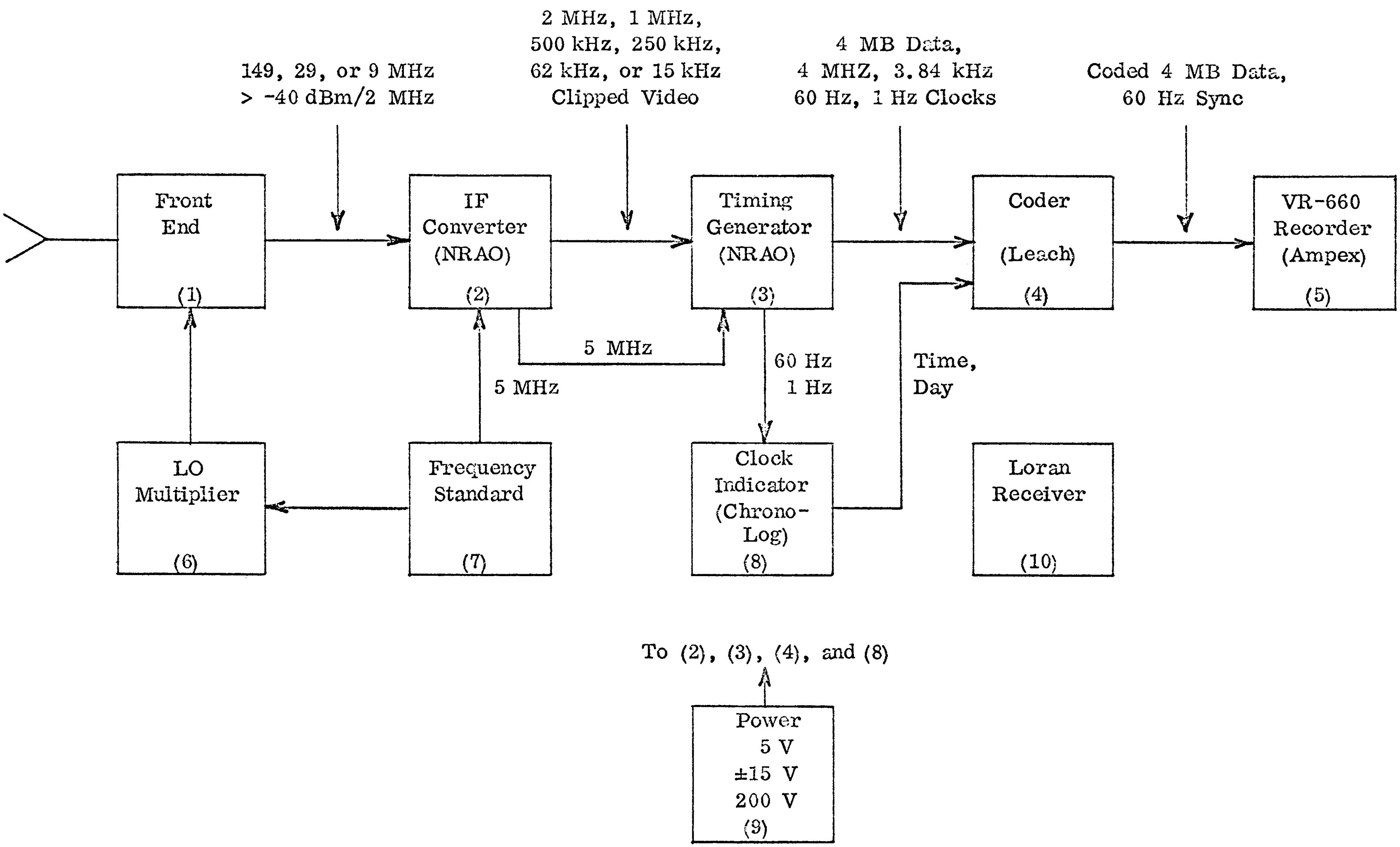


Figure 2 — VLB Terminal Description.

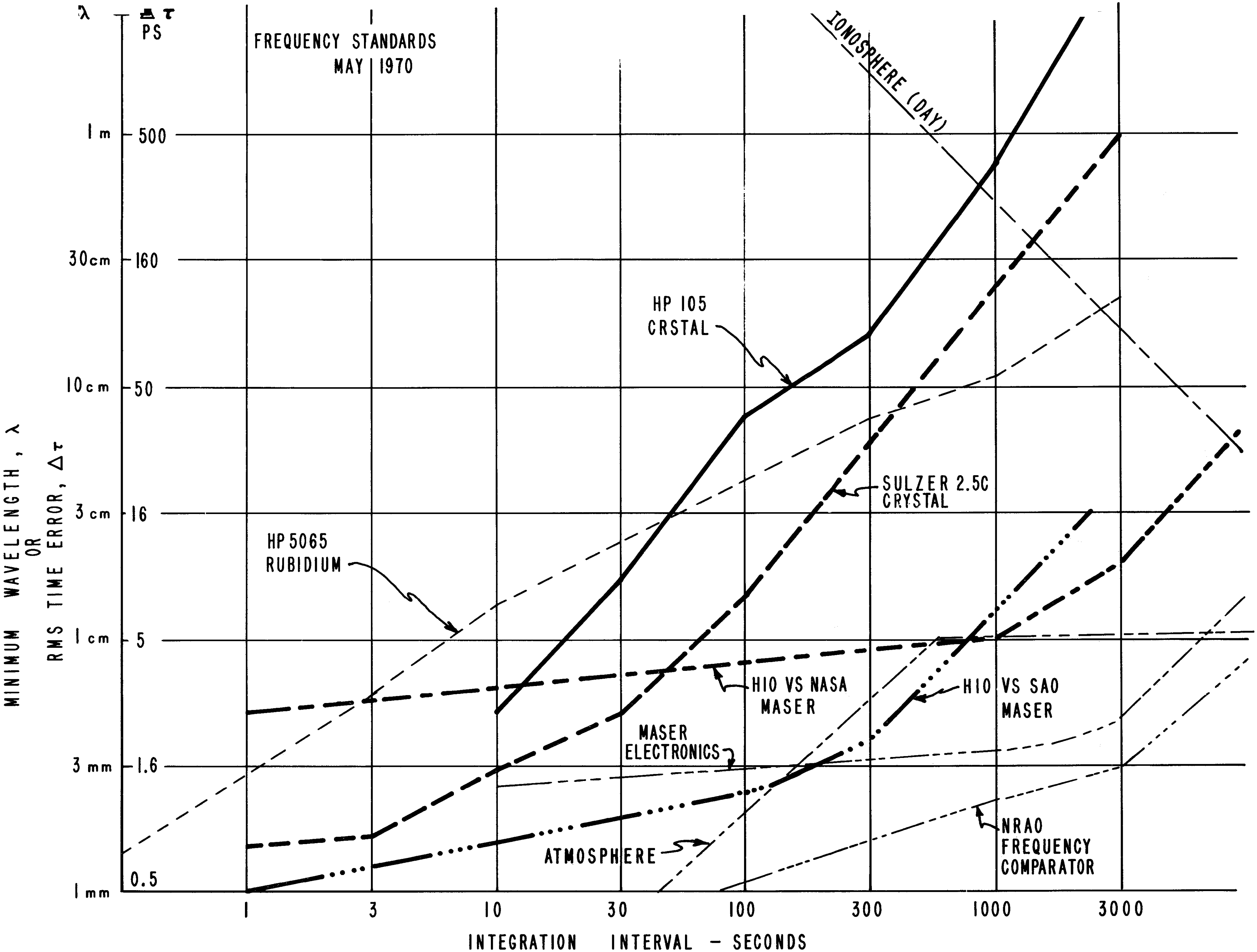

FREQUENCY STANDARDS
MAY 1970
λ
Δτ
PS
1 m
30cm
10 cm
3 cm
1 cm
3 mm
1 mm
500
160
50
16
5
1.6
0.5
MINIMUM WAVELENGTH, λ
OR
RMS TIME ERROR, Δτ
IONOSPHERE (DAY)
HP 105
CRSTAL
SULZER 2.5C
CRYSTAL
HP 5065
RUBIDIUM
H10 VS NASA
MASER
H10 VS SAO
MASER
MASER
ELECTRONICS
ATMOSPHERE
NRAO
FREQUENCY
COMPARATOR
1
3
10
30
100
300
1000
3000
INTEGRATION INTERVAL – SECONDS

FIG. 3

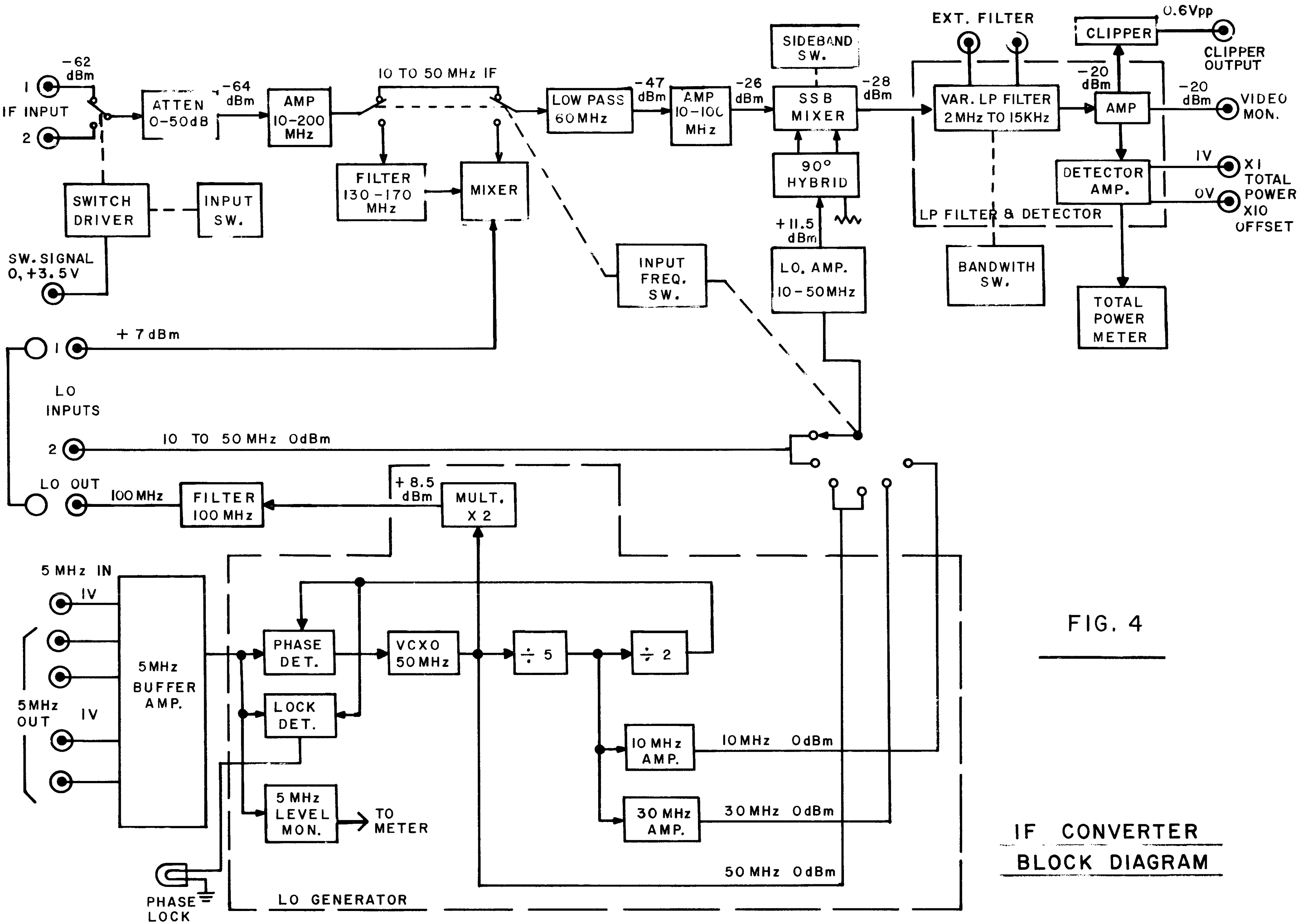


FIG. 4

IF CONVERTER
BLOCK DIAGRAM

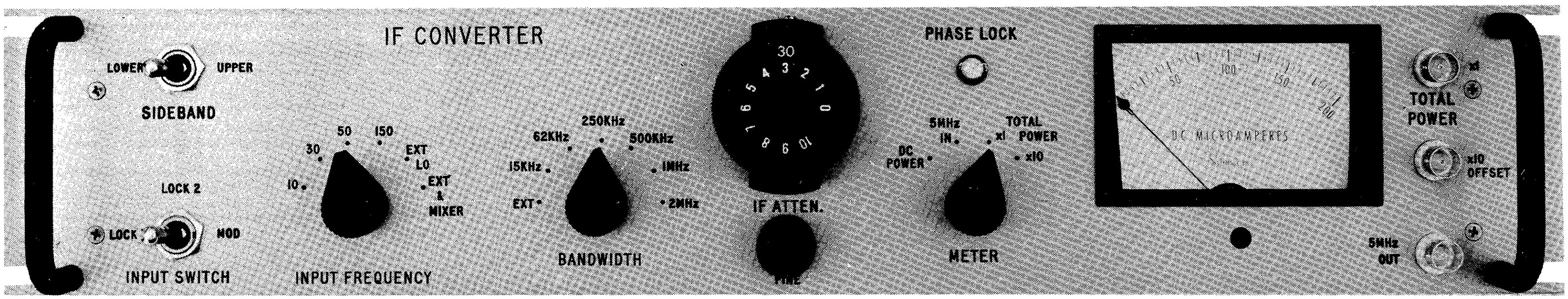

IF CONVERTER
LOWER
UPPER
SIDEBAND
LOCK 2
LOCK
MOD
INPUT SWITCH
10
30
50
150
EXT
LO
EXT
&
MIXER
INPUT FREQUENCY
15KHz
62KHz
250KHz
500KHz
1MHz
2MHz
EXT
BANDWIDTH
IF ATTEN.
PHASE LOCK
DC
POWER
5MHz
IN
TOTAL
x1
POWER
x10
METER
DC MICROAMPERES
x1
TOTAL
POWER
x10
OFFSET
5MHz
OUT

FIGURE 5

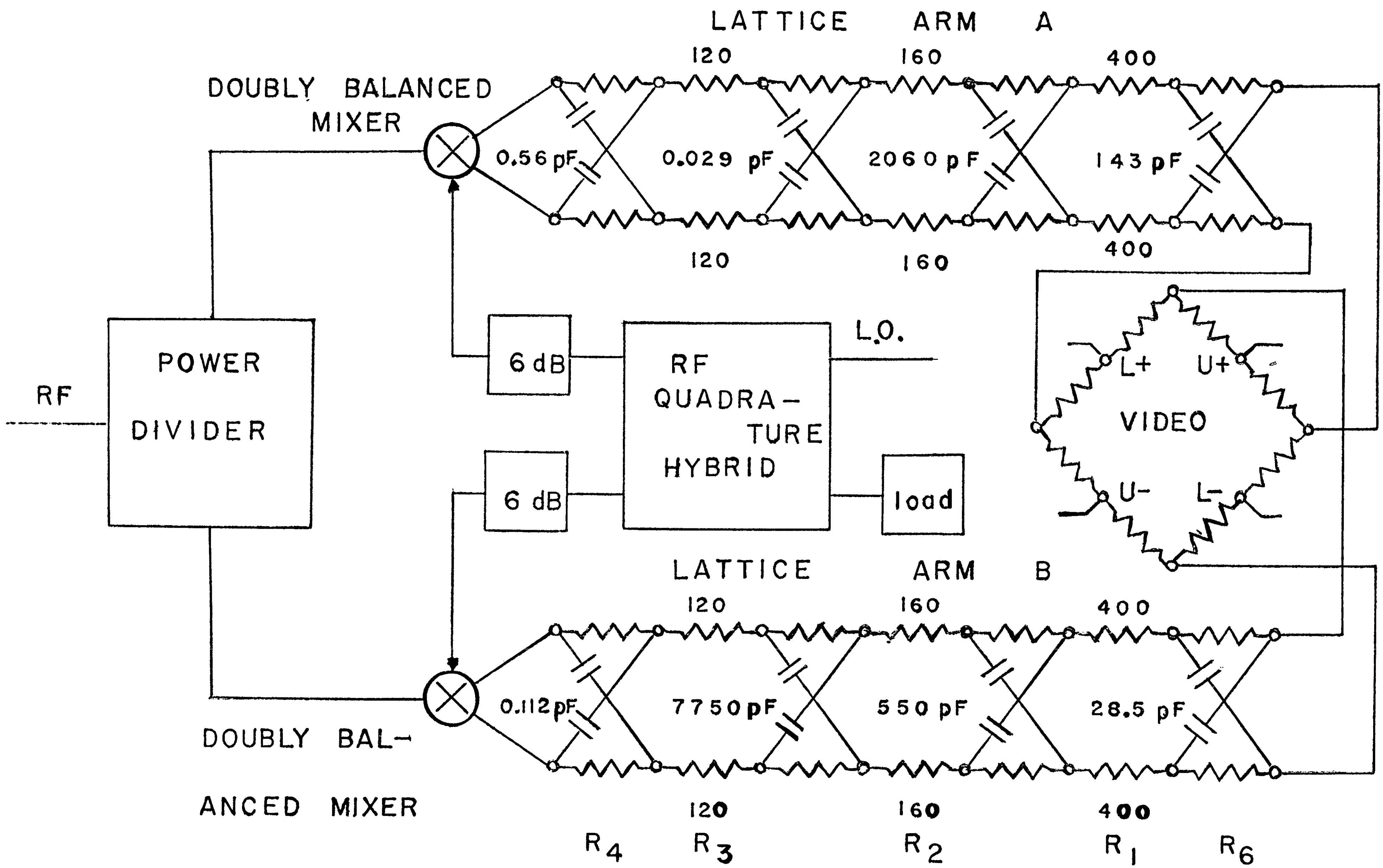


FIG. 6 — SINGLE-SIDEBAND MIXER.

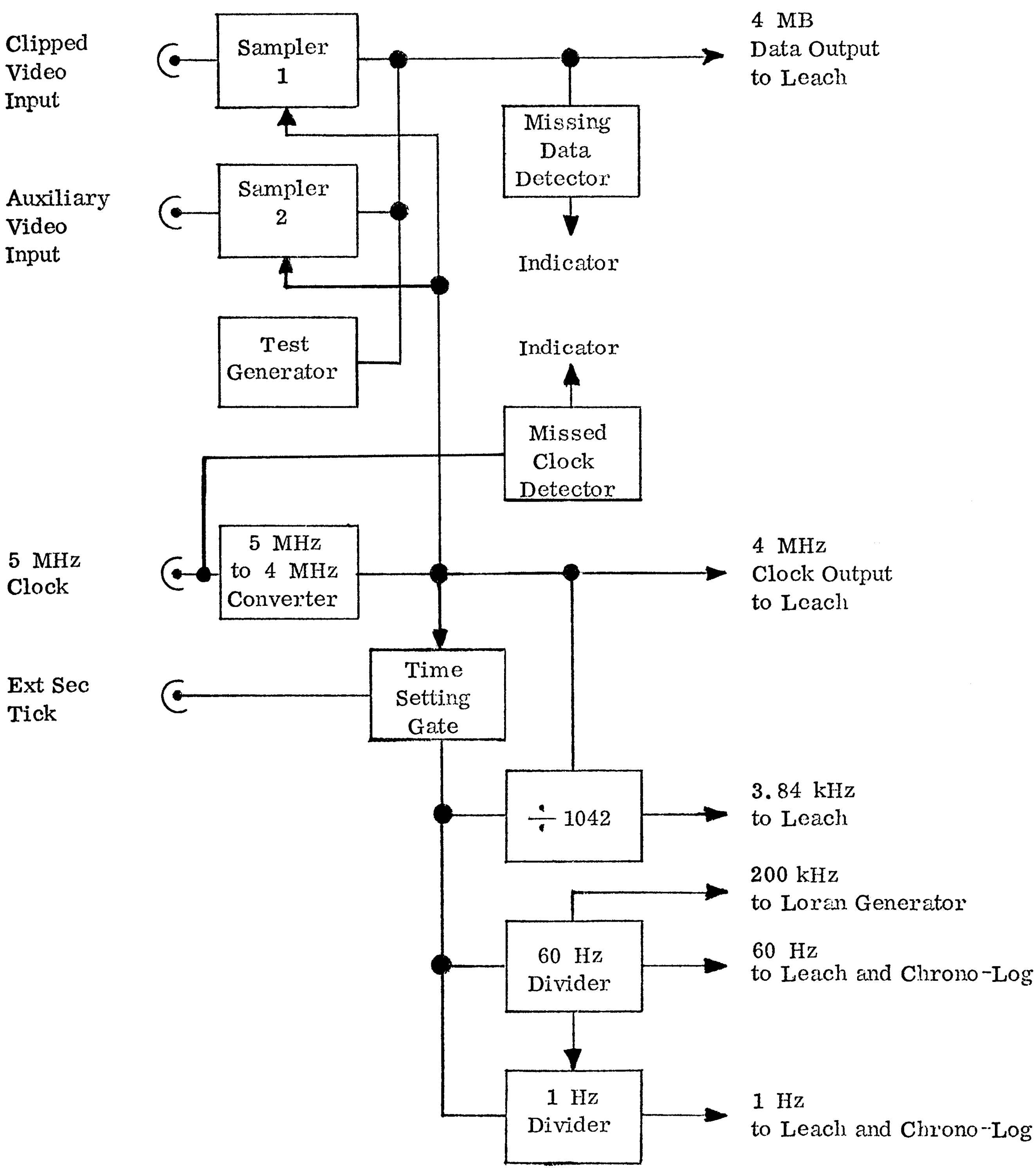
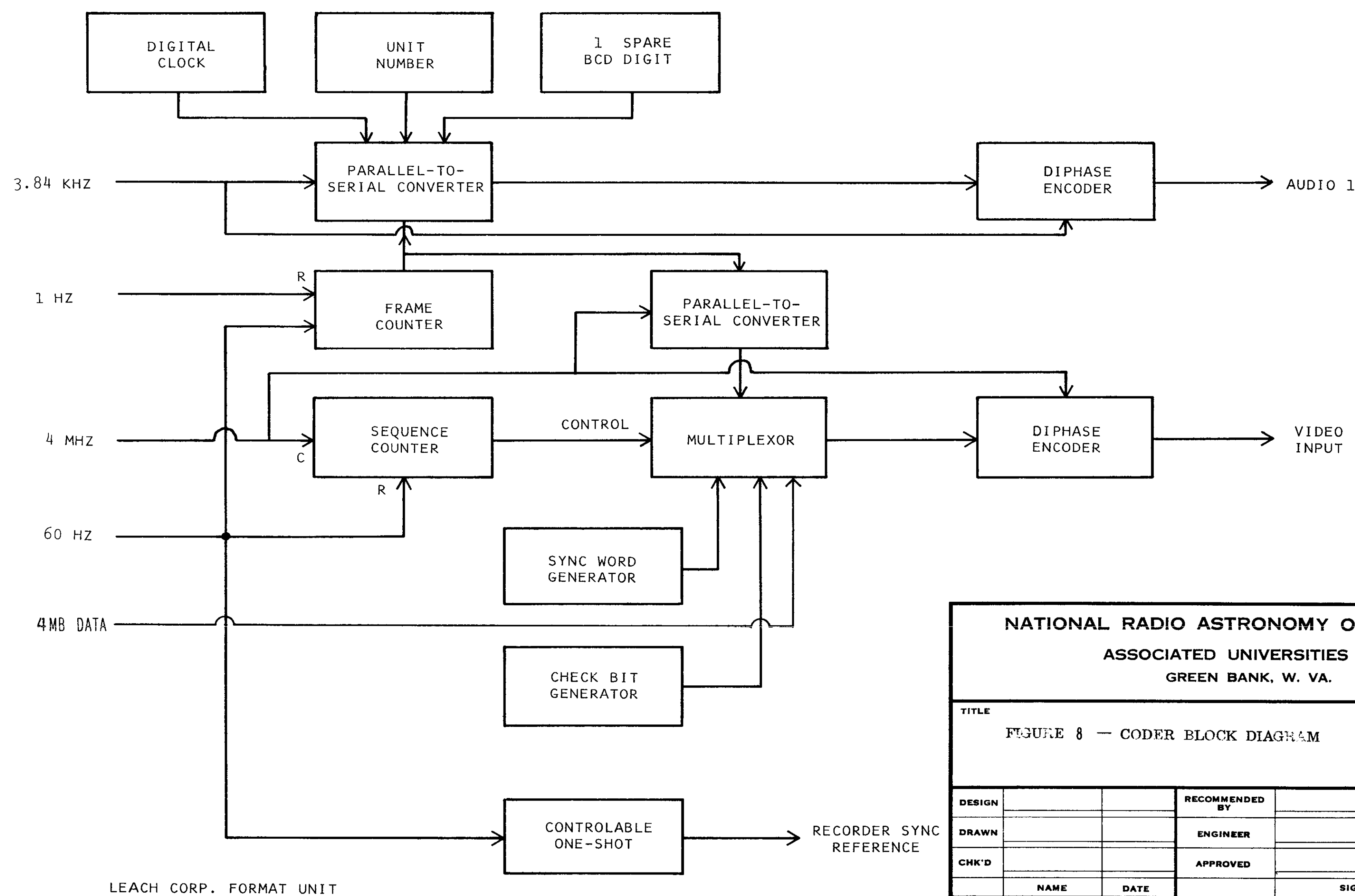


FIGURE 7 — VLB TIMING GENERATOR.



No.	DATE	BY
1	4-7-72	B.C.

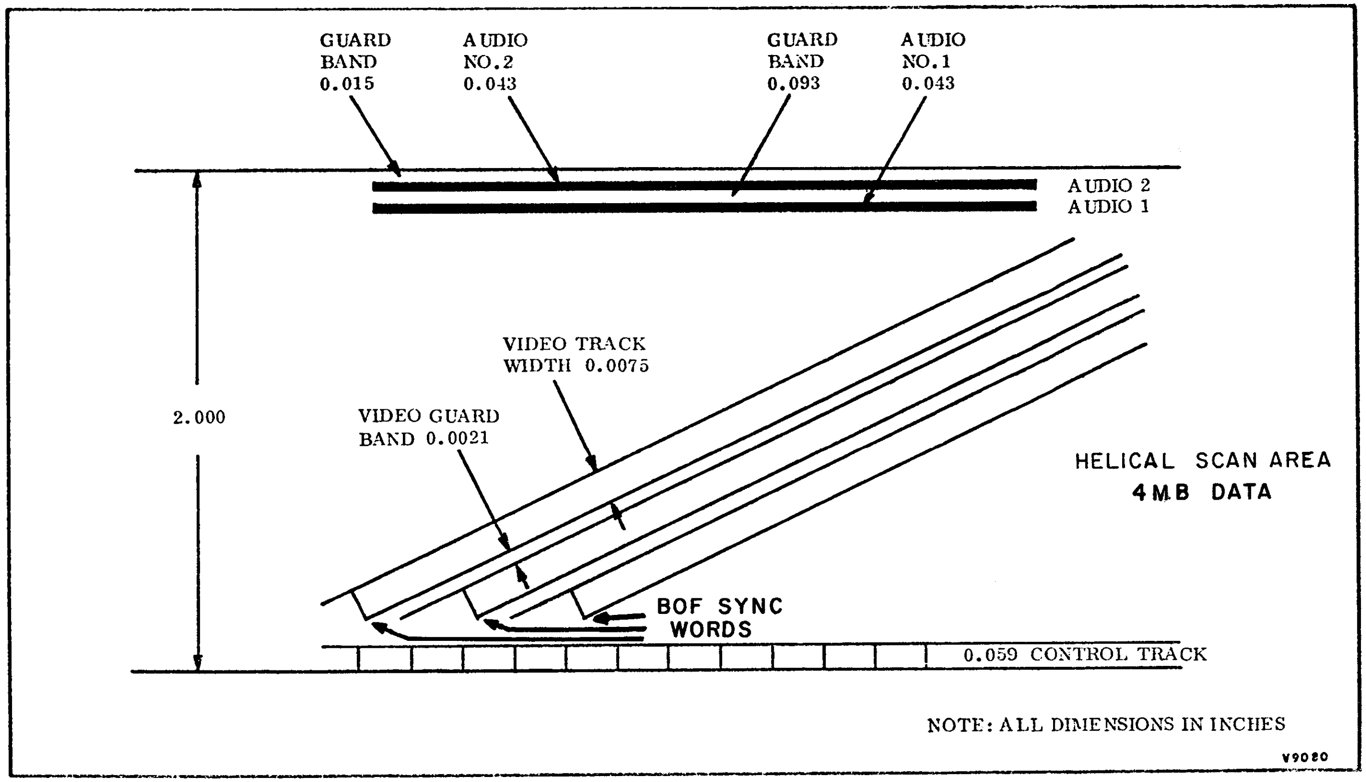
REVISIONS

NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC.
GREEN BANK, W. VA.

TITLE
FIGURE 8 — CODER BLOCK DIAGRAM

	NAME	DATE		SIGNATURE	DATE
DESIGN			RECOMMENDED BY		
DRAWN			ENGINEER		
CHK'D			APPROVED		

SCALE | NO. | REVISION



VR-660C Recorded Tape Track Pattern

FIGURE 9A

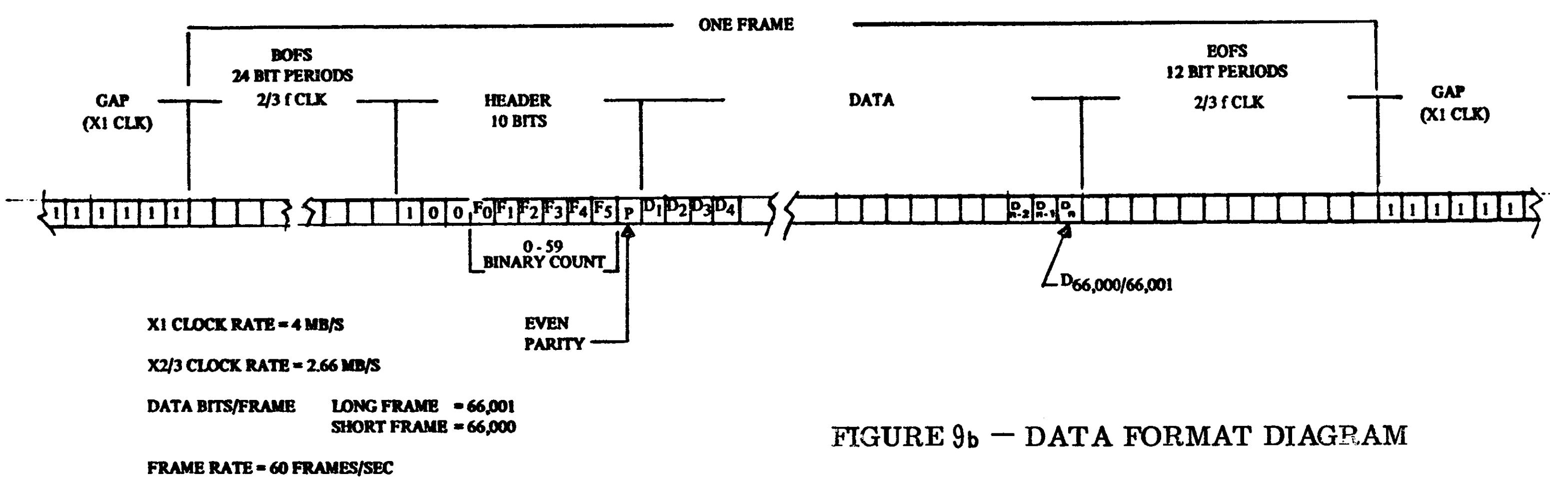
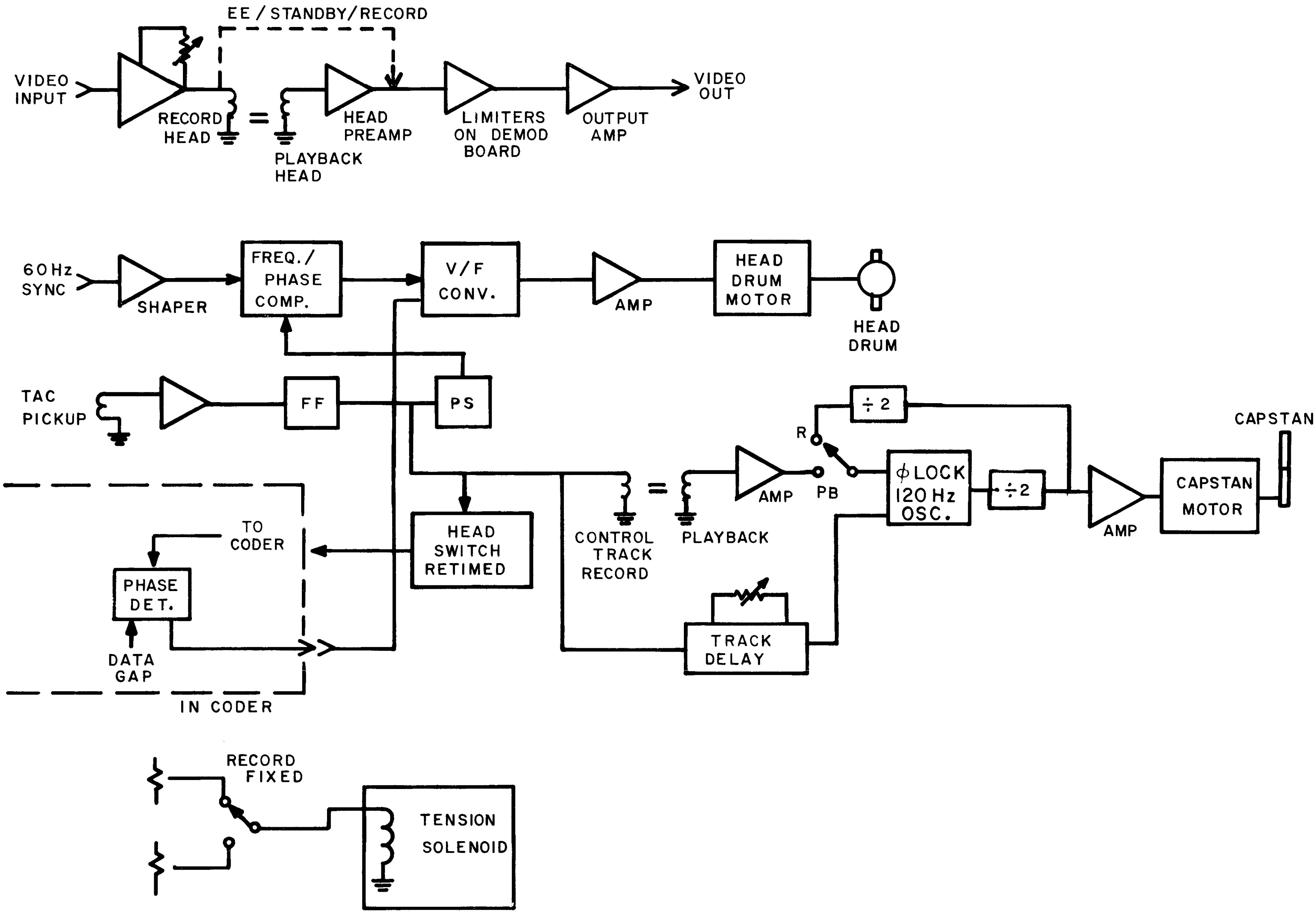
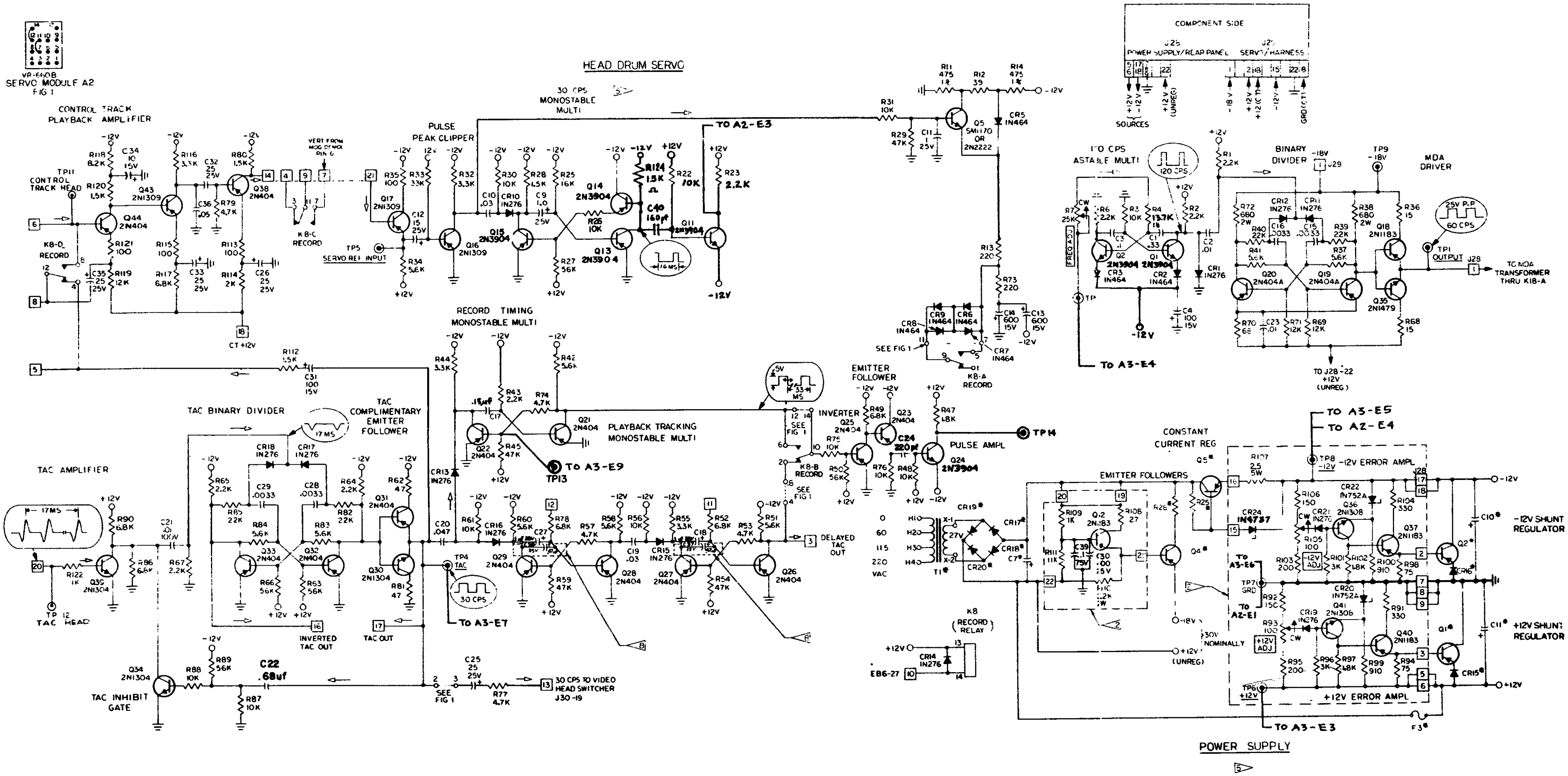


FIGURE 9b — DATA FORMAT DIAGRAM



AMPEX RECORDER SYSTEM DIAGRAM
FIG. 10



(Ref. Assy. 1211185)
A1

Leach Modified Head Drum Servo and Power Supply Schematic 01095
(Reference Ampex Dwg. No. 1240887)

FIGURE 11a

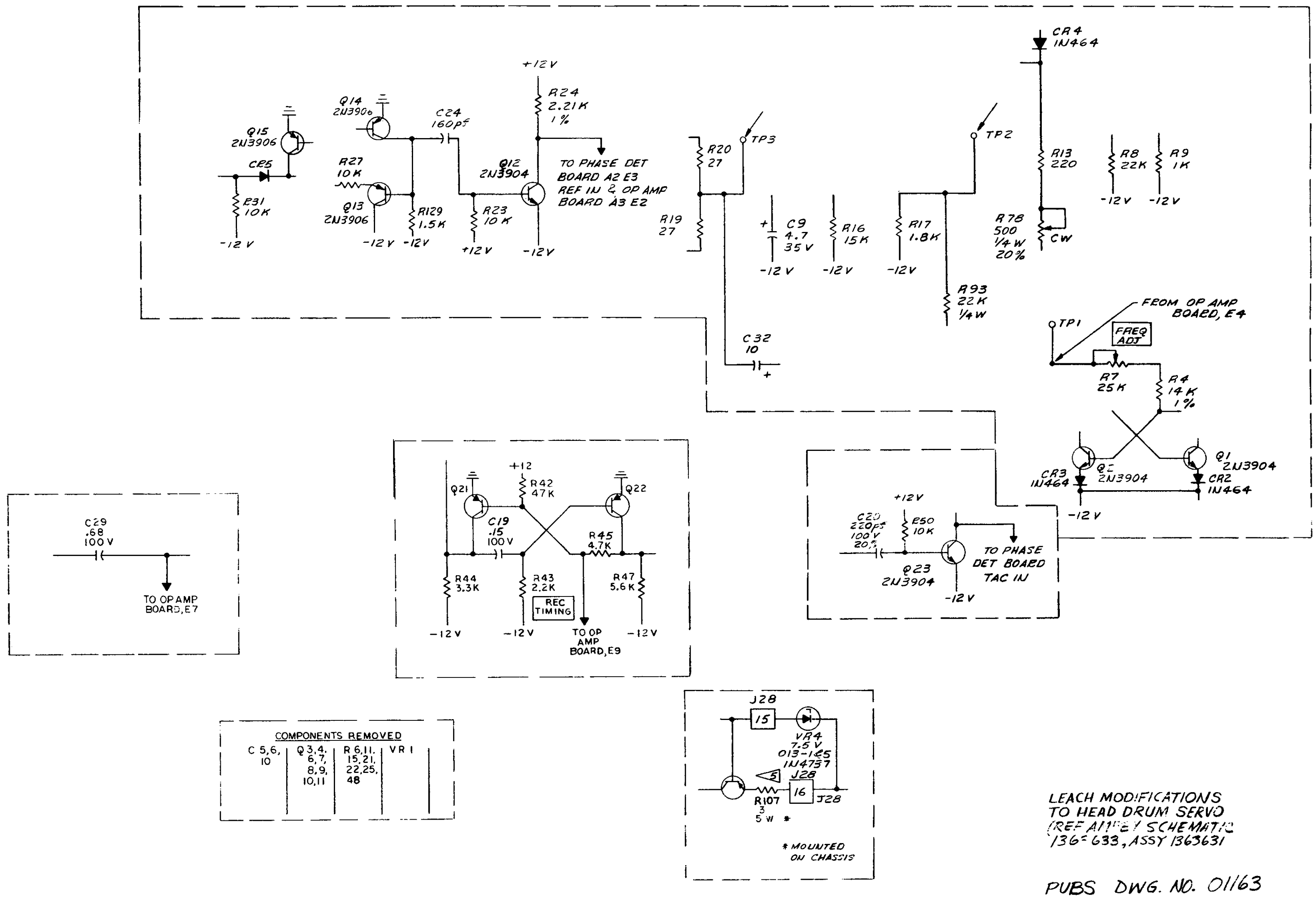

Q15 2N3906
CR5
R31 10K
-12 V
Q14 2N3906
R27 10K
Q13 2N3906
R129 1.5K
C24 160pf
R23 10K
+12 V
Q12 2N3904
R24 2.21K 1%
+12 V
TO PHASE DET BOARD A2 E3 REF IN & OP AMP BOARD A3 E2
R20 27
R19 27
TP3
C9 4.7 35 V
R16 15K
R17 1.8K
TP2
R93 22K 1/4 W
C32 10
CR4 1N464
R13 220
R78 500 1/4 W 20%
CW
R8 22K
R9 1K
FROM OP AMP BOARD, E4
TP1
FREQ ADJ
R7 25K
R4 14K 1%
Q1 2N3904
2N3904
CR3 1N464
CR2 1N464
C29 .68 100 V
TO OP AMP BOARD, E7
Q21
+12
R42 47K
Q22
C19 .15 100 V
R45 4.7K
R44 3.3K
R43 2.2K
REC TIMING
R47 5.6K
TO OP AMP BOARD, E9
+12V
E50 10K
Q23 2N3904
TO PHASE DET BOARD TAC IN
COMPONENTS REMOVED
C 5,6, 10
Q3,4, 6,7, 8,9, 10,11
R 6,11, 15,21, 22,25, 48
VR 1
J28
15
VR4 7.5 V 1N4737
J28
16
R107 3 5 W *
5
* MOUNTED ON CHASSIS
LEACH MODIFICATIONS TO HEAD DRUM SERVO
PUBS DWG. NO. 01163

FIGURE 11b

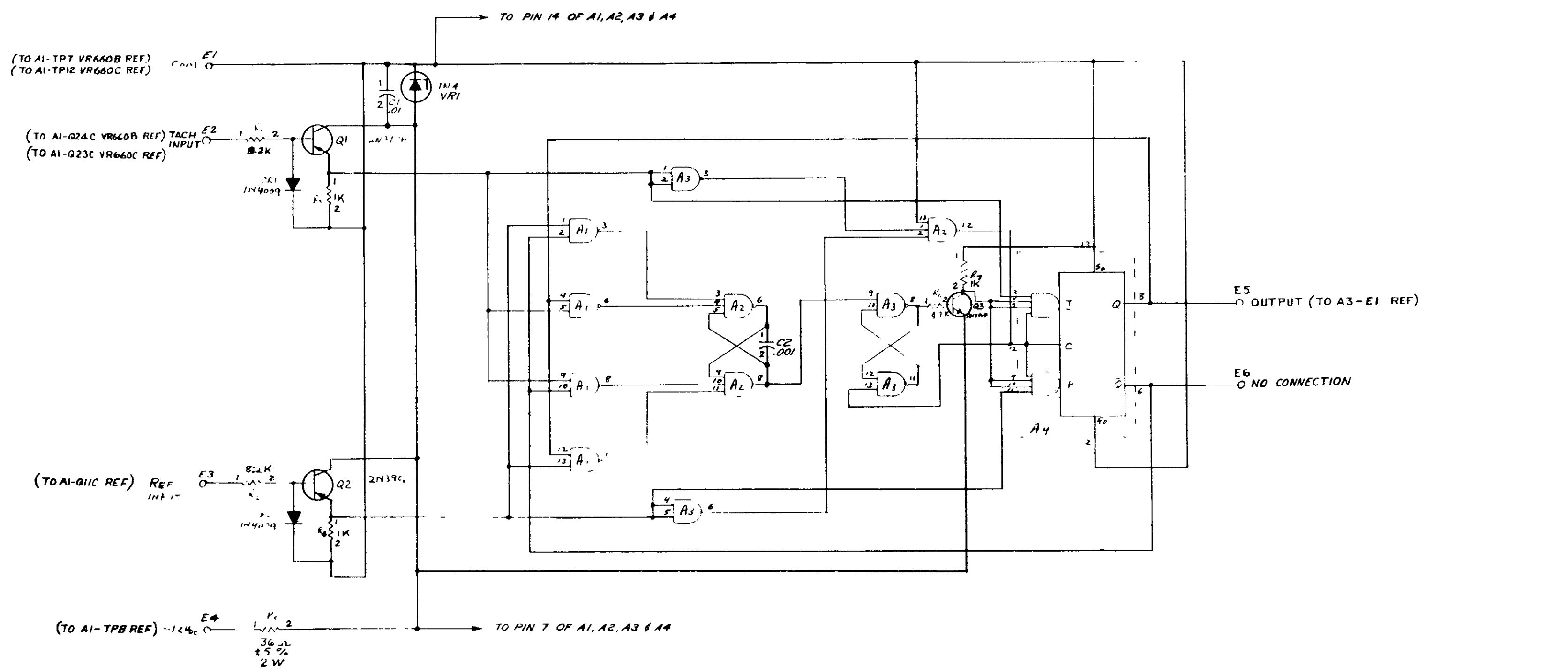


Figure 11c

6. FOR WIRE LIST SEE DWG NO. 202513.

5. INTEGRATED

CIRCUIT NO.	PART NO.	VENDOR CODE
A1, A3	SN7400N	01295
A2	SN7410N	01295
A4	SN7472N	01295

4. ALL CAPACITOR VALUES ARE IN MICROFARADS ±10% AND ARE 100V

3. ALL RESISTOR VALUES ARE IN OHMS 5% AND ARE 1/4 W

2. REFERENCE DESIGNATIONS ARE ABBREVIATED: PREFIX WITH UNIT NO. & APPLICABLE SUBASSEMBLY DESIGNATION A2

1. FOR ASSEMBLY SEE DWG NO 202236 SHT 1

NOTES UNLESS OTHERWISE SPECIFIED

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED

LIST OF MATERIALS OR PARTS LIST

QTY REQD	ITEM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	ZONE

HD40 — NEXT ASSEMBLY — USED ON — APPLICATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
FRACTIONS ± XX ±
ANGLES ± XXX ±
MATERIAL
FINISH
SURFACE ROUGHNESS

CONTRACT NO
DRAWN
CHECKED
DESIGN
ENGINEER
PROJECT
RELEASE
DESIGN APPROVAL

LEACH CORPORATION 717 NORTH CONEY AVE. CONTROLS DIVISION AZUSA, CALIFORNIA

SCHEMATIC DIAGRAM, PHASE DETECTOR, HEAD DRUM SERVO

SIZE D | CODE IDENT NO 96261 | DWG NO X202388

SCALE | SHEET

X202388

ZONE	LTR	DESCRIPTION	DATE	APPROVED
4	C	510K & 50K		

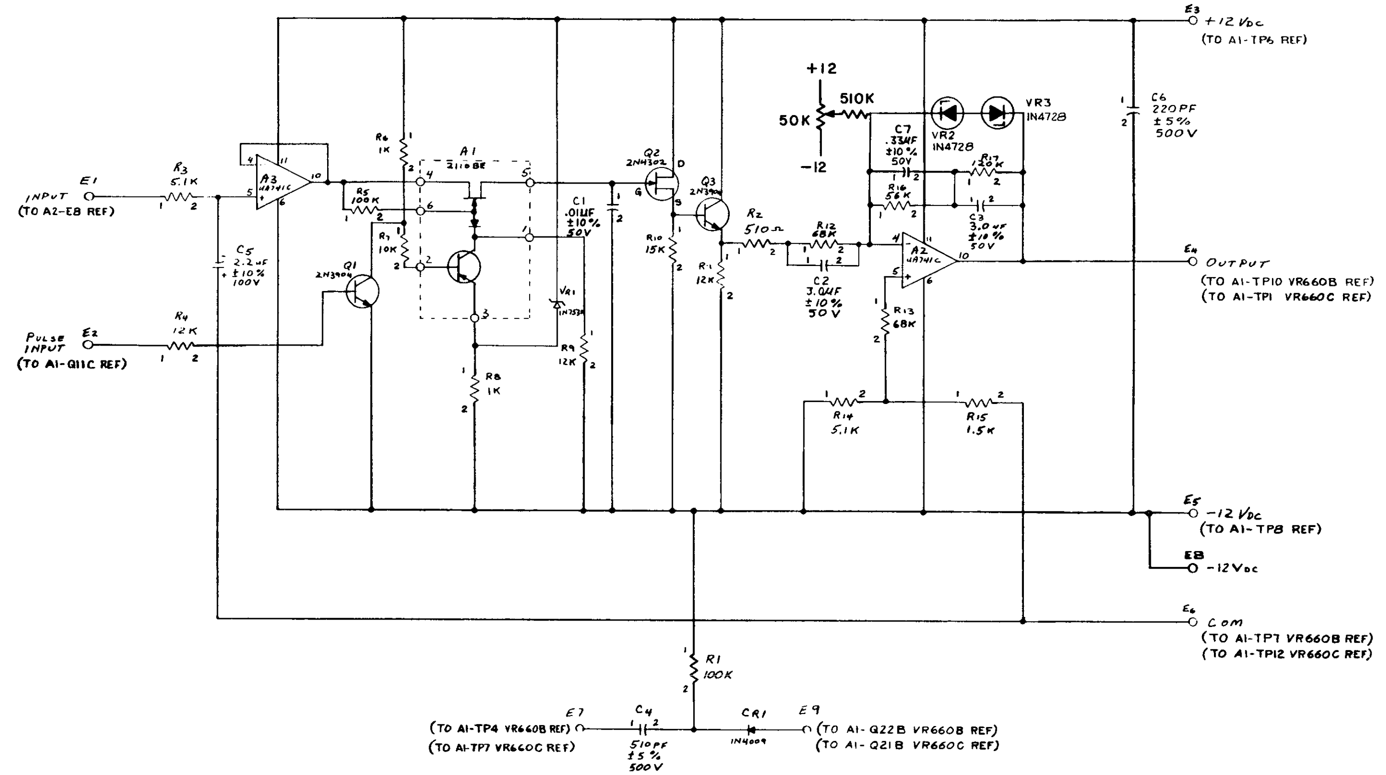


Figure 11d

5. FOR WIRE LIST SEE DWG NO 202517

4. REFERENCE DESIGNATIONS ARE ABBREVIATED: PREFIX WITH UNIT NO AND APPLICABLE ASSEMBLY DESIGNATION A5

3. INTEGRATED CIRCUIT NO. | PART NO | VENDOR CODE
A1 | 2110BE | AMELCO
A2,A3 | ... | ...

ALL RESISTOR VALUES ARE IN OHMS ±5%, 1/4 WATT.

NOTES UNLESS OTHERWISE SPECIFIED

QTY REQD	ITEM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	ZONE

LIST OF MATERIALS OR PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
FRACTIONS ± | .XX
ANGLES | .XXX
MATERIAL
FINISH
SURFACE ROUGHNESS

QTY | QTY | NEXT ASSEMBLY | USED ON
N/A | | HD402 | APPLICATION

CONTRACT NO
DRAWN
CHECKED
DESIGN
ENGINEER
PROJECT
RELEASE
DESIGN APPROVAL

LEACH CORPORATION CONTROLS DIVISION

SCHEMATIC DIAGRAM SERVO LOOP AMPLIFIER — DRUM SERVO

SIZE	CODE IDENT NO	DWG NO	REV
D	96261	X 202389	

SHEET

X202389

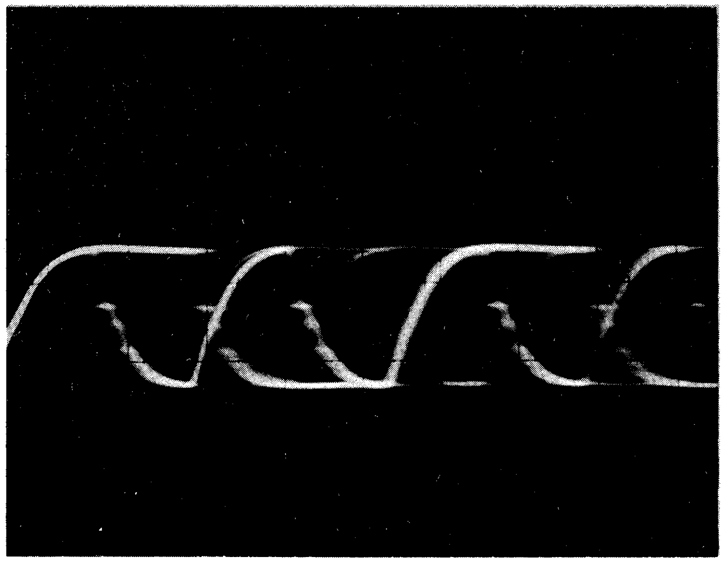


FIGURE 12

TEST POINT LIST FOR CODER

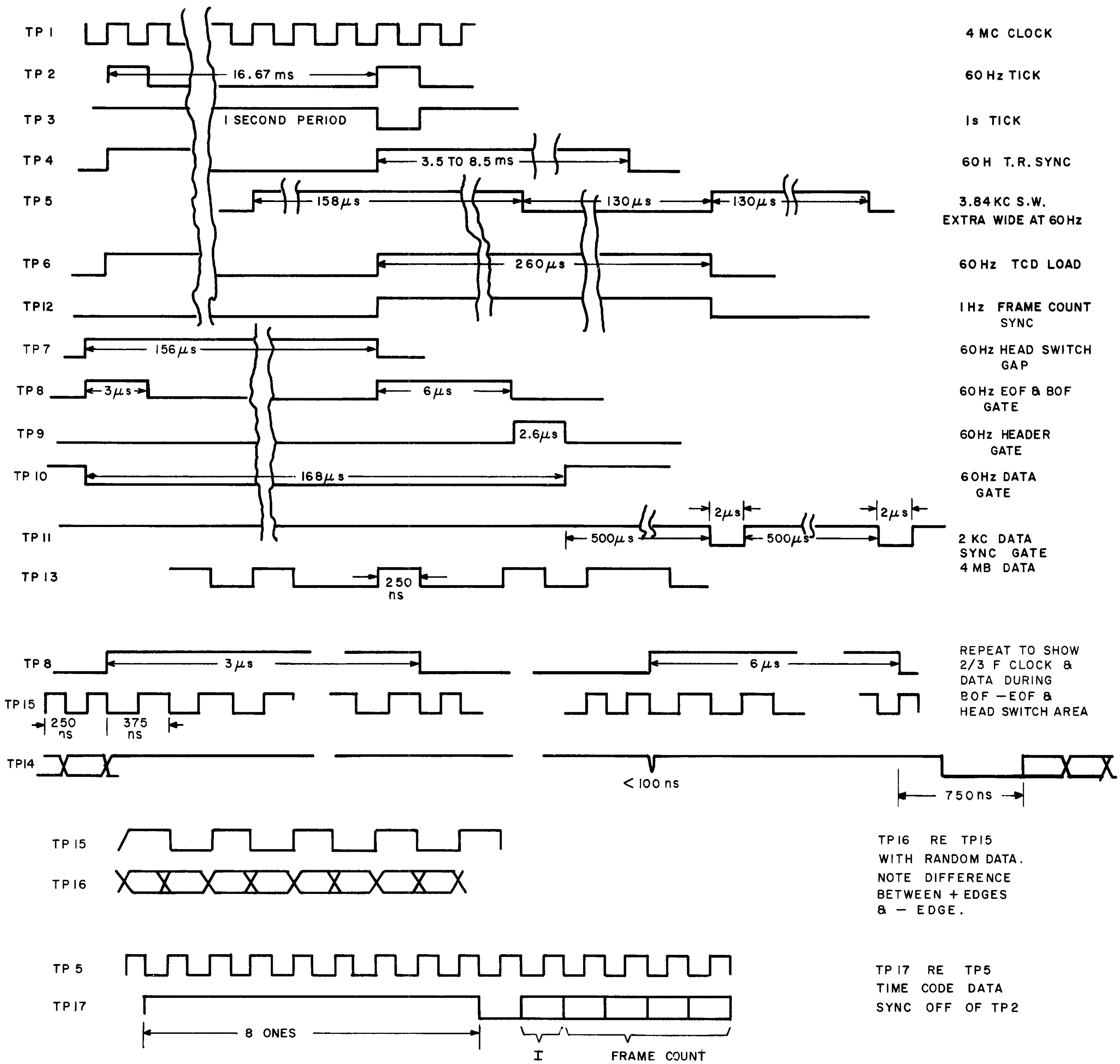


FIG. 13

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED

FIGURE 14

1	1	1	1	1	1	1	1	0	I	F_0	F_1	F_2	F_3	F_4	F_5	S_{00}	S_{01}	S_{02}	S_{03}	S_{10}	S_{11}	S_{12}	S_{13}	M_{00}	M_{01}	M_{02}	M_{03}	M_{10}	M_{11}	M_{12}	M_{13}
H_{00}	H_{01}	H_{02}	H_{03}	H_{10}	H_{11}	H_{12}	H_{13}	D_{00}	D_{01}	D_{02}	D_{03}	D_{10}	D_{11}	D_{12}	D_{13}	D_{20}	D_{21}	D_{22}	D_{23}	X_{00}	X_{01}	X_{02}	X_{03}	X_{10}	X_{11}	X_{12}	X_{13}	0	0	0	0

LEGEND

SYMBOL	WEIGHTING	FUNCTION
F_0	2^0	FRAME COUNT(0-59)
F_1	2^1	
F_2	2^2	
F_3	2^3	
F_4	2^4	
F_5	2^5	FRAME COUNT(0-59)
S_{00}	$10^0, 2^0$	SECONDS (UNITS)
S_{01}	$10^0, 2^1$	
S_{02}	$10^0, 2^2$	
S_{03}	$10^0, 2^3$	SECONDS (UNITS)
S_{10}	$10^1, 2^0$	SECONDS (TENS)
S_{11}	$10^1, 2^1$	
S_{12}	$10^1, 2^2$	
S_{13}	$10^1, 2^3$	SECONDS (TENS)
M_{00}	$10^0, 2^0$	MINUTES (UNITS)
M_{01}	$10^0, 2^1$	
M_{02}	$10^0, 2^2$	
M_{03}	$10^0, 2^3$	MINUTES (UNITS)
M_{10}	$10^1, 2^0$	MINUTES (TENS)
M_{11}	$10^1, 2^1$	
M_{12}	$10^1, 2^2$	
M_{13}	$10^1, 2^3$	MINUTES (TENS)
H_{00}	$10^0, 2^0$	HOURS (UNITS)
H_{01}	$10^0, 2^1$	
H_{02}	$10^0, 2^2$	
H_{03}	$10^0, 2^3$	HOURS (UNITS)
H_{10}	$10^1, 2^0$	HOURS (TENS)
H_{11}	$10^1, 2^1$	HOURS (TENS)
H_{12}	$10^1, 2^2$	HOURS (TENS)
H_{13}	$10^1, 2^3$	HOURS (TENS)
D_{00}	$10^0, 2^0$	DAYS (UNITS)
D_{01}	$10^0, 2^1$	
D_{02}	$10^0, 2^2$	
D_{03}	$10^0, 2^3$	DAYS (UNITS)
D_{10}	$10^1, 2^0$	DAYS (TENS)
D_{11}	$10^1, 2^1$	
D_{12}	$10^1, 2^2$	
D_{13}	$10^1, 2^3$	DAYS (TENS)
D_{20}	$10^2, 2^0$	DAYS (HUNDREDS)
D_{21}	$10^2, 2^1$	
D_{22}	$10^2, 2^2$	DAYS (HUNDREDS)
D_{23}	$10^2, 2^3$	DAYS (HUNDREDS)
X_{00}	$N_0, 2^0$	AUXILIARY INPUTS
X_{01}	$N_0, 2^1$	
X_{02}	$N_0, 2^2$	
X_{03}	$N_0, 2^3$	
X_{10}	$N_1, 2^0$	
X_{11}	$N_1, 2^1$	
X_{12}	$N_1, 2^2$	
X_{13}	$N_1, 2^3$	AUXILIARY INPUTS

5. ALL INPUTS ARE $\overline{DATA}$.
4. 1 BIT IS "1" FOR FRAME LENGTH OF 66.001 AND "0" FOR 66.000.
3. ALL EXTERNAL INPUTS MUST BE IN THE BCD FORMAT
2. LOGIC "0" IS A "HIGH" INPUT TO RECORD ENCODER.
1. LOGIC "1" IS A "LOW" INPUT TO RECORD ENCODER.

NOTE [illegible]

QTY REQD	ITEM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION	ZONE

QTY | QTY | NEXT ASSY | USED ON — APPLICATION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES
FRACTIONS ± .XX ±
ANGLES ± .XXX ±
MATERIAL
FINISH
SURFACE ROUGHNESS

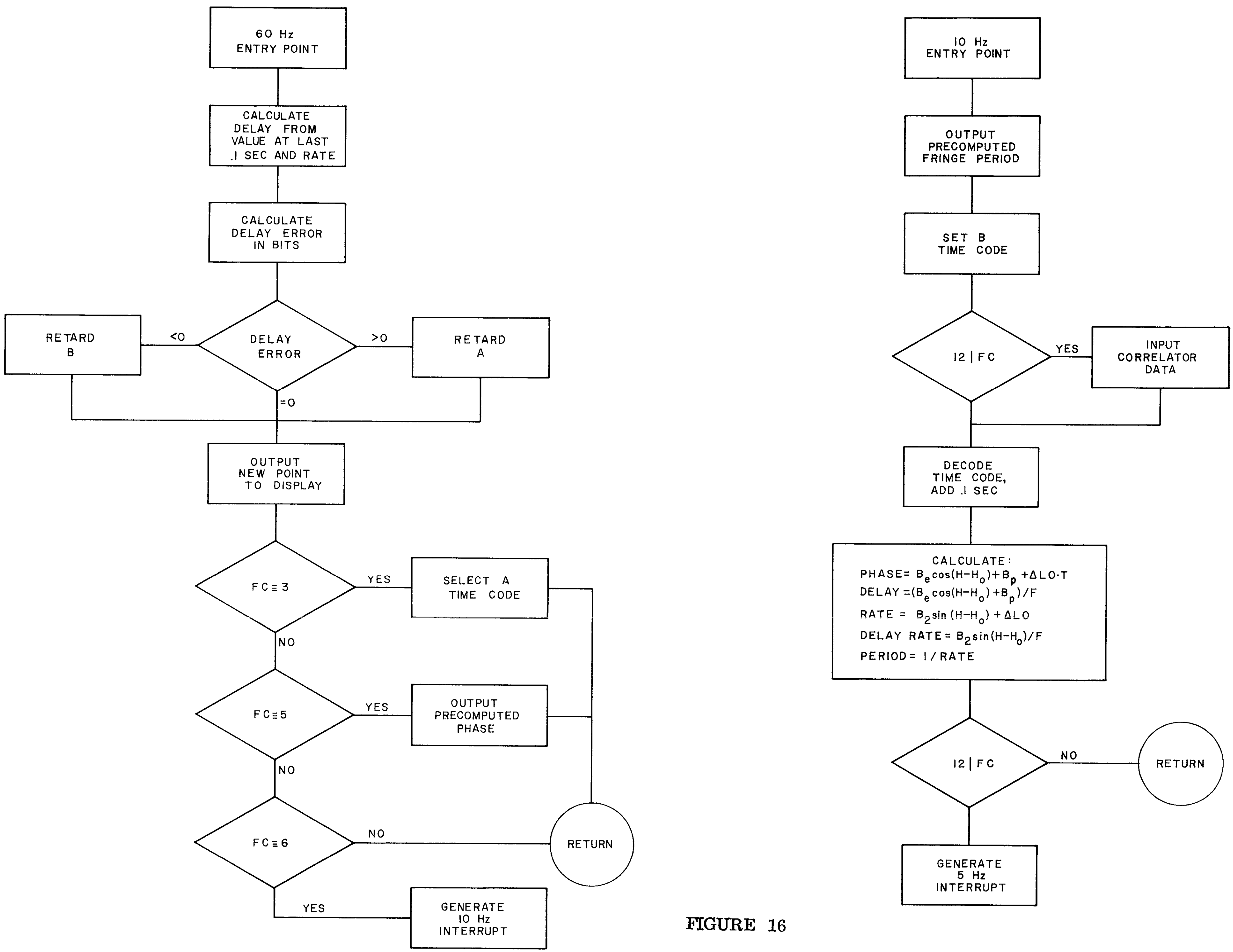
CONTRACT NO.
DRAWN
CHECKED
DESIGN ENGINEER
PROJECT RELEASE
DESIGN APPROVAL
DESIGN APPROVAL

LEACH CORPORATION
CONTROLS DIVISION
717 NORTH CONEY AVENUE AZUSA, CALIFORNIA

LONGITUDINAL TAPE FORMAT
TIME CODE DATA
NATIONAL RADIO ASTRONOMY OBSERVATORY

SIZE	CODE IDENT NO.	DWG NO.
B	96261	FIGURE 14

SCALE | SHEET 1 of 1



60 Hz ENTRY POINT
CALCULATE DELAY FROM VALUE AT LAST .I SEC AND RATE
CALCULATE DELAY ERROR IN BITS
DELAY ERROR
RETARD B
<O
>O
RETARD A
=O
OUTPUT NEW POINT TO DISPLAY
FC≡3
YES
SELECT A TIME CODE
NO
FC≡5
YES
OUTPUT PRECOMPUTED PHASE
NO
FC≡6
NO
RETURN
YES
GENERATE 10 Hz INTERRUPT
10 Hz ENTRY POINT
OUTPUT PRECOMPUTED FRINGE PERIOD
SET B TIME CODE
12 | FC
YES
INPUT CORRELATOR DATA
DECODE TIME CODE, ADD .I SEC
CALCULATE:
PHASE= $B_e\cos(H-H_o)+B_p+\Delta LO\cdot T$
DELAY $=(B_e\cos(H-H_o)+B_p)/F$
RATE = $B_2\sin(H-H_o)+\Delta LO$
DELAY RATE= $B_2\sin(H-H_o)/F$
PERIOD= 1/RATE
12 | FC
NO
RETURN
GENERATE 5 Hz INTERRUPT

FIGURE 16

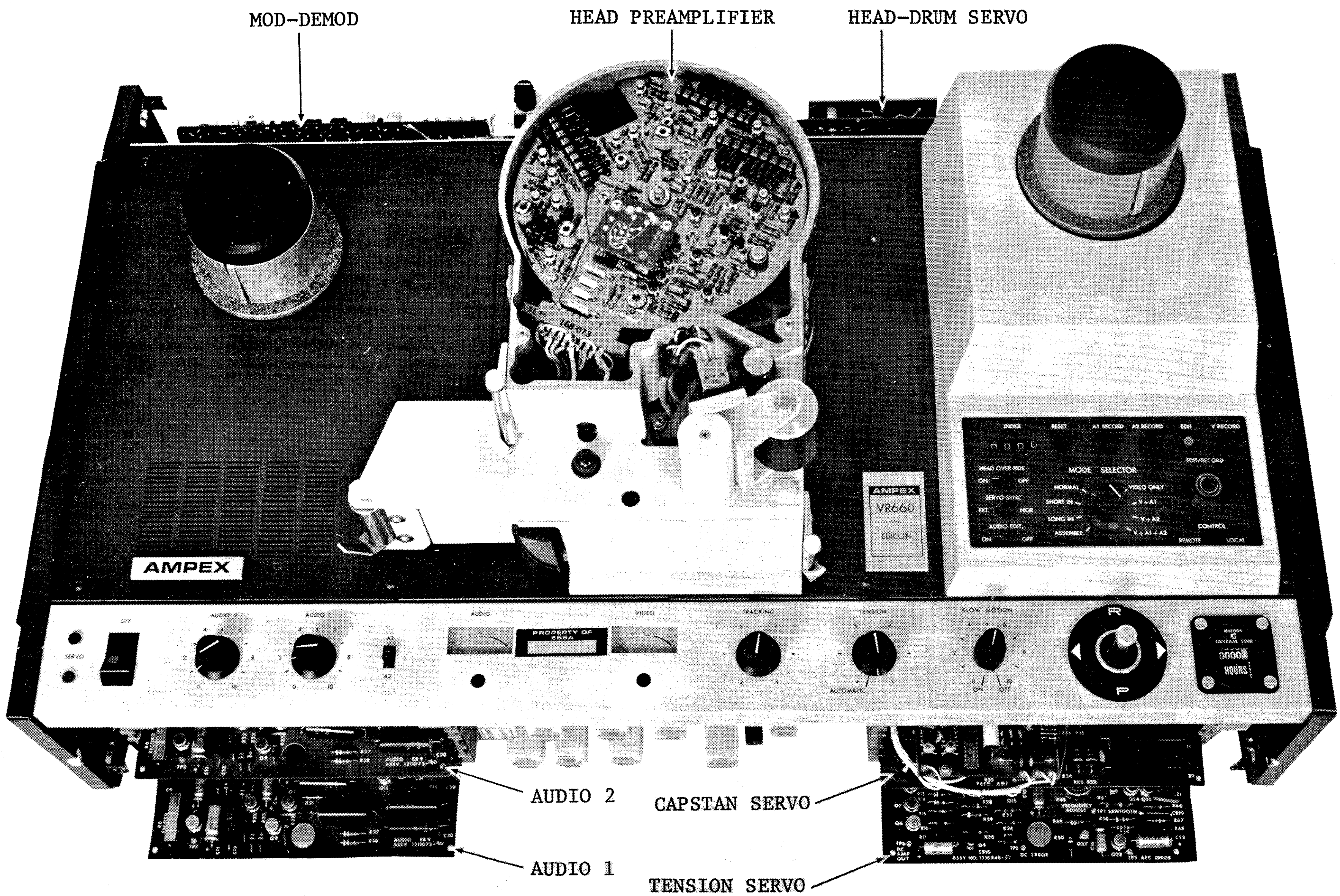

MOD-DEMOD
HEAD PREAMPLIFIER
HEAD-DRUM SERVO
AMPEX
VR660
AUDIO 2
AUDIO 1
CAPSTAN SERVO
TENSION SERVO

FIGURE 17

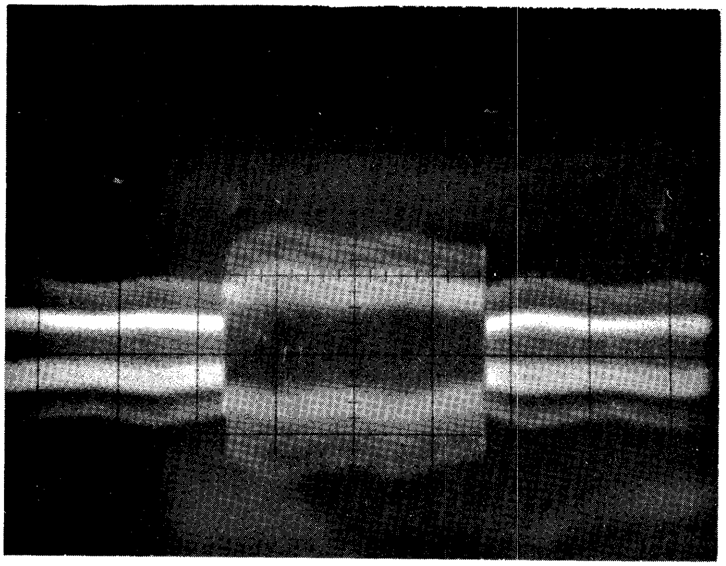


FIGURE 18a

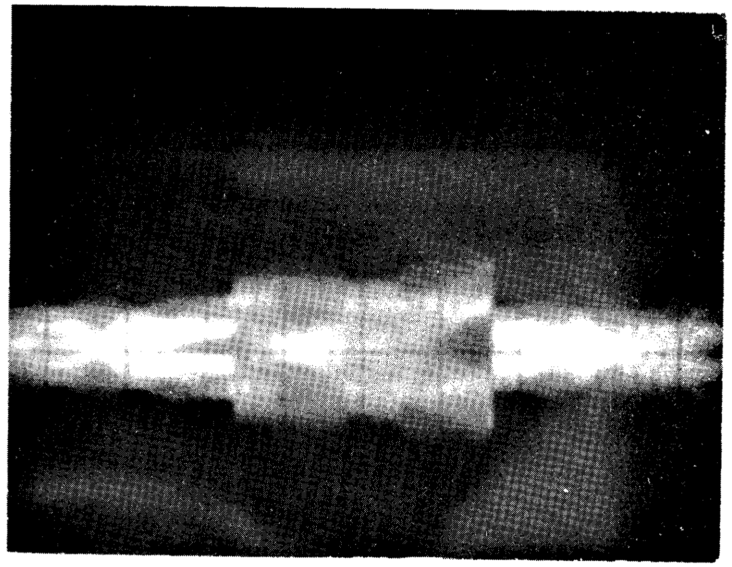


FIGURE 18b

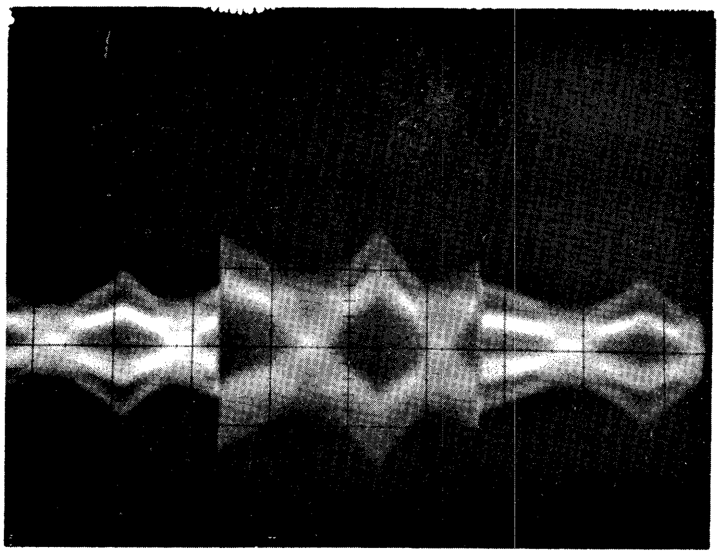


FIGURE 18c

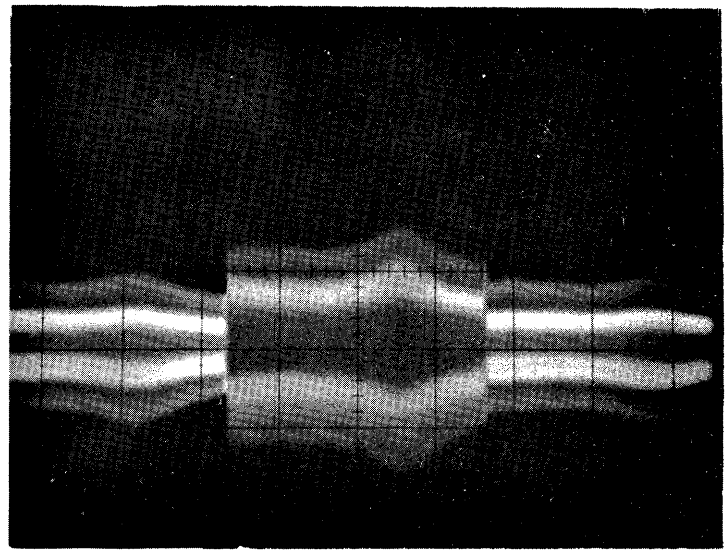


FIGURE 18d

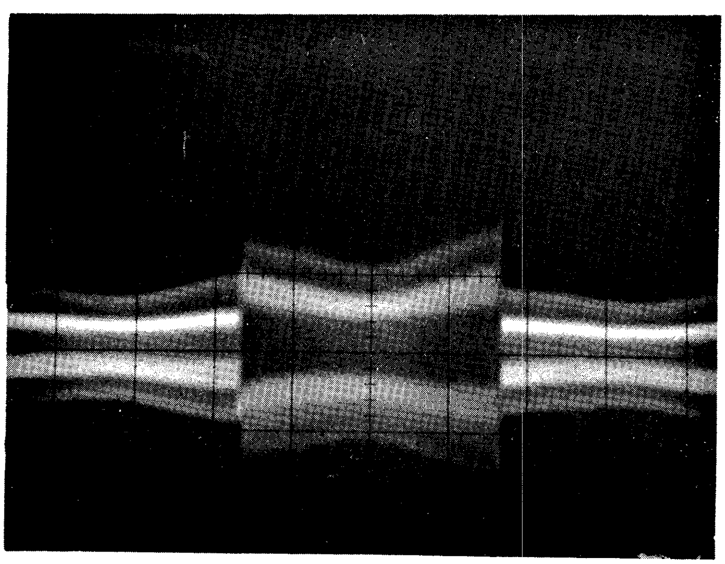


FIGURE 18e

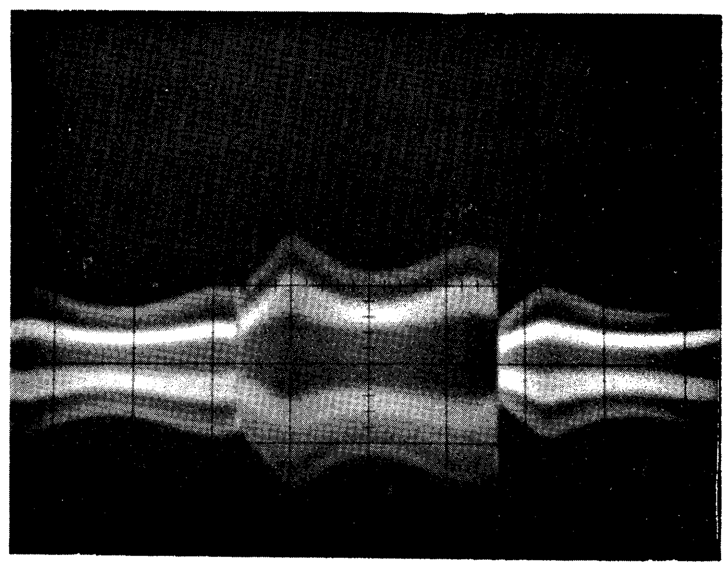


FIGURE 18f

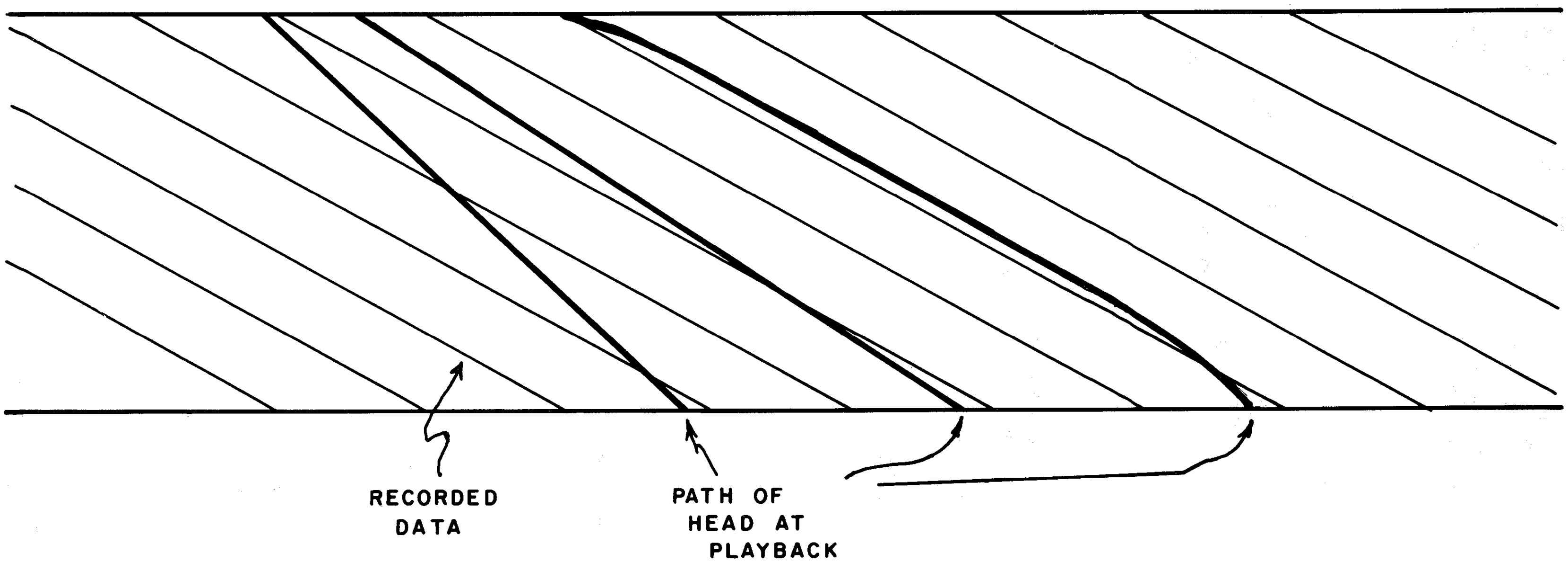


FIG. 18g

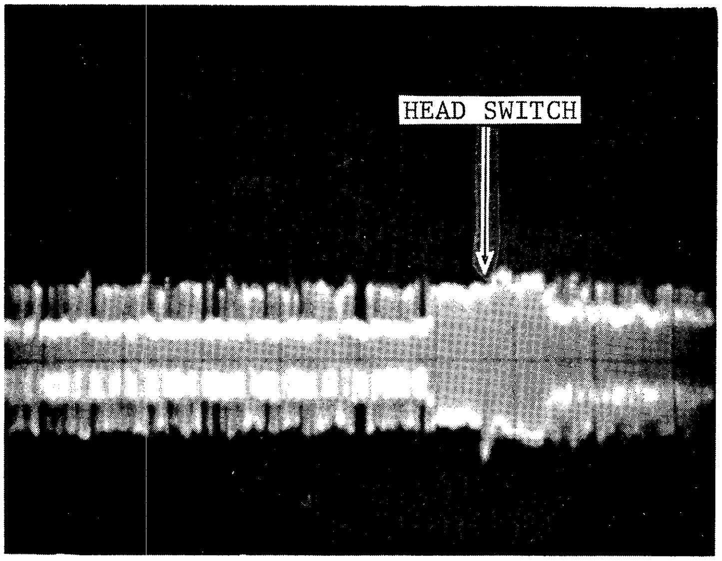


FIGURE 19a

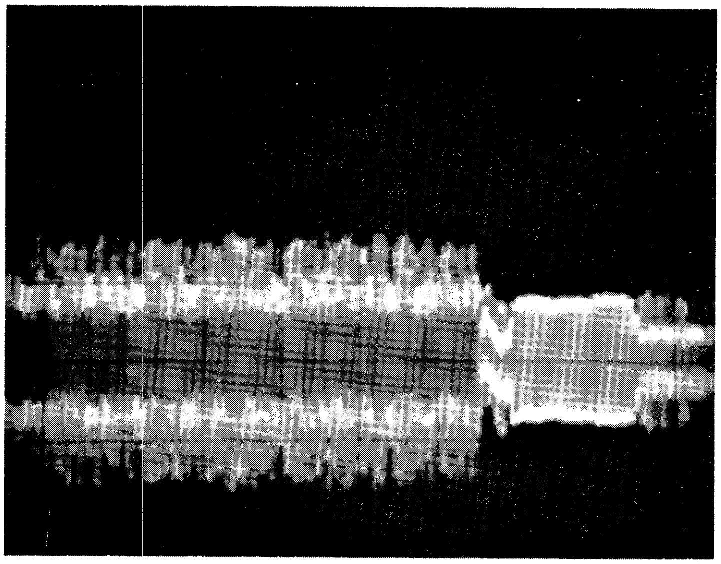


FIGURE 19b

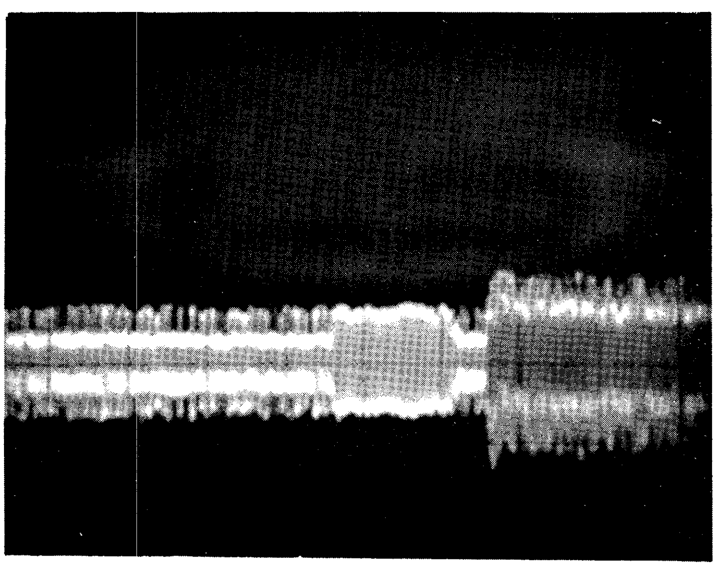


FIGURE 19c

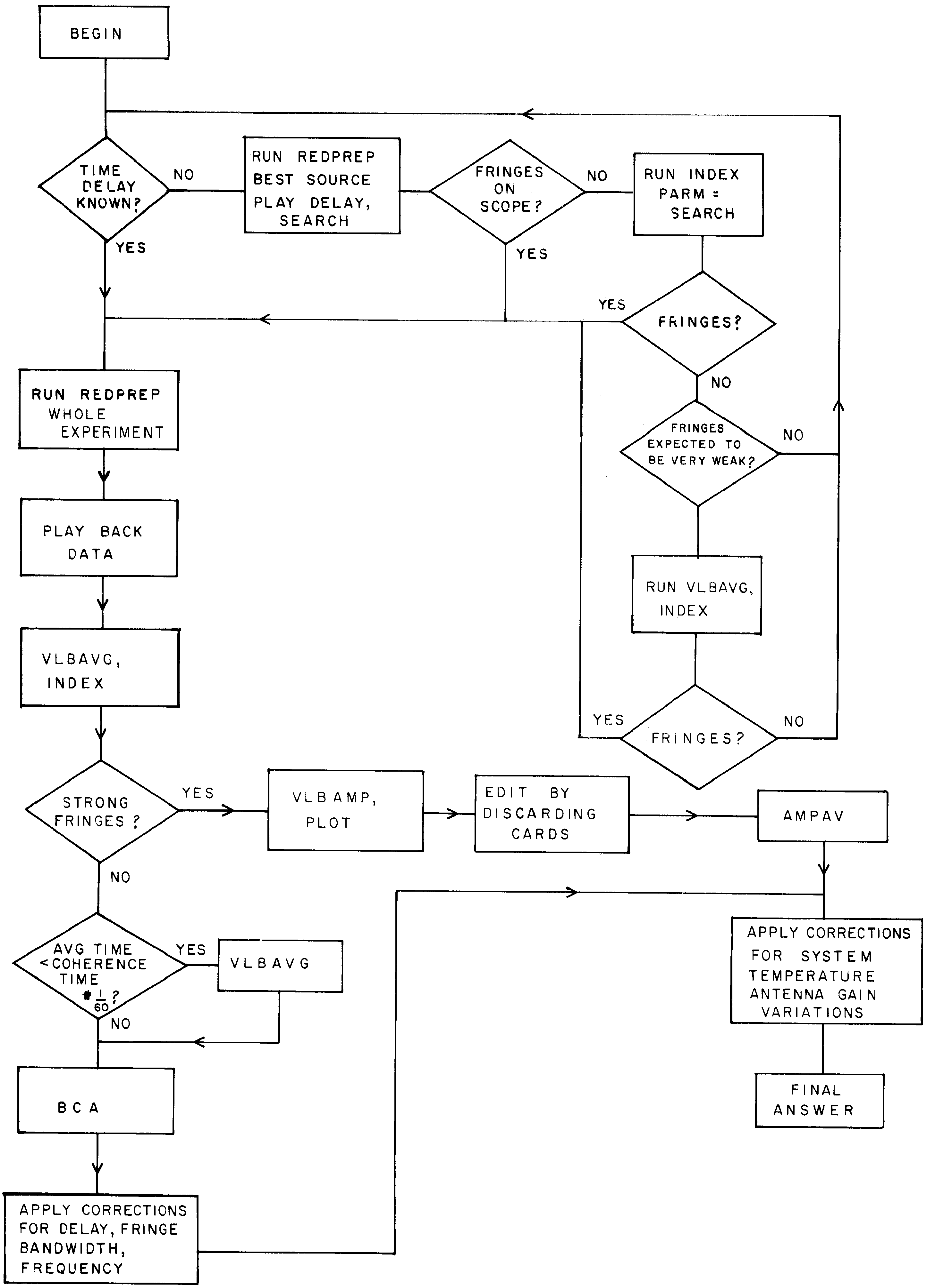

BEGIN
TIME DELAY KNOWN?
NO
YES
RUN REDPREP BEST SOURCE PLAY DELAY, SEARCH
FRINGES ON SCOPE?
NO
YES
RUN INDEX PARM = SEARCH
FRINGES?
YES
NO
FRINGES EXPECTED TO BE VERY WEAK?
NO
RUN VLBAVG, INDEX
FRINGES?
YES
NO
RUN REDPREP WHOLE EXPERIMENT
PLAY BACK DATA
VLBAVG, INDEX
STRONG FRINGES ?
YES
NO
VLBAMP, PLOT
EDIT BY DISCARDING CARDS
AMPAV
AVG TIME <COHERENCE TIME # 1/60 ?
YES
NO
VLBAVG
BCA
APPLY CORRECTIONS FOR DELAY, FRINGE BANDWIDTH, FREQUENCY
APPLY CORRECTIONS FOR SYSTEM TEMPERATURE ANTENNA GAIN VARIATIONS
FINAL ANSWER

FIG. 22

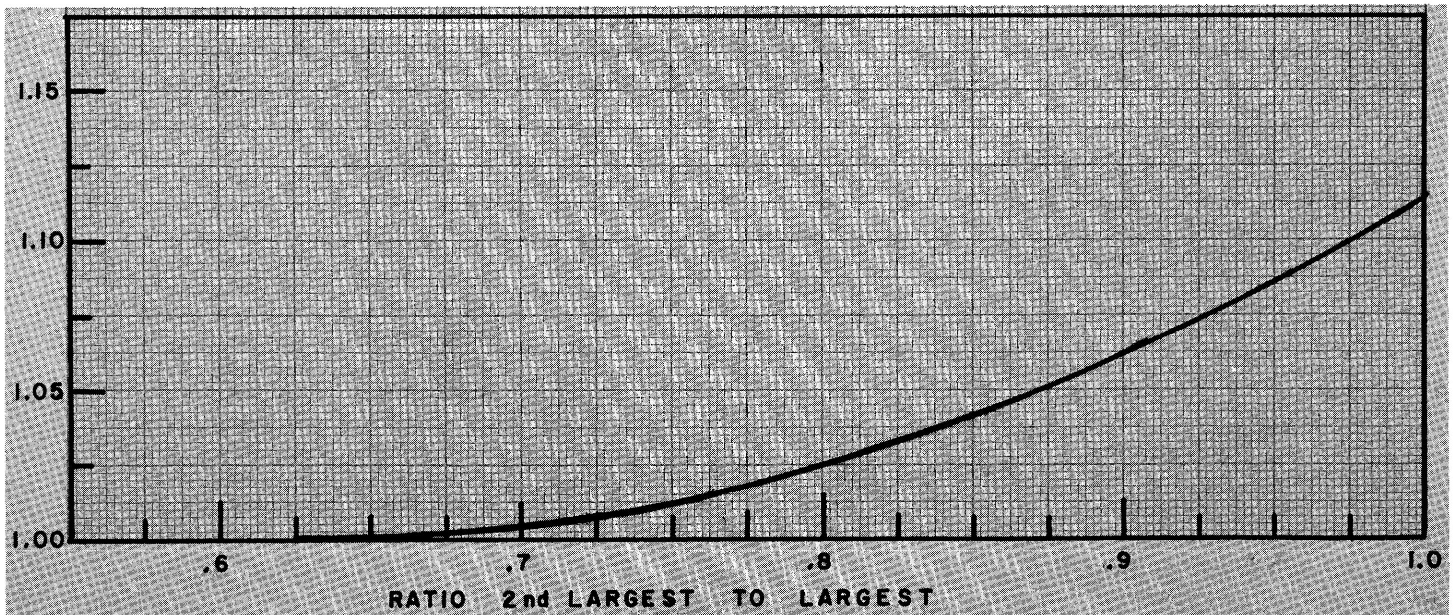


FIG. 25