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# A DATA HANDLING SYSTEM WITH EFFICIENT SYNCHRONIZATION FOR AN 8 BIT, BIORTHOGONAL TELEMETER

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# A DATA HANDLING SYSTEM WITH EFFICIENT SYNCHRONIZATION FOR AN 8 BIT, BIORTHOGONAL TELEMETER

## Summary

An experimental data handling system for an 8 bit phase-coherent biorthogonal, coded PCM telemeter has been developed and evaluated. It performs the following major functions. The received RF carrier frequency is used as the master clock for the telemeter. Synthesis of the receiver oscillator frequencies yields a telemetry reference clock. Virtual elimination of data recovery degradation due to tape transport time displacement error is achieved by multiplexing the reference clock with the data and recovering it with a second-order phase lock loop. The phase lock loop output is used as the source of all timing in the data handling system.

The system coherently accumulates synchronization energy over a sufficiently large number of frames, thus achieving arbitrarily low synchronization error probabilities.

Symbol and frame synchronization are obtained from a tone burst by means of a phase detection technique using a pair of matched filters in quadrature. Precision word synchronization is obtained from a modified two-component composite code. For flexibility, a real time computer performs the synchronization search, decision, and the phase up-dating functions.

An 8-bit, biorthogonal, pseudo-random decoder using only 2 analog elements is employed in the decoding of data. A high speed, digital correlator performs the function of 256 conventional correlators. The decoder performs within 1 db of theoretical.

## Introduction

The purpose of the ensuing discussion which is an extension of the companion report[5] "An 8-bit Biorthogonal Telemetry System With Efficient and Flexible Synchronization for Space Communications" is twofold: to present the techniques employed in the implementation of the Data Handling System for an 8-bit phase-coherent-biorthogonal coded PCM telemeter[1,2,3,4,5], and to discuss the measurement methods and performance results in the form of probability of word error versus ST/No. where:

$$ST/No = \frac{\text{signal energy per bit}}{\text{Noise power density}}.$$

The performance of the Data Handling System was investigated using the following system parameters:

Carrier frequency: 136.5 MHz

Modulation: PM ± 1 radian

System noise figure: 5 db

Predetection Bandwidth: 30 kHz

Data noise bandwidth: 11 kHz

Loop noise bandwidth: 10 Hz

Symbol rate ($f_c$): 2.77 kHz

Information bits per code word: 8(n = 8)

Information rate: 174 bits per second

Data code word length: 127 symbols

Data code word library: 256 biorthogonal code words

Frame length: 32 words

Number of frames used for synchronization energy accumulation: 4(K = 4)

Synchronization acquisition time for K = 4: 16 frames

The Data Handling System is comprised of two major subsystems, namely; the Carrier Coherent Telemetry Rates (CCTR) Receiver and the Data Processing Line.

## Carrier Coherent Telemetry Rates Receiver

The purpose of the ground based receiving station is to recover the TM data from the phase modulated, spacecraft transmitted RF carrier. In addition the repetition rate of the spacecraft TM system master clock is obtained from the RF carrier by judicious frequency division of the RF carrier frequency since the RF carrier is in frequency coherence with the TM data rate. Accurate phase determination is not made here but in the data processor unit as will be explained in the following section.

Figure 1 illustrates how these functions are performed. The RF signal is heterodyned by standard techniques and demodulated with the aid of a second order phase lock loop. The injection frequency of the first local oscillator is synthesized from two oscillators. These two oscillators are necessary to satisfy the generally conflicting requirements of high frequency stability and large signal tracking range (doppler) requirements. The noise limiting 5 kHz bandpass filter preceding the loop phase detector allows the phase detector to act as a true multiplier for minimal signal input levels. Only the carrier component of the received signal is required for operation of the phase lock loop. A 10 Hz loop bandwidth was found to be a happy compromise between inherent loop phase jitter and loop signal-to-noise ratio during the tests. Actually the inherent loop phase jitter is of little importance as long as the loop remains locked and causes no degradation to the PM detector. To band limit this

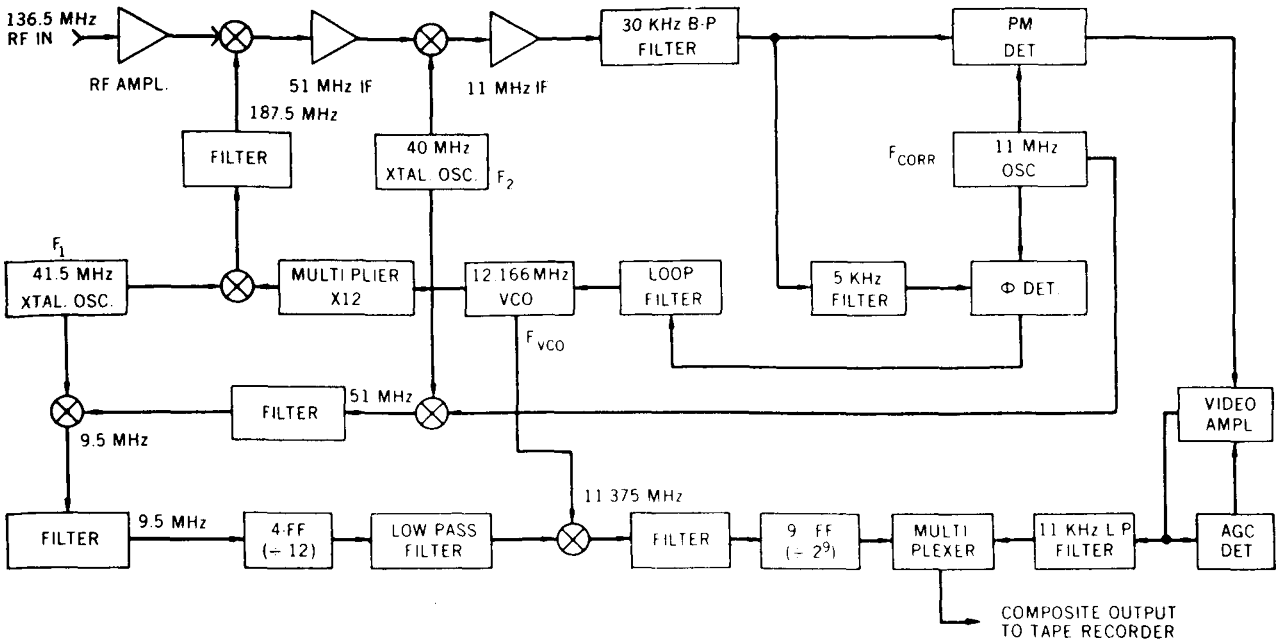


Figure 1. Carrier Coherent Telemetry Rates

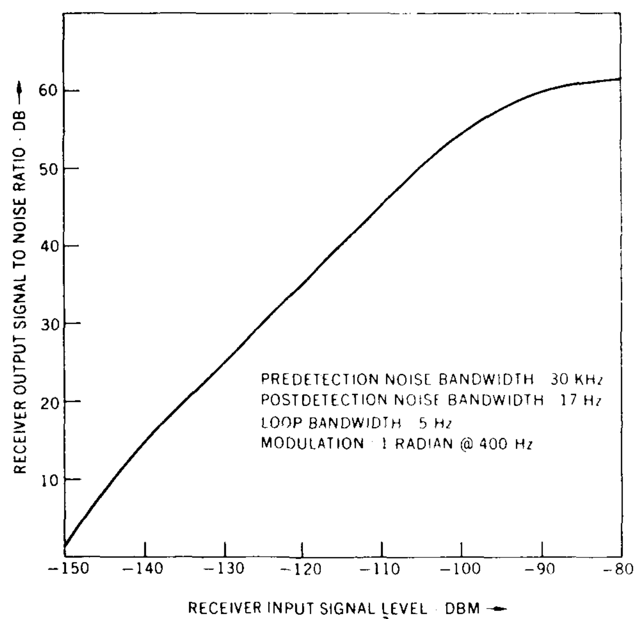


Figure 2. Receiver Performance

particular TM signal a 30 kHz predetection filter was employed. A post detection filter of 11 kHz established the signal-to-noise ratio of the PM detected output signal. This combination of predetection, post detection, and loop filters was such that PM data was recovered from the received signal with very little degradation of performance when the signal-to-noise ratio in the data bandwidth is -20 db. This performance was found sufficient for the purposes of this experiment. A plot of the PM detector output signal-to-noise ratio as a function of receiver input signal level is shown in Figure 2. The data noise bandwidth for this curve was reduced to 17 Hz in order to determine performance at very low input levels.

If the received signal experiences a doppler frequency shift proportional to the RF carrier frequency, then the modulation sidebands will also experience a doppler shift in proportion to the modulation rates. There are other phenomena of the transmitting medium that affect the relation of the data rate and the RF carrier, however, these effects are small.

For carrier coherent telemetry systems the received carrier frequency is an exact multiple of the data symbol rate ($f_c$). The multiplication factor for this particular system is 49,152 or $3 \times 2^{14}$. Thus if the received RF carrier frequency is divided by this factor, the TM system master clock repetition rate can be determined exactly. From a ground system network point of view it was decided that efficient overall operation would result from receiving signals at several remote stations and using a centrally located processor for further data reduction. This philosophy requires the received information to be stored; ordinarily magnetic tape is employed. In order to minimize tape transport time displacement error degradation the local reference clock frequency and the PM detected information are frequency multiplexed onto the same channel of the tape recorder. Naturally the exact master clock repetition rate cannot be recorded directly and thus 8 times the master clock repetition rate ($8f_c$) was chosen as a convenient compromise between data interference and minimum tape speed. These requirements then establish the divisional factor of the received RF carrier frequency to be recorded as $3 \times 2^{11}$.

Once the second order loop is locked to the received carrier, the carrier frequency may be regenerated by judicious addition of the oscillators within the receiver. (Refer again to Figure 1.) This may be seen more easily in equation form:

$$12 \times F_{vco} + F_1 - (F_2 + F_{corr}) = F_{RF\ in}$$

Since regeneration of the RF carrier will cause RFI problems, the process used to obtain $F_{RF\ in}$ divided by $3 \times 2^{11}$ was as follows: (see bottom portion of Figure 1) $F_2$ was added to $F_{corr}$ and the sum subtracted from $F_1$. The result was divided by the factor 12 (or $3 \times 2^2$) and this quotient added to $F_{vco}$. (Note: The product $12 \times F_{vco}$ divided by 12 is available directly at the VCO.) This sum is then divided by 512 (or $2^9$). In equation form the process might look like this:

$$\frac{\dfrac{12 \times F_{vco}}{3 \times 2^2} + \dfrac{F_1 - (F_2 + F_{corr})}{3 \times 2^2}}{2^9} = \frac{F_{RF\ in}}{3 \times 2^{11}}$$

In the interest of telemetry transmission efficiency, it is highly desirable to put as much power as possible into the modulation sidebands. This desire is contrasted by the requirement for RF carrier power necessary for the phase lock loop to operate. The phase lock loop provides not only demodulated PM information but the TM system master clock synchronization as well. The chief concern of this experiment was to determine the quality of telemetry transmission as a function of baseband signal-to-noise ratio and not on how little power could be used for the phase lock loop. Therefore a modulation index of 0.785 radian (45°) was chosen. If this system were to be used for space communication, a more compromising adjustment would necessarily be made between RF carrier power, sideband power, and phase lock loop bandwidth.

Figure 3 illustrates the baseband power spectrum (as observed at the tape recorder input) in units of $f_c$. The split phase PCM data, the sin X/X synch tone at $2f_c$, and the composite sync codes all originate from the spacecraft and appear at the ground station PM detector output. The post detection filter corners at approximately 11 kHz. This passes 92.5% of the data energy (0.34 db harmonic power loss). Preservation of all the sync code energy is not essential and only 85.6% of its power is passed by this filter. The $8f_c$ local reference is linearly added to this baseband signal and recorded. The amplitude of the PM detector output is automatically controlled to conserve the dynamic range of the tape recorder.

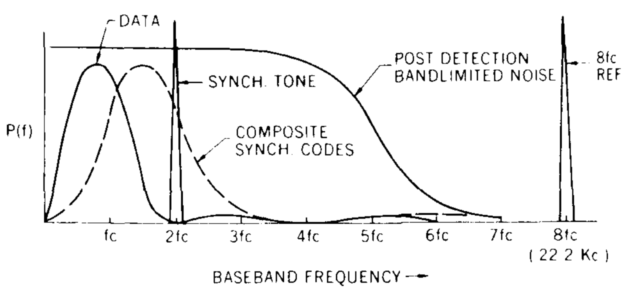


Figure 3. Baseband Power Spectrum as Observed at the Tape Recorder Input

## Processor Input Signal Characteristics

The signal appearing at the processor input consists of coded data and synchronization words in a 32 word format which is split-phase coded and linearly added to the $8f_c$ reference frequency. The signal format is shown in Figure 4.

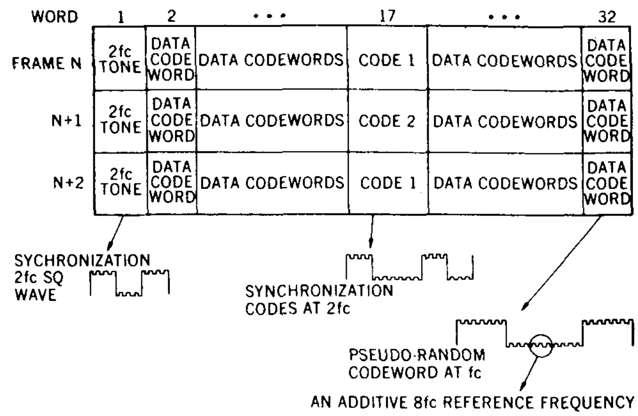


Figure 4. Signal Format

The reference frequency is used as the master clock within the Processor. The master clock is counted down to the local clock (symbol, word, and frame) rates.

The first word of the format is a square-wave tone burst equal to twice the data symbol rate. The $2f_c$ tone burst energy is used to obtain symbol and frame (± 1/4 word accuracy) synchronization.

Word 17 in each frame contains a modified two-component composite code, namely; code 1 and code 2 which alternate each frame. Codes 1 and 2 which are transmitted at the $2f_c$ symbol rate are used to obtain precision word synchronization and to resolve any possible input signal polarity inversions between the spacecraft and the Processor.

The remaining words in the format are the pseudo-random data code words. Each data code word is one of a possible 256 biorthogonal codewords. The data code word contains 127 symbols, and are transmitted at the $1f_c$ rate. The $2f_c$ tone, the composite codes and the data code words have low cross-correlation coefficients. This greatly simplifies search and acquisition procedures.

## General Data Processing Line Description

A block diagram of the Data Processing Line is shown in Figure 5. The signal at the Processor input is received from an analog tape transport. The received signal is AGC'd and applied to a Synchronization Symbol Correlator and A/D Converter, a phase lock loop, and a Data Symbol Correlator and A/D Converter.

The Phase Lock Loop acquires the $8f_c$ reference frequency and outputs $256f_c$ to yield a 7-bit (2.81 degrees) $2f_c$ phase resolution. The "Local Counters" count down the $256f_c$ to the local clock rates which are initially out of phase with the signal.

The Synchronization Symbol Correlators and A/D Converter in conjunction with an on-line digital computer performs a matched filter detection of the $2f_c$ tone and the

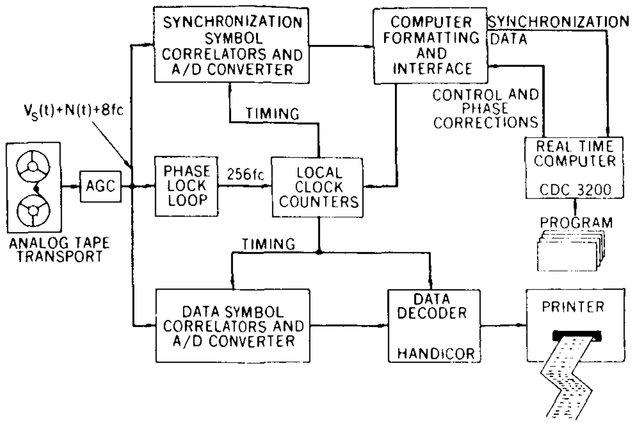


Figure 5. Data Processing Line Block Diagram

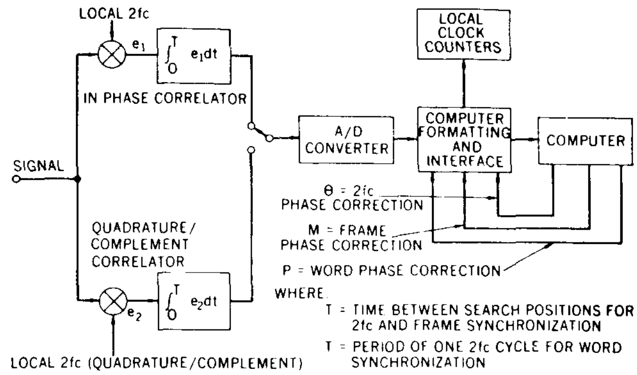


Figure 6. Synchronization Block Diagram

composite codes. The computer performs the arithmetic calculations, the maximum likelihood decisions, and transmits its best estimate of phase corrections to the local counters via the Computer Formatting and Interface Unit. The phase corrections are applied to the local clocks achieving symbol, word, and frame synchronization.

The Data Symbol Correlators and A/D Converter, in conjunction with Handicor, perform a matched filter detection of the data code words. The n = 8 information bits corresponding to the detected data codewords are outputed on an on-line printer.

## Synchronization

A two-step synchronization sequence provides symbol, word, frame, and signal polarity synchronization. Symbol and frame (± 1/4 word) synchronization are first achieved, followed by precision word and signal polarity synchronization. Format synchronization was not implemented in the experiment.

Since signal phase changes are negligible due to the CCTR subsystem, coherent energy accumulation can be performed over a total interval of K frames. An improvement in precision word and frame synchronization performance is obtained whenever K is increased. Doubling the value of K typically lowers the synchronization threshold by 3 db.

The 2fc tone burst in word 1 of the format provides the necessary information to obtain symbol and frame synchronization, using a non-phase coherent matched filter search technique[4].

### Symbol and Frame Synchronization

Figure 6 shows a block diagram of the synchronization process. The signal is routed to in-phase and quadrature correlators where multiplication and integration, over T = time between search positions, takes place. To achieve the desired resolution, four search positions per word (128 per frame) are searched. Under a worst case phase shift, midway between two search positions (± 1/8 word), a 1.2 db loss results. This value has been derived from the auto correlation envelope. The correlator outputs are digitized in the A/D converter and transmitted to the Computer. The Computer reads K = 4 frames of values and the energy is coherently accumulated over the 4 frames. Digital integration over one word period forms 128 "X" (in phase) and 128 "Y" (quadrature) components, each displaced by one search position. The sums of the squares of X and Y components are formed, namely: $(X_i^2 + Y_i^2)$ for i = 1 to 128.

A maximum liklihood decision is made and defined as $(X_M^2 + Y_M^2)$. The phase estimate of the 2fc tone, relative to the local 2fc clock is found as $\hat{\theta} = \tan^{-1} Y_M/X_M$. $\hat{M}$ is the estimate of 2fc tone position relative to the local frame clock. $\hat{\theta}$ and $\hat{M}$ are transmitted to the Processor where the local 2fc and frame clocks are adjusted to achieve 2fc and frame synchronization.

Allowing for losses totaling 2.2 db (1.2 db due to imperfect work synchronization during the 2fc tone burst search and 1 db due to filtering of the square wave harmonics), the confidence level of $\hat{\theta}$ has been calculated. Figure 7 is a plot of the maximum phase error $(\theta_0)$ that can occur versus ST/No for a specified percent confidence $([1 - P(\theta_0)]\ 100)$ level and K = 4. The curves show that a 0.8 db ST/No, there is 99% confidence that $\hat{\theta}$ is within 22 degrees or 6% of the data symbol period.

A point estimate of the input signal-to-noise ratio (SNR) is made from the ratio of the signal correlator output to the mean square value of all non-signal correlator outputs. This can be expressed as:

$$SNR = \frac{(X_M^2 + Y_M^2)}{\frac{1}{121}\left[\sum_{i=1}^{128} (X_i^2 + Y_i^2) - \sum_{i=M-3}^{i=M+3} (X_i^2 + Y_i^2)\right]}$$

By multiplying SNR by the proper constant K, an estimate of ST/No is made which is useful in the evaluation of synchronization strategy.

### Precision Word and signal Polarity Synchronization

The second step in the synchronization sequence is to obtain precision word and signal polarity synchronization. Word 17 in the format alternately contains codes 1 and 2 from which the synchronization information will be extracted. Since the location of word 17 is known to within ±1/4 word, a time window about word 17 will be searched.

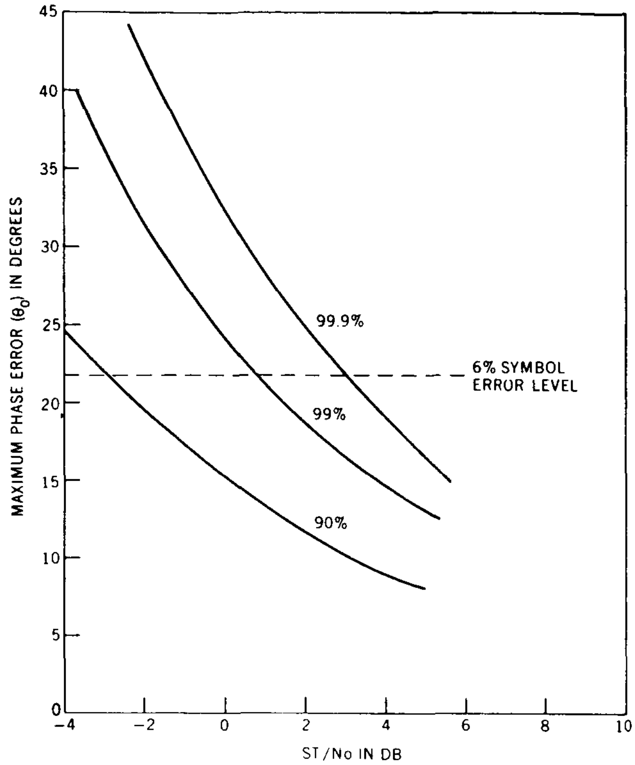


Figure 7. $\theta_0$ vs. ST/No for Various Confidence Levels for K = 4.

Code 1 is a 15 bit pseudo-random (PR) code repeated 17 times and Code 2 is a 17 bit PR code repeated 15 times. Codes 1 and 2 are transmitted at the 2fc rate and contain 255 bits. The code lengths 15 and 17 are relatively prime and a 15 times 17 or 255 bit (one word time) periodicity exists which serves as the basis from which word synchronization is achieved.

As shown in Figure 6 the outputs of the in-and-out-of-phase correlators are digitized and transmitted to the Computer. The Computer reads eight frames of word 17 time window values and the odd and even frame values are coherently accumulated. Code 1 is first detected. There are four possible sets of values in which Code 1 can exist, namely: odd frame-in phase, even frame-in-phase, odd frame-out of phase, and even frame-out of phase. Coherent accumulation in each set results in the formation of the 15 bit PR code accumulated 17 times with a phase shift $P_1$ relative to a reference 15 bit PR code in the Computer. A cross correlation between each phase shift of the reference code and each 15 bit set (60 correlations) followed by a maximum likelihood decision determines $P_1$.

Since the location of Code 1 is known, the set in which Code 2 appears is known. Coherent accumulation forms the 17 bit PR code accumulated 15 times with a phase shift $P_2$ relative to a reference 17 bit PR code. A cross correlation between each phase shift of the reference code and the 17 bit set (17 correlations) followed by a maximum likelihood decision determines $P_2$.

$P_1$ and $P_2$ are operated on by a simple program subroutine which calculates the word phase correction P which is transmitted to the Processor where the local word clock is adjusted to obtain precision word synchronization. If Codes 1 and 2 are detected in the out-of-phase sets, an inverted signal polarity exists which is automatically adjusted.

After the synchronization process has been completed, a command is sent to the Processor. When this command has been received Handicor begins to decode the data.

## Synchronization Updating and Verification

Synchronization updating and verification is accomplished while the data is being processed by Handicor. The computer alternately calculates the 2fc and word phase errors. The 2fc phase estimate updates the 2fc local clock and the work phase estimate is checked for deviation from zero. A word phase estimate other than zero indicates a loss of precision word synchronization caused by such disturbances as loss of signal, tape drop-outs, and below system ST/No thresholds. When the loss of precision synchronization is detected, the Processor is returned to the symbol and frame synchronization mode.

## Data Decoding

The experimental telemetry system described in this paper would typically require 256 correlators to perform the signal detection function. In this experimental data processing line a device known as HANDICOR* is utilized to perform the function of the 256 correlators. HANDICOR, shown in block diagram form on Figure 8, is a high speed hybrid (analog-digital) computing device in which the correlation process is performed sequentially. Each symbol of the input signal is digitized in an A/D converter and stored in a recirculating memory until a complete code word is assembled. The stored word is repeatedly correlated with 128 signed reference codes in a high-speed arithmetic unit. A maximum-likelihood detector, implemented in digital form follows the correlation process. The sequential correlation process is completed in one word time. The value and sign of each detected word is printed out. The HANDICOR approach reduces equipment complexity and cost considerable, since a bank of 256 correlators is no longer required. It is capable of processing up to 200 information bits/second.

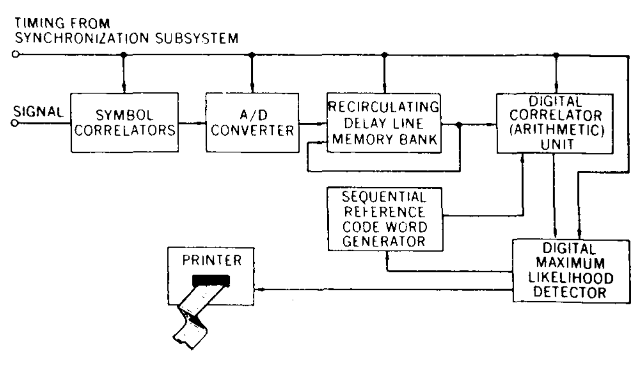


Figure 8. Handicor Block Diagram

*Hybrid Analog Digital Correlator.

## SYSTEM TESTING

System dynamic testing comprised the measurement of word error probability versus ST/No curves for various signal source inputs to the Processor. Figure 9 shows the diagram of the test system which was used in the measurements.

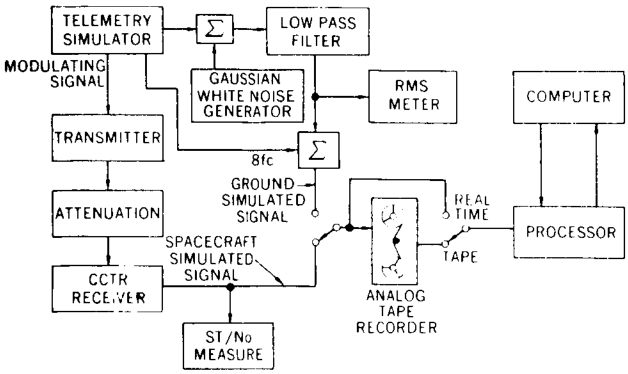


Figure 9. Test Block Diagram

The two major signal paths (Ground Simulated and Spacecraft Simulated Signal) permit comparison between a direct simulation of the system under ideal, closely controlled conditions (Ground Simulated Signal), and a realistic simulation which includes the major components of the telemetry link. This comparison gives a basis for estimating how well an actual system will approach optimum performance.

Reference to the test diagram shows that the ground-simulated signal is mixed with white Gaussian noise, passed through a filter of known equivalent noise bandwidth, and either recorded on analog tape and played back to the Processor or routed directly to the Processor for real-time processing.

The signal also phase-modulates the transmitter which transmits the modulated carrier, via calibrated attenuators, to the CCTR Receiver for various levels of attenuation. The ST/No Measure separately measures the signal and noise-power in a narrow band filter of precisely known center frequency and equivalent noise bandwidth.

Word error probability versus ST/No tests were performed under the following conditions:

| | | |
|---|---|---|
| 1. | Ground Simulated Signal: | real-time – perfect synchronization |
| 2. | Ground Simulated Signal: | real-time and tape playback – derived synchronization |
| 3. | Spacecraft Simulated Signal: | real-time and tape playback – derived synchronization. |

The results of test 1 and test 3 (tape playback) are plotted in Figure 10. These results indicate an overall Data Handling System performance within approximately 1db of the theoretical curve for an 8 bit phase-coherent-biorthogonal coded PCM system. An almost identical performance of the system with ideal synchronization (test 1) and a tape recorded signal (test 3) is of great significance.

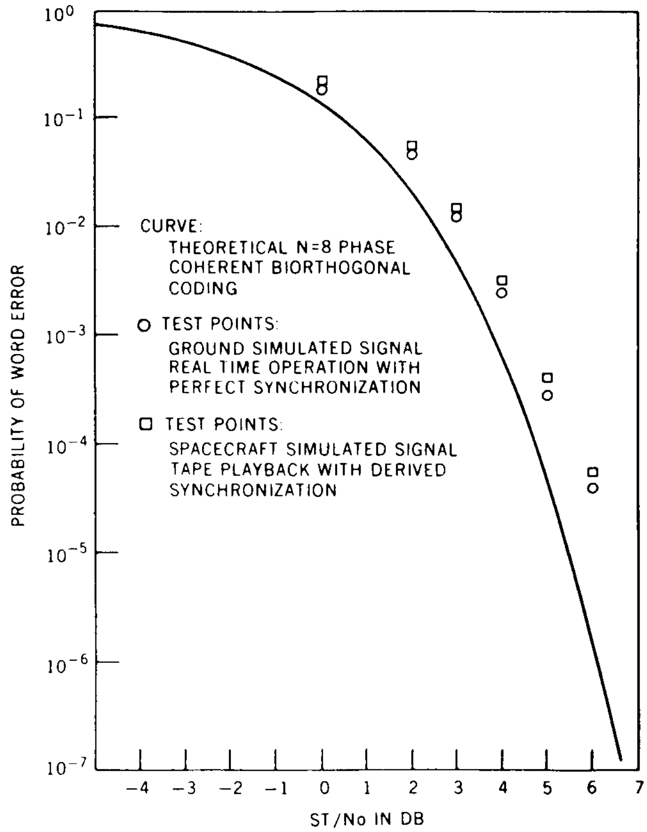


Figure 10. Probability of Word Error vs. ST/No

## Conclusions

The implementation and performance of the Data Handling System for the 8-bit phase-coherent-biorthogonal coded PCM telemeter has been shown. The use of the Carrier Coherent Telemetry Rate subsystem has allowed a flexible and efficient synchronization technique to be employed with the virtual elimination of tape transport time displacement error losses. The fast and simple data decoder, Handicor, has proven efficient and reliable in decoding the biorthogonal codes to within 1 db of theoretical. Although the synchronization subsystem could have been implemented in hardware, the use of a small general purpose computer offers the salient advantages of flexibility.

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