RECONSTRUCTING PULSE-CODE MODULATION TELEMETRY DATA WITH DROPOUTS

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ABSTRACT

A data handling system was developed which transfers serial pulse-code modulation (PCM) telemetry data from an analog tape to a digital tape for analysis on a digital computer. The PCM data were collected from field experiments in snow skiing which measured the excitation between the ski boot and the ski. PCM data were FM transmitted and stored on an analog tape recorder. In the laboratory, data were decoded from the tape and parallel input to a Nova minicomputer which buffered the data and wrote tapes compatible with a CDC 6400 computer. A custom-built PCM decoder provided control and status commands to drive the minicomputer interrupt logic. The data transfer rate was 50 kbits/s.

Special consideration was given to the problem of information losses. Lost data frames were not stored by the minicomputer and the data time series on the digital tape is discontinuous at each loss point. Spectral analysis of data with discontinuities produces erroneous results. Fourier coefficients and power spectra were computed for both continuous and discontinuous signals. Discontinuities caused significant reductions in amplitude and increase in bandwidth of spectrum estimates. Unique software eliminated data discontinuities by reconstructing the original time-base with linearly interpolated pseudo-data. Results are presented which show the enhanced accuracy obtained in spectrum estimates with the reconstructed data.

INTRODUCTION

In field applications involving remote data acquisition by RF telemetry a common and frustrating problem is that of telemetry dropouts. The word “dropout” usually refers to information lost in the telemetering process. As will be discussed, however, information losses may also stem from equipment used to handle stored data. The word “dropout” will be used herein synonymously with the words “information loss”. The word “dropout” will be qualified to denote whether data handling equipment or telemetry was the source. When the relative position between the transmit and receive antennas changes, nonoptimal telemetering situations may develop where the transmitted signal is actually not detected by the receiver. Accordingly, the information transmitted during this interval is lost. The mechanisms responsible for lost reception are difficult to isolate because of the complexity of the RF transmission process. At least three different mechanisms, however, are associated with transmission difficulty over short ranges (less than 10 km). Most RF telemetry is FM because of the inherent superior signal/noise. The quality of FM transmission is sensitive to maintaining a line-of-sight to the receiver. One telemetry dropout mechanism is objects which momentarily block the line-of-sight path between transmit and receive antennas. Signal strength drops below the receiver threshold and reception is lost. Another mechanism is the changing impedance of the transmit antenna as it receives RF signals reflected at varying signal levels from the immediate surrounding environment (1). Because the transmitter frequency depends on the load impedance, the transmitter carrier actually shifts and reception is lost when the receiver becomes detuned. This problem can be circumvented by incorporating an RF isolator into the path between the transmitter and transmit antenna. The isolator, by absorbing the reflected energy, maintains a nearly constant load impedance. A final mechanism is the cancellation of the received signal when reflected RF waves arrive ~180° out-of-phase with the line-of-sight RF transmission (2). This is a common problem at UHF telemetry carrier frequencies in the 215-250 MHz band. Reception improvements are possible by using a directional receiving antenna which is insensitive to reflected incident waves outside its radiation pattern.

To insure high quality telemetering, attention must be given to each of the three mechanisms. Even with line-of-sight transmission, an isolator and a directional receive antenna, telemetry dropouts may still be problematic, however. In telemetry over long distances, for example, transmission quality is affected by the ionization characteristics of the atmosphere. Also, even over distances less than a kilometer, the receive antenna may not be sufficiently directional to eliminate unwanted signals. Finally, the radiated signal strength at any point in space is dependent on the radiation pattern of the transmit antenna. if the orientation of the transmit antenna changes, then the radiated energy at the receive antenna may be sufficiently attenuated to lose reception (3). The severity of this problem is reduced by using omnidirectional antennas such as the helical dipole but the transmitter power requirements are increased (4). So, while in many cases the telemetry dropout problem can be minimized, dropouts cannot be completely eliminated.

The dropout problem is important because it bears not only on the quality of transmission, but also on the data reduction process and interpretation of results from data analyses. As noted, dropouts result in lost information. In certain situations it is possible to estimate or reconstruct the lost information. If the dropouts are long in duration compared to the lowest frequency of interest in the data, then it is not possible to reconstruct any meaningful information. If the dropouts are short compared to any frequency of interest, however, then it is possible to estimate lost information using some interpolation scheme. Estimating lost data (i.e. replacing noise with meaningful information) is critical for certain basic data analysis techniques where numerous short duration dropouts would preclude analysis altogether. An example is spectrum analysis where one wishes information regarding the frequency content of the data. Here, one must have a data segment free of noise at least twice the length of the period corresponding to the lowest frequency of interest. Without such a data segment, valid analysis is not possible.

This paper discusses a new technique for partial reconstruction of pulse-code modulation (PCM) telemetry data with dropouts. In the research application which yielded the PCM data, it was desired to compute power spectral density estimates. The enhanced accuracy of the spectrum estimates obtained with the reconstructed data are illustrated on a sample problem. The data reconstruction technique is actually one phase of a large intermediate data processing scheme which is also discussed.

TELEMETRY APPLICATION

The injury rate in snow skiing, approximately 3 lower extremity injuries per 1000 skier days, has been maintained over the past two decades. In 1974, a research program was undertaken at the University of California with the objective of measuring the resultant excitations between the ski boot and ski during both cruising skiing and the critical situations which call upon the ski release binding to release. This data is important to the design and adjustment of the ski release binding. These research objectives demanded that accurate data be remotely acquired. Accordingly, a complete instrumentation system was designed and developed for the skiing injury problem. A precision PCM-FM telemetry transmit system shown pictorially in Fig. I and schematically in Fig. 2 was custom built to transmit data from two six degree-of-freedom strain-gage dynamometers mounted inside the test ski to a receiving station about 3 km distant. In the telemetry package shown in Fig. 1, dynamometer signals were conditioned by a high gain, low noise carrier amplifier system. The 13 data channels were serially pulse-coded into 12 bit words each at a 520 words/s digitizing rate. The 16-word data frame also shown in Fig. 2 was completed by a sync word (word with a constant binary value for synchronization of data frames) and two

12-bit frame counter words. The 520 words/s digitization rate yielded a real time data transmission rate of 100 kbits/s. Subsequent to PCM encoding, data were further coded into bi-phase L(Bi-ϕ L) and FM transmitted.

DATA HANDLING SYSTEM

A data handling system is necessary in many telemetry applications because it is often not feasible to analyze data in real time at the receiving site. A bulk storage device is required so the data can be subsequently analyzed. PCM data analysis necessitates transferring the data from the field storage device to the computer. In this case, most data handling operations include the following:

1. An analog tape recorder which can record the data in real time and reproduce the data either in real time or at a reduced data rate;
2. A PCM bit and word decoder;
3. A hardware interface to the decoder which writes computer compatible tapes in real time or at a reduced data rate, or
4. A minicomputer with a data interface and the capability to write computer compatible tapes.

When the skiing excitation data were received (Fig. 2), they were decoded in two stages by the 12 bit, 16-word PCM decoder shown in Fig. 3. The bit synchronizer stage formed the serial PCM data and the word synchronizer stage blocked the PCM data into 12-bit words and 16-word data frames. To monitor system function, data were presented visually in rows of 12 (bit) panel lights and any two channels could be selected for D/A conversion.

The data consisted of a number of approximately 30 second skiing runs sequentially recorder on a 7 track, 250 kHz Sanborn instrumentation recorder. To achieve maximum data density, runs were recorded on one track until it was full and then recorded on the next track after the tape was rewound, etc. Recording data on all seven tracks at 60 ips gave a data density of ~12000 bpi.

In the laboratory, bi-phase data, reproduced from the analog recorder, were played into the custom built PCM decoder as depicted in Fig. 4. The decoder design is discussed in detail by Hull and Mote (5,6). As the serial bi-phase data were decoded, they were output along 12 parallel lines to the data interface in the Nova minicomputer. The PCM decoder provided status and control commands along three additional lines to drive the minicomputer interrupt logic. The timing diagram for command signals is shown in Fig. 5.

On one line, a 1 μsec FRAME PULSE denoted the beginning of each new data frame and on another line a WORD PULSE signified a new word. On the third SYNC LEVEL line, a transition from +4.0 V, or logical true, to 0.V signified a synchronization loss arising from an information dropout. The sync word recognition circuit in the decoder, which counted the number of properly timed sync words, controlled the level transition. If three consecutive sync words were 16 words apart, the circuit was synchronized (true); if three consecutive sync words failed to appear or were improperly timed, a lock-loss (false) was registered. Therefore, the minimum information loss for a recognized dropout was six data frames or 6/520s.

A Nova (Data General Corp.) minicomputer was used to buffer the data, check the timing of the control commands, and write CDC 6400 compatible tapes. According to the flow diagram in Fig. 6, word pulses were counted and checked against arriving frame pulses. Errors caused by a word count different from 16 effected a program halt. As data were accepted, they were stored in one of two 1500-word buffers which were alternately being loaded with data and written onto CDC 6400 tape. The sync word (word 0) at the beginning of each frame was not stored and each buffer contained 100 data frames. The CDC 6400 utilizes a 60-bit word so that the fifteen 12-bit words comprising a data frame were written onto digital tape in three 60-bit groups. Using software developed for the CDC 6400, data tapes were ultimately rewritten so that data frames consisted of fifteen 60-bit words each with 12-bits right justified. When synchronization was lost, storage of the data ceased while the machine waited for a SYNC LEVEL true. During this period, the computer backed up three frames and began storing from that point because those frames contained faulty information. The flow diagram in Fig. 6 does not show the alternating buffers. This feature in itself did not increase complexity but rather the software became more involved because synchronization (sync) losses might have occurred just prior to the buffer transition. For example, if a sync loss appeared after one frame had been stored in buffer 10 (the 10th buffer to be filled), then the last two frames in buffer 9 would have to be erased in addition to the frame in buffer 10. In spite of the additional machine time required for this programming feature, the data transfer rate from analog tape to computer compatible tape was 50 kbits/s or half the original data transmission rate.

To make the data handling process easy to operate and provide monitoring and checking capabilities, a number of program features were added. Program control was achieved through two teletype commands which initiated or terminated data storage. When the termination command was typed, storage in the current buffer was completed, the buffer was written onto tape, and the last data word was followed by an end-of-file mark. Since these commands could be utilized at any time during the data transfer, the user had great flexibility in determining what segments of data were desired for analysis. The program also incorporated a display feature such that any two data channels could be selected through the accumulator switches, D/A converted, and displayed on an oscilloscope. Data could be displayed whether or not the initiate-data-storage command had been entered. In this way, the data were scanned so that only those sections of interest were written onto digital tape. Computer costs were reduced since the volume of data was minimized. A final software package was written to facilitate the tape handling. This package also enabled checking the data transfer by playing back the data tapes and displaying channels on the oscilloscope.

INFORMATION LOSSES

One type of data loss occasionally encountered in the current program was due to the receiver becoming detuned when RF reflection patterns changed as the skier moved down the mountain. The duration of the losses ranged from .1 to .3 seconds and a typical loss record is shown in Fig. 7. A type of synchronization loss, which also occurred, was accountable to the Sanborn instrumentation recorder. The bi-phase waveform (serial PCM data), which was recorded at the 100 kHz bit rate, was degraded by the limited frequency response (3 db down @ 250 kHz) of the direct record-reproduce amplifiers. Losses appeared during data playback when the waveform degradation became too severe for the decoder to function properly. These data losses, which appear as sharp spikes in Fig. 7, were usually short in duration (~ .02 s) so that only 6 to 10 data frames were lost.

In the minicomputer process, data storage ceased when an information loss was encountered and began when data again became valid. This resulted in a data discontinuity or time base shift at the loss point. If the data sampling interval is Δt, then for data with no information loss

$$t(i + 1) = t(i) + \Delta t \tag{1}$$

where the i represents data points on the digital tape and t is the time relative to the start of the data. In the case of an information loss of say P frames between i and i + 1

$$t(i + 1) = t(i) + P \cdot \Delta t \tag{2}$$

This discontinuity is displayed in the 2 Hz sine wave of Fig. 8 with P = 50 frames or ~.1 seconds.

Spectral analyses of data segments with discontinuities do not accurately give the frequency content of the original data. Figures 8a and 8b compare the power spectral density estimates for the signal waveforms shown and illustrate the inaccuracy for this particular example. These power spectrum estimates were obtained by using the Cooley-Tukey Fast Fourier Transform (FFT) method (7) to compute Fourier coefficients F_k

$$F_k = \sum_{n=0}^{N-1} A_n \exp \left[\frac{-i2\pi kn}{N} \right] \tag{3}$$

k is the kth frequency component, N the total number of data points and A_n the data point values referenced to zero mean. The sampling rate for this example was 1024 points/s. Data preprocessing included cosign tapering of the boxcar filter shape to achieve minimum leakage as recommended by Bendat and Piersol (8). Raw power spectrum estimates G_k were formed by

$$G_k = \frac{2h}{N} \left[F_k \right]^2 \tag{4}$$

where the data time interval h is .976 ms. After scaling raw estimates for tapering effects, frequency smoothing was employed to reduce the normalized standard error. The dropout spectrum in Fig. 8b exhibits a 30% reduction in power at the 2 Hz estimate and a bandwidth increase from ~ 9 Hz to ~ 19 Hz at the 20 db power level. These result from the high frequency components in the discontinuity. Clearly, interpretation of such results may lead to erroneous conclusions and it is desirable to minimize these errors.

Errors resulting from data discontinuities were minimized here by reconstructing the original time base. The simplified flow chart in Fig. 9 shows a software technique coded in Fortran which was used to rewrite data tapes on the CDC 6400. After a data physical record had been read by the CDC 6400, dropouts were monitored by checking for sequential counts in the least significant frame counter word. A result +1 caused buffered storage of a single frame with program control returning to check the next count. Counts different from +1, except for a counter turnover, originated an information loss. When a loss was encountered, the exact number of lost frames was determined from the word count difference. Lost data frames were reconstructed by storing pseudo data word values linearly interpolated from the verified data bounding the information loss. A record of the data loss was provided by replacing the most significant frame counter word (See Fig. 2) with a dropout flag. When data histories were plotted and analyzed, this separated the actual data and interpolated pseudo data. Data intervals with either a high dropout density or a long duration dropout were not analyzed. When the fixed length buffer was full, it was written onto an intermediate file. Control returned to the dropout checking program which processed and read more data as required. Program logic became complex because a buffer could become full during a dropout, in the middle of a physical record unit (PRU), between PRU's, etc. when processing was completed, the intermediate file was written onto a new tape which was then used for data reduction.

It should be noted that when a dropout is longer than half the period of the lowest frequency component in a signal, then interpolating the pseudo-data points cannot enhance the accuracy of the waveform and these data sections should not be analyzed. More generally, if a dropout is longer than half the period of any frequency component, that information is not retrievable and the error of the spectral density in this component may be large.

CONCLUDING REMARKS

The data preprocessing system outlined features ease of operation, versatility, and flexibility. The system can be easily adapted to accommodate any length data frame or bit rate. Regarding the bit rate, the real-time data transfer is 50 kbits/s as discussed. Much higher telemetered bit rates can be handled by utilizing an analog recorder with compatible frequency response and reducing the data playback speed. The real-time data transfer capability is dependent primarily on the minicomputer cycle time rather than the writing capabilities of digital tape machines. Minicomputers such as the PDP-11 are available with cycle times at least 6 times greater than the Nova, so that the data transfer rate could be faster. Different data frame lengths will require various degrees of software modification depending on the types of computers used. The present system with equal sampling rates on all 16 channels, 15 words/frame, and 12-bit words fitting nicely into three 60-bit words, is probably the simplest case. For a lesser number of channels, the extra 12-bit words can be loaded with zero. This maintains simplicity of the tape format at the expense of decreased data density. A multichannel system which encodes data channels at varying rates would present unique problems in the interpolation process. Not only will the number of lost frames have to be computed, but also the interpolated points must be based on knowledge of the frame structure (sampling sequence).

Another note concerns the two frame counter words (see Fig. 2). In the restructured data frames, the most significant frame counter word was replaced with a dropout flag as discussed. It is, of course, not necessary to have an unused word in the transmitted data frame to eventually use for dropout identification. This flag word might be created by the software and incorporated as part of the data frames written on the final reconstructed data tape. For the application here, one 12-bit frame counter word is adequate because it turns over every 7.88s at the 520/s sampling rate. Information losses are shorter than this time so that one can account for all data frames. If the original time base is to be known, then the counter turnover must be long enough to include any duration loss possibly encountered.

A final point concerns when the data reconstructing is actually performed. Here, all reconstructing was done in a batch process on the CDC 6400 computer. While this method was workable in the present program, it augmented the cost of data analysis and degraded data handling efficiency. These undesirables could be eliminated by reconstructing data in real-time with the minicomputer. This would, of course, complicate the minicomputer software and probably degrade the data transfer rate. Inasmuch as the technique of real-time reconstructing is currently under development, rates cannot be estimated as yet.

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REFERENCES

1. Mozer, F., Acting Head, Space Sciences Laboratory, University of California, Berkeley, personal communication, 1976.

2. Vreeland, R. W., Rutkin, B. B., and Yeager, C. L., “Tuned Loop Receiving Antennas for Indoor Telemetry”, Biotelemetry III, Academic Press Inc., San Francisco, 1976, pp. 333-336.

3. Terman, F. E., Electronic and Radio Engineering, McGraw-Hill, New York, 1955, pp. 86-4 -934.

4. Neukomm, P. A., “Body Mounted Transmitting Antennas: Radiation Patterns and Design of Helical Dipole Antennas”, Biotelemetry III, Academic Press Inc., San Francisco, 1976, pp. 345-348.

5. Hull, M. L., and Mote, C. D., Jr., “PCM Telemetry in Ski Injury Research: I. Instrumentation”, Biotelemetry, Vol. 1, No. 4, 1974, pp. 182-191.

6. Hull, M. L., and Mote, C. D., Jr., “Skiing Injuries: Field Loading and Analysis”, Dept. of Mech. Engr., University of California, Berkeley, Nov. 1975, pp. 116.

7. Cooley, J. W., and Tukey, J. W., “An Algorithm for the Machine Calculation of Complex Fourier Series”, Mathematics of Computation, Vol. 19, April 1965, pp. 297-301.

8. Bendat, J. S., and Piersol, A. G., Random Data: Analysis and Measurement Procedures, Wiley - Interscience, New York, 1971, pp. 286-330.

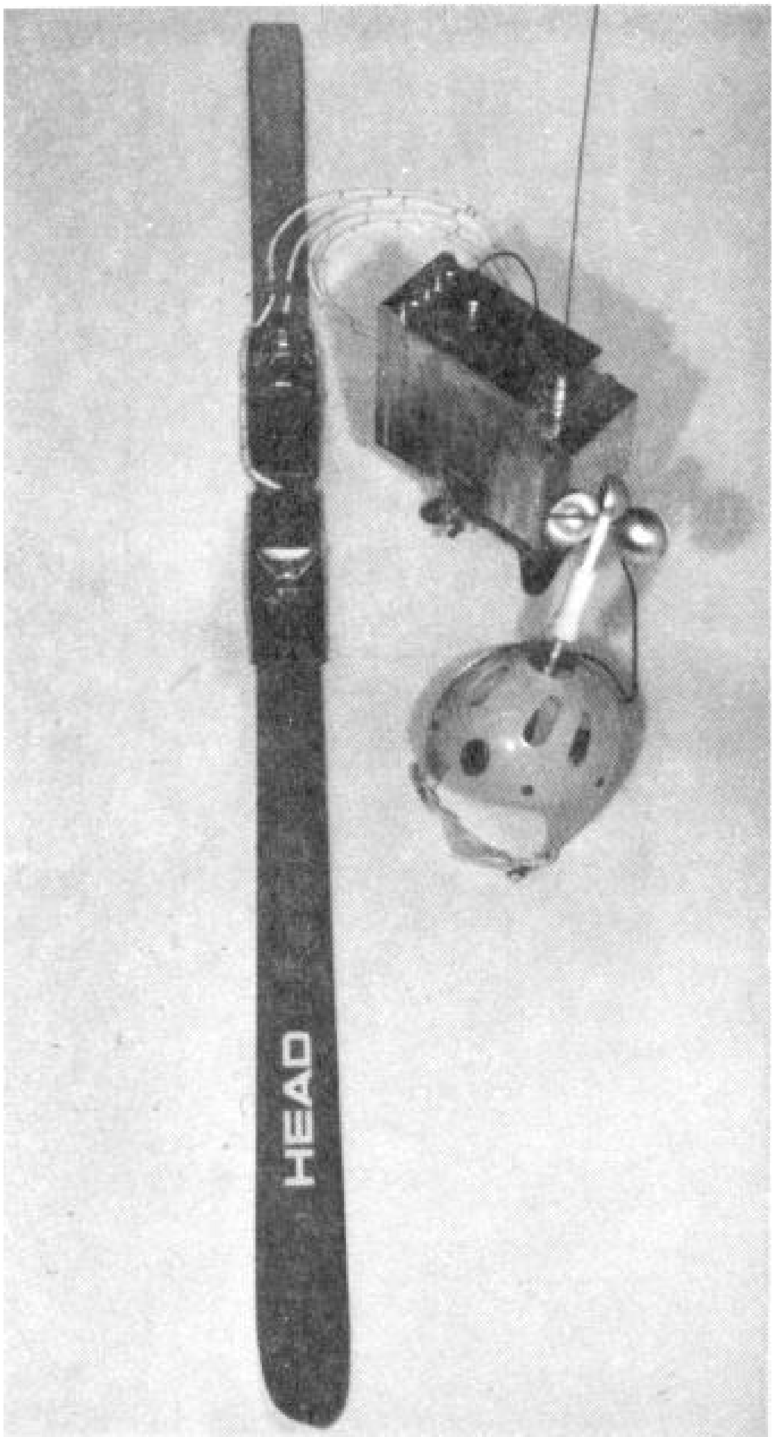

Figure 1. **Test Ski With Dynamometers, Anemometer, and Telemetry Package Containing Transmit Electonics.**

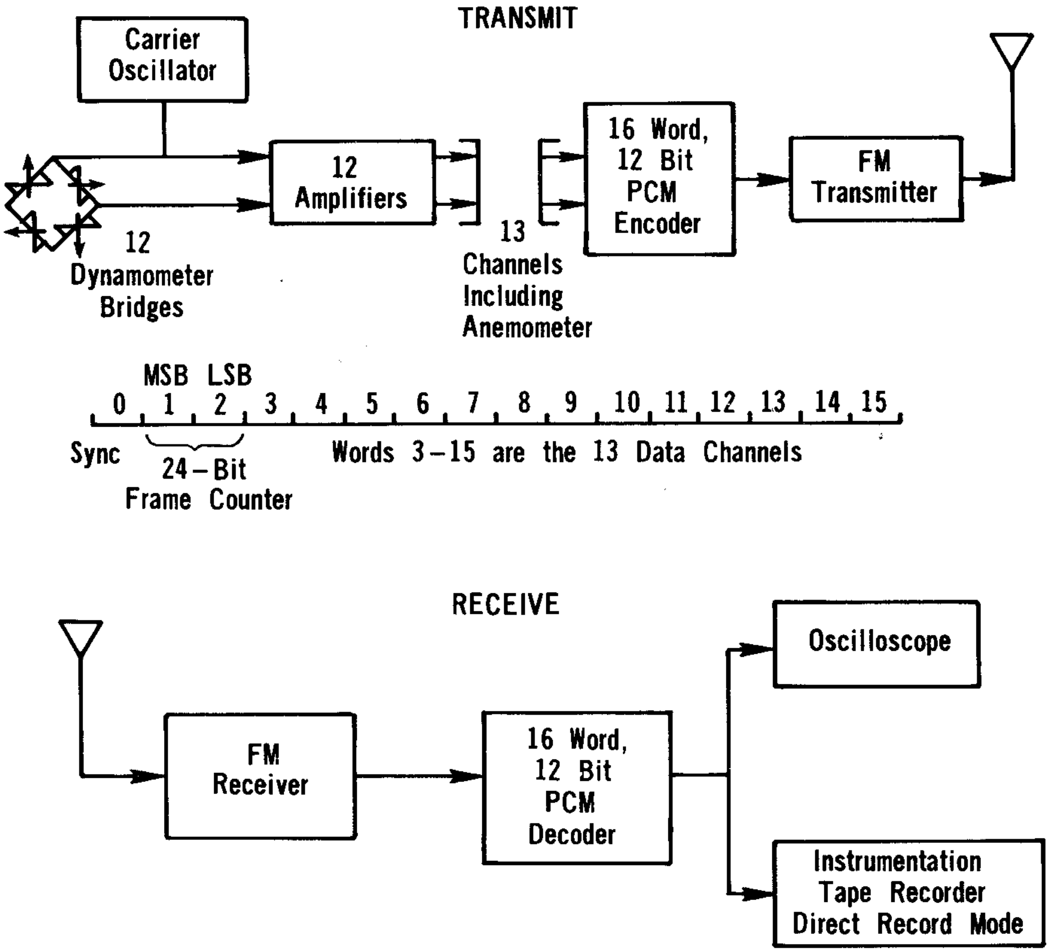

Figure 2. Telemetry Transmit and Receive Systems.

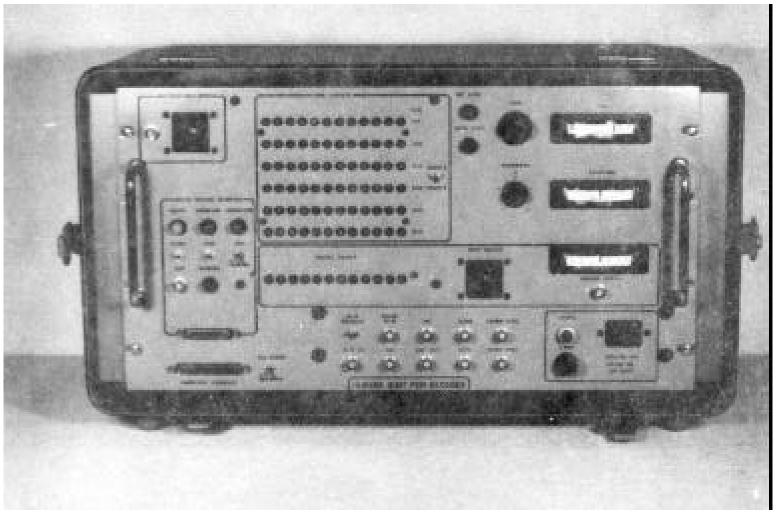

Figure 3. 12-Bit, 16-Word PCM

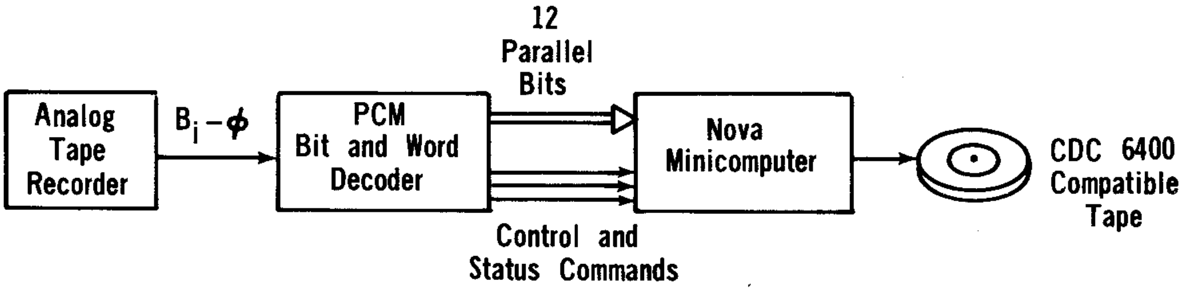

Figure 4. Data Handling System.

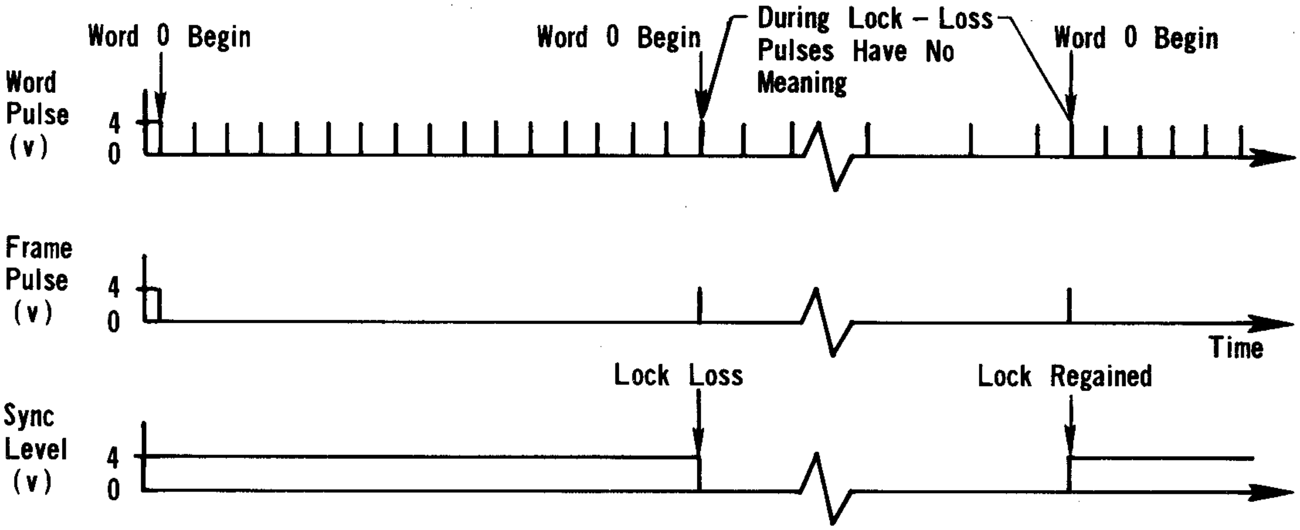

Figure 5. Control and Status Command Timing Showing Lock - loss.

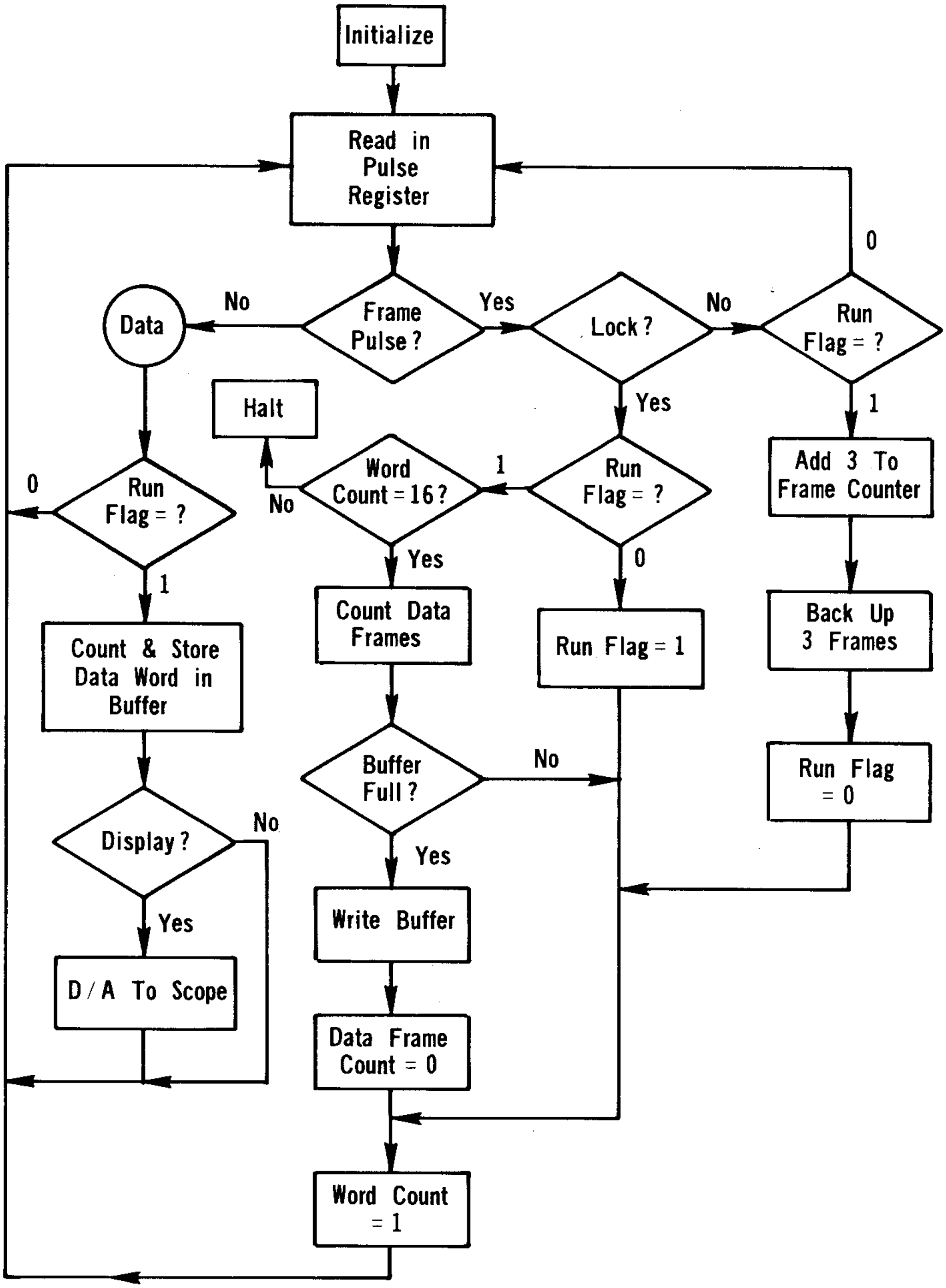

Figure 6. Simplified Flow Diagram of Minicomputer Software.

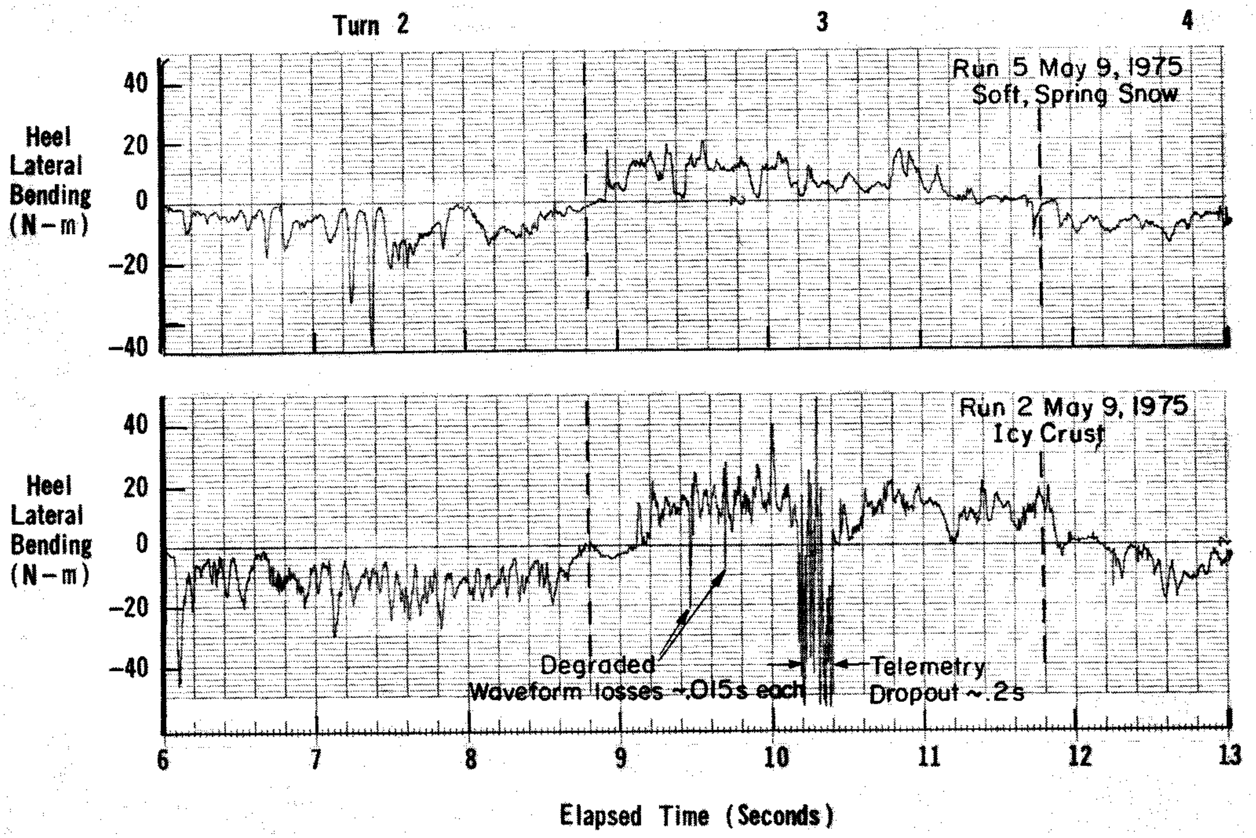

Figure 7. Loading Histories With and Without Information Losses.

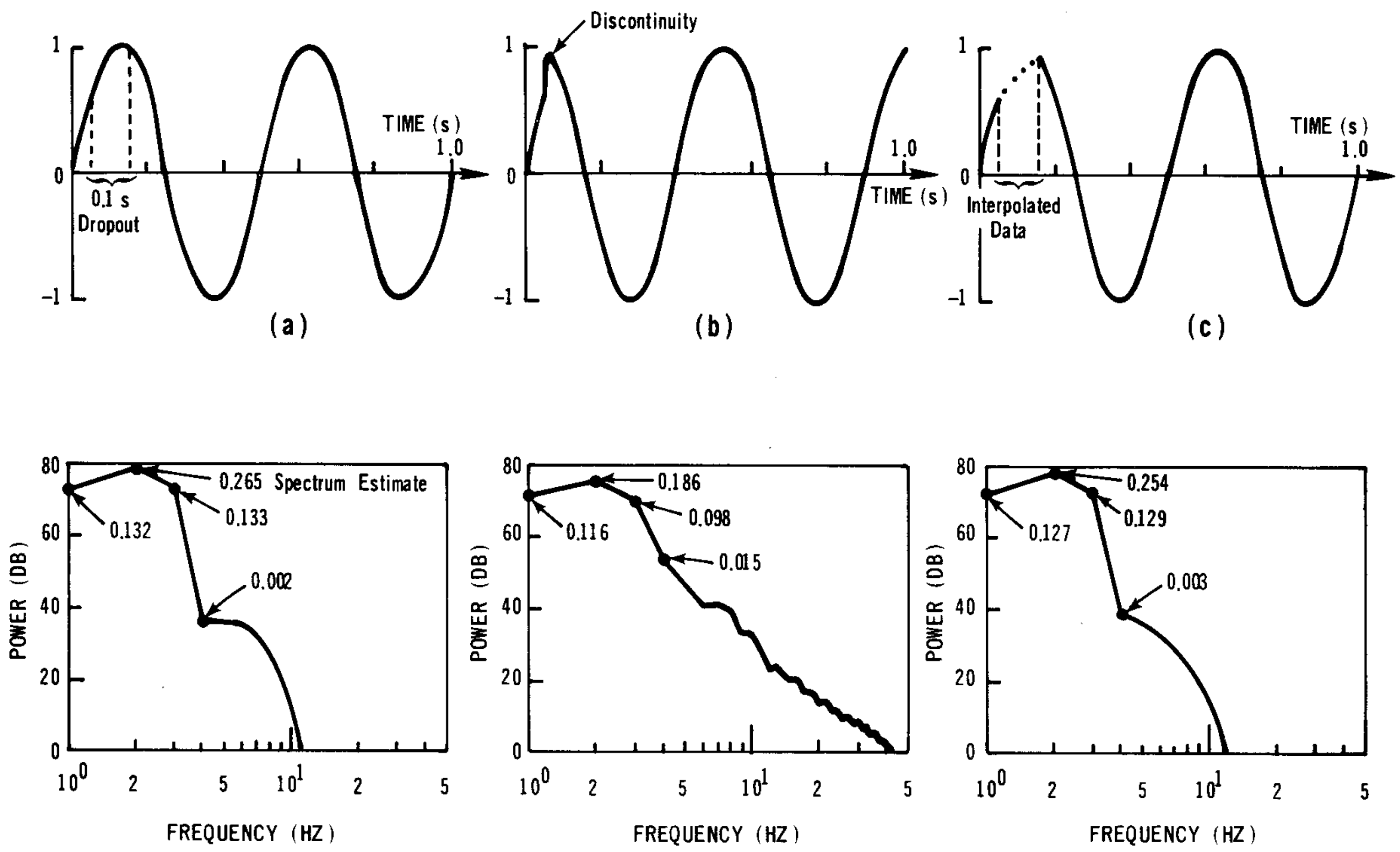

Figure 8. Signal Enhancement for 2 Hz Sine Wave With 0.1s Dropout and Comparison of Power Spectra a) Actual Data; b) Minicomputer Processed Data; c) Reconstructed Data.

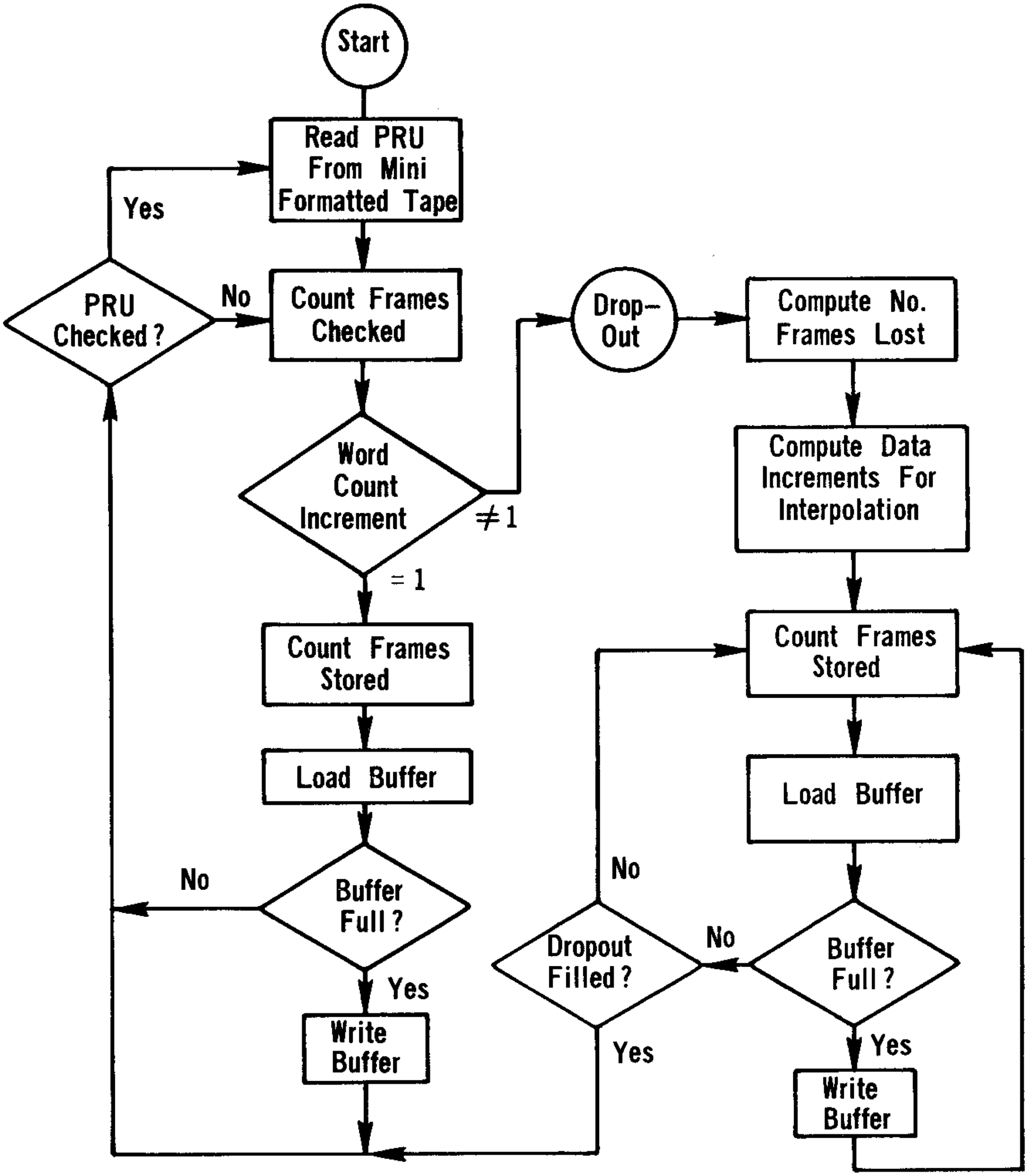

Figure 9. Simplified Flow Diagram of Software to Enhance Data Waveform Accuracy.