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FINAL SUMMARY REPORT

FOR

A STUDY OF MULTIPLEX DATA BUS TECHNIQUES

FOR THE SPACE SHUTTLE

CONTRACT NO. NAS8-26378

REPORT NO. 2635-M15

NOVEMBER 1972

SCI SYSTEMS, INC.

HUNTSVILLE DIVISION

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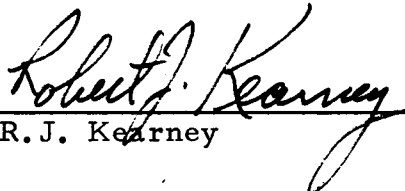
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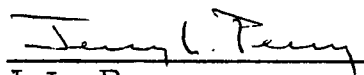
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ABSTRACT

This is the Final Summary Report (presented in satisfaction of Data Requirements List DRD MA-061) for "A Study of Multiplex Data Bus Techniques For The Space Shuttle". SCI Systems, Inc.(formerly SCI Electronics, Inc.) performed the study for the George C. Marshall Space Flight Center, NASA, Huntsville, Alabama under contract No. NAS8-26378.

This study provides a comprehensive technology base for the design of a multiplexed data bus subsystem suitable for space shuttle vehicles. Extensive analyses, both analytical and empirical, have been performed in satisfaction of the statement of work. Subjects covered by this study have been classified under the following headings:

    A.   Requirements Identification and Analysis

    B.   Transmission Media Studies

    C.   Signal Design and Detection Studies

    D.   Synchronization, Timing and Control Studies

    E.   User-Subsystem Interface Studies

    F.   Operational Reliability Analyses

    G.   Design of Candidate Data Bus Configurations

    H.   Evaluation of Candidate Data Bus Designs

This report provides a summary of the work performed under this contract, with appendices I, II, and III listing Terms and Abbreviations, Technical Phase Reports published, and References, respectively.

FINAL SUMMARY REPORT

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1.0 STUDY REQUIREMENTS DESCRIPTION

1.1 INTRODUCTION

This study, "Multiplex Data Bus Techniques for the Space Shuttle" has been performed by SCI Systems, Inc. (formerly SCI Electronics, Inc.) under contract No. NAS8-26378 for George C. Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, during the period November 1970 to October 1972. Mr. W.O. Frost, NASA, S & E-ASTR-IT, has had technical cognizance of the program, and Mr. D.H. Ellis has been SCI Program Manager.

The study was performed in two technical phases, Phase I and Phase II, and is summarized in this Final Report. Phase I concentrated on identification of all reasonable design alternatives which might be considered for the data bus, and Phase II involved the studies themselves. Principle topics were as follows:

- Requirements Identification and Analysis
- Transmission Media
- Signal Design and Detection
- Synchronization Timing and Control
- User Subsystems Interfaces
- Operational Reliability
- Design and Evaluation of Candidate Data Bus Designs.

The findings and results of these studies have been published in technical notes, in Technical Phase Reports (as listed in Appendix II), and in this Final Summary Report.

1.2   OBJECTIVE

The objective of this study has been to provide a comprehensive technology base for the design of a multiplexed data bus subsystem suitable for the space shuttle vehicle. Necessary analytical and empirical analyses have been performed, but have not extended to design and development of final equipment. The subjects covered were given in paragraph 1.1.

SCI has performed comprehensive trade-off studies on all reasonable alternatives, and has applied the results to the evaluation of data bus designs.

2.0   SUMMARY

2.1   APPROACH

This study program was classified into three parts as follows: 1) requirements, identification and analysis; 2) comparative analysis of techniques, and 3) the design and analysis of candidate data bus configurations.

Phase "B" vehicle studies for the Space Shuttle proceeded in parallel with this program. Definitive requirements for a multiplex data bus were used from these studies, as they became available. SCI organized, classified, placed on punched cards for computer analysis and printout, documented and updated this information, providing a requirements baseline for these multiplex studies. Supplementary requirements information was also secured through liaison with approved sources.

Comparative analyses of the applicable alternatives and techniques was performed in each of the following areas:

- transmission media
- Signal design and detection
- synchronization, timing and control
- user-subsystem interfaces
- operational reliability

Analyses included in-depth analytical and empirical studies of applicable alternatives in each area, resulting in exposure of significant factors involved in optimizing the multiplex data bus design. Hardware proofs were exhibited from tests made on cabling for the data bus media.

Prototype Data Terminals which employed masking redundancy were designed and developed as proof units. They were coupled to the twisted-shielded pair data bus, which in turn coupled to the Bus Control Unit under computer control.

Analytical comparisons were made of the candidate data bus systems based upon results of the study and approved criteria.

The following summarizes the subtasks initially identified for investigation under each task:

A. Requirements Identification and Analysis

- devise suitable data presentation methods.
- establish and maintain data flow models.
- identify and describe input/output characteristics.
- classify messages.
- based upon information supplied by MSFC and other approved sources, prepare and maintain physical and environmental models.

B. Transmission Media

- identify types of media, and investigate their properties.
- investigate and compare operating modes.
- identify and investigate design techniques of all reasonable alternatives - branching of paths, coupling and physical connections at input/output locations, and termination and loading of cables.
- perform media survey.

- define environmental effects for each potentially applicable type/mode of electrical cable or other medium.

- define media characteristics.

- define media specifications.

- show and define interference characterization.

- consider interactive aspects.

- make data presentations.

C.   Signal Design and Detection

- identify, investigate and select multiplexing/modulation alternatives having significant potential for the data bus.

- define spectral characteristics and transmission bandwidth requirements of each alternative.

- define the requirements, limitations and constraints of each affected element of the data bus subsystem. i.e, transmission media, coupling elements, amplifiers, etc.

- define, analyze, verify and compare the applicable methods for generation, demodulation and detection of signals, covering various techniques.

- define, analyze and compare methods of redundant coding potentially applicable to the data bus subsystem.

- similarily examine message format arrangements.

- consider interactive aspects.

- present results and conclusions.

D. Synchronization, Timing and Control

- identify and analyze bus access control alternatives.
- identify and analyze message routing control alternatives.
- identify and analyze timing and synchronization alternatives.
- identify and analyze problems and alternatives relating to the programming of data acquisition and distribution operations.
- consider interactive aspects.
- present results and conclusions.

E. User-Subsystem Interfaces

- determine the electronic operations necessary to interface user subsystems with the transmission medium and identify all reasonable design alternatives for accomplishing each operation.
- define, analyze and compare applicable alternatives for information transfer between the data bus subsystem and various user subsystems.
- define, describe, analyze and compare alternatives for a) packaging of the interface elements, and b) the electrical interconnections required for information interchange between data bus and user subsystems.
- define and describe applicable methods for standardization of interface terminals and/or elements.
- consider interactive aspects.
- present results.

F.   Operational Reliability

- Identify and analyze all reasonable design alternatives for satisfying operational reliability and failure criteria.

- identify and analyze design alternatives for determining and monitoring operational readiness of the data bus subsystem and status of redundant elements.

- identify and analyze problems and alternatives relating to data bus subsystem maintainability.

- give appropriate and thorough consideration of interactive aspects.

- present results.

G.   Design of Candidate Data Bus Configurations

- derive a maximum of four data bus designs for the space shuttle vehicle.

H.   Evaluation of Candidate Data Bus Designs

- perform comprehensive evaluation of each data bus sub-system design.

2.2   RESULTS AND CONCLUSIONS

The overall result of this study has been to identify, analyze and consolidate information on methods and techniques applicable to Space Shuttle Vehicles multiplex data bus designs, with design guidelines and traded preferences presented. This body of information should be of technological, and consequently economic, benefit to those commissioned with the task of designing the Data Multiplex Subsystem for the SSV's.

A summary of accomplishments is presented here by each of the seven major study areas.

2.2.1   Requirements, Identification and Analysis

The results of this task are published in the following documents:

- "Technical Phase Report No. 1, For A Study of Multiplex Data Bus Techniques for the Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

- Volume III, Technical Phase Report Number 2, "Requirements Identification and Analysis for a Study of Multiplex Data Bus Techniques for the Space Shuttle", report number 2635-M6-03, dated May 1972.

- Appendix B to Volume III, Technical Phase Report Number 2, "GD Space Shuttle Booster Data and Control Requirements Listing".

This was an information gathering, organization and tabulation task. As such, it did not culminate in a set of conclusions, other than what the data and conditions applicable to the Space Shuttle Data Bus system are. Therefore, only a capsule treatment of the results is related here. Section 3.1, "Requirements Identification and Analysis" should be consulted for this task's results.

Data presentation methods were devised early in the job. Data on each booster measurement and control signal to be communicated over the data bus system was stored on one or more 80-column IBM cards, suitable for input to a computer for analytical purposes, or for printout. Included on the punched cards are the following:

- Designation, including User Subsystem Functional Element.
- Signal name.
- Mission phase(s) applicable.
- Location in SSV
- Signal classification - Aperiodic/periodic, control/measure, analog/discrete/digital.

- Bits-per-word.
- Samples (words)-per-second.
- Signal destination(s).
- Reference back to source GD listing.
- Signal Type.

This body of data was the source data input for a great amount of the in-depth analyses performed. It was translated into forms suitable for the data bus study, and came from the GD listings for the B9U SSV Booster of mid-1971.

Orbiter signal data was not stored on punched cards, but it was suitably translated from the NAR Orbiter Data List (of 9/14/71) in summary form to be used for data bus considerations.

SSV temperature profiles were established, and it was found that temperature conditioning avionic equipment was required for both booster and orbiter vehicles. This led to the clustering of avionic equipment into bays in various regions of the vehicle.

Raw data bit rate for each mission phase was derived. For the booster, data flow modeling resulted in topographies of bit rate per location within the vehicle per signal classification. This was also shown for the ten subsystems.

Seventeen SSV signal types were identified, and a count of signals per type was made for each avionic bay. Data flow topographies of the distribution of signal types within the booster were generated. Also, a count was made of signals by classification for the ten subsystems.

Although data flow modeling was not done for the orbiter vehicle, the data was identified and counted per type signals, per subsystems, per OFI and DFI buses, and per avionic area.

Environmental data was gathered from Phase "B" contractors.

Mission operation times for booster and orbiter were established.

Finally, various comparisons were made between the booster and orbiter with regard to data bus related characteristics and their data.

2.2.2   Transmission Media

The results of this task are published in the following documents:

- "Technical Phase Report Number 1, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

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- Volume I, Technical Phase Report Number 2, "Transmission Media, For A Study of Multiplex Data Bus Techniques For the Space Shuttle", report number 2635-M6-01, dated January 14, 1972.

2.2.2.1   Transmission Media Study Results

The work done in the Phase I portion of the Transmission Media Study covered a wide range of transmission media, operational modes and design techniques that were identified as having potential application to the SSV data bus. In review, the Phase I investigation effort of the Multiplex Data Busing Techniques consisted of certain areas covered in the preliminary transmission media study. These areas are listed below.

- Application rationale was given for the intended use — environment.
- Criteria for media selection was stated.
- Types of Transmission Media were listed.
- A listing of alternative Operational Modes was given.
- Design technique alternatives were listed.
- The media characteristics which are of interest were listed.
- An impulsive interference model was suggested, after an investigation into the possible sources of EMI on board the SSV vehicle.
- A literature survey was conducted (the resulting bibliography was published in the form of a Technical Note).

The study in these areas led to the following conclusions.

- The transmission media were selected:
  - Wire cable was determined to be the most likely candidate for data bus transmission medium.
  - Optical links may be considered for special purpose data links.

- Operational modes were identified as being applicable to the data bus transmission media. They are:

  . Matched/Unmatched Operation

  . Matched/Loaded Operation

  . Lossy Operation

  . Current/Voltage Operation

  . Baseband/Carrier Modulation

- The most likely source of impulsive interference was identified:

  . Unsuppressed Relay Operation

  . Solenoid Valve Operation

- It was recommended that the above devices be used in the interference characterization tests and study.

The Phase II Transmission Media Study portion of the Multiplex Data Busing Techniques was based on the conclusions and recommendations called out in the Phase I Report. The areas of investigation covered in the Phase II Report are listed below.

- The basic types of cable best suited for detailed tests and study were selected.

- Test procedures for measurement of media characteristics were established.

- The Operational Modes set forth in Phase I were studied and analyzed.

- Particular Design Techniques identified in Phase I were discussed and analyzed in view of their application to a data bus system.

- Based on the rationale given in the Phase I Report the impulsive EMI model was selected and tested.

- Problems associated with the electromagnetic interference (EMI) problem were discussed.

- Environmental conditions and the properties of the most likely insulation materials for the data bus are discussed.

- Interrelated factors in the Multiplex Data Bus Techniques for the Space Shuttle were considered and studied.

These areas investigated led to the following conclusions.

- Wire cable is most suitable for the main data bus transmission medium on the Space Shuttle.

- Measurement of Media Characteristics should follow good RF practice to obtain valid cable characteristics and parameters.

- Some of the cable characteristics observed from the test results were:
    - The attenuation approached a slope of 1/2 of the log-log plot of DB loss versus frequency.
    - The phase shift is directly proportional to frequency in the upper frequency ranges.
    - The characteristic impedance varies considerably with frequency.

- There are no major problems encountered with current mode operation.

- Resistive termination is all that is necessary for baseband signals having their energy concentrated, primarily at high frequency (above 50 KHz) and having no significant DC component.

- Transformers used for coupling transmitters and receivers to a transmission line is one of the more favorable coupling techniques.

- Direct coupling, photo-coupling, capacitive coupling and high-impedance coupling techniques have no advantage for use on the Space Shuttle.

- From a signal transfer standpoint it appears that the best technique is to bring the transmission line to the remote terminal and back out again (daisy-chaining).

- In view of the low level of radiated interference resulting from the data bus transmission line, it should not be necessary to filter the transmitted data bus signals as a means of reducing the radiated interference (EMI) levels.

- It is recommended that a balanced transmission line and receivers be used.

- It is recommended that the cable shield be grounded as near receiver ground as possible.

- Neither radiated interference nor susceptibility present a problem to the operation of a baseband data bus system of the nature envisaged for the SSV assuming reasonable care is taken in packaging design.

- The added loss incurred at high temperatures by the cables must be accounted for in the data bus design and that changes in characteristic impedance and phase shift may be ignored when a fluorocarbon insulation is used.

Elaboration of some conclusions can be found in the Section 3.2 text associated with the various subjects.

2.2.3   Signal Design and Detection

The results of this task are published in the following documents:

- "Technical Phase Report Number 1, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

- Volume II, Technical Phase Report Number 2, "Signal Design and Detection, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M6-01.

Principal subjects and outputs resulting from the study in the form of conclusions and recommendations are summarized in Table 2.2-1.

Much of the work performed involved laboratory investigations and tests, the results of which were previously reported in the technical notes listed in Appendix II, and the Phase II, Volume II Report.

Signal design and detection studies during Phase I considered all reasonable design alternatives associated with each of the following:

- Multiplexing Techniques
- Forms of Data Transmission (Analog and Digital)
- Carrier Modulation Techniques (AM, FM and PM)
- Baseband Signal Designs

PRINCIPAL SUBJECT	CONCLUSIONS AND/OR RECOMMENDATIONS
Signal Generation	Techniques Described in Paragraph 3.3.2.2.
Transmitter Output Filter	None Required (see Paragraph 3.3.2.4).
Receiver Input Filter	Filter Described in Paragraph 3.3.2.4.
Frequency Distortion of Cable	Compensation Not Required (Paragraphs 3.3.2.3 and 3.3.2.4.
Signal Designs for Primary Transmission Medium	Biphase-Level or Bipolar NRZ (Paragraph 3.3.2.5).
Signal Designs for Direct Coupled Local Buses	Polar RZ (Paragraph 3.3.2.5).
Signal Designs for Transformer Coupled Local Buses	Biphase-Level (Paragraph 3.3.2.5).
Biphase Receiver for Distributed Timing Applications	The AIB Receiver Described in Paragraph 3.3.2.4.
Biphase Receiver for Centralized Timing Applications	Synchronous Receiver Described in Paragraph 3.3.2.4.
Biphase Receiver for Local Bus Applications	Simple Asynchronous Receiver Described in Paragraph 3.3.2.4.
Polar RZ Receiver for Local Bus Applications	Simple Asynchronous Receiver Described in Paragraph 3.3.2.4.
Math Model of Impulsive Noise	The GIN Unique Waveform Model in Paragraph 3.3.2.4.
Worst Case Gaussian Noise Model	The Model Described in Paragraph 3.3.2.4.

TABLE 2.2-1 KEY ISSUES, CONCLUSIONS AND RECOMMENDATIONS

- Redundant Coding Techniques
- Message Formatting Arrangements

These considerations led to the following conclusions:

- TDM should be the primary multiplexing technique in the SSV data bus.

- The TDM data bus should not be required to convey audio or video signals, and these signals should be communicated by some other means.

- Digital (rather than analog) data transmission techniques should be employed in the TDM data bus.

- Baseband (rather than carrier) signaling methods should be employed in the TDM data bus.

- Elaborate coding for error control does not appear suitable, but simple parity, two-dimensional block parity, and repetition codes should receive further study.

- Final investigations regarding the use of redundant coding interact with, and should await:
  - Determination of the required data rate and the significance of high overhead to the data bus design.
  - Definition of basic data bus configurations and requirements for error detection/correction.
  - Characterization of an interference model.

- The choice of specific formatting arrangements should follow the selection of basic data bus configurations and appropriate synchronization timing and control techniques.

● The recommended signal set was selected and is as follows:

1. Unipolar NRZ-Level

2. Polar NRZ-Level

3. Polar RZ

4. Biphase-Level

5. Bipolar NRZ

6. Delay Modulation (Miller Code)

7. Duobinary

During Phase II, analysis and practical application of the seven candidate signaling methods selected during Phase I was of primary concern. The following associated subjects were treated in their regard:

● Signal Descriptions and Power Spectra

● Signal Generation

● Data Bus Elements Effects

● Signal Detection

● Redundant Coding

The different signaling techniques were compared using evaluation criteria derived during Phase II. The following conclusions were drawn.

● All members of the recommended signal set may be easily and precisely generated using standard digital techniques.

● Signal set grouping per bandwidth:

Bandwidth = f_s: Polar RZ and Biphase-Level

Bandwidth = $f_{s/2}$: Unipolar and polar NRZ-Level, Bipolar NRZ, and Delay Modulation.

Bandwidth = $f_{s/4}$: Duobinary

- Linear filters used to reduce noise should produce a raised cosine frequency response characteristic when driven by NRZ data. This is to minimize both signal bandwidth and intersymbol interference.

- Transmission medium alone does not produce serious or significantly deleterious frequency distortion for data rates of 1 Mbps or less, and cable lengths of 500 feet or less.

- By far the most serious element effect was caused by transformer coupling between transmission medium and transmitters, and receivers.

- Only Bipolar NRZ, Biphase-Level and Delay Modulation are compatible with transformer coupling, which however complicates the receiver design for Delay Modulation.

- Because of detection considerations, Duobinary was found less suitable than any of the other six methods.

- A filter between a transmitter and the transmission medium is neither necessary nor desirable.

- A filter at the input to a receiver markedly enhances the predetection signal-to-noise ratio.

- Two noise models were defined: one to characterize impulsive noise based on the Generalized Impulsive Noise (GIN) unique waveform; and the other a "worse case" Additive White Gaussian (AWG) noise model. These were used to make meaningful estimates of bit error ratio for a given modulation/detection technique.

- Simple parity provides sufficient error detection capability and requires fewer overhead bits than any of the other techniques considered, including conventional block (horizontal and vertical) parity, repetition coding and BCH codes.

2.2.4   Synchronization, Timing and Control

The results of this task are published in the following documents:

- "Technical Phase Report Number 1, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

- Volume IV, Technical Phase Report No. 2, "Synchronization, Timing and Control, User Subsystems Interfaces, and Operational Reliability, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M5-04, Dated October, 1972.

During Phase I the following study results were accomplished:

- Six major functional categories were identified which comprise the system operation of synchronization, timing and control.

- Issues and reasonable design alternatives were identified in the six major areas: (1) timing and synchronization, (2) bus access control, (3) message routing, (4) message formatting, including function and message identification, (5) programming, and (6) channeling arrangements.

- Bus access control utilizing time reference, command-response, handover and contention techniques were discussed. A recommendation was presented to limit future study to command-response techniques and hybrid command response/time reference techniques.

- Message routing was proposed to be flexible for transfer of messages directly from subsystem to subsystem or through a central or special processor as required for maximum efficiency.

- Overall programming complexity was identified, but its impact upon data bus design trade-offs was mollified by certain operational realizations.

- Plans and objectives for Phase II were identified as related to synchronization, timing and control aspects of data bus operation.

During Phase II the following work applicable to synchronization, timing and control was accomplished.

- Numerous bit synchronization techniques were identified for each member of the recommended signal set. These results are reported in Volume II.

- An appropriate word synchronization pattern for use with an intermittent Biphase-Level signaling scheme is recommended. It consists of the unique waveform illustrated in Figure 2.2-1. The rationale for this choice are presented in paragraph 3.4.1.1.

- The centralized command-response method of bus access control is recommended as the preferred technique with supporting rationale supplied in paragraph 3.4.1.2.

Bit Intervals | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |

Word Sync Pattern
Plus Biphase Data

No
Data

Word
Sync

Biphase
Data
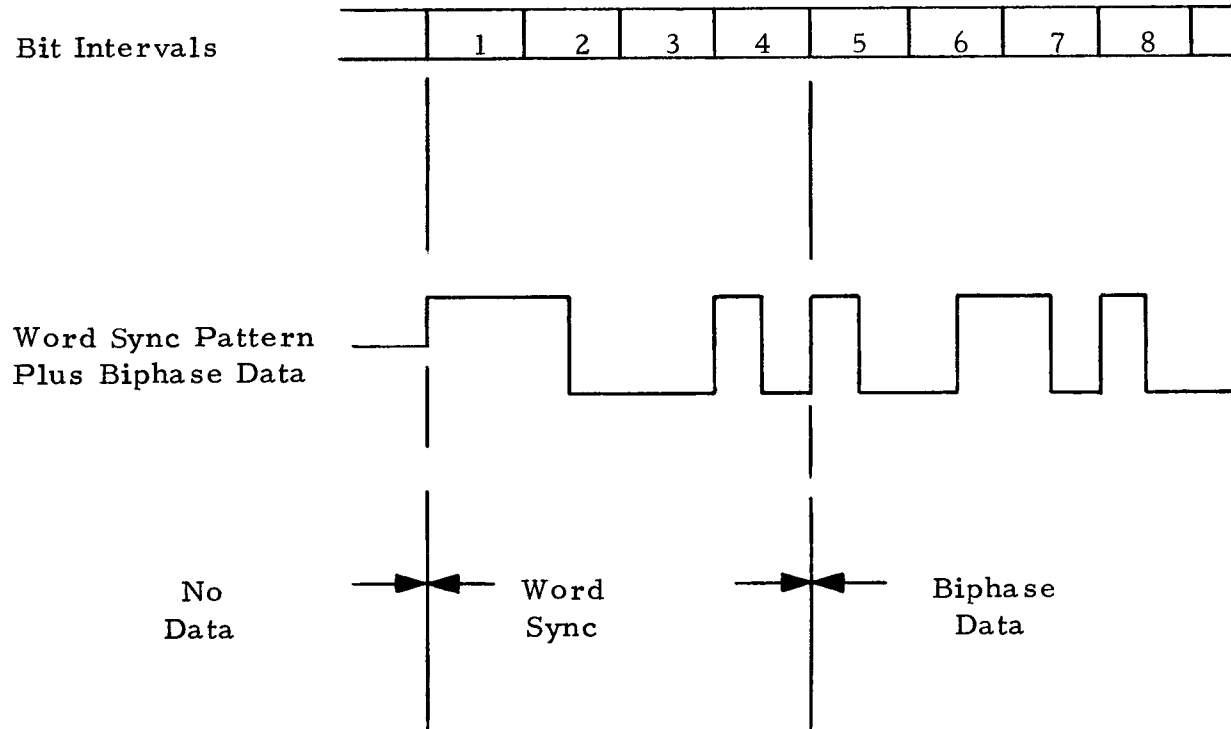
FIGURE 2.2-1.   RECOMMENDED WORD SYNC PATTERN
FOR AN INTERMITTENT BI-∅-L DIGITAL
SIGNAL

● The salient characteristics of numerous message formatting, routing, and channeling methods were identified.

● Eight preferred combinations of message formatting, routing and channeling were selected for further examination, and their impact on data rate, programming, and hardware complexity was assessed.

From the large number of possible combinations listed in Table 3.4-3, eight were selected as attractive for comparison purposes. As shown in Table 2.2-2, Alternatives I, II, III and IV form a group which have in common P1 packing — packing only discretes which are not aperiodic commands, and not packing analogs. Eleven (11) bits per word was the maximum considered for this case because 11 bit data resolution was the greatest required and 11 bits per word resulted in better economy of bandwidth than 6 or 8 bpw. Variations in blocking, channeling and routing resulted then in the evaluation seen at the right in Table 2.2-2 as relative numeric rankings. Apparently, within this group, alternatives II and IV ranked highest with a slight edge given to IV.

Alternatives V, VI, VII and VIII form a group which have in common P2 packing — packing all data except aperiodic commands. The P2 packing scheme made reasonable the consideration of larger data words, which resulted in an optimum size of 24 bits per word. Comparing 24 bpw to 11 bpw, the greatest improvement appeared in the supervisory line.

The highest ranked methods differed in routing and channeling methods. Methods VII and VIII ranked highest of the four in this group, resulting primarily from bandwidth economy and adaptability to multiple users.

TABLE 2.2-2

COMPARISON OF SELECTED DESIGN ALTERNATIVES

Alternative	Packing	Blocking	Channeling	Routing	Bits Per Word (bpw)	Max. Cable Rate (Single; or either Cable) Mbps	Economy of Bandwidth (1 - 10)	Economy of Hardware (1 - 10)	Adaptability to Multiple Users (1 - 10)
I	P1	B1	C3	R1	11	1.52	4	9	4
II	P1	B1	C4	R2	11	0.98	8	7	10
III	P1	B2	C1	R1	11	1.18	7	8	3
IV	P1	B1	C2	R3	11	0.99	8	8	10
V	P2	B1	C3	R1	24	0.92	8	7	4
VI	P2	B1	C1	R3	24	0.92	8	6	7
VII	P2	B1	C2	R3	24	0.54	10	6	10
VIII	P2	B1	C4	R2	24	0.53	10	5	10

DEFINITIONS:

1. ● Data Packing

   - P1: Pack only discretes which are not aperiodic commands.
   - P2: Pack all data except aperiodic commands.

   ● Data Blocking

   - B1: No blocking.
   - B2: Block all data except aperiodic commands.

   ● Channeling Methods

   - C1: Single half-duplex cable.
   - C2: Separate supervisory and data cables.
   - C3: Separate transmit and receive cables (through central).
   - C4: Separate supervisory cables to multiple destinations with data on another cable which goes to all destinations.

   ● Message Routing

   - R1: Indirect terminal-to-terminal transfers via central.
   - R2: Direct terminal-to-terminal transfers with source and sink addresses supplied by central.
   - R3: Direct terminal-to-terminal transfers with sink address implicitly derived from the source address.

2. Weightings, "Economy of Hardware" (1 - 10)

P1	10	B1	10
P2	2	B2	2
C1	10	R1	10
C2	8	R2	8
C3	6	R3	4
C4	2		

The highest ranked of the two groups, Alternatives IV and VII, were numerically ranked equal. Note that except for packing and bits-per-word differences, they employed the same methods for blocking, channeling and routing. The four selected alternatives and their peak data rates are as follows:

- Alternative II

    . 0.98 Mbps on Supervisory Cable, 0.64 Mbps on Data Cable.

    . P1 Packing — Pack only discretes which are not aperiodic commands.

    . B1 Blocking — No blocking of any data.

    . C4 Channeling — Separate supervisory cables to multiple destinations with data on another cable which goes to all destinations.

    . R2 Routing — Direct terminal-to-terminal transfers with source and sink addresses supplied by central.

    . 11 bits per word.

    . Relative ranking points — 25.

- Alternative IV

    . 0.99 Mbps on Supervisory Cable and 0.64 Mbps on Data Cable.

    . P1 Packing — Pack only discretes which are not aperiodic commands.

    . B1 Blocking — No blocking of any data.

    . C2 Channeling — Separate supervisory and data cables.

- R3 Routing — Direct terminal-to-terminal transfers with sink address implicitly derived from the source address.

- 11 bits per word.

- Relative ranking points — 26.

● Alternative VII

- 0.42 Mbps on Supervisory Cable and 0.54 Mbps on Data Cable.

- P2 Packing — Pack <u>all</u> data except aperiodic commands.

- B1 Blocking — No blocking of any data.

- C2 Channeling — Separate supervisory and data cables.

- R3 Routing — Direct terminal-to-terminal transfers with sink address implicitly derived from the source address.

- 24 bits per word.

- Relative ranking points — 26.

○ Alternative VIII

- 0.42 Mbps on Supervisory Cable and 0.53 Mbps on Data Cable.

- P2 Packing — Pack <u>all</u> data except aperiodic commands.

- B1 Blocking — No blocking of any data.

- C4 Channeling — Separate supervisory cables to multiple destinations with data on another cable which goes to all destinations.

- R2 Routing — Direct terminal-to-terminal transfers with source and sink addresses supplied by central.

- 24 bits per word.

- Relative ranking points — 25.

A comment should be made about the blocking method, seen in Alternative III. Blocking does make single cable half-duplex operation feasible with the simplest possible routing scheme at an acceptable low data rate. The prime disadvantages of blocking in general are:

- Additional hardware complexity.
- Blocking limits bus access. Aperiodic commands must await the completion of block transfers before they can be transmitted.
- Blocking and unblocking hardware must be programmed at each data terminal.

2.2.5   User Subsystems Interfaces

The results of this task are published in the following documents:

- "Technical Phase Report Number 1, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

- Volume IV, Technical Phase Report Number 2, "Synchronization, Timing and Control, User Subsystems Interfaces, and Operational Reliability, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M8-04, dated October 1972.

Recommendations for the SSV application are given below:

- The RT should be modular, consisting of an SIU, several SIA's, and several I/O modules per SIA.

- The SIA should accept a variable number and types of I/O modules.

- A number of standard I/O modules should be developed. These modules would include several types such as analog input and output, digital input and output, and signal conditioning types.

- The SIA should be capable of being operated remotely from the SIA by use of a local bus. A tentative choice of a parallel local bus is made.

- The grouping of electronic equipment into five (5) conditioned equipment bays has had a strong influence upon the RT configuration. The suggested configuration of the RT is given below:

Number of RT's on board SSV	16 max.
Number of SIA's per SIU	8 max.
Number of I/O Modules per SIA	8 max.
Number of Channels per SIA	128 max.
Channels per I/O Module — Varies depending upon signal type.	

- The above RT configurations imply 14 bits for addressing in the supervisory word. This assumes no "blocking" or "packing" of data bytes.

- A special purpose RT should be developed which can strip data in an eavesdropping mode.

- A special purpose RT should be used in the control and display area which is capable of channel translation.

- There is opportunity to "pack" data or block data words, as determined from an analysis of the distribution of signals. However, there is no large advantage in doing so unless particular routing or formatting techniques are chosen.

- From the data available, it appears that the scratch pad memory is not required in data acquisition. However, additional constraints imposed by the software on data access time, or the use of certain techniques to insure operational reliability could cause the memory to be required.

2.2.6   Operational Reliability

The results of this task are published in the following documents:

- "Technical Phase Report Number 1, For A Study of Multiplex Data Techniques For The Space Shuttle", report number 2635-M5-02, dated May 17, 1971.

- Volume IV, Technical Phase Report Number 2, "Synchronization, Timing and Control, User Subsystems Interfaces, and Operational Reliability, For A Study of Multiplex Data Bus Techniques For The Space Shuttle", report number 2635-M8-04, dated October 1972.

With regard to operational reliability, this study effort yielded the following principle recommendations:

- A modified (rather than a strict) FO-FO-FO design approach should be explored.

- Rigorous configuration controls should be devised and enforced with regard to the physical location and wiring of all data bus cables.

- Data necessary for the determination of the "total reliability" of various proposed monitors should be obtained.

- Data regarding the critical parameters listed in paragraph 3.6.2.4 should be obtained.

Reliability and Fault Tolerance

This report presents a summary of both (1) concepts offering a given feasibility of predicted reliability and (2) designs with a given level of fault tolerance more specifically, FO^3. Detailed treatment with proofs can be found in Volume IV of the $\emptyset$2 report.

In numerous publications of worldwide distribution, NASA has defined reliability exclusively as the probability of successful completion of a mission. The first approach given above appears to be most acceptable in a report devoted to reliability, hence this definition has been used throughout this report.

Yet the second approach, a stipulated fault tolerance, has for the last ten years been the subject of many NASA management directives, starting with astrionics equipment for the Apollo program. Unlike the widely distributed publications on reliability, these management directives have been more or less restricted to in-house and contractor distribution. Together with the choice of subsystems for which a FO^2-FS tolerance is prescribed, this report has indicated that the directives are tantamount to a practical basis for choosing a feasible and sensible unreliability of an avionic-astrionic system. This fact will now be summarized briefly.

The SSV Data Bus is one such avionic-astrionics subsystem. With a pure standby system, the FO^3 criterion (FO^2-FS for a Data Bus is FO^3) immediately and obviously implies three standby channels. As the formulas for system unreliability show the three standby channels mean that the unreliability of the whole Data Bus cannot be less than the order of magnitude of the fourth power (f^4) of the channel unreliability (f). If the channel unreliability is 3×10^{-3} per mission, then the FO^3 criterion is thus tantamount to specifying a level of unreliability of about 10^{-10} for the Data Bus. This level is decided by the near-annihilation of the channel unreliability due to the fact that three standby channels are provided.

One recommendation of this report is that the strict FO^3 criterion be used until this point, but afterwards used in a modified form. For further and detailed exploration of circuits, topology and those triple combinations of component failures causing system failure, one further criterion should accompany it. This is that the triple product of unreliabilities (e.g. one monitor and two switches) should be within 2 or 3 orders of magnitude (i.e. 10^{-12} to 10^{-13}) of the desired system level of 10^{-10}; if the triple product is less than 10^{-13}, then the particular triple failure combination should be

omitted from further serious consideration. Properly used, a FO^3 examination of a circuit should seek to systematically identify considerable bottlenecks of reliability caused by SIGNIFICANT triple products of the unreliabilities of components which if they fail simultaneously disable the system.

An example of improved logic of this procedure arises in the case of the extremely reliable toggle relays mentioned in Section 3.6.2.1. Each switch has a typical mission unreliability of about 10^{-8}. This is 100 times greater than the desired level of 10^{-10} so common sense says that pairs of switches are necessary, and each pair has an unreliability of 10^{-16}. This is already 6 orders of magnitude less than the desired level. Therefore, a ridiculous situation arises if circuit topology and the FO^3 criterion together insist on 4 redundant switches (to withstand 3 failures), since the probabilities of three and four failures are 10^{-24} and 10^{-32}, respectively. Such figures are completely nonrepresentative of a balanced allocation of reliability amongst the possible modes of failure of the system. Such a procedure can result in unnecessary complexity and decreased reliability. In short, the FO^3 criterion at the permissible gross level of the complete channels of the Data Bus is drastically less severe (by orders of magnitude to 10^{22}) than the same criterion applied at the component level. Simultaneous application at the two levels is therefore inconsistent and incongruous. As another example, simultaneous failure of three monitors (an unreliability product of possibly 10^{-12}) is a significant triple product, but the simultaneous failure of one monitor and two of the toggle relays has a completely insignificant chance (10^{-20}) of occurrence and should therefore not cause a more elaborate and complicated circuit.

Stated in another way, the strict FO^3 criterion, applied without discretion treads on ground notoriously dangerous for reliability. That is to say that the strict FO^3 criterion may lead to unnecessary and undesirable complexity, and Public Enemy Number One for reliability is complexity, especially when unnecessary. However, the modified FO^3 procedure, wherein insignificant triple products of reliabilities represent ignorable failure combinations, is of completely positive help in establishing a reliable design of minimal complexity. The key to understanding this procedure is that the order of magnitude of system unreliability can never be less than that of any combination of failures which will disable the system; but if the product of the relevant unreliabilities is 10^{-24}, and if the channels in standby configuration establish 10^{-10}, the former can be ignored both as a number and as an influence on a "modified FO^3" design.

Data Bus Reliability in Terms of Channel Reliability

The criterion of fault tolerance of the Data Bus has been taken to be triple fail operational (FO-FO-FO) since the Data Bus has to fail operational in order to fail safe. In truth, the importance of different components of the Data Bus varies according to the extent to which they have joint usage by a plurality of channels, each servicing a different LRU. This is a major point of difference between the importance of reliability per channel, as analyzed in this report, and reliability per Data Bus. For example, in a centralized system wherein the Data Bus is a conglomerate of channels each providing communication between a central unit and a Line Replaceable Unit (LRU), the closer a component is to "central", the more it has common use by a number of channels, and hence the greater its criticality in reliability studies.

Indeed, components of "central" itself are precisely as important as the entire concentration of all the LRU's. Hence it may be more appropriate to consider a quadruple fail operational (FO^4) for "central". However, it probably should not be a "strict FO^4" criterion, but a "modified FO^4" as discussed earlier.

System Constraints and Required Coverage

Standby schemes, analyzed from the two different viewpoints of this report, have emerged with two sets of conditions and constraints. The more fundamental and enduring set of conditions and constraints are those of section 3.6.2.1. For a system with three standby channels, the critical factors were shown to be:

(1)   The monitor itself must have triple redundancy.

(2)   The monitor must have a negligible probability ($\ll 10^{-10}$) of sending a false open signal to all switches in sequence.

(3)   Any one switch unit must operate independently of other switch units.

(4)   Each switch unit must have a negligible probability ($\ll 10^{-10}$) of failing to open when instructed to do so.

These criteria result from some broad assumptions, largely independent of hardware mechanization, together with an examination of the simple expression derived for system unreliability. The presence of the four channels establishes that the system unreliability is of fourth order (f^4) of smallness in relation to the unreliability (f) of individual channels; the terms other than f^4 which appear in the equation for system unreliability have to be of the same order of smallness as f^4, and the conditions of the preceding paragraph result.

The synthesis of a triple failure (FO^3) tolerant standby system given in Section 3.6.2.6 is subject to two uncertainties and factors of change, and to this extent, Section 3.6.2.6 is not as fundamental as Section 3.6.2.1. The two uncertainties are (1) the ingenuity of the circuit designer and (2) the assumed state-of-the-art concerning NASA-approved components. Both factors have a strong effect on circuit topology. Therefore, both have a strong influence on the impact of the "strict FO^3" criterion on any candidate configuration. Both factors would have less influence if a "modified FO^3" approach were used, as recommended earlier.

A survey of eight different kinds of voters in Section 3.6.2.2 include hybrid schemes with spares and switching. As is found with pure standby schemes, equations for unreliability are far simpler and far more meaningful than those for reliability. Hence unreliability, which is always used for evaluating the transmission-checking ability of a monitor in the presence of channel noise (e.g. simple parity is $\binom{n}{2} f_B^2$ in the presence of bit noise f_B), is found to be the most suitable for the calculation of an evaluation of the fallibilities of hardware as well as noisy channels. Furthermore, in all cases Mean Time to Failure (MTBF) is found to be a misleading and untrustworthy index of reliability.

In many respects, the analysis of pure standby schemes in Section 3.6.2.1 was done in more detail than the examination of the pure voters and hybrid arrangements of Section 3.6.2.2. Moreover, there was a gradual transition between a pure voter, various hybrid schemes and a standby scheme. In other words, some types of hybrid redundancy were only one step (a switching operation) removed from a pure voter, while other hybrid designs were more closely related to a pure standby scheme. In short, all these schemes can be considered as adjacent states in a spectrum of redundancy. Therefore, the four conclusions, resulting from the detailed examination of standby

redundancy, are transferable to varying degrees to all of the hybrid schemes. Hybrid schemes are critically affected by unsatisfactory switches, just like pure standby schemes, and similar constraints apply to monitors. With pure voting, the counterpart requirements exist in the absolute necessity for redundancy in the voting device itself.

Two concepts of a standby scheme were examined. The Poisson Panacea, philosophically elegant but definitely impractical even in the 21st century, is the usual theory displayed in texts. The Credible Configuration is a practical goal which is possibly achievable sometime in the future, but the best that can be done with recent components and a "strict FO^3" criterion is constrained as cited in Section 3.6.2.6.

Comparison of Systems

A comparison of the Credible Configuration of a three-standby scheme with a pure 4-out-of-7 voter showed the former to be much better provided two important assumptions were satisfied. The first assumption was that persistent induced noise does not occur in the channels of sufficient magnitude to cause frequent word errors; otherwise an unsophisticated standby scheme will quickly perform unnecessary switching and exhaust itself. The second assumption was that the necessary diagnostic time of the standby scheme was less than the minimum allowable interruption in the flow of correct information across the Data Bus.

The characteristics of the induced noise in the channels have a decisive effect on most aspects of the design of a Data Bus. Not only is it the major unknown in deciding between a pure standby scheme and a pure voting scheme as indicated above, but it determines whether any monitor will be useful or useless. For instance horizontal parity, in the presence of noise which is independent between adjacent bits, performs quite well; but let the noise

assume burst characteristics of the duration of one word, then one word becomes as likely as any other, and horizontal parity degrades to the useless transmission reliability of one-half. Longer periods of burse noise degrade all types of monitoring schemes, even BCH codes. Recommended answers to this problem are (1) complete physical separation of the different bus channels as far as possible, (2) rigorous configuration control to ensure that no long cables of any kind run close to the Data Bus cables, (3) possible cooperation with the structural designers of the shuttle vehicles to see if stiffening ribs can be built as box sections and provide additional "free" shielding for the Data Bus cables running inside them.

Monitor Reliability

Section 3.6.2.3 puts forward what is believed to be an original concept of the total unreliability associated with a monitor. This total unreliability is a combination of hardware unreliability (over the duration of a word or small number of words) and the transmission unreliability. Using this concept a best monitor or combination of monitors can be formulated. Radical differences in the choice of monitors for the proposals A, B, C and D were very apparent.

Evaluation of Proposed Systems

Section 3.6.2.4 points out that none of the four proposals managed to give any real information concerning their operational reliability. In other words, none of the critical parameters were mentioned, no reliability logic diagram was given and little evidence was given that the subject had been studied. The critical parameters which have to be specified, with supporting data, are listed in Section 3.6.2.4.

One of the proposals (proposal B) talked about the most sophisticated of the hybrid systems (Voter H) without any mention as to how to mechanize it. The other proposals were less extravagant in their forms of redundancy.

Another important issue, in which proposal B differed from all others, was whether the LRU's (existing designs) would decide the redundancy of the Data Bus System, or vice versa. The opposite situation is that the best form of redundancy is decided for the Data Bus and LRU's as a whole avionic-astrionic system, and the coordinated design effort direct the design of the LRU's. This report suggests that Data Bus technology is presently in its infancy, and the correct long term trend to be identified is that coordinated new design, where the LRU's are changed if necessary, will become the rule in the time frame of the Space Shuttle.

Recommended Improvements in Proposals

Because reliability, fault tolerance and redundancy are of extreme importance, the following should be a necessary part of the proposals for a data bus.

(a) FO-FO-FO designs should be specified in detail. If some components are only FO-FO (e.g. switches) this should be justified on a basis of probability.

(b) A reliability block diagram in sufficient detail should be provided. All monitors, switches and channels should be clearly shown.

(c) The approximate complexity of each block should be given.

(d) The number of monitors selected, as well as the type of redundancy, must be justified.

E

(e)   If elaborate switching and voting devices are proposed, their mechani-
zation and reliability and possible redundancy must be given.

(f)   The characteristics of the LRU's must be adequately investigated,
especially in relation to permissible redundancy and their tolerance
of a series of faulty words.

(g)   Assumptions regarding channel noise, and the sensitivity of monitor
performance of these assumptions must be clearly stated.

(h)   Monitor coverages must be given.

(i)   The independent operation of switches must be demonstrated. The
three characteristic reliabilities of each switch must be given along
with the type of switch.

2.2.7   Candidate Data Bus Designs, Evaluation of

A considerable amount of evaluation of the four candidate data bus designs
of the two major Phase B contractors, MSFC, and MSC was performed as
part of other sections of this study, including Synchronization, Timing and
Control, Signal Design and Detection, User Subsystems Interfaces, and
Operational Reliability. The evaluation is summarized in this report in
Section 3.7, Evaluation of Candidate Data Bus Designs, with results and
conclusions as follows:

- Specific Requirements (ref. 3.7.1.1), Key Characteristics
  and Relationships (ref. 3.7.1.2), and Features, Characteris-
  tics and Capabilities of the Systems (ref. 3.7.1.3) were cited
  in the formulation of an evaluation criteria. Upon examination,
  it was found that 1) all the required characteristics of the SSV
  data bus were not sufficiently defined, and 2) that certain
  specific capabilities of the four candidate data bus systems were
  not readily determined in terms of their descriptive parameters.
  This resulted in certain inconclusive areas of evaluation.

- Key characteristics and relationships are the following:
  - a) Reliability - transmission and hardware
  - b) System Throughout Efficiency
  - c) Programming
  - d) Terminal Hardware Architecture
  - e) Computer/Bus Controller Organization
  - f) Cost, weight, size and power consumption
  - g) Growth Potential and Flexibility

- Evaluation of hardware complexity of the reliability monitor methods of the four systems resulted in the following relative order of complexity (equated to equivalent NAND Gates required):

System D	36
System A	66
System C	145
System B	308

  System D requires the least amount of hardware in this case, and System B requires the most.

- The numerics of "Reliability" were simplified by re-forming them into "unreliability" figures. In terms of Transmission Unreliability, the four systems ranked as follows (undetected errors, taken over 50 words):

System C	8×10^{-27}
System D	4.8×10^{-26}
System B	4.59×10^{-20}
System A	1.8×10^{-9}

  Systems C and D are superior, System B may be satisfactory, and System A is inferior.

- However, the type redundancy used is important. System A and C employ standby redundancy, System B uses masking redundancy for 90% of the LRU's and standby redundancy for the other 10%, and System D uses masking redundancy. Standby redundancy may not be the only method a system can employ if any of the following constraining characteristics of standby redundancy cannot be tolerated in the Data Bus Subsystem:

  a) fallibility to repetitive bursts of noise

  b) finite switchover time

  c) minimum acceptable switch unreliability

  d) imperfect coverage

  e) unreliable monitors

  Specific parameters of the SSV were not sufficiently defined in order to make necessary determinations with regard to the suitability of standby redundancy.

- System Throughput Efficiency

  Using the Pre-Launch Mission Phase raw data bit rate requirement of 422 Kbps, and the 1 Mbps design limit of the Data Bus, the minimum acceptable system data and command throughput efficiency was found to be 42.2%. The following was determined with respect to acquisition of measurement data and the issuance of command data:

  System A, data and commands - could not meet minimum requirements without blocking. Average block lengths of six 8-bit data words and ten 8-bit command words required.

System B, data and commands - could not meet minimum
requirements without blocking. Average block
lengths of five 8-bit data words and eight 8-bit
command words required.

System C, data - meets minimum requirement at two 8-bit
bytes per standard 33 bit word.

System C, commands - does not meet minimum requirements,
even with blocks of four 8-bit bytes per two standard
33 bit command words out. However, System C
could meet total requirements when operated at
5 Mbps, its design goal.

System D, data and commands - exceeds minimum requirements
by nearly a factor of 2 when operating at two 8-bit
bytes per 20 bit word.

System D is superior with regard to system throughput efficiency.
This represents spare capacity, which consequently enhances the data
bus for operational peaks and expansion capability without redesign or
constraint to operation, while affording excellent flexibility of random
addressing, terminal-to-terminal transfer and multiple destination
terminal addressing. Blocking is not required.

● Blocking has been determined to be an undesirable - in extremes,
unacceptable - method for use in a SSV Data Bus Subsystem.
Therefore, to that end Systems A and B are undesirable with
regard to data acquisition and may be unacceptable with regards
to commands.

- <u>Hardware Complexity</u> - The various elements of each system were listed, but insufficient detailed information was available to make meaningful evaluations. This includes subjects such as design, logic, cost, weight, size, power, etc.

- <u>Data Transfer Methods:</u> 1) Terminal-to-terminal (TTT) transfer, 2) editing and 3) multiple destinations transfer of data. These were deemed applicable and highly desirable in the SSV Data Bus Subsystem.

  System D is capable of direct TTT transfers within a single data request message.

  System A is capable of some TTT transfer, using two messages: 1) "primary" signal (to terminal which is to receive message), and 2) the normal data request message (tells source terminal to transmit message).

  Editing is performed by a programmable function in the Bus Controller in System D. Data is selected for tape recorder and telemetry. Systems A, B and C would require special terminals for the editing operation.

- Programming changes could be made at central for each of the four systems, and also at remote terminals (RT) for Systems B and D.

- Systems A, C and D are modular within their respective RT's. System B offers either of three type terminals, which is the least flexible method.

- Systems B and D offer some greater degree of low level and signal conditioning interfacing. System A puts more of that type burden on LRU's.

- Systems A and B use power strobing to conserve power.

- System D appears to have the best potential for growth.

In retrospect, System D appears to be the superior system of the four.

2.3   ASSESSMENT

The major objectives of this study were accomplished. Space Shuttle Vehicle requirements were identified and analyzed toward use by the other study tasks; transmission media were surveyed, reduced to best candidates and thoroughly analyzed both empirically and theoretically; signals design and detection methods were analyzed, presenting spectrum characteristics and representative circuits; synchronization patterns were studied, resulting in a recommended sync-word. Various timing and control schemes were presented, including schemes for packing, channeling, and routing data for a number of message sizes. These were optimized by computer aided analysis, giving data bit rates; interface considerations with various SSV user subsystems were examined, and based upon require-ments inputs, optimized remote terminal modules were given; operational reliability was put in perspective and thoroughly analyzed. SCI presented a simpler method of analyses termed Unreliability. The methodology is basic to any data bus similar to that of SSV; test model data bus terminals were built and operated in a data bus built by NASA and others; and four candidate data bus subsystems were evaluated.

Changes in Space Shuttle Booster and Orbiter configurations and designs curtailed the progression toward details by Phase B contractors. Conse-quently, SCI was compelled to take the mid-1971 designs as baseline input to their methods and techniques type study. This resulted in a great deal

of difficulty in ascertaining requirements inputs, which was felt throughout the study. It also resulted in the use of "old" numbers being used to check certain schemes. To this point, the study is not "up-to-date".

Phase B contractor data was not readily convertable to data useful in this study. Manual interpretation and translation was required, resulting in a deck of punched cards for the SSV Booster Data. The time required to accomplish this, and its difficulty led to the decision to treat orbiter data in summary form only.

In spite of these shortcomings, the results of this study should be useful to those commissioned with the Space Shuttle Data Bus designs. It is summarized in the Final Report. Refer to the applicable Phase I and II reports for detailed information.

3.0 TECHNICAL DESCRIPTION

3.1 REQUIREMENTS IDENTIFICATION AND ANALYSIS

This summary is taken from Technical Reports (reference Appendix III-A) and Technical Notes (Reference Appendix II) written during the Requirements Identification and Analysis (RIA) period of study, and focuses upon the Space Shuttle Vehicle Booster and the Orbiter. The data base for the multiplex study of these two vehicles was primarily the Phase B listings and reports (reference Appendix III-A). An early decision to concentrate on the analysis of the Booster resulted in a detailed data listing for the Booster, as converted from the GD Space Shuttle Booster Data and Control Requirements Listing (reference Appendix II-4). Each point is maintained on a punch card, and the card deck is available for further analytical uses. Orbiter data was derived from the NAR Orbiter Data List dated 9-14-71 (reference Appendix III-A).

A characteristic that greatly influenced the configuration and location of electronic equipment within the SSV was temperature. Except for the cabin area that was already conditioned for the occupants, each local area that was assigned electronic equipment had to be furnished with cold rails or cold plates. The following is the expected SSV environment:

Booster:	External Structure	$-50^{\circ}F$ to $2500^{\circ}F$
	Cryogenic Structure & Systems	$-320^{\circ}F$ to $300^{\circ}F$
	Other Structures & Systems	$-50^{\circ}F$ to $+650^{\circ}F$
	Cabin	(Not identified. Assumed to be same as in Orbiter)
Orbiter:	External Insulation	$-300^{\circ}F$ to $+2600^{\circ}F$
	Cryogenic Structure & Systems	$-44^{\circ}F$ to $+400^{\circ}F$
	Other Structure & Systems	$-50^{\circ}F$ to $+650^{\circ}F$
	Cabin	$0^{\circ}F$ to $+120^{\circ}F$

According to MSFC 85M03929, the recommended maximum acceptable temperature within the avionic box was 85°C (185°F). From this and the above it can be seen why temperature conditioning the electronic equipment was necessary.

Another SSV characteristic that influenced the multiplex system and its requirements were the vehicle sizes, respectively. The booster was about 270 feet long by 34 feet in diameter, and the orbiter was about 175 feet long by 28 feet in diameter. The high price per pound in space gave rise to trading off the weight of wire for a data multiplex configuration. This became particularly attractive upon identification of the large numbers of points needed.

3.1.1   Booster

The SSV Booster requirements study was approached in two parts, 1) Requirements Identification, and 2) Requirements Analysis.

3.1.1.1   Booster Requirements Identification

Identification included data and control requirements that were put on punched cards, as follows:

- Signal identification.

- Signal designation (which also inferred it to be a signal source).

- Signal destination(s).

- Signal active period, by mission phase.

- Location station, which approximated the signal's location in the SSV.

- Classification as to aperiodic or periodic, control or measurement, and analog or discrete or digital.

- Bits per word for each signal (accuracy).

- Samples per second rate for each signal (resolution).

- Remarks, which included a signal type identification (e. g. pressure, temperature, strain, flow, rate, etc.).

Other booster signal characteristics identified include the following:

- Signal types—the quantity of various type signals, their required measurement range and accuracy, and candidate methods of instrumenting them.

- Based upon the SSV temperature constraints and Phase B contractors recommended grouping of signals into certain locations, representative avionic bay locations were determined.

- The quantity of signals was determined.

- Acoustic and vibration environment identified.

Those characteristics listed as stored on punched cards are too numerous to list here again. A major task of the analysis was to group and summarize this data. Some of the general items identified follow.

Avionic Areas

The bay areas identified for placement of electronic equipment are as follows:

1. Nose Bays - Two areas, one on the left side the other on the right, located about midway vertical and about 18 feet back from the tip of the nose.

2.   <u>Crew Station</u> - Two areas, left and right, within the crew module directly behind the crewmen.

3.   <u>Midship Bays</u> - Two areas, located some 84 feet back from the nose, in the lower area between the LH_2 and LOX fuel tanks.

4.   <u>APU Areas</u> - Two on each side (one each side reserved for DFI), some 222 feet back from the nose and to the lower outside positions of the hull.

5.   <u>Aft Area</u> - One larger more central area, behind the fuel tank, some 234 feet from the nose.

<u>Types of Signals</u>

The more than 9500 signals in the booster were identified by some nineteen categories of signal types, as follows:

<u>Symbol</u>	<u>General Parameter</u>
P	Pressure
T	Temperature
F	Flow
D	Differential Pressure
S	Strain
A	Acceleration
V	Vibration
L	Sound
R	Rate (Speed)
Q	Quantity
O	Occurrence (Event/Time Ind.)
Y	Position
I	Current
E	Voltage (Power and Signal)
H	Hertz
N	Light Intensity (i.e., Lube Oil Analysis)
M	Thrust
G	Gas (i.e., Analyzer)
X	Ratio

A representation of the types and ranges of signals includes the following:

Temperature

Ranges: $-300^{\circ}F$ to $+2700^{\circ}F$

                     $- 50^{\circ}F$ to $+ 650^{\circ}F$

                     $-440^{\circ}F$ to $+ 400^{\circ}F$

Accuracy: Generally 5%

Suitable Sensors: Thermocouples (TC), Types

                     T (Copper-Constantan)

                     K (Chromel-Alumel),

                     R (Platinum w/13% Rhodium-Platinum)

High Temperature Optional Sensors:

                     30% Rhodium Platinum - 6% Rhodium

                     Platinum; and Tungsten - 26%

                     Rhenium Tungsten

                     Also, resistance temperature elements

                     (RTE) for sensing temperatures from

                     cryogenic $(-445^{\circ}F)$ to moderately high

                     ranges $(+1700^{\circ}F)$.

Strain

Ranges: 0-2000 μstrain $-440^{\circ}F$ to $+400^{\circ}F$

                     0-4000 μstrain $- 50^{\circ}F$ to $+650^{\circ}F$

                     $\pm$ 0.1 in/in $- 50^{\circ}F$ to $+650^{\circ}F$

                     0-7000 μstrain $-300^{\circ}F$ to $+2500^{\circ}F$

Strain measurements listed in the BAC DFI measurements list were as follows:

± 0.002 in/in	0 to 20 Hz
± 0.002 in/in	0 to 100 Hz
± 0.01 in/in	-----------
± 0.01 in/in	100 sps

accuracy: 5% generally, with 10% to 20% more likely at higher temperatures (to $+650^{\circ}F$).

suitable sensors: wire and foil resistance strain gages for all but the large range (± 0.1 in/in). Linear displacement transducers employed there. Strain gages temperature limited to about $+750^{\circ}F$ for static measurements and $+1800^{\circ}F$ for dynamic measurements. Capacitive transducers are candidates for use at higher temperatures.

Force

ranges: 0 - 500 lbs. ($0^{\circ}F$ to $+200^{\circ}F$)
           0 - 500,000 lbs. ($-440^{\circ}F$ to $+400^{\circ}F$)

accuracies: (similar to strain gages above)

suitable sensors: load cells (strain gages mounted on test unit); inductive transducers (i.e. LVDT); piezoresistive strain gaging

F

Displacement, Linear

Range Overall: 0 to 8 inches max.

Accuracy Required: Generally 5%.

Environment Temperature: $-300°F$ to $+650°F$

Suitable Sensors: Either LVDT's (linear variable differential transformers), other magnetic devices, potentiometers, and capacitive. Of these, the LVDT is generally employed.

Displacement, Rotary (and Control Position)

Three general environmental temperature ranges:

1) $0°F$ to $+200°F$

2) $-50°F$ to $+650°F$

3) $-440°F$ to $+400°F$

First range, transduction employing potentiometers, synchros, capacitance, or RVDT (rotary variable differential transformer) and other inductive types can be used. RVDT's are preferable on limited angle measurements ($\pm 30°$) and synchros are suitable for continuous-angle measurements. Quasi-static requirements could be met by a potentiometer, within its constraints.

Next two severe environmental ranges:
> Contactless devices preferred.
> Capacitive devices have limitations.
> RVDT's used directly coupled or through angle-extending linkage and gearing are preferrable.

Acceleration and Vibration

Ranges: Acceleration - ± 8G; 0 - 20G

Accuracy Required: ± 5%

                                     Vibration - 0 to 10 mils (70 to 220 Hz)

Temperature Environment: Static Measurements - 0°F to +200°F

                                     Dynamic Measurements - to about 1150°F

Suitable Sensors: For dynamic acceleration measurements,
                                     piezoelectric accelerometers.

Both Static (Zero Frequency) and Dynamic Accelerometer Measurements:
                                     Strain-gage accelerometers.

Other static acceleration transducers are the servo accelerometer, and the
type employing seismic mass and inductive transduction, either LVDT or
variable reluctance.

Vibration measurements can be made by integrating the dynamic accelera-
tion measurements.

Noise, Acoustic

Range: 70 - 140 db (0°F to +200°F)

Also Listed: 140 to 170 db (20 Hz to 2 KHz)

                                     ± 0.1 to ± 3 psi (20 Hz to 7 KHz)

Suitable Sensor: Piezoelectric microphones.

Pressure

Ranges: Various from 0 to 0.25 psia and 0 to 3000 psig

Also, various ranges listed in BAC DFI list:

$\pm$ 20 to $\pm$ 100 psi (0 - 30 Hz), 0 - 10 psi, 0 - 100 psi,
0 - 1500 psia (continuous), 0 - 500 psi, 0.05 - 1.0 psia,
2.5 - 70 psia, 0 - 300 psig, 0 - 50 psia, 0 - 450 psia, 5 - 35 psia,
-10 to +100 psig, 0 - 65 psia, 0 - 300 psia, 1 - 25 psi, 2 - 20 psi.

Accuracy Requirements: 2% and 5% achievable.

Environmental Temperature:

Ranges Cited: $-440^{\circ}F$ to $+400^{\circ}F$ and
$-50^{\circ}F$ to $+650^{\circ}F$

Suitable Sensors: Transducers employing strain gage and LVDT transduction methods, coupled to such sensors as diaphragms, bellows, pistons, or bourdon tubes - "C" or twist type. Capacitive and variable inductance transducers also can be used.

Dynamic Pressure Measurements:

Piezoelectric crystal transducers.

Pressure Ratio

Ranges: 1.05 to 3.2 (ABES engines)

Temperature Environment: -50° to $+650^{\circ}F$

Suitable Sensors: Suitably made by direct measurement of each pressure, subsequently ratioing them electrically in conditioning units.

Vacuum

Range:
10^{-2} to 10^{-7} mmHg

Candidate Sensors:
Gages - Pirani, Ionization, Penning-Nienhuis, Edwards High Vacuum ionization gage, heated-filament type, and Redhead or inverted magnetron gage.

Low Leak Rate Transducer:
Haven cyclic pressure gage.

Speed (Angular)

Ranges:
0 - 14,000 RPM

1,200 - 15,000 RPM

Accuracies:
$\pm$ 0.5% to $\pm$ 5% nominal.

Suitable Sensors:
Magnetic pick-ups (about -430°F to $+800^{\circ}$F).

Fuel Flow

Ranges:
0 to 3 lbs./sec.

0 to 16,000 lbs./sec.

JP4-Suitable Sensor:
Turbine type. 1% to 2% accuracies nominal.

LO_2 & LH_2 - Candidate Sensors:

1) Thermal using TC's (preferred method).
2) Magnetic resonance.
3) Fluid dynamics (pressure drop along the pipe monitored).

<u>Quantity, Level, Mass</u>

LO_2, LH_2, JP4 Quantities

Range: 0 to 100%

Suitable Continuous Sensors: Capacitance Probe (preferred), with
accuracy in the order of 10 bits (0. 1%).

Suitable Point Sensors: 1) Capacitance probes that activate
switch-outputs.

2) Resistance wire elements configured
in a Wheatstone Bridge circuit.

Other Measuring Methods for Level, Mass or Quantity:

Dielectric, buoyancy, cavity resonance,
conductivity, heat transfer, nuclear
radiation, optical, pressure, sonic
damped oscillation, and weight.

Other Candidate Measurements:

Voltage and current, power, frequency,
radiometer, EKG, heart rate, lung
flow, radiation, partial pressure, silver
ion concentration, humidity, and events
(switch-closures).

<u>Environmental Conditions - Acceleration, Vibration, Acoustic</u>

<u>Acoustic</u> environment was listed by MDAC as being 155 db (ref. to 0.0002
dynes/sq. cm) for Area DIU (digital interface unit) operational, at two-hour
exposure, with a spectrum from 100 to 1400 Hz.

The following acoustic levels were listed for the GD-NAR Expendable Second
Stage (ESS):

- Forward Skirt Area   161.5 db overall
- Aft Skirt Area   162.5 db overall
- Thrust Cone Area   (Less than either forward or aft skirt areas.)

Vibration listed by MDAC as overall random vibration by mission phase for area DIU's is as follows:

Mission Phases	Equipment Operating Grms
Launch & Land	16
Ascent	7.5
All Other	2

The associated spectra is listed as follows:

Launch and Land	$0.48G^2$/Hz from 50 to 300 Hz
Ascent	$0.065G^2$/Hz from 50 to 500 Hz
All Other Mission Phases	$0.008G^2$/Hz from 50 to 500 Hz

Booster dynamic acceleration listed by General Dynamics is as follows:

at Lift-Off (± G's Peak):

Zone	Longitudinal		Lateral
	(0 - 35 Hz)	(35 - 50 Hz)	(0 - 35 Hz)
Forward	2.0	1.0	1.0
Intertank	3.0	1.0	1.0
Aft	5.0	2.0	1.5

at Engine Cut-Off/Separation (± G's Peak):

Forward	3.0	1.0	2.0
Intertank	3.0	2.0	2.0
Aft	3.5	1.5	2.0

Aperiodic Data

The source data for the DCRL did not provide time correlation of data points to a resolution better by mission phase effectivity. Therefore, for aperiodic data minimum sample rates were applied and the rates were treated like periodic data over the particular mission phase which permitted normalizing bit rate per mission phase. Although this tends to make the bit rates appear higher than they are actually, the error is minimal because of the few aperiodics and the relatively low bit rate assigned to them.

3.1.1.2   Booster Requirements Analyses

Analysis of the data was aided by computer processing, resulting in tabulations and topographies (data per location within the SSV) which served as models of the data flow. Conclusions take the form of summary comments and tables about the data because the requirements study is not an end product in itself, but is a "tool" for other study phases. The following were analyzed:

- Bit rate per location per mission phase.

- Total bit rate per mission phase.

- Total bit rate per mission phase per avionic location.

- Topography of bit rate per mission phase (phase PL was presented. Other phases can be generated as needed by employing computer program SCI-E077).

- Bit rates for "measure" signals by mission phase, and topography (phase PL again presented as representative; use program SCI-E079 to generate other phases also).

- Bit rates for "control" signals by mission phase, and topography (phase PL presented as representative. Use program SCI-E079 to generate other phases also).

- Bit rate per mission phase per subsystem.

- Periodic and aperiodic bit rate per mission phase.

- Count of signal types by location, and their topography ("T" temperature signals presented as representative. Use computer program SCI-E083).

- Summary of type signals per avionic areas.

- Signal types per location per subsystem.

- Count of analog, discrete and digital numerics per subsystem.

The raw data (data bits, without sync, address, operation codes, check bits or other overhead bits) bit rates have been identified per seven mission phases, the best general time segments available. The values are conservative—higher than actual—because worse case conditions were taken: in converting to bits-per-word the worse case accuracy figure over a range spread was used, the faster sampling rate of a range was used, and the rate per a point over the entire mission phase was used even when activity might be for only part of a phase. The bit rate per mission phase is summarized in Table 3.1-1.

The bit rate for each phase can be further identified by use of a computer program SCI-E077, presenting a topography of bit rates per location within the booster. This is shown in Figure 3.1-1 which also shows the areas of data assignment per avionic bay. The area assignments were based upon 1) location of stations within the vehicle, and 2) proximity of the signals to the various stations.

TABLE 3.1-1

TOTAL BIT RATE PER MISSION PHASE

Mission Phase	Grand Total Bit Rates
Prelaunch (PL)	422,443
Launch & Ascent (LA)	398,717
Orbit Operations (OO)	174,330
Re-Entry (RE)	226,290
Fly-Back (FB)	225,207
Approach & Landing (AL)	218,461
Ferry (F)	221,094

The effect on the various assigned avionic equipment locations is shown in Table 3.1-2 for each mission phase (rate rounded to nearest Kilobits per second).

TABLE 3.1-2

TOTAL BIT RATE PER PHASE PER AVIONIC LOCATIONS

Location	Bit Rate (Kbps)						
	PL	LA	OO	RE	FB	AL	F
Nose Bay (2)	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Crew Area (2)	45	35	29	40	38	32	35
Midship Bays (2)	10	9	8	7	6	6	6
APU Areas (2)	19	11	14	161	157	154	155
Aft Area (1)	348	344	123	18	23	27	25

The data rate information was borken down further in order to gain insight into what was the nature of the data and where was it coming from. Another computer program, SCI-E-079, was used to present topographics of measurement, and of control per data rate. Summaries of this data and of the correlation to Booster subsystems is given in the following two tables.

Note: One increment= 3 feet

TAIL - ON - VIEW

LONGITUDINAL VIEW

3.1-16

03-02-72

Bay region labels within the grid: **(CREW STATION)**, **(NOSE BAYS)**, **(MID BAYS)**, **(APU BAYS)**, **(AFT BAY)**

LOC	A	B	C	D	E	F	G	H	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	J	TOTAL
4				50	.390				1181				6													1,627
5					23144																					23,144
6			112		62		8342																			8,516
7					62												56									118
8			56		1532				72																	1,772
9				1388	1496		2752	23	682	2784	37	44		2			57							112		9,370
10									373															105		373
11			56		56		56			56			56				56									336
12			56	56						112																224
14													135				56									191
24				6	156						6			6												174
28					378	36	1219	431	447	1000	420			420			12									4,363
29									99																	99
30			56		156	9	80	9		127	1				66			56								560
31				372											1											373
32					56																					112
33								212					56													1,728
34													620			840					56					
35							112																			
36								336																		448
40			56		112		56		56						56		56	56								448
46				6	106		112		336		6			100		1										667
51					106										50											156
52			56		56		56		56						6			56								286
54					56												112									168
56							62		336																	398
57																	1	5								6
58																	1									1
59													55													55
60											1	6	6							2		56		56		127
61												36	36							1						73
62												36	36				1									73
63																	1				50					51
64											3	3	4				3				231			282		526
67			2654																							2,671
68																	1	16								
70			6		56		50		56		56	30	30				56		3451	3383						7,174
72											3532						3238									6,770
74		56			6						390						604									1,056
75																		8								8
76											685	62	62				704									1,513
78	56	112									1		35792													35,961
79	250		56		56			11	85		56	60					56									630
81				324	384		354	324	354	346	354	354	354	354		354	366				168					4,390
82			11	484	422	11	443	443	422	422	443	443	422	422	10	445	517	11								5,371
83		638		24893	24893		24893	24893	24893	24893	24893	24893	24893	24893		24893	24893									299,354
84	732																									732
89					250																					250

GRAND TOTAL FOR PL IS 422,443

FIGURE 3.1-1 GD BOOSTER-BIT RATE FOR MISSION PHASE PL

3.1-17

TABLE 3.1-3

BIT RATE PER PHASE

Mission Phase vs.	Measurements Total Bit Rates	Control Total Bit Rates
PL	323,028	99,415
LA	298,588	100,129
OO	159,856	14,474
RE	209,257	17,033
FB	204,044	21,163
AL	199,093	19,368
F	200,476	20,618

TABLE 3.1-4

GD BOOSTER BIT RATE PER MISSION PHASE PER SUBSYSTEM

Subsystem	Mission Phase (in bps)						
	PL	LA	OO	RE	FB	AL	F
JE	0	0	0	134,028	134,028	134,028	134,028
AP	24,657	23,661	17,242	11,740	12,238	17,316	14,255
CS	236	236	0	236	236	0	236
CR	100,247	100,808	14,349	17,794	23,079	17,122	22,534
GD	3,729	4,388	939	4,248	4,061	3,988	4,062
EL	15,315	15,315	15,314	15,314	15,314	15,314	15,314
GN	38,490	27,339	23,121	18,564	19,824	19,824	19,824
ME	219,516	219,516	88,044	0	0	0	0
RS	13,560	90	7,965	13,470	5,660	102	80
SM	7,427	8,134	8,136	11,660	11,501	11,501	11,495

Another analytical viewpoint of data rate information was presented in terms of "periodic" and "aperiodic" bit rates per mission phase. Aperiodic data were not readily presentable in their actual time segments and had to be taken over the full mission period of their occurrence. As Table 3.1-5 shows, the rates were low and therefore did not contribute much error to the overall bit rate data.

TABLE 3.1-5

PERIODIC/APERIODIC RATES PER MISSION PHASE

Mission Phase	Periodic	Aperiodic
PL	414,439	8,004
LA	390,814	7,903
OO	174,258	72
RE	224,841	1,449
FB	223,727	1,480
AL	218,222	239
F	219,681	1,413

The signals were then examined as to type, location and quantity per various categories. Another computer program, SCI-E083, was used to prevent topographies of the quantities per signal types, although not shown here, flow topographies of each type signal has been generated. A summary of type signals per avionic areas is shown in Table 3.1-6.

TABLE 3.1-6

TYPE SIGNALS PER AVIONIC AREAS

Type Signals \ Avionic Areas	Nosebay (2)	Crew Station (2)	Midbay (2)	APU Bay (2)	Aft Bay (1)
Acceleration (A)	—	4	2	—	156
Acoustic (L)	—	1	1	1	2
Flow (F)	—	4	6	24	—
Vibration (V)	—	2	16	103	6
Temperature (T)	11	112	123	131	294
Strain (S)	8	18	57	12	16
Pressure (P)	4	179	46	223	578
Position (Y)	36	1,236	170	431	1,098
Voltage Signals (E)	15	2,000	55	498	1,012
Current Signals (I)	5	24	32	50	72
Quantity (Q)	—	28	46	16	16
Rate (R)	—	9	6	52	96
Gas (G)	—	2	11	—	—
Thrust (M)	—	—	—	—	36
Frequency (H)	—	5	—	—	—
Ratio (X)	—	—	—	—	36
Light Intensity (N)	—	—	—	12	—

A review of the type signals per location per subsystem yielded the following summary table. It can be seen that of the 9,549 signals identified, 2,952 are control signals and 6,597 are measurement signals. Of these, 5,014 are analog (A), 3,807 are bilevels (D), and 728 are digital numerics

G

TABLE 3.1-7

BOOSTER MIX TABLE

Station Assignment Classification / Subsystems	Nosebay (2) M A	Nosebay M D/W	Nosebay C A	Nosebay C D/W	Crew Station (2) M A	Crew M D/W	Crew C A	Crew C D/W	Mid Bay (2) M A	Mid M D/W	Mid C A	Mid C D/W	APU Bay (2) M A	APU M D/W	APU C A	APU C D/W	Aft Bay (1) M A	Aft M D/W	Aft C A	Aft C D/W	Subsystem Totals A	Totals D	Totals W
JE													360	12							360	12	0
AP	15	11			43	26			177	156			72	152			396	105			703	450	0
RS					148				28				133								309	0	0
SM	20				51				128				66				48				313	0	0
CD					1	20	10	518													11	448	90
EL					572	31							186	28			172	66			930	125	0
GN					179	163							47	22			467	4			693	31	158
CS	4	7			12	32							8					6			24	31	14
ME																	1200				1200	0	0
CR				22	121	860	56	903			1	85		90	12	382	1	151	280	683	471	2710	466
Totals per Station	39	18	0	22	1127	1132	66	1421	333	156	1	85	872	304	12	382	2284	332	280	683	5014	3807	728
Grand Totals	79				3746				575				1570				3579				9549		

(W). Heaviest signal concentrations are found in the Crew Station and the Aft Bay.

An examination was made of the DCRL to determine the number of signals terminating in more than one destination because this could influence the User Subsystem addressing structure. Most signal flow is to and from the central multiprocessor, with some being retransmitted to other destinations.

- Approximately 2,500 signals go to both CD04 (Subsystem Control and Status, Caution and Warning) and CD03 (CRT).

- 1550 signals go to both CD04 and CD01 (Manual Flight Controls). Of the above signals, some 850 are common to all three of the above destinations.

- Subsystem <u>Communications and Radio Ranging</u> has two functional elements which are secondary destinations for signals going to the central multiprocessor:

    CS05 (Telemetry)   10
    CS06 (Tape Recorder)   636

The optimum method of providing for the retransmission loading on the data bus is addressed in the study section, <u>Sync, Timing and Control.</u>

The greatest amount of terminal—to-terminal transfer of data identified— not going to the central multiprocessor—is found between the ME (Main Engines) subsystem and the various CD (Control and Display) subsystem elements. These are analog signals which create a high data bus bit rate. This subject is also taken up in the <u>Sync, Timing and Control</u> section.

3.1-22

3.1.2   Orbiter

The data base for the orbiter was taken from the NAR Orbiter Data List dated 9-14-71. As agreed upon with NASA, this data was not put on punched cards and computer analyzed, but was examined and analyzed by the study investigator. "Raw" data presented for the orbiter bears similar characteristics to that of the booster in that 1) the data list was a tabulation based on a central station data flow configuration, and 2) that the data is without overhead. Also the types of signals, ranges and kinds of sensors (ref. paragraph 3.1.1) encountered in the orbiter are much the same as those found in the booster, except that with the longer flights more attention is given to biomedical monitoring.

3.1.2.1   Orbiter Requirements Identification

A data listing comparable to the booster DCRL was not generated for the orbiter and consequently data was gathered and is presented in summary form. Topographies were not generated, but complements of signals associated with the various subsystems—both OFI and DFI, quantity of signals by types, data rates per subsystems, and signals assignments to avionic areas were identified.

Avionic Areas

Temperature constraints on the orbiter avionic equipment was cited in paragraph 3.1. Each of the Phase B contractors used temperature conditioning mechanisms, from which was derived the representative avionic equipment locations shown in Figure 3.1-2.

Wheelwell Bays

Aft Bays

Nav. Bay

& Crew Station

Forward Bays

Nose Bays
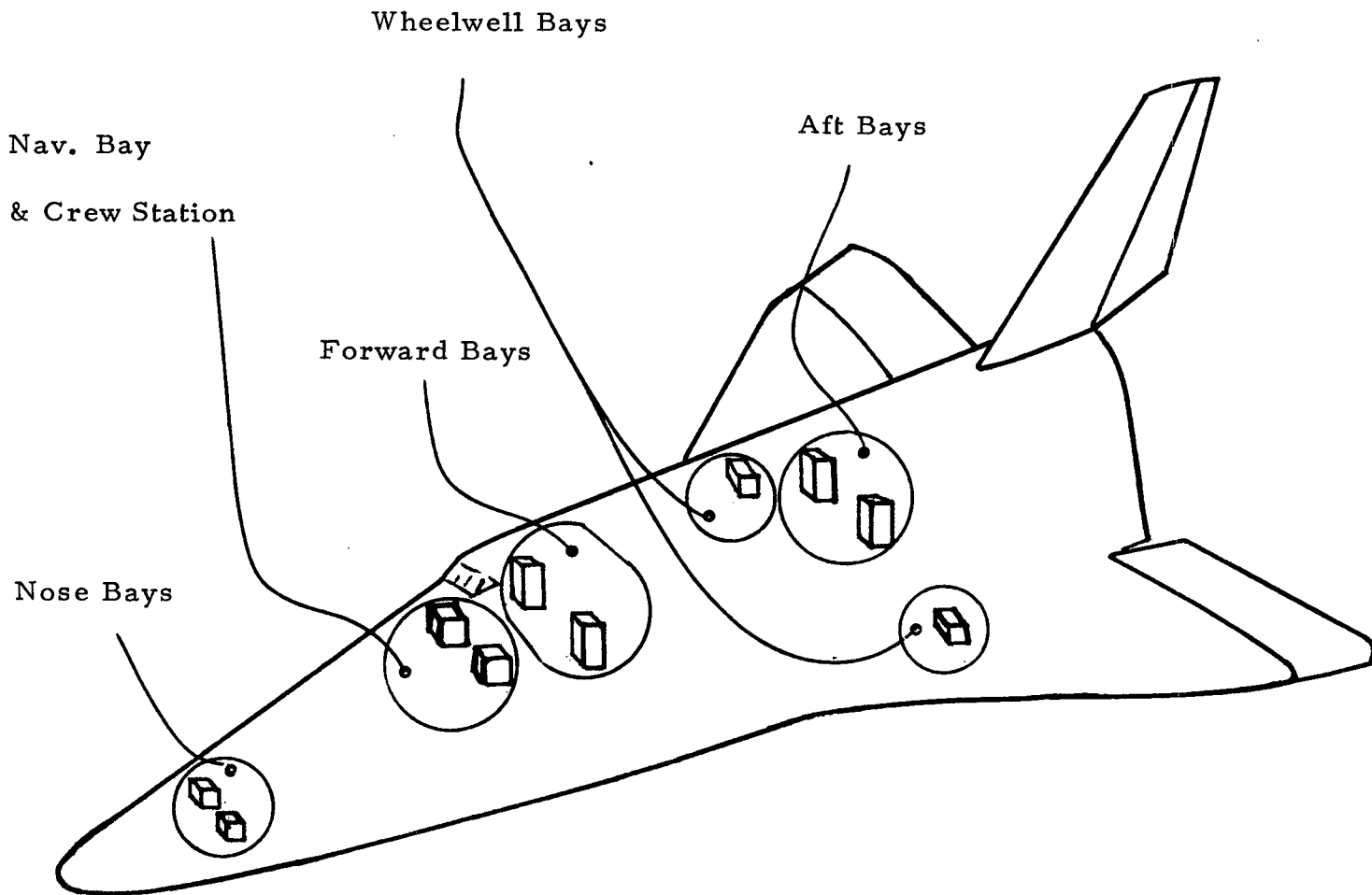
FIGURE 3.1-2

3.1-24

ORBITER AVIONIC LOCATIONS

3.1.2.2   Orbiter Requirements Analyses

Analyses have concentrated on signal types and bit rates.

Signal Types

Table 3.1-8 contains an overall summary of OFI and DFI measurement and control points which are found in the NAR Orbiter Data List. The tabulations are subdivided into analog and digital/discretes. The "Measure" columns contain monitored points; "Control" heads a tabulation of control signals, and one of monitors which are associated with controls. Total OFI measurements total 4,338 and controls 1,319; DFI measurements total 4,269 and controls 4. "Continuous" signals are not included because they are handled by other transmission means.

The following brief observations of Tables 3.1-8 and 3.1-9 are made:

● Aero Surfaces. Half are surface pressure measurements and half are surface heat rate measurements. All are DFI only.

● Vehicle Structure. Only 41 low level analog strain and temperature measurements are OFI. The DFI complement of 1,185 includes eight types of analog measurements, mixed high level and low level, 40 discretes, and some "continuous" monitors. The latter are not subject to pcm adaption.

● Thermal Protection. OFI measurements include low level pressure and temperature surface monitors. All but five of the 1,562 DFI analog measurements are temperature, covering a wide range with many at high temperatures.

TABLE 3.1-8

NAR ORBITER DATA LIST

SUMMARY

SUBSYSTEM	OFI MEAS. A	OFI MEAS. D	OFI CONTROL MEAS. A	OFI CONTROL MEAS. D	OFI CONTROL SIG. A	OFI CONTROL SIG. D	OFI TOTAL	DFI MEAS. A	DFI MEAS. D	DFI CONTROL MEAS. A	DFI CONTROL MEAS. D	DFI CONTROL SIG. A	DFI CONTROL SIG. D	DFI TOTAL	TOTAL OFI/DFI
Aero Surface	---	---	---	---	---	---	---	650	---	---	---	---	---	650	650
Vehicle Structures	41	---	---	---	---	---	41	1,145	40	---	---	---	---	1,185	1,226
Thermal Protection	554	---	---	---	---	---	554	1,562	---	---	---	---	---	1,562	2,116
Main Propulsion	75	54	---	---	---	57	186	28	---	---	---	---	---	28	214
Orbit Maneuver	143	88	6	78	4	51	370	75	14	---	---	---	---	89	459
ACPS	4	99	99	62	---	---	264	59	27	---	12	---	---	98	362
ABE	256	69	---	4	---	---	329	142	---	---	---	---	---	142	471
Cryo Tank	35	70	3	---	---	---	108	---	---	---	---	---	---	---	108
GN & C	340	259	30	---	173	571	1,373	199	---	---	---	---	---	199	1,572
DCM	44	338	57	---	---	18	457	---	---	---	---	---	---	---	457
ID/C (none)	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
Hydraulic Power *	83	8	---	---	---	---	91	24	---	---	---	---	---	24	115
ECLSS*	167	93	8	---	---	---	268	---	---	---	---	---	---	---	268
Flt. Crew Sup. *	13	---	---	---	---	---	13	36	---	---	---	---	---	36	49
Instrumentation *	---	---	---	---	---	---	---	40	---	---	---	---	---	40	40
Communications*	17	26	1	---	10	144	198	14	44	---	---	---	---	58	256
Electrical Power	101	1,013	---	---	---	291	1,405	139	19	---	---	---	4	162	1,567
Totals	1,873	2,117	204	144	187	1,132	5,657	4,113	144	---	12	---	4	4,273	9,930

Total Meas.	4,338	4,269
Total Contr.	1,319	4

Legend: *Estimates

TABLE 3.1-9

ORBITER ANALOGS TABULATION

System		OFI										DFI										System
	Accel.	Posit/ Attit.	Press.	Strain/ Stress	Temp.	Undefined eg. Humid. Chroma.	Vibra.	Signal (Hi Lev)	Qty **	Rate	Qty.	Signal (Hi Lev)	Event	Vibra.	Undefined eg. Humid. Chroma.	Temp.	Strain/ Stress	Press.	Posit/ Attit.	Acceler.	
• Aero Surface															(LL) 325			(LL) 325			A.S.
• Vehicle Structure				(LL) 31	(LL) 10								(HL) 67*	*(LL) 235	(LL) *8		(LL)*165	(LL)*16	(HL)*3	(LL)*90	V.S.
• Thermal Protection			(LL) 24		(LL) 530											(LL) 152	(LL) 357	(LL) 42	(HL) 10		T.P.
• Main Propulsion	(LL) *6		(LL) *21 (LL) 16		(LL) 20			(HL) 8	(HL) 4			(HL)^{B}1				(LL)1557	(LL) 1	(LL) 21^{E-B}	(HL) 4	(LL *6)^B	M.P.
• Orbit Mnvr.		(HL) 16	(LL) 111						(HL) 4	(HL) 12								(LL)^{B}63	(HL)12^B		O.M.
• ACPS			(LL) 57		(LL) 46							(HL) 35				(LL) 12	(LL) 12				ACPS
• ABE		(HL) 16	(LL) 143		(LL) 68		(LL) 8		5	(HL) 16						(LL)^{B}68	(LL)74^B				ABE
• Cryo Tank		(HL) 12	(LL) 26									(none)									C.T.
• GN & C		(HL) 41	(LL) 66		LL: 11 HL: 79			(HL) 143				132^B				^{B}67					GN & C
• DCM			(HL) 3		(HL) 44			(HL) 54				(none)									DCM
• I D/C (None)																					IDC
• Hydraulic Power (E)								(HL) 83				(HL) 24									H.P.
• ECLSS (E)			LL: 30 HL: 50		LL: 20 HL: 30			(HL) 31	(HL)^{E}14			(None)									ECLSS
• Flt. Crew Support (E)								(HL)^{E}13				(HL) 36									FCS
• Instrumentation (E)												(HL) 40									I
• Communication (E)								(HL) 28				(HL) 14									C
• Electric Power			LL: 12 HL: 12		(LL) 23			(HL) 47	(HL) 4	(HL) 3	B 4	(HL) 8		(LL) 6		(LL) 72 14^B		(LL) 17 18^B			EP
ΣOFI = 2,031 Meas.	6	85	571	31	891	none	8	407	31	31	B 4	157 +133^B	67	241	333	1,793 +149^B	523	412 +176^B	17 +12^B	90 +6^B	

** Bal. method of direct digital output and analog output

NOTES:

Per NAR Orbiter DL/9-14-71

Analogs Only

* "C" (Continuous)

B: both OFI & DFI. DFI comes from OFI.

E: Estimate

ΣDFI = 3,633 + 470 both

- Main Propulsion. Most of the analog measurements are OFI. Besides the signals being high level, the quantity measurements (i.e. LOX or LH_2 level) are also high level. All digitals are "Events", or discretes.

- Orbit Maneuver. Only the pressure measurements of the OFI analogs are low level. DFI points are "stripped off" the OFI line, including pressure and position/altitude.

  All OFI and DFI digitals are discretes. Both digitals and analogs have signals that are listed as both "measurements" and "controls".

- ACPS. A large number of the OFI analog measurements are used for purposes of control, whereas the DFI analogs are monitors only. Digitals are all discretes. Some are used for control as well as monitoring.

- Air Breathing Engines. Six types of measurements make up the OFI analog complement. Seventy-four of the pressure measurements and all 68 of the temperature measurements are "stripped off" for DFI use.

  All digitals are discretes, and all are used in OFI.

- Cryo Tank. No cryogenic points are picked up for DFI. Three of the 38 analogs are directly associated with controls.

  All digitals are discretes.

- GN&C. DFI measurements are "stripped off" the OFI. OFI includes 173 analog commands and 571 discrete commands in its complement of some 1,373 signals.

- DCM. No DFI points. OFI points include measurement/control signals for computer and main memory storage; and discrete commands are associated with the main memory storage. Analogs are high level.

- The following subsystems data lists are missing. Data was taken from the summary list and extrapolated from similar subsystems found elsewhere:

  Hydraulic Power

  ECLSS

  Flight Crew Support

  Instrumentation

  Communication

- Electrical Power. Most of these signals are discretes, found in the OFI. Some DFI points are "stripped off" the OFI data bus.

Table 3.1-10 is a summary of orbiter analogs broken down by type signal versus Low Level or High Level, again subdivided into OFI and DFI groupings.

Tables 3.1-11, 3.1-12 and 3.1-13 present the signals with reference to avionics areas instead of by subsystems.

TABLE 3.1-10

SUMMARY, ORBITER ANALOGS BY TYPES

NR ORBITER, OFI HI-LEV AND LO-LEV

	LL	HL
Accel.	6	——
Posit./Attit.	——	85
Pressure	506	65
Strain/Stress	31	——
Temperature	807	74
Humidity/Chromo.	——	——
Vibration	8	——
Signals	——	407
Quantity	——	* 31
Rate	——	31
	1,358	693

NR ORBITER, DFI HI-LEV AND LO-LEV

	LL New	LL both DFI & OFI	HL New	HL both DFI & OFI
Accel.	90	6	——	——
Posit./Attit.	——	——	17	12
Pressure	412	176	——	——
Strain/Stress	523	——	——	——
Temperature	1,793	149	——	——
Humidity/Chromotog.	333	——	——	——
Vibration	241	——	——	——
Event (Ana.)	——	——	67	——
Signals	——	——	157	133
Quantity	——	——	——	4
	3,392	331	241	149

3,633

*Specially conditioned to output in digital and discrete and analog form.

NOTE: Terms "Hi Lev and Lo Lev" used with respect to input to Remote Unit (RU). Signal conditioners either external to RU; or could be internal to RU.

TABLE 3.1-11

ORBITER MIX TABLE
MEASUREMENTS

		OFI				DFI				Remarks
		Analogs				Analogs				
		H.L.	L.L.	Contin.	D.*	H.L.	L.L.	Contin.	D.*	
1.	Nose Bay Areas	---	136	---	166	8	494	120	17	*Discretes & a few digital
2.	NAV. Bay & Crew Station Bay Areas	461	128	---	423	76	---	---	---	
3.	Forward Bay Areas	168	92	---	602	30	504	118	69	
4.	Aft Bay Areas	226	580	28	645	52	932	120	64	
5.	Wheelwell Bay Areas	---	234	---	166	8	954	---	4	
		855	1,170	28	2,002	174	2,884	358	154	
		4,055				3,570				

TABLE 3.1-12

ORBITER SIGNAL MIX - OFI

ORBITER LOC	Accal.			Pos.Att.			Press			S/S			Tem.			Misc. (2)			Event			Vibra.			Sig.			Qty.			Rate		
	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con	Hi	Lo	Con
1. Left Nose Bay								6			5			57																			
2. Right Nose Bay								6			5			57																			
3. Left Nav. Bay			21					33				40		6										72									
4. Right Nav Bay			21					33				40		6										72									
5. Crew Station Bay						50		30				33		20										98			14						
6. Left Fwd. Bay			6			2		25			5	62		21										14									
7. Right Fwd. Bay			6			2		25			5	62		21										14									
8. Left Aft Bay		3	16			6		156	11		6			121									4	69			6			3			16
9. Right Aft Bay		3	16			6		156	11		6			121									4	69			6			3			16
10. Left Wheel-well Bay								8						109																			
11. Right Wheel-well Bay								8						109																			
		6	86			66		486	22		32	237		648									8	408			26			6			32

REMARKS

1. "Hi"-High level "Lo"-Low level "Con"-Continuous. These are either hardwired or FDM's
2. Undefined- e.g., humidity, chromotography heat flow

TABLE 3.1-13

ORBITER SIGNAL MIX - DFI

ORBITER LOC — TYPE SIGNALS - ANALOGS

ORBITER LOC	Accel			Pos-Att			Press.			S/S			Temp.			Misc(2)			Event			Vibra.			Sigs.			Qty.			Rate		
	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C	H	L	C
Left Nose Bay	15	2				1			6			3	60	28	181						1			12	2								
Right Nose Bay	15	2				1			6			3	60	28	181						1			12	2								
Left Nav Bay																																	
Right Nav Bay																																	
Crew Station Bay																									76								
Left Fwd Bay	15	2				1			9			3	60	28	183						1			11	13								
Right Fwd Bay	15	2				1			9			3	60	28	183						1			11	13								
Left Aft Bay	15	2				1			100			3	60	28	222			81			2	3		11	24								
Right Aft Bay	15	2				1			100			3	60	28	222			81			2	3		11	24								
Left Wheel well Bay		2							82						313			82							2								
Right Wheel well Bay		2							82						313			82							2								
Total	90	16				6			394			18	360	168	1798			326			8	6		68	158								

REMARKS

1. "H" High Level
   "L" Low Level
   "C" Continuous

Bit Rate Per Mission Phase per Subsystem

Raw data bit rates are shown in Tables 3.1-14 and 3.1-15 for each mission phase per subsystem and totaled, for each the OFI and DFI buses, respectively.

3.1.3 Conclusions

Conclusions drawn from the identification and analyses of SSV requirements are found in summary tables in the text. It was found that great similarity exists between the booster and orbiter space shuttle vehicles, including 1) the environment for each, 2) allocation of temperature conditioned areas for avionic equipment, 3) type measurements made and candidate transducers, and 4) to a lesser degree the quantity of signals and data bus rates. Various booster-orbiter comparisons follow:

TABLE 3.1-16
BOOSTER/ORBITER OPERATION TIMES

ITEM	BOOSTER	ORBITER
1. Maximum number of Vehicles	Four	Four
2. Number of Flights	100 flights each booster	100 flights each orbiter
3. Maximum time data bus must function per complete mission	Per flight: checkout: 6 shifts x 8 hrs/shift= 48 hrs. Prelaunch = 8 hrs. Flight Time = 2 hrs. 58 hrs/flt.	Per flight: checkout: 6 shifts x 8 hrs/shift = 48 hrs. Prelaunch = 8 hrs. Flight Time =168 hrs. 224 hrs/flt.
4. Per each Vehicle:	58Hx100 flts = 5800H	224H x 100 flts = 22,400H
5. Grand total data bus time, all vehicles and total number of flights.	58H x 400 = 23,200 hrs.	224H x 400 = 89,600 hrs.

C2

3.1-35

Table 3.1-14

OPERATIONAL FLIGHT INSTRUMENTATION (OFI) DATA RATES

	A Gnd.	B Final CD	C Mate ASC	D Rendezv.	E Sta. Keep.	F Docking	G Docked	H Deorbit	I Ent/ Tran.	J Aero Flt.	K Ferry	L O/P Flt
Aero Surface	------	------	------	------	------	------	------	------	------	------	------	------
Vehicle Structures (52)[2]	------	15,505	15,505	15,505	-------	15,505	15,500	15,505	15,505	15,505	------	------
Thermal Prot. (588)[2]	1,155[1]	1,155	1,155	1,155	1,155	1,155	1,155	1,155	1,155	1,155	------	------
Main Propuls. (151)	252	1,075	997	993	117	117	117	117	76	76	51	------
Orbiter Mnvr. (276)	16,315	10,417	3,944	8,235	9,429	9,423	6,429	11,835	9,429	11,959	1,168	------
ACPS (262)	5,389	5,389	1,049	7,129	7,129	7,129	1,049	7,129	7,129	7,125	None	7,125
ABE (187)	6,207	45	------	------	------	------	6	30	125	6,133	6,221	------
Cryo Tank	348	348	72	417	552	552	431	79	79	39	19	------
GN & C (1,111)	32,159	32,159	31,754	31,759	32,430	32,430	21,553	32,430	31,574	26,384	26,384	------
DCM (456)	300	800	800	800	800	800	800	800	800	800	800	------
ID/C	------	------	------	------	------	------	------	------	------	------	------	------
Hydraulic Power[5] (91)	11,838[5]	11,838	11,838	11,838	11,838	11,838	11,838	11,838	11,838	11,838	11,838	11,838
ECLSS[5] (268)	1,493	1,493	1,493	1,493	1,493	1,493	1,493	1,493	1,493	1,493	1,493	------
Flt. Crew Sup.[5] (13)	104	104	104	104	104	104	104	104	104	104	104	104
Instru.[5] (None)	------	------	------	------	------	------	------	------	------	------	------	------
Comm[5] (198)	394	394	394	------	------	------	------	------	394	394	394	------
Electric Pwr. (1,401	2,085	1,991	1,754	1,706	1,156	1,163	1,159	1,887	1,941	1,971	1,219	None
Bit Rate (BPS)	78,539	82,713	70,859	81,134	66,203	81,709	62,134	84,402	81,642	84,976	49,691	19,067

Notes

1. Rate - bits per sec.

2. Number of signals, OPN, Flt C/O Gnd C/O

3. Number of Sig DFI

4. Plus "C" 27.

5. Guesstimates— No Orbiter List. Got from booster or other.

6. Per NAR Orbiter 9-14-71 Data List

Table 3.1-15

DEVELOPMENTAL FLIGHT INSTRUMENTATION(DFI)DATA RATES

	A Gnd	B Final CD	C Mate ASC	D Rendv.	E Sta. Keep	F Docking	G Docked	H Deorbit	I Ent/ Tran.	J Aero Flt.	K Ferry	L O/P Flt.		
Aero Surface (650) 3	-------	-------	3,250	-------	-------	-------	-------	-------	3,250	3,250	-------	-------		
Vehicle Structure (1,140)	-------	101,146	106,261	101,086	9	124,565	146,565	105,056	142,161	138,056	32,000	-------		
Thermal Prot. (1,446)	757	757	3,458	3,458	3,458	3,458	3,458	3,458	3,458	3,458	-------	-------		
Main Propul. (28) 4	-------	6	6	6	-------	-------	-------	-------	-------	-------	-------	-------		
Orbit Mnvr (84)	14,290	14,290	12,000	16,690	17,890	17,890	14,890	17,890	17,890	10,090	1,152	-------		
ACPS (96)	21,857	21,857	159	21,857	21,857	21,857	132	21,857	21,857	21,857	-------	21,857		
ABE (142)	988	-------	-------	-------	-------	-------	-------	-------	-------	988	988	-------		
Cryo Tank	-------	-------	-------	-------	-------	-------	-------	-------	-------	684	684	-------		
GN & C (199)	1,374	1,374	1,374	1,374	1,374	1,374	1,374	1,374	1,374	684	684	-------		
DCM	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------		
ID/C	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------		
Hydraulic Power (24) 5	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000		
ECL SS	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------		
Flt Crew Sup. (36) 5	288	288	288	288	288	288	288	288	288	288	288	288		
Instru. (40) 5	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200	3,200		
Commun. (86)	197	197	197	-------	-------	-------	-------	-------	197	197	197	-------		
Elect. Power (176)	812	812	776	742	727	727	727	737	776	776	48	-------		
	49,763	139,927	136,969	154,701	54,803	179,359	166,634	159,860	200,451	188,844	44,557	31,345	BPS	DFI
	78,539	82,713	70,859	81,134	66,203	81,709	62,134	84,402	81,642	84,976	49,691	19,067	BPS	OFI
	128,302	222,640	207,828	235,835	121,006	261,068	228,768	244,262	282,093	273,820	94,248	50,412	BPS	Total

Booster-Orbiter Comparison by Signal Classification

Table 3.1-17 shows the comparison. As can be seen, similar signal types did not always reside in subsystems of comparable names. This resulted in the first three columns, showing equivalents per item number. The OFI data of the Orbiter was listed next to comparable booster data. Conclusions can be drawn from an examination of the table.

Booster-Orbiter Bit Rate Comparisons

The orbiter mission phases were aligned with comparable booster phases in order to facilitate bit rate comparisons. These are shown in Table 3.1-18.

TABLE 3.1-17

BOOSTER-ORBITER COMPARISON BY SIGNAL CLASSIFICATION

Item	MSFC Booster User Subsystems	GD Booster Subsystems Included in MSFC Subsystems	Comparable NAR Orbiter Subsystems	Signals by Classification			
				MSFC - Booster		NAR-Orbiter	
				Analog	Discretes/Digitals	Analogs	Discretes/Digitals
1.	Airbreathing Engines (JE)	Airbreathing Propulsion Engines	ABE	336	12	256	73
2.	Auxiliary Pumping and Propellant (AP)	Hydraulic Pwr. Distr. Main Propulsion Fuel; Airbreathing Propulsion Fuel; Attitude Control Propulsion/ Aux. Pwr. Unit Fuel.	Hydraulic Pwr.	684	469	83	8
3.	Communications and Radio Ranging (CS)	Communications	Communications	24	45	28	170
4.	Computation (CR)	Data Processing	DCM	471	2,894	103	356
5.	Crew Controls and Displays (CD)	Data Displays and Controls	Flt. Crew Sup.; Instrumentation	11	538	13	0
6.	Electrical Pwr (EL)	Aux. Pwr. Unit Engine; Electrical Pwr. Supply; AC Elect. Pwr. Distr.; DC Elect. Pwr. Distr.	Electrical Pwr.	931	124	101	1,304
7.	Guidance, Navigation and Control (GN)	Integrated Guidance and Navigation	GN&C	693	189	543	830
8.	Main Engines (ME)	Main Rocket Engines	Main Propulsion	1164	0	75	111
9.	Re-action Control (RS)	Attitude Control Propulsion Sys. (ACPS)	ACPS	309	0	103	161
10.	Structural/ Mechanical Elements (SM)	Orbiter/Booster Links; Hold Down Fitting; Body TPS; Wings; Fuselage Structure; Vertical Stabilizer Fuselage Compartments Landing Gear; Flt. Cntrls:, ABE Installation; Environmental Cntr. Syst.	Aero Surface; Vehicle Structures Thermal Protection Orbit Maneuver Cryo Tank ECLSS	345	0	961	380
				4,968	4,271	2,266	3,393

TABLE 3.1-18

BOOSTER - ORBITER COMPARISON BY MISSION PHASE

Booster Phases	Comparable Orbiter Phases	Booster Bit Rates	Orbiter Bit Rate
Pre-Launch	Ground	422,443	78,539
Launch & Ascent	Final Count Down	398,717	82,713
	Mate ASC		70,859
Orbit Operations	Rendezvous	174,330	81,134
	Station Keeping		66,203
	Docking		81,709
	Docked		62,134
Re-Entry	De-Orbit	226,290	84,402
Fly-Back	Ent/Trans.	225,207	81,642
Approach and Landing	Aero Flight	218,461	84,976
Ferry	Ferry	221,094	49,691
	O/P Flt.		19,067

3.2   TRANSMISSION MEDIA STUDY

3.2.1   Introduction

This section summarizes the results of the Transmission Media Study performed as part of the Multiplex Data Bus Techniques Study for the Space Shuttle. Detailed analysis and discussions are found in the Phase I report and the Phase II, Volume I report. Much of this work involved empirical test of cables.

Section 3.2.2 of this report presents the types of media selected for further examination. Section 3.2.3 addresses the measurement of these media characteristics.

Section 3.2.4, Operation Modes, deals with the basic methods of transmission, line operation, i.e., matched, loaded or lossy.

Section 3.2.5, Design Techniques, involves particular techniques employed in transmission network design; i.e., coupling techniques, methods of stubbing or branching.

Section 3.2.6 points up the effort made to characterize the impulsive EMI likely to be encountered by the SSV data bus.

Section 3.2.7, Environmental Considerations, and section 3.2.8, Interrelated Factors completes this task.

3.2.2 Type of Media Selected

Of the widely varying types of transmission media investigated in the Phase I Study effort, it was concluded that the most likely candidate was some form of wire cable. This decision was based on its ability to adequately transfer the data at rates which may be expected, and upon cost, reliability, size, weight, environmental properties and availability. Optical links were concluded to be a possible candidate on special purpose data links, but were not well suited for the main data bus transmission medium.

Wire cable is available in a wide range of forms. The basic types which were selected as being most suitable for detailed tests and study were:

- Twisted Shielded Pair
- Planar-Parallel
- Twin-Axial
- Triaxial
- Coaxial
- Shielded Balanced Pair (4 conductor)

The above cable types were procured and tested to determine their electrical characteristics. Several different wire sizes and insulation types were procured of the above types to determine their effects on cable characteristics.

3.2.3 Measurement of Media Characteristics

One of the most important tasks performed in Phase II was the measurement of transmission line characteristics and parameters. The results of this effort allowed comparisons of candidate cables; and knowing the nature of cable behavior in the frequency range of interest allowed further analysis of design techniques under consideration.

The frequency range considered was from 1 KHz to 100 MHz. This region was considered of interest because baseband signals may have spectral components from DC to 10 MHz. One KHz is as low as was considered practical to test, however. It was found that 100 MHz could be obtained quite easily in the test procedure used, and since little information is available on many cables in this region, it was decided to extend the test to 100 MHz.

3.2.3.1   Recommended Measurement Technique

The method chosen for making the measurements involved the measurement of complex impedances into a line of known length whose far end is opened and shorted. Such a procedure used instruments which were easy to use, and measurements could be made rapidly without highly unskilled technicians. The calculation of the cable characteristics and parameters involved the manipulation of complex equations, but a program was written which allowed this to be done on a digital computer.

The transmission line parameters of interest are R, G, L. C, Z_O and γ where

R is the series resistance in ohms per meter

G is the shunt conductance in ohms per meter

L is the series inductance in henries per meter

C is the shunt capacitance in farads per meter

Z_O is the characteristic impedance in ohms

γ is the complex propagation constant where

$\gamma = \alpha + j\beta$ and

α = attenuation constant in nepers per meter

β = phase constant in radians per meter.

The recommended measurement technique required the measurement of Z_{sc} and Z_{oc}, the short circuit and open circuit input impedances respectively, to a line of known length. With this information, all the transmission line parameters were computed using the following relationships:

$$Z_o = \sqrt{Z_{sc} \cdot Z_{oc}} \tag{1}$$

$$\alpha = -\frac{1}{2\lambda} \cdot \ell n \left| \frac{1 - \sqrt{Z_{sc}/Z_{oc}}}{1 + \sqrt{Z_{sc}/Z_{oc}}} \right| \tag{2}$$

$$\beta = -\frac{1}{2\lambda} \cdot \sqrt{\frac{1 - \sqrt{Z_{sc}/Z_{oc}}}{1 + \sqrt{Z_{sc}/Z_{oc}}}} \tag{3}$$

$$\gamma = \alpha + j\beta \tag{4}$$

$$R + j\omega L = \gamma Z_o \tag{5}$$

$$G + j\omega C = \gamma / Z_o \tag{6}$$

A computer program was written to perform the required computations.

The instruments used for these tests were the Hewlett-Packard 4800 Impedance Meter, and the Hewlett-Packard 4815A.

Because the Hewlett-Packard 4815A did not have a balanced input, and certain lines such as the twisted shielded pair operate in a balanced condition, a balun was inserted between the line and the impedance meter.

The balun constructed used two pieces of small coaxial cable wound upon a ferrite toroid. Using the balun, the short and open circuit impedance used in the preceeding equations were modified. The resulting equations were

complex, and in view of the large number of measurements taken, a computer program was developed for performing the calculations and listing the parameters (see Appendices A, B, C and D of Phase II, Volume I report).

3.2.3.2　Test Procedure

Quite simply, the values were obtained by directly reading the magnitude and phase of the input impedance from the front panel meters. Certain procedural recommendations resulted from making these tests:

- Tests using HP4800 should be made with instrument and cable within a shielded room.
- Using HP4800, tie lower impedance terminal to coax shield and leave floating.
- More than one length of cable be tested - recommended lenght is about 100 feet.

3.2.3.3　Test Results

Detailed results of these tests can be found in Appendix D of Volume I, Phase II report, and a Technical Note.

The cables tested included the following.

Balanced Cable

TWC-78-2 (Twin-Axial)	TSP #22, Kapton
TWC-124-2 (Twin Axial)	TSP #24, Kapton
TSP #22, Teflon	TSP #28, Kapton
TSP #24, Teflon	TS-4 Wire, Configuration A
	TS-4 Wire, Configuration B

Coaxial

TRC-50-2 (Triaxial)	RF-178
TRC-75-2 (Triaxial)	RG-180

The balanced four wire configuration was used in two configurations. Configuration A was obtained connecting opposite conductors together, such that the four wires are used as one balanced circuit. Configuration B used two opposite conductors as the circuit, while the other pair was connected together and grounded.

The curves were useful in comparing the characteristics of the candidate cables. Some general observations concerning the test results are pointed out.

- The attenuation was seen to approach a slope of 1/2 on the log-log plot of DB loss versus frequency. This agrees with the theory that most of the loss at high frequency is due to skin effect where the DB loss varies as a function of the square root of frequency. In the lower frequency ranges, the attenuation departs from this relationship because of the frequency dependent nature of the propagation constants.

- The phase shift was seen to be directly proportional to frequency in the upper frequency ranges, again agreeing with theory. In the lower frequency ranges the phase shift again departed from the linear phase shift. This departure was seen to be more noticeable in some cables than in others. This departure had a distorting effect upon signals, and a linear characteristic was one of the attributes sought in the candidate cable.

It was remarkable that the phase shift of all the cables became so linear in the upper ranges of frequency. Apparently the effects of dielectric dispersion are not significant at frequencies below 100 MHz. It was also noted that the phase shift was not significantly different between any of the cable types at the upper frequency ranges.

● The characteristic impedance was seen to vary considerably with frequency. The RG-178 cable hardly had any range over which it could be considered "flat", while the TRC-50-2 had a fairly broad range. Also the phase angle of the characteristic impedance behaved in the following manner with frequency: for coaxial types it always started at the low frequency highly negative (capacitive), continuously decreased and became inductive, while the balanced type seemed to vary in a more random manner with frequency, but were always nearer to zero (resistive). This behavior clearly had an effect upon the ability to terminate the cable.
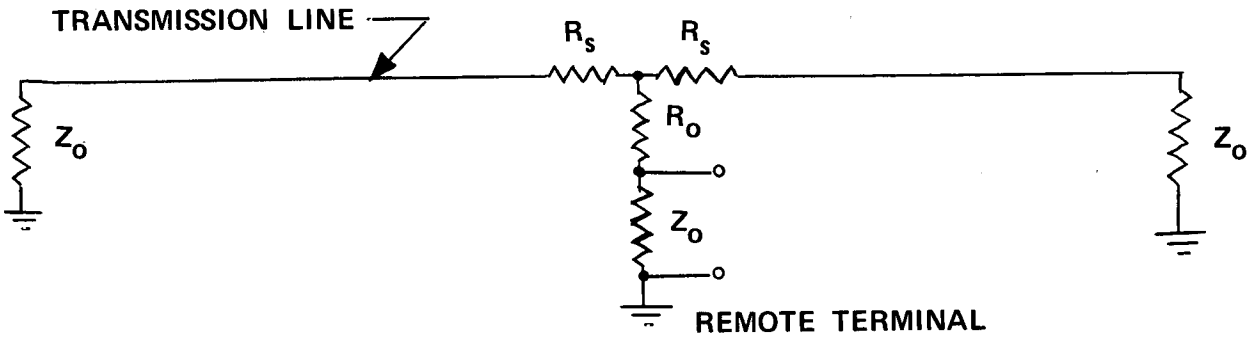
3.2.4   Operational Modes

Several different methods of operating the transmission medium network were identified in the Phase I report. The method chosen will have a great effect on the overall design of the data bus system. The possible methods were identified as follows.

● Matched/Unmatched—A perfectly matched line is one in which the impedance into any terminal of a junction is matched to the characteristic impedance of the line. If the impedance of a remote terminal is anything other than the line impedance, the line is said to be unmatched. In order to match the line a network is required as is shown in Figure 3.2-1a.
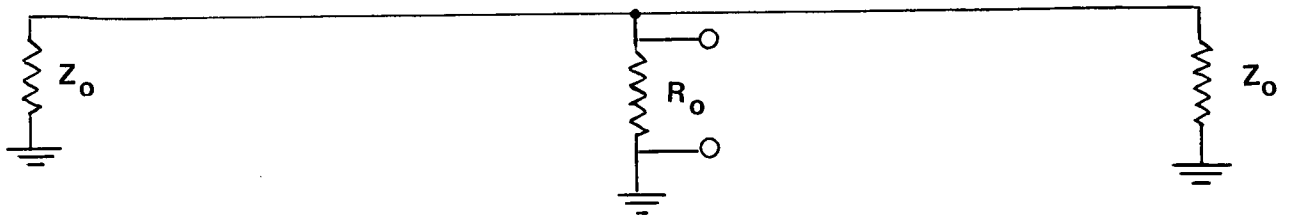
ℬ

- Matched/Loaded—The impedance of a remote terminal may be on the order of Z_o, in which case the line is said to become loaded. Or it may be something other than Z_o. The configuration of this operation is shown in Figure 3.2-1b.

- Lossy Operation—A network may be inserted at a remote terminal to deliberately introduce some loss into the transmission line to provide fault isolation, as shown in Figure 3.2-1c. When operating in the lossy mode, the transmission line is usually looped back upon itself, or two lines are coupled together through a lossy network to provide the signal path when the line becomes faulted.

- Current Versus Voltage Operation—Two distinct methods of operation are possible; the voltage mode where the signal is transmitted and detected basically as a voltage across some point on the transmission line, and the current mode where some series element is placed in the line and the current through the element is sensed.
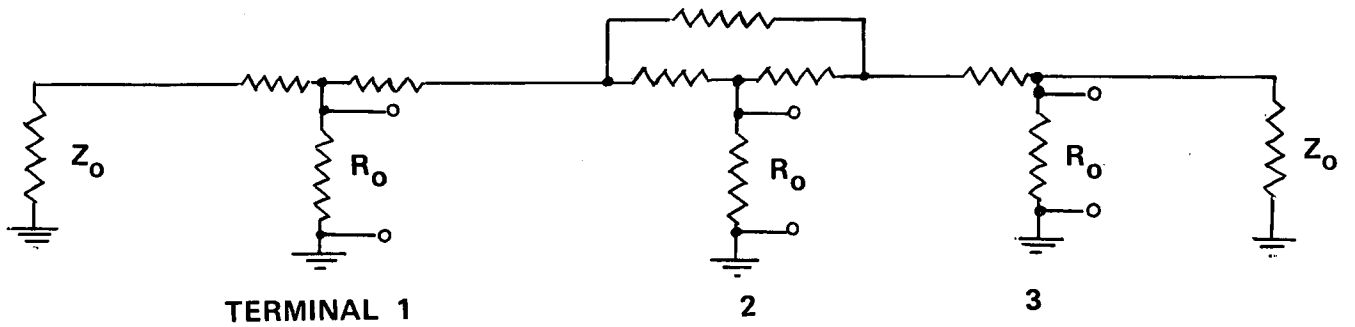
3.2.4.1   Matched/Unmatched

The matching into every terminal of a junction is sometimes necessary with certain devices or a certain frequency. For the data bus under consideration, using baseband modulation, this technique was neither necessary nor desirable. The disadvantage to this technique was the high losses involved. A resistive network in the form of that shown in Figure 3.2-1a would cause a 6 db loss at every terminal. When the fact that the bus may transmit to a large number of terminals (20 to 100 have been estimated) then the large loss incurred was clearly prohibitive.

TRANSMISSION LINE

R_s R_s

Z_0 R_0 Z_0

Z_0

REMOTE TERMINAL

(a) MATCHED OPERATION

Z_0 R_0 Z_0

(b) MATCHED/LOADED OPERATION

Z_0 R_0 R_0 R_0 Z_0

TERMINAL 1 2 3

(c) FORMS OF LOSSY OPERATION

FIGURE 3.2-1   BASIC OPERATING MODES

3.2.4.2   Matched/Loaded

The configuration in Figure 3.2.-1b is often used in data bus operations because the terminal impedance can usually be made high enough to cause only a light loading of the transmission line and consequently little loss along the line. When a voltage wave (V) is transmitted down the transmission line, a wave is reflected back at each terminal.

The fully loaded line, in which $R_o = Z_o$, lead to $\rho = -\frac{1}{3}$ and $\alpha = \frac{2}{3}$. The negative reflection coefficient is significant in that reflections traveling backward on the line subtract from the forward signal. The severity of this depends upon the delay along the line and the type of waveforms (modulation technique) used.

A light loading of a transmission line is sometimes used to introduce some loss along the line, thereby decreasing the effects of multiple reflections which occur in the event that a severe mismatch occurs somewhere on the line.

3.2.4.3   Lossy Operation

The lossy configuration shown in Figure 3.2-1c is very useful in maintaining operation when a fault develops somewhere in the bus network. The fault may be an open or short on the transmission line, or may be at the junction of a remote terminal. Connectors in the transmission line are a common point of a faulted line. By looping the line and providing isolating resistors between terminals, a path exists for the signal under faulted conditions. Figure 3.2-1c shows several ways that a network can be arranged at a remote terminal to provide the lossy coupling network.

Terminal #2 of the figure can be shown to be equivalent to #1 terminal, through a "delta-to-wye" conversion, and terminal #3 is a special case of terminal #1. Further, terminal #1 resembles the network of Figure 3.2-1a under certain conditions, such that an analysis of the lossy network was restricted to terminal #1. It was also evident that this network can either be a matched network or unmatched.

An analysis of the lossy configuration was made possible with some simplifying assumptions; the loss and delay of the line was assumed to be negligible, and the transmitter was a constant voltage source. Such a simplified case should reveal an upper bound for this operation.

The first network that was treated was the matched network, that is the impedance into terminal 1 or 3 equaled Z_0. From this setup the values of R_s and R_0 and the coefficients β and γ were found.

The total gain of the signal, which is a minimum using the optimum α ; $\alpha = (\frac{n-2}{n-1})$, is

$$G = (\frac{n-2}{n-1})^n \frac{1}{(n-1)} \tag{7}$$

For further explanation of the above equations see Volume I, Transmission Media Technical Phase Report No. II, Section 4.1.3, Lossy Operation.

This equation is plotted in Figure 3.2-2. Thus it can be seen that using the lossy technique, one must either transmit more power as the number of terminals increases, or increase the receiver sensitivity (and its resulting susceptibility to noise).
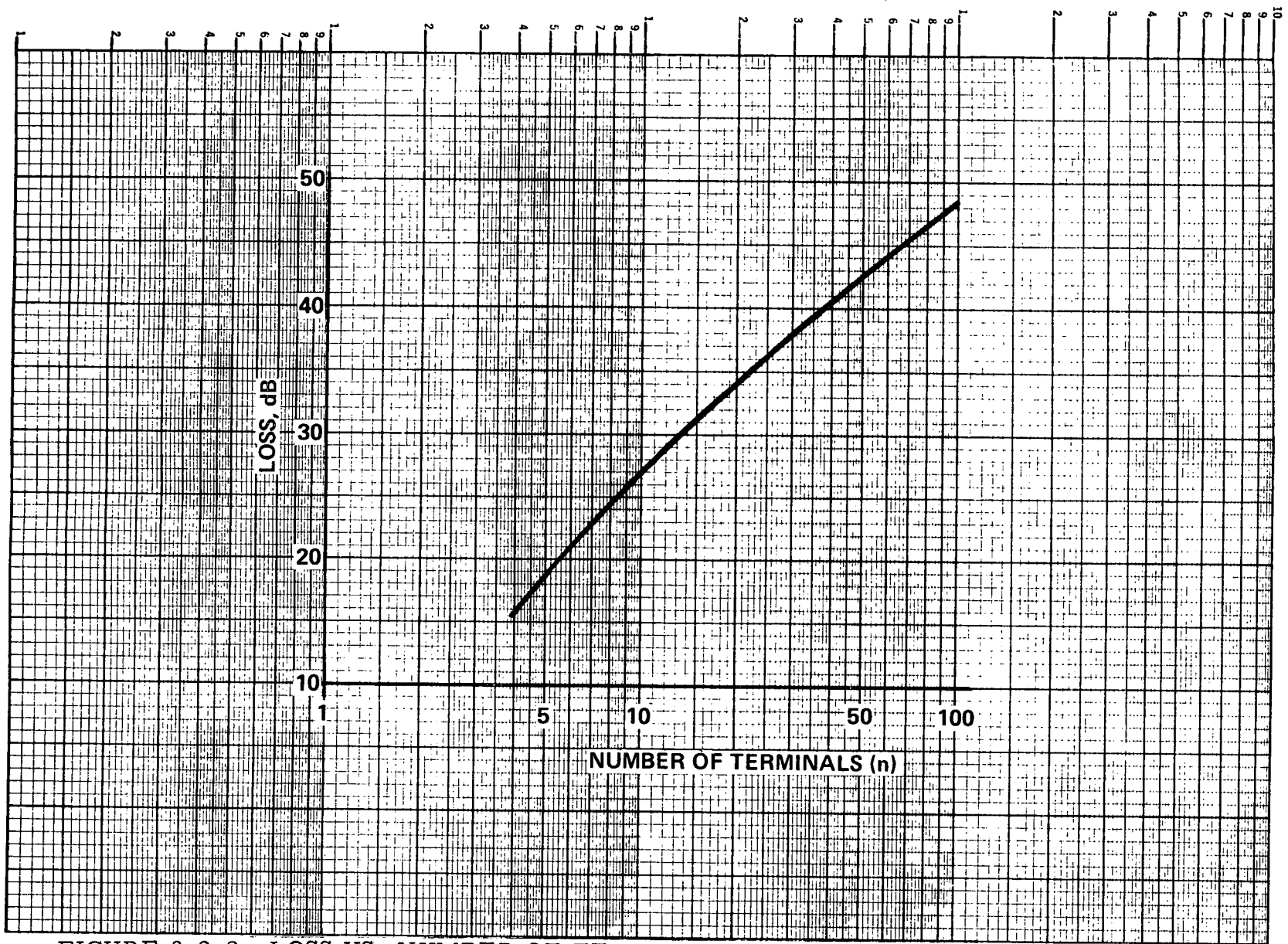
FIGURE 3.2-2 LOSS VS. NUMBER OF TERMINALS, MATCHED LOSSY

The unmatched, lossy case was much more difficult to solve because another variable was introduced. This reflection coefficient caused more distortion and more possible paths. An optimum combination was found, however. Whether an optimum combination of α and ρ exists determined, optimum being defined as the combination of values which give the greatest overall gain.

One approach to the problem may be in determining the maximum amount of signal reflection that is tolerable for a particular signal structure and detection process. This could be determined experimentally.

3.2.4.4 Current/Voltage Mode of Operation

Two distinct modes of transmission line operation were identified in the Phase I report: the voltage mode and the current mode of operation. The voltage mode, the more familiar mode of the two, transmits signals by placing a voltage across the line and receives signals at some other point on the line by detecting the voltage appearing across the line. The current mode transmitter injects current into the line with some series element, and at the receiver location a receiver detects current in the line with a series element. Actually the transmission line voltage to current ratio is Z_o for a long line, regardless of the way in which the signal is transmitted or received, and it is more appropriate to speak of the current versus voltage coupling technique. The signal transfer characteristics of the transmission line remain the same regardless of which mode is being used.

On a data system, where many transmitters and receivers may be coupled to the line, and where the distance from one coupling point to the other may vary considerably, the coupling technique should be one in which low loss is involved, isolation is maintained, and implementation is not difficult.
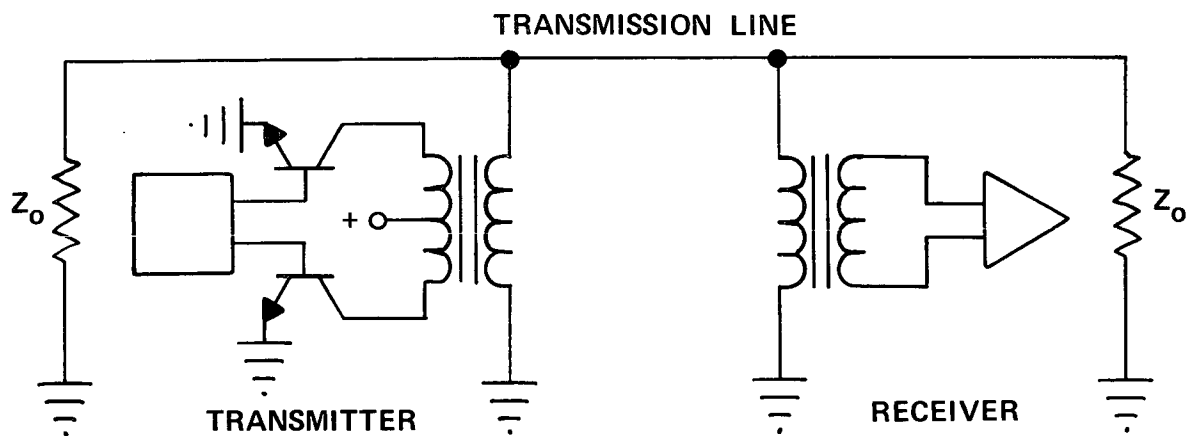
TRANSMISSION LINE
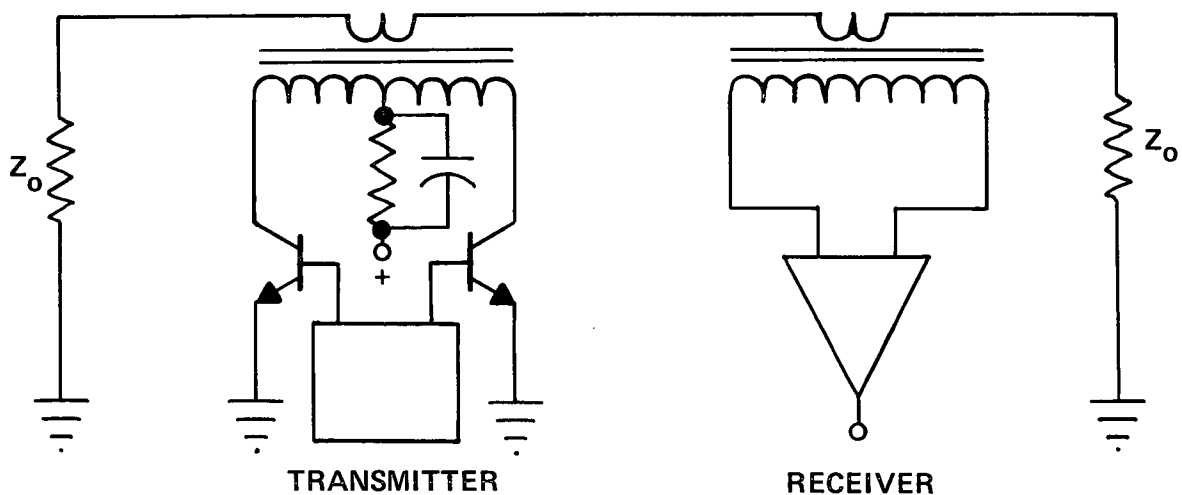
(a) THE VOLTAGE MODE

(b) THE CURRENT MODE

FIGURE 3.2-3   THE CURRENT AND VOLTAGE MODE TRANSMISSION SYSTEMS
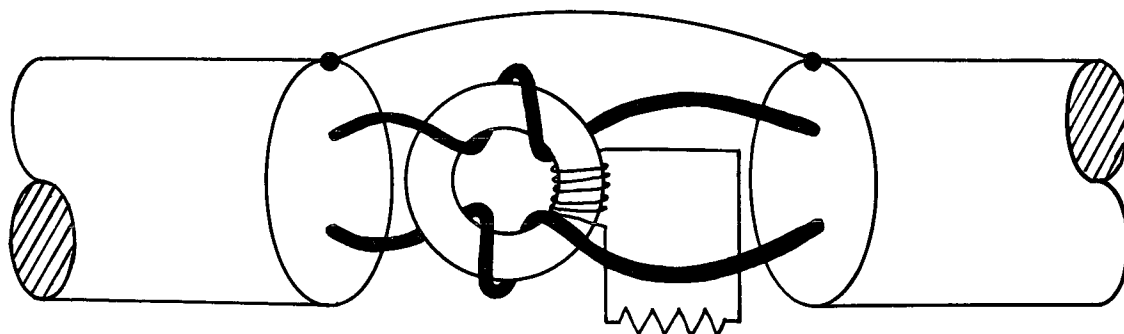

FIGURE 3.2-4   CURRENT MODE TRANSFORMER

As a basis for comparison both the requirements of a transformer-coupled voltage mode data bus and of a transformer-coupled current mode system were examined. These two distinct modes of transmission line operation are shown in Figures 3.2-3a and 3.2-3b.

In the voltage mode system the transformer primary (connected to the line) should have a high impedance and the secondary should operate into a fairly high impedance receiver. A low impedance transmitter output (a voltage source) should be used and when the transmitter is turned off a high impedance should be presented to the line. This is accomplished very effectively by using a push-pull type transistor transmitter. This technique is found in Figure 3.2-3a.

With the current mode system the receiver transformer primary is placed in series with the line. The transmitter is also coupled into the line as shown in Figure 3.2-3b. It is apparent that the transformer coupling should have a low turns ratio to achieve broadband operation, which means that a very low impedance receiver should be used. One advantage of the current mode transformer hook-up is that when it is coupled to the transmission line no cutting or soldering is necessary. The basis for selecting the voltage or current mode operation depends on several minor things. Some of the possible advantages and disadvantages are listed.

Voltage Mode

      Implementation - well-known transmitting/receiving techniques.
                      - high impedance integrated circuit receivers are readily available.
      Fault Immunity - A short at the transmitter or receiver could impair the transmission line.
                      - An open at these points would not impair the line.

Current Mode

        Implementation - Low impedance receiving amplifiers must be developed.

The technique for shorting the transmitter primary has not been well-proven in operation.

Coupling to the line is possible without cutting or soldering the transmission line.

Wideband transformers can be constructed, as long as the turns ratio is not high.

        Fault Immunity - A short at the transmitter or receiver or the stub line will not impair operation but an open circuit at these points will.

The use of a hybrid system, consisting of voltage transmitters and current receivers (or vice versa) was studied and it is recommended that a hybrid system of this type not be used on a data bus.

One of the advantages of the current mode is that a remote connection to the data bus transmission line may be made without solder joints in the line. It has also been shown that a moderate length of a stub can be tolerated. This remote connection is bulky, however, and if the line could be brought to the terminal (sometimes called daisy-chaining) the use of a stub is avoided. In the latter case the advantage of the current transformer seems to vanish. Tests have also shown that a line with no stubs at all is superior in terms of signal distortion. But stubs or branching may have to be used for convenience in the mechanical layout and installation of the system.

3.2.5 Design Techniques

There are many different techniques which have been used in data transmission over wire cable. Some of the alternate techniques were identified in Phase I. In a data bus system, however, where there are many transmitters and receivers located at many different locations on the transmission line (bus), conventional design techniques may not be applicable. In this section, particular techniques are discussed and analyzed in view of their application to a data bus system.

3.5.2.1 Methods of Cable Termination

In the early phases of the transmission cable testing Z_o, the characteristics impedance, was found experimentally by pulsing short sections of the transmission line (20 to 50 feet) and placing resistive loads on the end of the cable. The reflection was a minimum when the resistor value was equal to Z_o.

The test results of Section 3.2.3 revealed that Z_o was complex and varied with frequency. The magnitude of Z_o for all cables was plotted as a function of frequency. A negative angle at a given frequency indicated that at that frequency Z_o is capacitive. Z_o for most cables was equivalent to a resistor and capacitor in series, such that for optimum matching the complex conjugate should be used: a resistor and inductor in series. If a narrowband signal is to be used, optimum matching could be obtained; but for a wideband signal the matching network would be very complex. The general behavior of Z_o was seen to be highly capacitive at low frequencies and became resistive at high frequencies.

A complex conjugate matching network for wideband use would have to be highly inductive at low frequencies and become resistive at high frequencies, with a real component, R_o, matching that of the cable.

FIGURE 3.2-5

Characteristic Impedance

Z_o vs. Frequency

TWC-78-2

Frequency – MHz

Z_o – Magnitude (ohms)
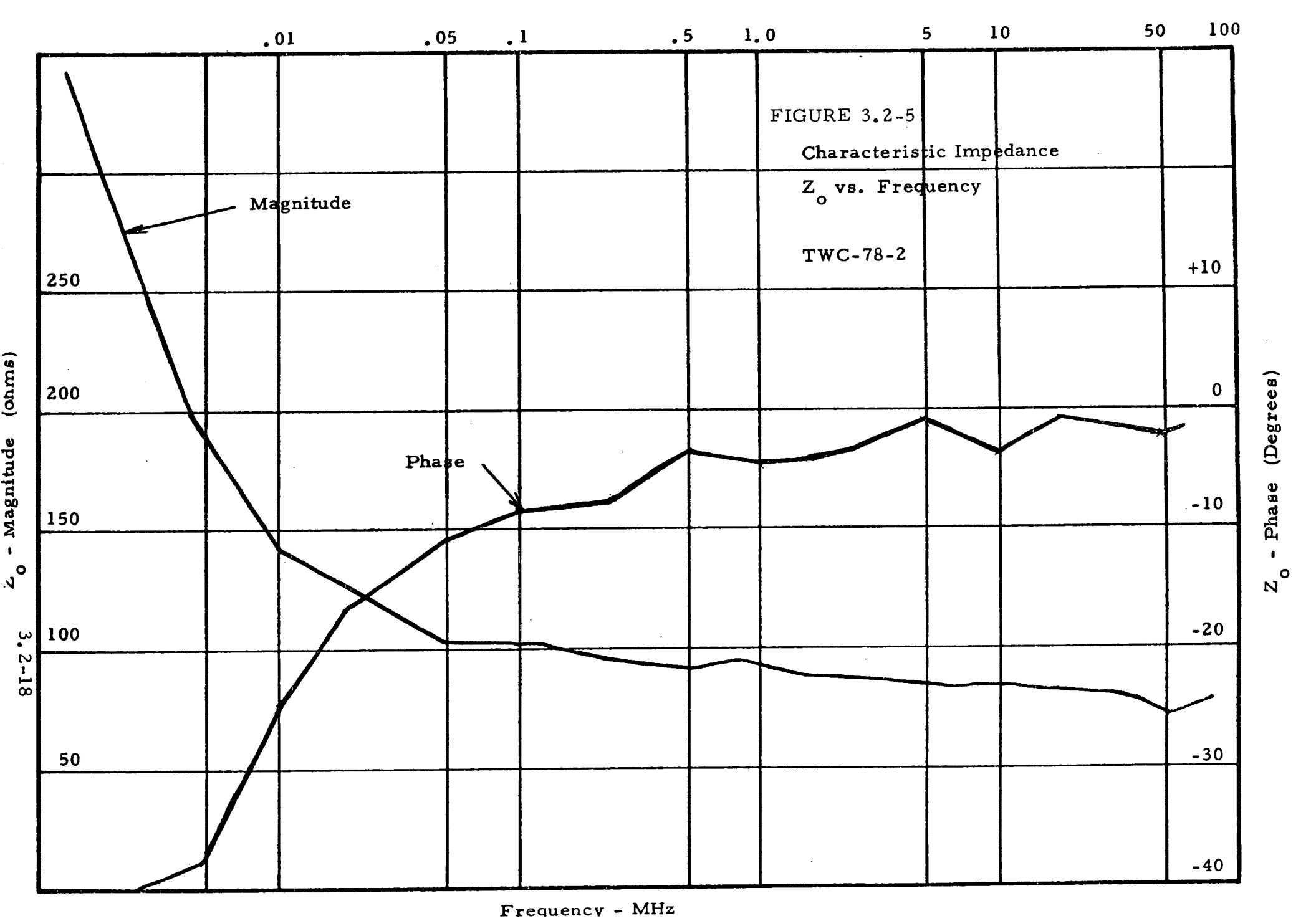
Z_o – Phase (Degrees)

3.2-18

Figure 3.2-5 is a plot of the magnitude and phase of Z_0 for TWC-78-2 twin-axial cable. As may be seen, the greatest variation with frequency was below 100 KHz. Z_0 was close to being resistive for frequencies above 500 KHz.

Based on the observed behavior of the measured Z_0 for a number of cables, it did not appear that the synthesis of the complex conjugate of Z_0 was easily obtained. The use of a simple reactive termination for Z_0 would only be beneficial over a narrow band of frequencies. Furthermore, it did not appear that anything but resistive termination was necessary for baseband signals having their energy concentrated, primarily at high frequency (above 50 KHz) and having no significant DC component.

As an alternate to trying to optimally terminate the cable, it is recommended that the behavior of Z_0 (both magnitude and phase) should be a consideration in cable selection. The results of Section 3.2.3 show a large variation between the various cables tested in this respect.

3.2.5.2 Coupling Techniques

Candidate coupling techniques examined were: 1) photo-coupling, 2) transformer coupling, 3) direct coupling, and 4) capacitive coupling.

The Photo-Coupled Device

This technique was investigated and reported in a TN. It should be pointed out that this was essentially only a receiving technique, and should multiple transmitters be required on a data bus, numerous other problems arise. The transmitters must be isolated from each other, and if a transformer is used for that purpose, much of the advantages of the photo-coupled device are lost.

Transformer Coupling

The use of transformers as the means of coupling transmitters and receivers to a transmission line appeared to be one of the more favorable techniques. Several of their characteristics appeared suitable: they maintain isolation, are relatively inexpensive, are not extremely lossy, they help achieve a high common mode rejection, and impedances may be altered for each of interfacing with available circuits. The obvious disadvantage was that since they cannot pass DC, there are some restrictions upon the type of modulation that may be used.

Some of the more important design equations for broadband transformers were given, and from these equations some general guidelines were established. These included recommendations concerning high and low frequency responses.

A sample design has been done using the well-known equations. Actually these design equations are only used to allow the designer to make a first approximation at the design, which is then refined experimentally.

The design given shows that design of transformers are not extremely complicated, and that good performance can be obtained with reasonably small sizes.

Direct Coupling

Direct coupling to a transmission line with various devices is a common practice on data bus lines of extremely short length, such as may be found in some special purpose computers and their periphery equipment. This is a limited technique for a number of reasons: obviously no isolation can be maintained, D.C. power for the output devices is placed on the bus,

and only a small number of outputs can be placed on the bus. The problem of matching becomes severe if more than a few devices must transmit over an electrically long (> λ/10) line. Various types of devices have been used on short buses. Integrated circuit drivers and receivers using TTL logic have been used. A problem with this technique is that due to leakage, only a small number of transmitters may be connected to the line, without severe loading.

Tristate logic has been used to overcome some of these problems. Tristate logic employs complementary MOS transistors at the output, which when turned off, present a high impedance to the line. The main problems associated with these devices is speed.

While in certain applications the direct coupling to a bus transmission line shows advantages, for the use in transmission lines of the nature found on the Space Shuttle, there appears to be no advantage in this technique.

Capacitive Coupling

Capacitive coupling to the line is an extremely simple technique to implement, and does achieve DC isolation. However, complete blocking of ground loops is not possible.

Even in the transformer coupling method, the capacitance from primary to secondary allows a slight ground loop path to exist. *

---

* The transformer could employ electrostatic shielding between primary and secondary, or could be wound such that the capacitance is distributed to both terminals equally.

Conclusions

For the data bus on the SSV it is highly recommended that transformer coupling be used. Transformer coupling can in fact be used on data bus systems where the operational frequency greatly exceeds the SSV requirements. As was seen in other study reports, unbalanced modulation waveforms are not well suited for data transmission over cable even with DC coupling, and that the lack of DC response by the transformer would not be a significant factor in data transmission over cable.

3.2.5.3   Nonuniformities in Transmission Lines

The transmission media studies largely dealt with the characteristics of the transmission lines as a uniform, terminated line. Some of the conditions which may have contributed to the transmission line being nonuniform were investigated. In an actual data bus line, the cable had connectors placed at various points, had deformities in the line, and had loads of various types at these connectors.

A 270 foot length of cable TSP #24, Teflon insulated and terminated at both ends in its characteristic impedance, was tested to simulate points of nonuniformity. The uniform cable was driven by a pulse. Photos of CRT waveforms were taken. It was difficult to determine whether the slight irregularities in the waveform were due to cable nonuniformities, a slight mismatch, or the instrumentation. No amount of physical deformation, short of causing permanent cable damage, could be seen to cause a change in the waveforms shown.

A number of other tests were performed on different cable configurations. In one cable test the cable was cut and respliced at eight different points. Each splice was made to simulate a connector at a data terminal, with a short length of internal circuitry attached.

Another test consisted of placing various resistive loads across the end of the additional length of wire at each splice.

In still another test, one of the resistors was replaced by a stub line, consisting of a length of TSP #24 cable placed across the line. The stub line had a very large effect on the waveform on the bus. The degradation was so serious that the problem received special consideration and is found in section 3.2.5.4 under branching and stubbing techniques.

After reviewing the test results, it was concluded that there does exist non-uniformities in cable of this type. Such nonuniformities probably arise due to a slight variation of cable cross-sectional geometry through its length, and a resulting variation of parameters with length. However, the effect of such nonuniformities are negligible when considering a data bus of the nature envisaged for the SSV.

The conclusion is that cable nonuniformities, or those caused by connectors (assuming reasonably good engineering design practice in the mechanical packaging of data terminals), are not a significant factor in the transmission of data over a data bus of the type envisaged for the Space Shuttle Vehicle.

3.2.5.4   Stubbing and Branching of Transmission Lines

In the Phase I Report stubbing and branching of the data bus transmission lines were identified as design alternatives. Tests and analyses were performed which revealed the ramifications of such practices. Stubbing is a method wherein a separate line is connected between the primary data bus line and a remote data terminal (DT). Branching can be considered as a splitting of the primary data bus line into several paths, where each path may have several DT's connected to it. The two techniques may be

differentiated by their length (stubs are normally much shorter than a branch) and by the number of DT's connected to it, although in practice the difference may be arbitrary. As will be noted, there is a great deal of similarity between the techniques employed to stub and branch, and the basic operational modes discussed in Section 3.2.4.

Stubbing

An analysis of stubbing can be approached by further defining the stub, and by considering the reason the stub exists. As was pointed out in the discussion on cable nonuniformities, the direct connection of a stub line causes a mismatch, which appeared on the waveforms. However, in some cases, depending on the modulation used, filtering at the receiver reduces the severity of the mismatch. It was found that using Biphase modulation with a raised cosine filter, a high degree of stubbing could not be tolerated. The data bus used had the following characteristics:

Length of Primary Transmission Line	300 ft.
Length of Stub Lines	20 ft.
Type of Cable	TWC-78-2
Number of Stubs	29
Data Rate	1 Mbps
Method of Terminating	Z_0 at ends of main line, open at end of stubs
Mismatch Loss Introduced Stubs	1.26 db
Line Loss of Cable	1.95 db
Mismatch Loss from Transmitter to Bus via 20 ft. stub	.90 db
Total Loss	4.11 db

In this case the reflection did not distort the biphase waveform significantly. It appeared therefore that stubs could be tolerated as long as the length did not approach one-quarter wavelength. The exact limit to stubbing depends upon the number of stubs, length, type of modulation and the degree of filtering used.

Stubs are often employed not only as a convenience in bus layout but as a means of coupling a unit to the line in such a manner that a fault on the stub or terminal will not greatly affect the transmission line operation. In this case a network is employed somewhere in the stub line to provide isolation from the fault. In this case the networks described previously in the Operational Modes Section, Section 3.2.4, will provide this function.

In stubs that are of such length that the mismatch and reflection degrades bus operation, some form of network is also required. In Figure 3.2-6 A through F, several methods of coupling a long stub to the transmission line are shown. In this case, the stub is of such a length that the stub must be terminated into Z_0 as well as the primary transmission line. In Figure F, the receiver impedance is shown as Z_0, but when transmitting the transmitter impedance is very low. If the distorting effect of the reflections are ignored, the resulting overall loss of the bus can be calculated as a function of the number of stubs (n). These calculations were plotted in Figure 3.2-7, where the letter of the curve corresponds to the network shown in Figure 3.2-6. It is evident that the use of a transformer at the junction of the stub incurs less loss than a resistive network. The transformers shown are voltage mode transformers, but current mode transformers may also be used.
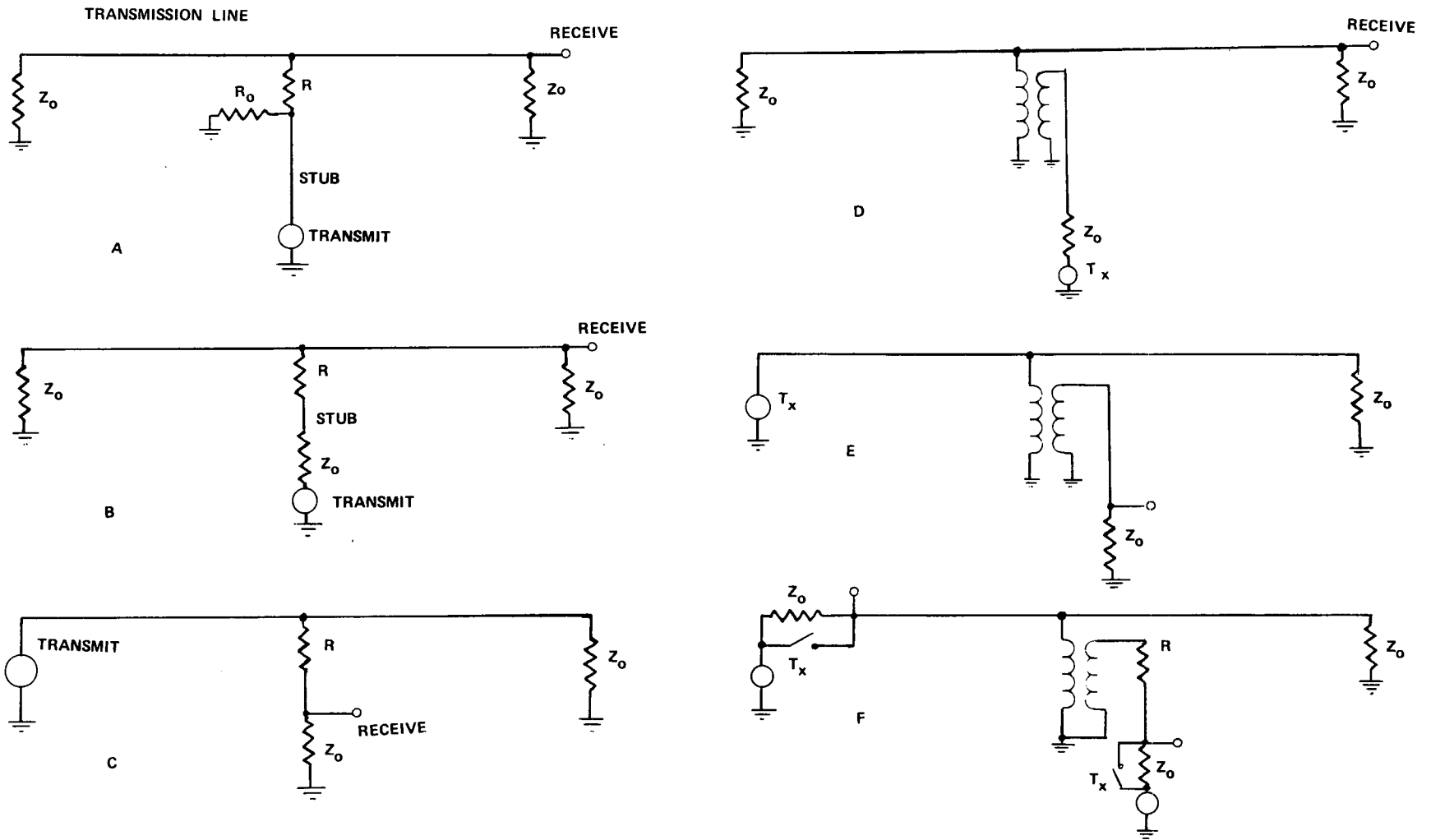
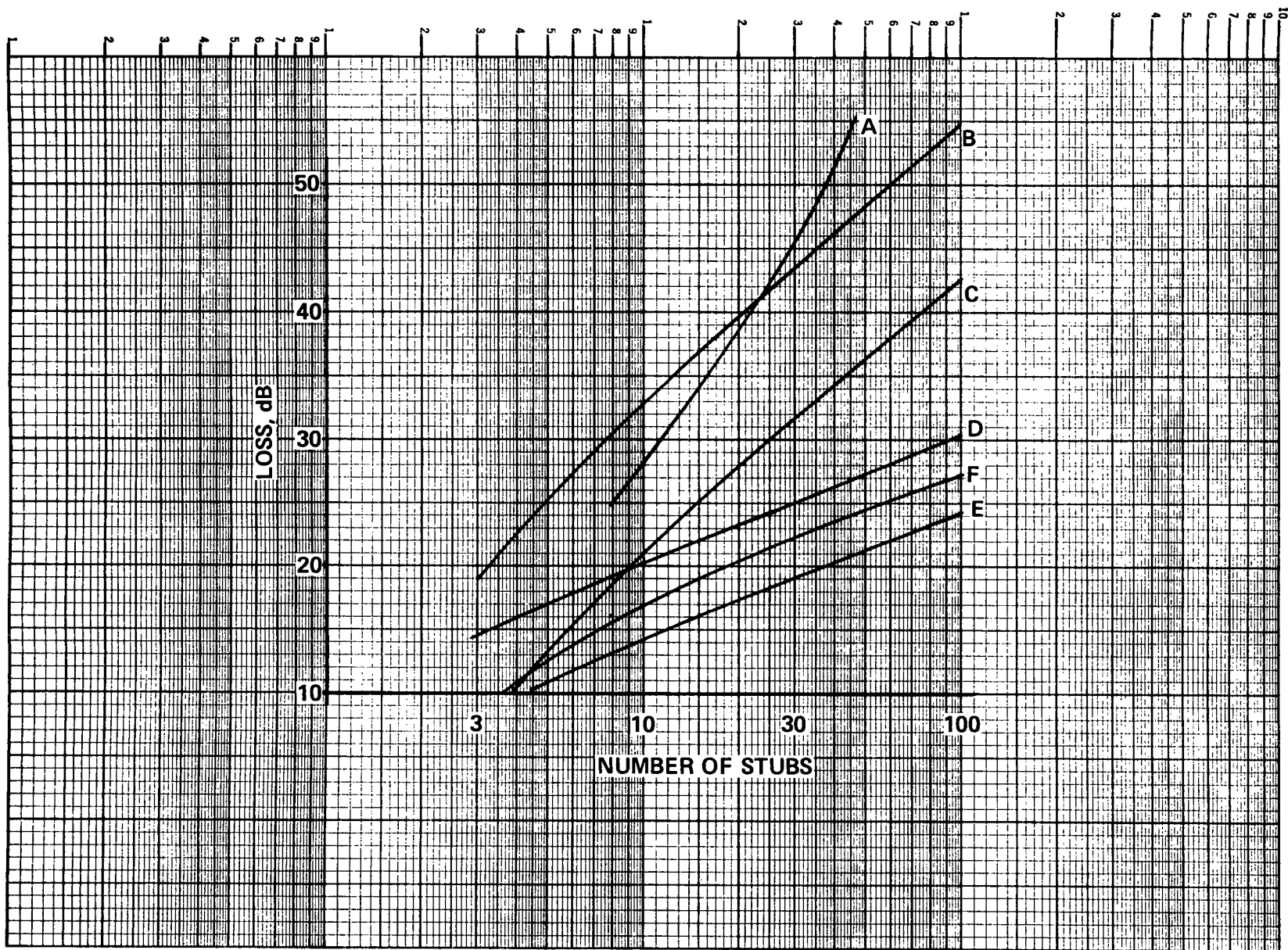FIGURE 3.2-6 METHODS OF CONNECTING LONG STUBS TO TRANSMISSION LINE

FIGURE 3.2-7   TOTAL LOSS OF STUBBED LINE VS. NUMBER OF STUBS

It may be well to note that stubbing is <u>not</u> a preferred method of bus configuration, but that it is sometimes necessary or convenient in the physical layout or installation of the transmission line. From a signal transfer standpoint it appears that the best technique is to bring the transmission line to the remote terminal and back out again. This technique is called daisy-chaining.

Since the overall configuration of a data bus can vary considerably, with regard to stubbing, it is strongly recommended that any proposed configuration be evaluated. A simple evaluation technique is using "eye pattern" tests with the modulation method to be used.

Branching

In the design of a data bus system for the SSV it may be inevitable that the transmission line branches into two or more paths. The branch point must be matched if serious distortion due to reflections is to be avoided. A resistive matching network for a three-way and a four-way branch is shown below in Figure 3.2-8 for a single ended line.

The loss due to the three-way branch is 6 db while for the four-way branch is 9.45 db.

For a simpler system, or for a half-duplex system which does not require communication between DT's, an alternate technique is possible using hybrid transformers. A four port hybrid transformer when receiving a signal on a port transmits the signal to the two adjacent ports with only the 3 db power split plus a small insertion loss (typically .5 db). The diagonally opposite port receives no signal provided all ports are properly terminated. The configuration and signal flow are shown in Figure 3.2-9.

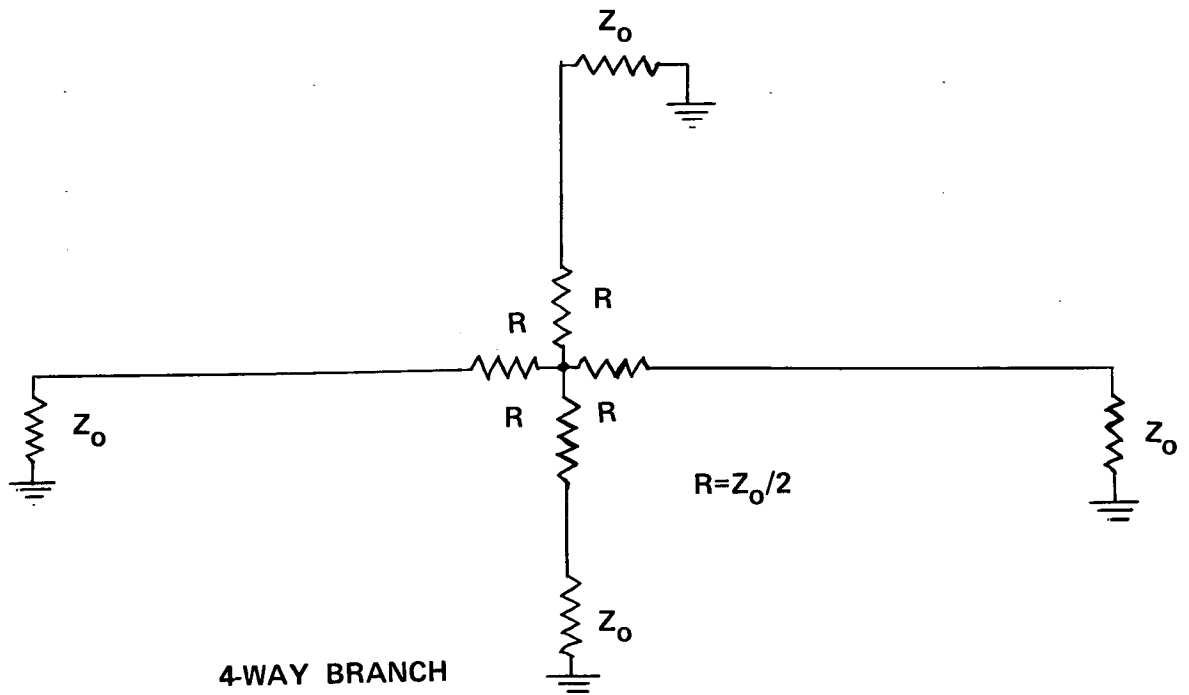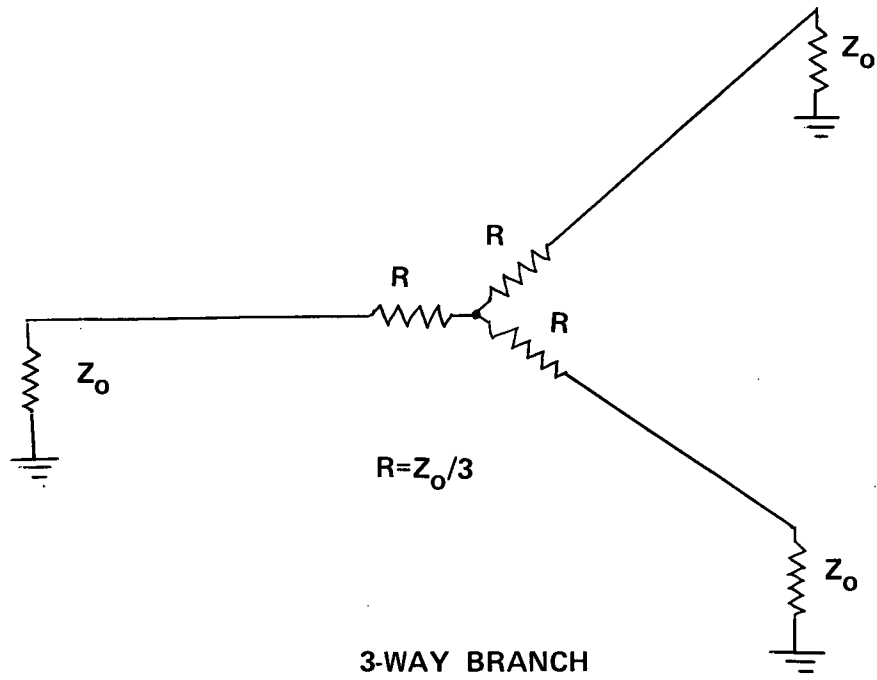3-WAY BRANCH

$R = Z_0/3$

4-WAY BRANCH

$R = Z_0/2$

FIGURE 3.2-8   RESISTIVE BRANCHING NETWORKS

A four-way split could be arranged as shown in Figure 3.2-10. The resulting loss to the distant branches is 7 db, but this is not as great as the -9.45 db incurred with the resistive four-way splitter.

Another alternate to the branching problem may also be considered. In the branching techniques given, equal power splitting was assumed. It is also possible to branch, or split power unequally. If this is done resistively, a large additional insertion loss is encountered; if done reactively, bandwidth must be considered. A nonresistive device which is often used in the manner described is the directional coupler.

It does not appear that the SSV data bus would require the use of either the hybrid or directional coupler, but if the data rates were to increase to the point of using RF carrier techniques, then the use of such devices may become necessary.

3.2.5.5   Filtering, Equalization, Predistortion and Inductive Loading

There are design techniques which have been used in data transmission to improve the signal characteristics or for S/N enhancement in some manner.

Many of these techniques are closely interrelated with the Signal Design and Detection studies. These topics are treated briefly here for clarity and continuity, in view of their possible application to the data bus system on the SSV, and because their use is closely related to characteristics and configuration of the transmission line.

-3.5dB → DT

BUS
CONTROLLER → HYBRID

-3.5dB → DT
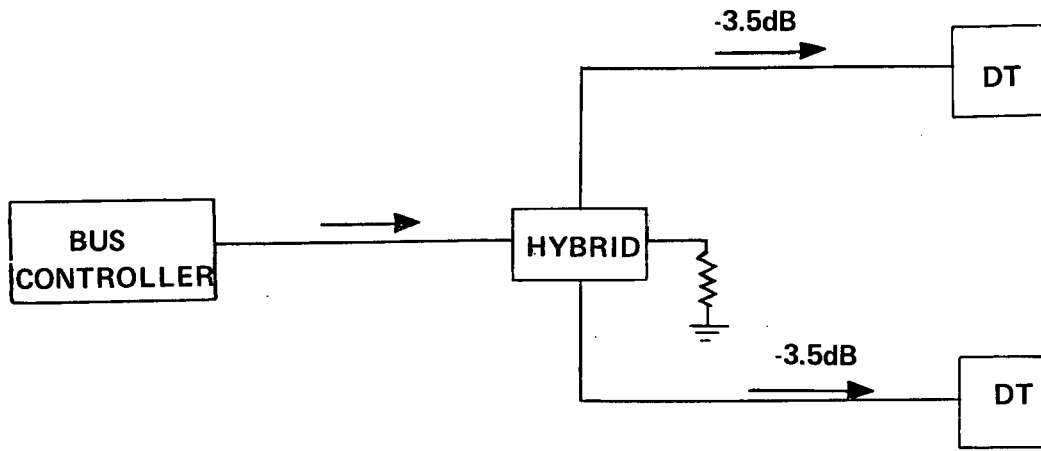
TRANSMISSION FROM BUS CONTROLLER

DT ←

B.C. ← -3.5dB ← H -3.5dB

NO SIGNAL DT
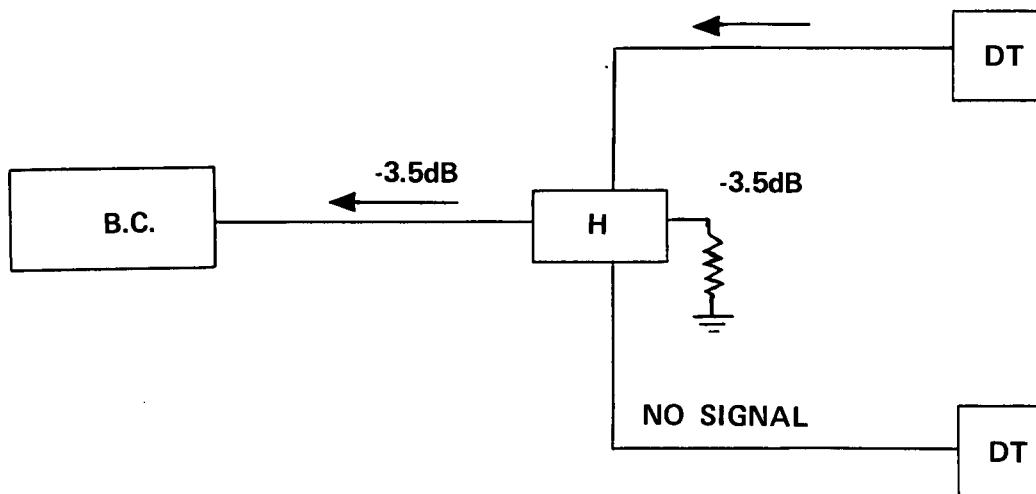
TRANSMISSION FROM DATA TERMINAL

FIGURE 3.2-9   HYBRID TRANSFORMER BRANCHING
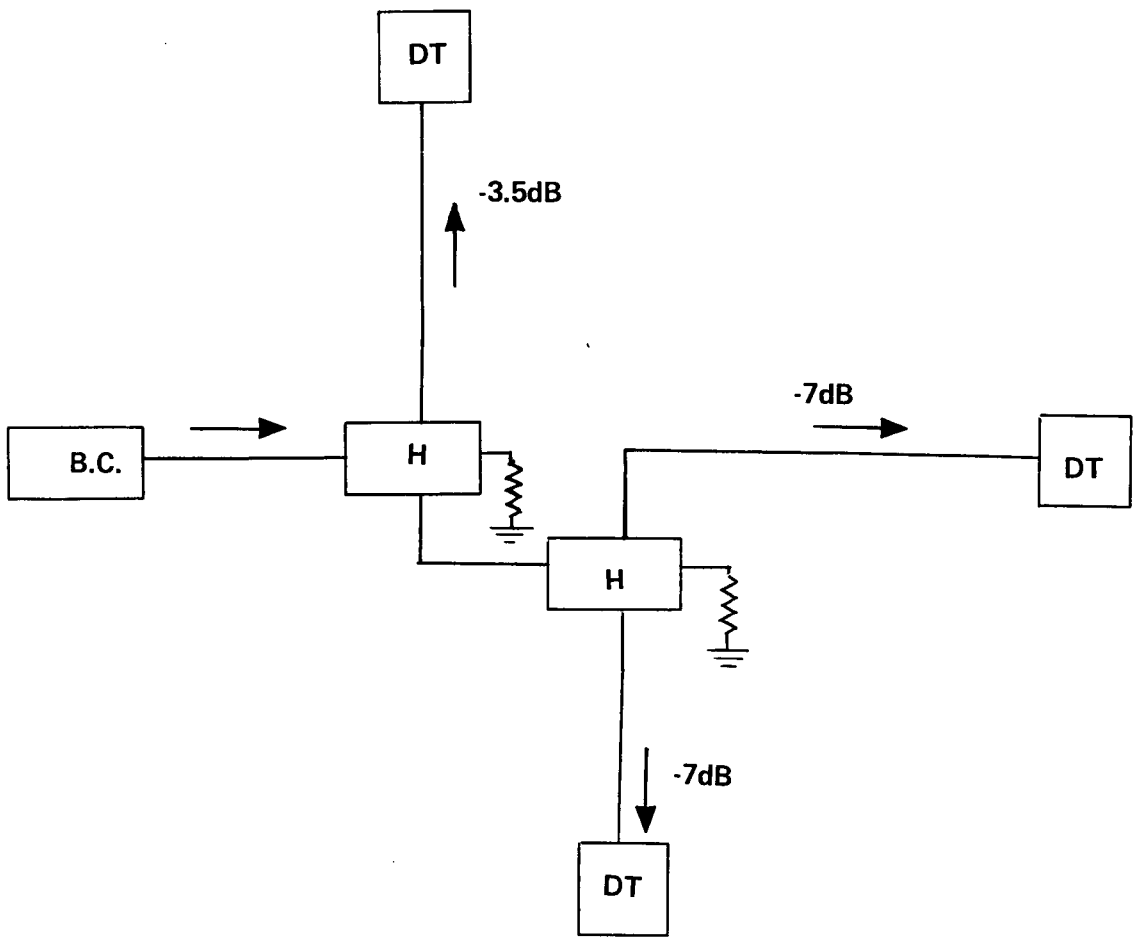
FIGURE 3.2-10   FOUR-WAY BRANCH USING HYBRID

Filtering

The use of a low pass filter at the receiver has been shown to be very effective in the reduction of transient EMI. Some filtering of the transmitted waveform is necessary to prevent the emission of EMI from the data bus. However, filtering at the transmitter as a means of improving the waveform or enhancing its reception is of little value. This is because the transmission line behaves as a low pass filter (although less than ideal) and further low pass filtering is merely redundant.

There is much discussion in the literature of matched filters. Matched filters are those whose response is identical to the spectrum of the transmitted signal, and while not always readily realizable, they are used in comparing practical filters. There are problems associated with using the matched filter with the data bus. The distorting effect of the transmission line must somehow be compensated for if the matched filter is to be used, and since the terminal may receive from more than one transmitter the required compensation could vary from one transmission to the next. Furthermore, matched filters are only cost-effective when the S/N is low. The improvement of the optimum matched filter can be shown to be only about 1 db better in performance than the ideal low-pass and the 1 stage RC low pass filter. [1]

The transversal filter may be employed at a receiver to compensate for the effect of multipath signals or reflections due to an improperly terminated cable. The transversal filter is composed of a tapped delay line, whose weighted output may be varied and summed.

1. "Information, Transmission, Modulation and Noise", M. Schwartz, McGraw-Hill, 1959, see curve on page 289.

The transversal filter does not seem applicable at first because of the complexity and because of the same reason that other compensation devices do not seem applicable. Any compensation device is designed or adjusted to compensate for a specific length of the cable, but on a data bus the length over which the message is transmitted could vary from transmission to transmission. However, this type of filter is variable, and because of an emerging technology the use of this technique seems promising. The new technology is surface wave electronics, particularly in combination with MOS devices. [1] As this technology matures, allowing fairly long delays in a small package, the use of automatic transversal filters will become practical. At the present time, however, this technique does not appear practical for application to the SSV data bus.

Equalization

Equalization networks which have attenuation and phase characteristics have been used in data transmission over cables to compensate for the attenuation and phase response. Here again, in a data bus the received signal may be from one of several transmitters which means that this technique is somewhat limited.

There may be certain circumstances where this technique would improve data bus operation. Consider a bus which has terminals concentrated at either end of a cable. It may be that terminals could communicate with each other if they were located at the same end of the cable, but could not communicate over the entire length without compensation. A partial compensation might allow all the terminals to operate satisfactorily, although the terminals which were close together may be over-compensated and slightly degraded.

1. "MOS Technology Squeezes Its Way Into Surface Acoustics"
   Electronics, January 18, 1971, McGraw-Hill, Inc.

It does not appear that a data bus for the SSV would require compensation. The results of the cable test show that the phase response of the cables tested are fairly linear, except near zero frequency, and that transmission over 500 feet of cable at up to four (4) Mbps is possible using balanced modulation methods without compensation. Compensation of the attenuation characteristics of the cable would tend to have the reverse effect of the low-pass filter and could make the receiver more susceptible to impulsive interference.

Predistortion

Predistortion is a technique where the pulse shape is altered at the transmitter in such a manner that the pulses have the desired shape after transmission through the cable. There are several forms of predistortion which might be used but they are all unsuitable for a data bus. This is because a transmitted signal must most often be received by several receivers simultaneously, each of which could require different amounts of predistortion.

Inductive Loading

Inductive loading of a transmission line is frequently used in transmission of signals over cable. This method is used for improving the low frequency response of cables by attempting to meet the criteria for "distortionless" cable: $\frac{R}{G} = \frac{L}{C}$.

In most cables the ratio of R/G is much higher than L/C, so that by introducing some lumped L the ratios become more equal. The lumped inductance must be placed closer than $\lambda/2$ on the line, and it also has a tendency to give the cable a sharp low pass filter effect. It would require frequent cutting of the line, which is undesirable from a reliability standpoint, and in addition it is not considered necessary if the balanced waveforms with no DC component are used in transmission. The same effect can be

achieved by placing resistive loads across the transmission line, in order to decrease R/B. This test was performed in Section 3.2.4.3 and attenuation is the only noted signal degradation. Loading of transmission lines to improve cable response is apparently useful only on very long lines, and when the signal spectrum is concentrated in the low frequency region.

Equalization by Quantized Feedback

The quantized feedback technique [1] is useful for correcting for the poor DC response of a transmission line, or a coupling device such as a transformer. It may be implemented with a delay in the feedback path of an amplifier.

Conclusions and Recommendations

Most of the techniques investigated in this report do not appear necessary for the transmission of data on the data bus for the SSV in view of the present data bus requirements. Should the scope of the requirements increase, i.e. a much higher data rate, or longer lengths of cable, then these techniques would appear more favorable. At present it is recommended that a low pass filter be used for EMI protection, and possibly a small degree of filtering (rise time limiting) at the transmitter to prevent EMI generation.

Developments in the field of surface wave electronics should be followed to determine if sophisticated techniques such as transversal filters become practical.

The properties of the equalizer with quantized feedback should receive further investigation.

1. "Data Transmission", Bennett and Davey, McGraw-Hill, 1965.

In general all of these devices had a shortcoming when used on the data bus, and this is because they were designed to compensate for a particular path or length of cable. On a data bus the length may vary. While a device which could automatically compensate for a changing length could be designed, it would require additional overhead bits in the message to denote physical position of the transmitter.

3.2.6   Electromagnetic Interference Characterization

In this section some of the problems associated with the electromagnetic interference (EMI) problem are discussed. The task was composed of (1) identifying the most probable sources of EMI to the data bus, (2) test to obtain waveforms and magnitudes using an appropriate EMI model of the impulsive source, (3) compare shielding and cable arrangements as to their effectiveness, and (4) investigate other sources of EMI and evaluate their probable effect on the data bus.

Several different kinds of EMI could exist on board the SSV. In general, the basic types are low frequency, steady state fields which are typically generated by large AC power alternators, high frequency steady-state fields, which may be generated by communication equipment or radar, and impulsive noise. The latter noise is considered to be the most detrimental to baseband data communications, and is the type that will receive the greatest emphasis.

3.2.6.1   Selection of Impulsive EMI Model

In the Phase I Study the rationale for selecting the impulsive device as the model for the EMI impulsive characterization was given. A representative list of sources was given:

1. Relays
2. Solenoid Valves
3. Spark Ignitor (EBW)
4. Alternator

5. Coolant Pumps
6. Electrical Contactors
7. Inverters

By far the most numerous of the above devices are the relays. Relays and the lines connecting the coil with the switch that energizes them are found virtually everywhere in a large space vehicle, and it is assumed that some of the lines would unavoidably be in close proximity to the data bus transmission medium. Typical relays that would be used are the 2 amp and 10 amp relays conforming to Specification 40M37496. The coils on these relays are used with 28 VDC, and draw 50 ma and 200 ma respectively. Based on the rationale given in the Phase I report (and in a TN) the method of the interference circuit was given.

3.2.6.2   Impulsive EMI Test

The purpose of the impulsive EMI test was to describe the nature of the induced transients which may be received on the SSV data bus so that measures could be taken to insure error-free information transfer.

Noise Source

Unsuppressed relays were selected as the noise source because of the large number used on large space vehicles, the likelihood of close proximity operation, and the fact that they are cable of producing large voltage transients.

Preliminary Test

Before the main portions of the test were run, some preliminary laboratory work was performed to insure the validity of the test. From the preliminary

test runs it was found that certain precautions had to be taken with the hook-up of the measuring instruments. Also the arrangement of the cable had a large effect on the values being measured.

Comparison of Relays

Waveforms generated at the relay coil upon opening of the circuit when connected to 1000 ft. line, then a 100 ft. line, were examined. A 10 amp relay, then a smaller 600 ohm relay, were used in the tests. The longer line resulted in increased symmetry about zero and causes the burst to last longer. Peak voltages were about the same, but total energy of the transient is less for the smaller relay.

A comparison of the induced voltages in a twin-axial cable was made, using a 10 A, 150 ohm relay, a 2A, 600 ohm relay, and a 2 A, 750 ohm relay, respectively. Between the three, there was a slightly diminished peak voltage.

Comparison of Switch Opening/Closing

Transients are produced on both closure and opening of the relay circuit, but by comparing the magnitude of the two it was seen that the opening transient was several times the magnitude of the closure transient. For the remainder of the test, all transients were opening transients, unless otherwise stated.

Grounding Arrangement of Shield

In the preliminary test it was found that grounding the shields at the receiving end resulted in large decreases in the magnitude of the induced transient voltages. As much as 10 to 1 reductions were made by grounding at the receiving end instead of the far end. Grounding both ends did not seem to

produce additional immunity. This was true for both balanced and coaxial cables. Some questions regarding triaxial cables arose concerning grounding of the outer shield. Grounding the outer shield of this type of cable at the receiving end also proved beneficial from 4 volts peak to .4 volts peak by doing so.

Comparison of Cable Types

Four types of cables were used in these tests:

1. RG-180, a small diameter coaxial cable.
2. TRC-75-2, a triaxial cable.
3. Twisted Shielded Pair, #22 AWG, Teflon Insulated.
4. TWC-124-2, a twinaxial cable.

These cables are representative of their types. The peak voltage observed were 2V, 1V, .5V and .3V. By observing a large number of waveforms, it was noted that the above list of cable types are listed in reverse order to the degree of EMI rejection they provide.

Characteristics of Impulsive EMI

After performing a variety of tests some general characteristics were noticed which are common to all of the transients observed. First, there is a large variation in any two pulses observed. The first part of the noise burst, lasting from 50 to 100 microseconds, consists of a very random type of noise. No evidence of periodicity seems to occur in this portion of the burst. It was also found impossible to obtain a good photograph of this portion at high sweep speeds. Gradually the burst becomes impulsive and periodic. The period seems to decrease with time, while the voltage peak increases with time. The total time of the noise burst lasts between 150 to 300 microseconds.

Coupling Mechanism

Several explanations of the coupling between the interfering wire and the signal conducting wire (inside the shield) were suggested. The coupling could be magnetic, where the changing current induces current in the signal wires, or electric-static, where a finite capacitance exists between the interfering wire and the shield, and even through openings in the shield to the signal conductors.

It is likely that both modes contribute to the induced EMI. However, the predominant coupling mode is believed to be due to displacement currents flowing in the shield, in conjunction with the finite surface transfer impedance that is found in braided shields. The surface transfer impedance is defined as the ratio of the voltage appearing longitudinally inside the shield to the surface currents flowing on the outside of the shield. The surface transfer impedance of braided shields is not easily calculated, but values have been measured experiementally. These values generally increase with frequency, and are also greatly dependent on the "per cent coverage" that the shield affords. This is in contrast to the theoretical equation developed by Schelkunoff[1], for the solid cylindrical shield. This equation shows an ever-decreasing transfer impedance with frequency.

Apparently the more complex shape of the shield of the twisted shielded pair leads to a higher value for the surface impedance than does the more nearly cylindrical shield of the twin-axial cable. Both shields are 90% coverage shields, yet the twin-axial cable has slightly better noise rejection.

1. Schelkunoff, S.A., The Electromagnetic Theory of Coaxial Transmission Lines and Cylindrical Shields, The Bell System Technical Journal, 1934.

Additional tests were conducted to obtain more insight into this coupling mechanism. A high power amplifier was connected to the interfering line instead of the relay circuit. With a current flowing through the interfering wire, I_1, and the voltage at the transmission line terminal (V_2) were read. Values obtained are given in Table 3.2-1 as follows.

Frequency	I_1	V_2	V_2/I_1
10 KHz	2A	.036 mv	18×10^{-6} ohms
12.5 KHz	3.34A	.050 mv	15×10^{-6} ohms
100 KHz	.832A	.044 mv	53×10^{-6} ohms

TABLE 3.2-1 LOW FREQUENCY NOISE COUPLING

The above tests were run using RG-180 coaxial cable, and 100 foot lengths.

In view of the small amount of coupling measured using this technique it is almost certain that the magnetic coupling is not the major coupling mechanism at these frequencies, and with the cable and interfering wire configured in the manner described.

Measurement of Spectrum

By examining the interference waveforms, it was reasoned that the transients consist of high frequency components, possibly beyond the viewing capability of the scope. A measurement of the spectral content was made, using a noise measurement receiver (an Empire Devices NF-105). The results of this measurement showed that the spectrum extends to very high frequencies and has peaks at about 3.4 MHz and 24 MHz. Spectral components below 1.5 MHz could not be detected with the instrument used.

The measurement of this spectrum also reveals that the cable shield and the twisted balanced signal wires are very effective in providing immunity to these transient at frequencies up to several MHz. The cable used was the TSP #22, Teflon insulated, of 100 foot length.

Recommended Protected Measures

The spectral measurements indicate that low-pass filtering at the receiver may be an effective method of reducing the magnitude of the transient interference. To design the proper filter, the bandwidth necessary for the data must be known. Using the assumption that a 6 db bandwidth of 2 MHz was sufficient, a simple two stage RC filter was constructed. Using the TSP cable of the above test and the filter, the transients were observed on the scope. Without the filter, peaks of about .2 volts and lasted 200 μsecs. Using the filter, the peak voltages were reduced to about .05 volts. The total burst of the transients were reduced in time to about 20 to 30 μsec.

Based on the investigations conducted in those series of tests, it is recommended that:

- A balanced transmission line and receivers be used.

- The cable shield be grounded as near receiver ground as possible.

- Low-pass filtering should be employed at the receiver.

Summary of Tests

In all the below cases, the line length was 100 feet, the shields were grounded at the receiving end, and the transient was produced upon opening of the relay coil. The coil supply voltage was 28 VDC.

Cable Type	Filtering	Relay Type	Peak Voltage	Length of Noise Burst
RG-180 (Coaxial)	None	10A, 150 ohm coil	2V	200 μsec
TRC-75-2 (Triaxial)	None	10A, 150 ohm coil	1V	150 μsec
Twisted Shielded Pair-#22 AWG	None	10A, 150 ohm coil	.5	200 μsec
	None	2A, 600 ohm coil	.2	200 μsec
	6 db @ 2 MHz	2A, 600 ohm coil	.05	30 μsec
TWX-124-2 (Twin-Axial)	None	10A, 150 ohm coil	.3	200 μsec
	None	2A, 600	.2	200 μsec
	None	2A, 750	.2	200 μsec

TABLE 3.2-2   SUMMARY OF TESTS

In order to postulate the impulsive interference model, certain assumptions were made concerning the design of the data bus:

- TSP #22 or twin-axial cable should be used.

- The worst case condition is the 100 foot configuration described in the test set-up, with the 10 amp relay.

- That some filtering should be used at the receiver.

Based upon the above assumptions, the interference model used was a .1 volt peak burst of noise lasting for 30 usec.

3.2.6.3   EMI Rejection to Low Frequency Fields

In the design of communication systems involving transmission of data over cables through a space vehicle there is concern over the effect that power

distribution circuits could have. An attempt was made to correlate the findings of several independent reports, and to perform tests to evaluate the effectiveness of cables in shielding against fields of power line frequency.

The objectives were to determine the severity of the problem, and to evaluate some representative cables in order to compare their effectiveness.

One report that has often been cited in comparing cables was based upon an experiment in which several cable types were wound upon a wooden spool, and excited by a similarly wound cable. The results of this test are shown in Figure 3.2-11. As may be noted the balanced cable configuration shows a clear superiority in rejecting these fields. While this test set-up was not extremely realistic in terms of the configuration of vehicle wiring and cable configurations, it did show the effectiveness of the various cables in rejecting magnetic fields.

A test was conducted using 400 Hz power line cable placed adjacent to 100 feet of the candidate data bus cable. The same test fixture was used that was used for the impulsive interference test, with the exception that a much heavier interfering wire was used (#12 AWG). All cables were resistively terminated in their characteristic impedance.

With 5 amps RMS current in the interfering wire, the resulting voltage level (V_2) was recorded:

1. Twisted Shielded Pair #22, shield grounded at scope, $V_2 = 5$ mv p-p

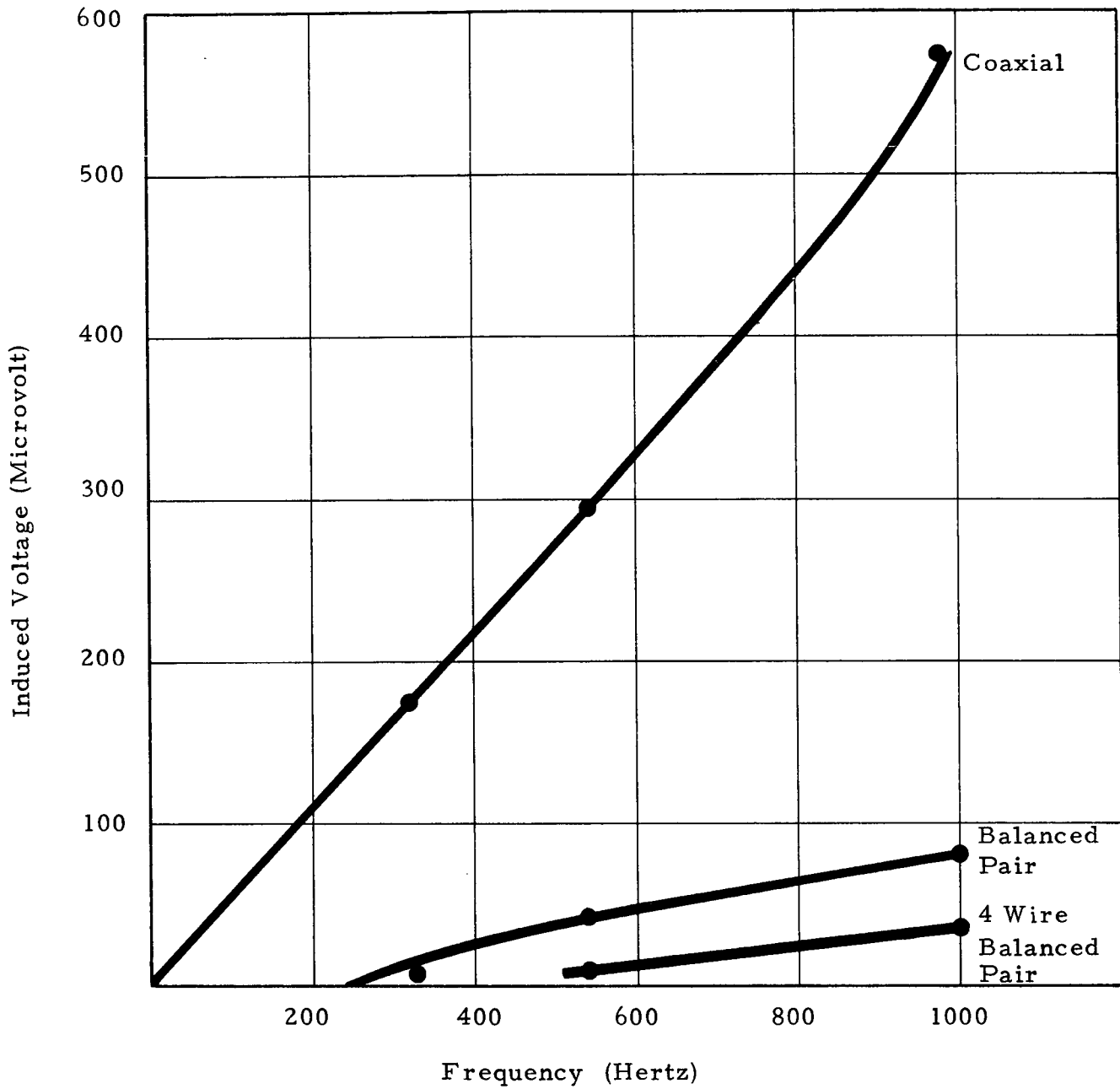2. TWC-124-2, shield grounded at scope, $V_2 = 2$ mv p-p

FIGURE 3.2-11   NOISE SUSCEPTIVENESS OF CABLES AT LOW FREQUENCY

3. TWC-124-2, shield grounded at both ends, V_2 = 6 mv p-p

4. TWC-124-2, shield grounded at far end, V_2 = 10 mv p-p

5. RG-180, shield grounded at both ends, V_2 = 380 mv p-p

6. TG-180, shield grounded at far end. V_2 = 700 mv p-p

As a result of the test, it can be seen that the twin-axial cable is superior in rejecting these fields, followed by the TSP, and that the coaxial type is worse. It can also be noticed that the voltage levels picked up on the cables are of a very low level, except for the coaxial type and should not be a major factor in selecting cables or in data bus design. The conditions of the tests were more severe than those anticipated for SSV's.

3.2.6.4   Radiated EMI, Properties of Cables

The purpose of this subsection was to investigate the shielding properties of various types of cable to radiated electromagnetic interference. The nature of this investigation was threefold: 1) to determine the degree of radiated interference that the data bus may radiate, 2) to obtain the degree of protection which the cables may give to external EMI fields, and 3) to compare the relative shielding effectiveness of four different cable types.

The tests conducted in the investigation reported in this subsection were performed using the general procedures and instruments given in several widely used EMI specifications such as MIL-I-6181D.

The four cables chosen for this test represent four different cable types. They are:

RG-180 Coaxial - This is an ordinary coaxial cable similar to RG-58.

TRC-50-2 - A triaxial cable, whose outer shield is isolated from the interior shield.

3.2-47

<u>Twisted Shielded Pair (TSP 22)</u> - This is the common type of twisted shielded pair cable (conductor size #22 AWG).

<u>TWC-78-2</u> - A twinaxial cable consisting of two twisted pair conductors and two dielectric spacers with an overall shield.

A considerable amount of thought went into the procedures and test configurations. The test condition should reflect a realistic, but worst case condition, and should be repeatable. Repeatability is often difficult to achieve in a test of this type, but is of importance if the comparison of cable types are to be valid. It was decided that the plywood test fixture described in Section 6.2 of Volume I would be used to position the cable and that 100 feet of cable would be used. The test was conducted within a shielded room, with the test cable penetrating the wall of the screen room and the shield grounded at the point of penetration. Outside the screen room calibrated signal generators were located to deliver a signal to the cable.

This method was chosen because it was easy to implement and it was reasoned that the theory of reciprocity should hold (for the case where radiated fields are emitted from antennas as in a susceptibility test).

The measurement techniques were done in accordance with the procedures set forth in MIL-I-6181D. At each test frequency a known signal level was delivered to the test cable, and by measuring the radiated field given off, a total loss figure was obtained, and plotted in Figure 3.2-12 for all cables.
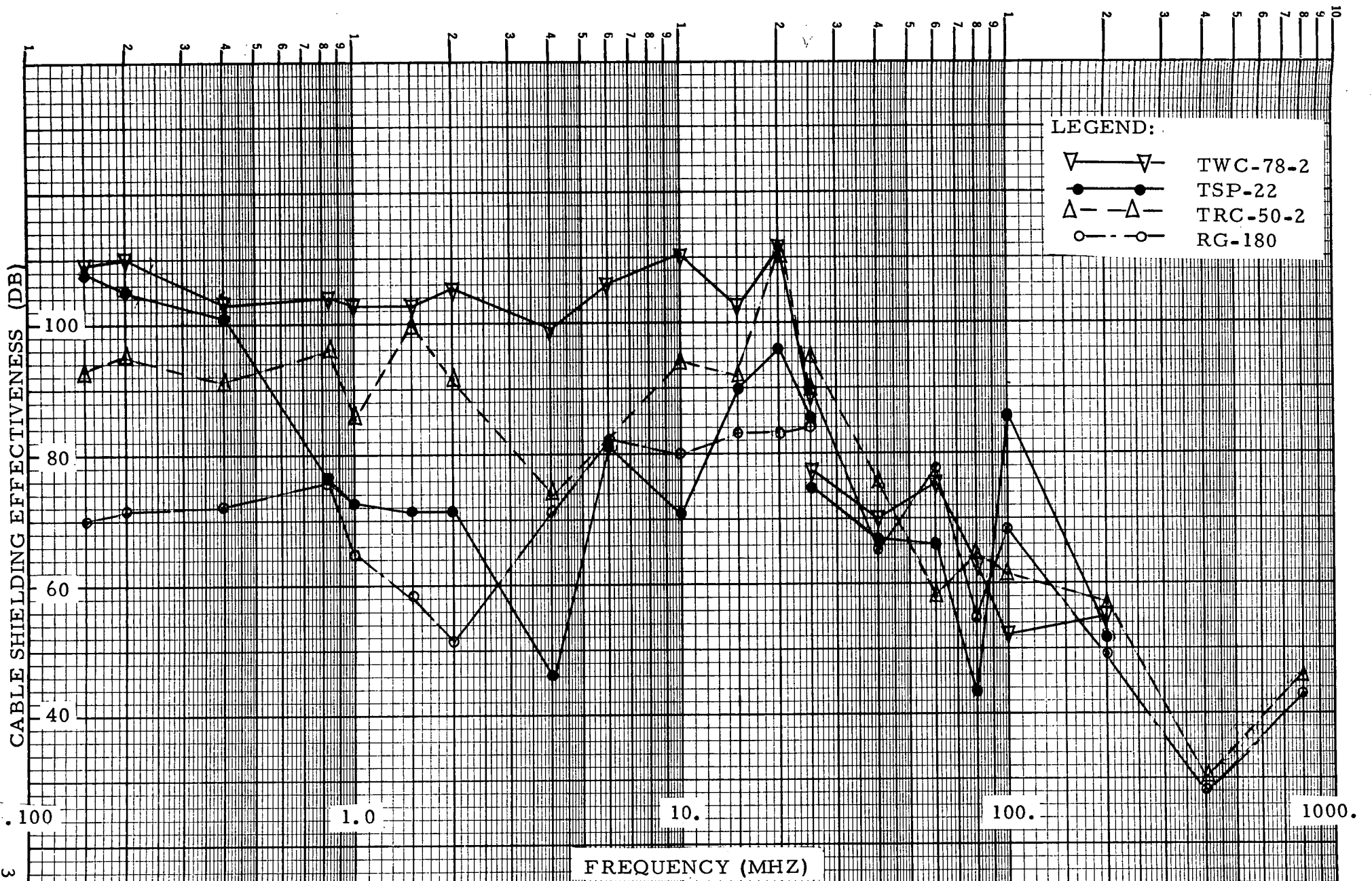
FIGURE 3.2-12   Shielding Effectiveness of Various Cable Types

LEGEND:

▽——▽ TWC-78-2
●——● TSP-22
△— —△ TRC-50-2
○— -○ RG-180

CABLE SHIELDING EFFECTIVENESS (DB)

FREQUENCY (MHZ)

3.2-49

A balun was used in the two balanced cables between the signal generator and cable. At higher frequencies the balun loss was appreciable. For this reason, the portion of the balanced cable curves shown above 100 MHz was questionable. Furthermore, the use of these cables (TSP-22 and TWC-78-2) is not anticipated at very high frequencies.

Cable Comparison

The results plotted in Figure 3.2-12 indicate that at the low frequency portion of the curve, the TWC-78-2 is superior followed by the TSP-22, then the TRC-50-2 and finally the RG-180. The TSP-22 is seen to fall rapidly with frequency until at 10 MHz it appears to be inferior cable. Beyond 10 MHz the results become increasingly less reliable. One reason that the TSP-22 and RG-180 appear to perform well up to 100 MHz is the high attenuation of the signal within the cable at these frequencies. The TSP-22 and TWC-78-2 cables were not tested past 200 MHz as it is believed the balun loss would lead to invalid conclusions. The coaxial and triaxial cables were tested to 800 MHz, as there was no balun and it is possible to transmit signals over these cables at these frequencies. The triaxial cable (TRC-50-2) had the outer shield grounded at the screen room penetration point and had both inner and outer shields tied together at the signal generator.

Susceptibility

The curves presented in Figure 3.2-12 may be used in calculating susceptibility levels due to a signal transmitted from an antenna similar to the antennas used in the test. For instance, a 1 KW signal was injected into the antenna terminals at one MHz. The power that appeared on the signal line was merely

$$P_r = P_T \text{ (dbm)} - \text{Loss (from curves)}$$

RG-180 cable was about 65 db at this frequency, so that P_r = +60 dbm -
65 db = -5 dbm. This signal was much less than the baseband data bus
signals now envisaged for the SSV.

Interference

To obtain some idea of the radiated interference, the type of signal which
may be used on the data bus was examined. A Biphase (Manchester II)
signal of up to 1 watt may be transmitted. The power spectral density
is given by

$$S(\omega) = \left| \frac{4 \sin^2 \frac{\omega T}{4}}{\omega} \right| \quad \text{watts/Hz}$$

For a 1Mbps data rate, $T = 10^{-6}$ seconds. The spectral power density at 1
megahertz was found to be -123.7 dbω/Hz.

Converting this to db μv/MHz across 50 ohms gives +73.3 $\frac{db\ (\mu v)}{MHz}$. At
1 MHz the loss of the RG-180 cable is seen to be 65 db, so that the measured
antenna induced voltage would be 8.3 db (μv)/MHz. This is much less than
the MIL-I-6181D broadband radiated interference limit of 69 db (μv)/MHz.

The Biphase signal spectrum falls at 20 db per decade from the above
given value.

Interference Test Using Biphase Signals

The predicted interference levels were verified by actually transmitting
a Biphase waveform into the cable and measuring the interference levels.

The results of the test showed that although the interference emitted was
well within the Broadband Radiated limits of specification MIL-I-6181D,
it was considerably higher than was expected. The levels recorded are

shown plotted in Figure 3.2-13, curve 1. The cause of the interference was concluded to be the clock signal from the data pulse generator driving the lines in a common mode fashion. To further demonstrate the levels produced by an imbalance drive condition, the data pulse generator was connected directly to the line and with only 5 mw of power, the levels shown in curve 2 in Figure 3.2-13 were measured.

By merely inserting a balun transformer between the pulse generator and the line, the level shown by curve 3 of Figure 3.2-13 was recorded with 80 mw input. Thus the balun reduced the EMI levels by 52 db at 1.1 MHz. The Biphase generator was connected and the balun inserted with the results that the interference level could not be detected above the receiver ambient noise level.

The results of the test and investigation pointed out that most often the difference between a system which is relatively free from the effects of EMI and one that is not, is in the careful application of good engineering and design practices, rather than the selection of elaborate techniques. Moreover, as pointed out in the test the balanced driving methods are very important, and conversely the use of balanced receiving techniques are equally important. The prevention of EMI might require shielding of the transformer from other circuits within an enclosure, with the leads between the transformer and the transmission line as short as possible. While the selection of a good balanced cable may be important to the transfer of signals, the use of the rather inexpensive and lightweight TSP #22 appears adequate for EMI considerations, providing attention to certain details are maintained. One important detail that is often overlooked in the application of cable shields is that the shield must use connectors that provide a continuous shield. The practice of electrically connecting the shield with a wire through a connector (a common practice) is not recommended.
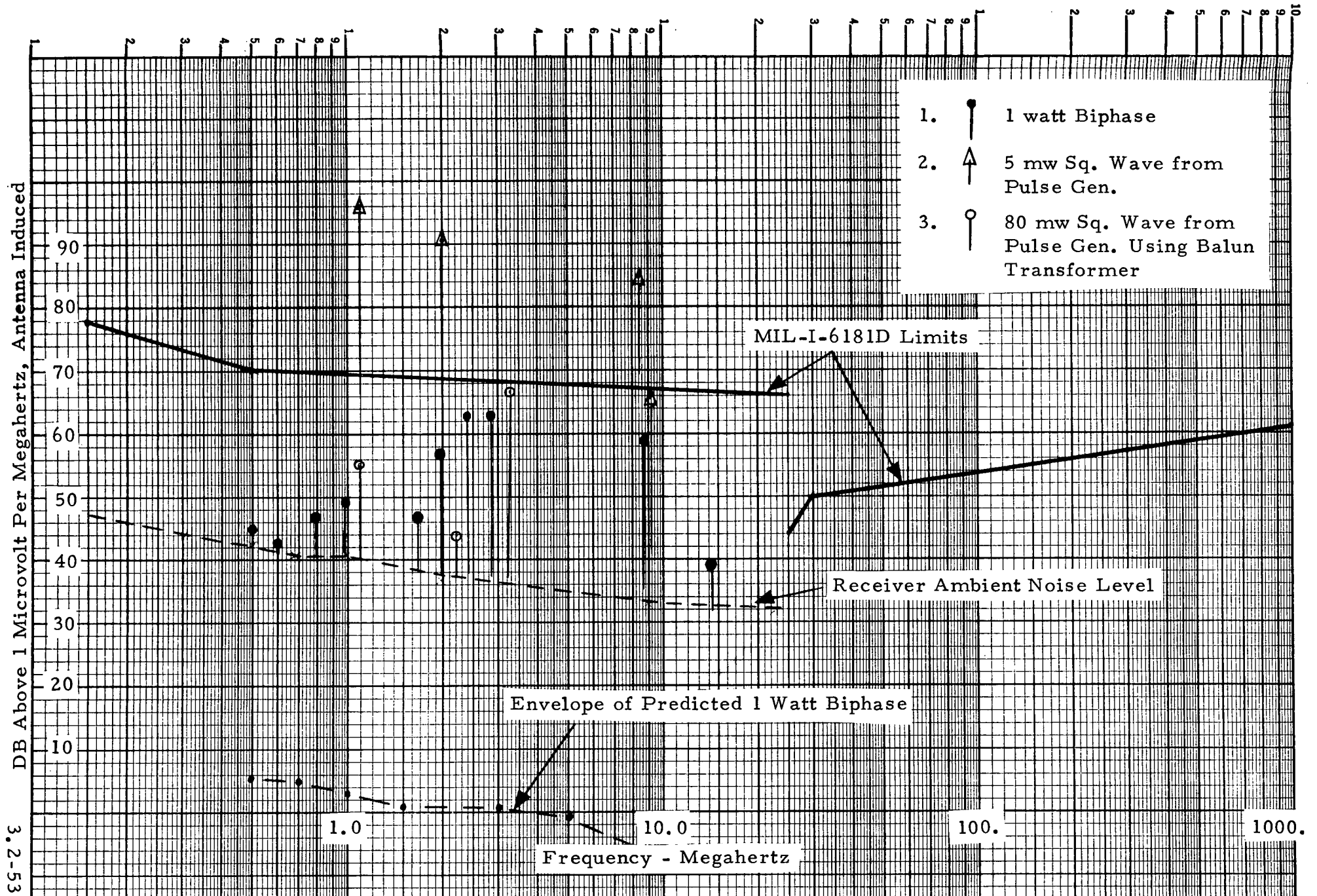
3.2-52

FIGURE 3.2-13   BROADBAND RADIATIAL EMI LEVELS

Conclusions

The results of this test indicate that neither radiated interference not susceptibility present a problem to the operation of a baseband data bus system of the nature envisaged for the SSV assuming reasonable care is taken in packaging design. The major consideration remains the impulsive interference of the type described in previous subsections in which the interfering signals were induced into the transmission line by near field coupling.

In view of the low level of radiated interference resulting from the data bus transmission lines, it did not appear necessary to filter the transmitted data bus signals as a means of reducing the radiated interference (EMI) levels. This conclusion was based on data bus signals with baseband modulation techniques that were under consideration in the study.

3.2.7   Environmental Considerations

The environmental requirements for the data bus transmission medium have not been defined. The requirements will be similar to those imposed upon other space vehicles. For the transmission medium the primary concern is the temperature range over which the cable must operate. Some of the cables that were tested would certainly not meet space environment conditions. But it was assumed that the cable would be manufactured of the proper materials if necessary. The mechanical properties of cables under space environmental conditions were not investigated in this section. It was reasoned that of the many space vehicles successfully operated in the past, the mechanical problems associated with cables must be well known. A more relevant problem to the data bus is the behavior of the signal transfer characteristics under temperature. This facet will be discussed after a brief review of the properties of insulation materials.

3.2.7.1   Properties of Various Insulation Materials

This discussion covers only the most likely material candidates and only the most important properties of the material. These properties are summarized in Table 3.2-3. Of particular interest to aerospace applications are the fluoroplastic resins; TFE and FEP (Teflon*), Kapton* and ETFE (Tefzel*). TFE (tetrafluoroethylene) is a homopolymer—it contains TFE monomer units exclusively in long molecular chains. FEP (fluorinated ethylene propylene) contains fractions of hexafluoropropylene which modifies its physical properties. The upper temperature limit of FEP is lower than TFE, but it is more like a normal thermoplastic and can be handled in practical manufacturing processes. Both materials may be mixed with materials such as fiberglas to increase the temperature limit, but often the temperature rating of the wire itself is the limiting factor. For example, the following ratings are given for various conductor materials:

Material	Temperature, $^{\circ}$C
Copper	200
Tin Coated Copper	135
Silver Plated Copper	200
Nickel Plated Copper	260
Nickel Clad Copper (Ni 27% by weight)	538

Kapton (polymide-fluorocarbon) is a more recent material, and has outstanding mechanical properties, and will bond readily. When required, Kapton may be coated with Teflon to provide higher immunity to chemical reaction.

*Trademark of DuPont—These materials are also available from other manufacturers under different names.

TABLE 3.2-3   COMPARISON OF INSULATION MATERIALS

Thermal	PVC	Nylon	PVC-Mylar	Kynar	Polypropylene	FEP	Kapton	TFE	ETFE
1. Max. Continuous Rating (^{o}C)	105	110	105	135	125	200	200	260	180
2. Low Temp. (^{o}C)	-50	-50	-60	-70	-50	-200	-200	-200	-100
3. Nonflammability	VG	F	VG	E	G	E	E	E	E
4. Solder Resistance	G	G	VG	VG	G	E	E	E	E
5. Smoke	M	H	M	S	M	N	N	N	S
Electrical									
1. Volume Resistivity (ohm-cm)	10^{12}	4×10^{12}	10^{16}	2×10^{14}	10^{15}	2×10^{18}	10^{18}	10^{18}	10^{16}
2. Dielectric Strength (VPM)	350	410	350	450	750	430	420	430	400
3. Dielectric Constant	5.70	4.5	3.5	7.7	2.25	2.0	2.4	2.0	2.6
4. Dissipation Factor @ 1 kHz	.09	.04	.03	.02	.0005	.004	.001	.0002	.0008
5. Dielectric Dispersion	F	G	G	P	G	E	E	E	E
Mechanical									
1. Density (gm/cc)	1.36	1.09	1.48	1.76	.9	2.18	1.68	2.2	1.7
2. Tensile, psi	4000	8000	15,000	6000	7000	2700	17,000	2500	6500
3. Abrasion Resistance	F	VG	G	E	E	G	E	G	E
4. Bondability	G	F	G	G	F	P	E	P	G
Environmental									
1. Nuclear Radiation	F	F	F	E	G	F	E	F	E
2. Chemical									
Water Absorption	.7%	.4%	.6%	.04%	.03%	.01%	.8%	.9%	.1%
Acids	G	P	G	VG	G	E	F	E	E
Alkali	G	G	P	VG	G	E	VG	E	E
Hydrocarbons	P	G	F	VG	G	E	VG	E	E
3. Long Term Stability	F	G	G	VG	G	E	E	E	E

NOTE

P – Poor
F – Fair
G – Good
VG – Very Good
E – Excellent

M – Moderate
S – Slight
H – Heavy
N – None

The fluorocarbons also have the advantage that no toxic outgassing occurs at low pressures.

The cost of various materials is difficult to tabulate because of the large number of factors which influence the cost of production. In general, the fluorocarbons are more expensive than the other materials shown on the chart, primarily because there is much less commercial usage.

There are a large number of existing NASA and military specifications for wire and cable which may be applied to the Space Shuttle data bus transmission lines as the environmental factors become better defined.

3.2.7.2   Signal Transfer Characteristics Under Temperature

If the transmission line equations for γ and Z_o are examined at frequencies where $j\omega L \gg R$, and $j\omega c \gg G$, the equations reduce to the form

$$\alpha = \frac{R}{2} \sqrt{\frac{C}{L}} + \frac{G}{2} \sqrt{\frac{L}{C}}$$

$$\beta = \omega \sqrt{LC}$$

$$Z_o = \sqrt{\frac{L}{C}}$$

Since the ratio of $\frac{C}{L}$ is large, the first term of the equation for α is large, which shows that the loss is proportional to R. Due to skin effect, R is proportional to $\sqrt{f}$, so that an increase in R, due to temperature, shifts the entire curve of α vs. frequency upwards.

Copper is known to have a temperature coefficient η. $\eta = .0039 \frac{ohms}{C^o}$. The resistivity is $R = R_{20} [1 + \eta (T - 20)]$, where $R_{20} = 1.724 \times 10^{-6}$ ohm-cm = resistivity at 20^oC. The change in R over a given temperature span can be calculated.

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From the above it is seen that the change in cable loss through the temperature range of 25°C to 200°C is 68% (in db).

The change in phase shift, β , and Z_O comes about due to a change in C, which in turn is caused by a change in the dielectric constant. According to the manufacturer of Kapton, the dielectric constant, ϵ , changes from 3.5 at 25°C to 3.0 at 200°C. This 14.3% change in ϵ gives a 7% decrease in β at high temperatures and a 7% increase in Z_O for the change of temperature from 25°C to 200°C.

Since all the fluorocarbons are similar in properties, it is expected that TFE or FEP would cause similar changes.

It is concluded that while changes in β and Z_O are negligible with temperature, the increase in α must be accounted for in the design of the data bus. At low frequencies, where the cable characteristics are complex, the behavior is less predictable.

Temperature Test of Cables

Two types of cable were tested: RG-180 coaxial and TSP #22. These two cables represent two different types of cable designs, and are both Teflon insulated.

The test procedure previously used at 25°C was now used at 75°C, and the results were compared. The only differences found were in attenuation, as can be seen in Figures 3.2-14 and 3.2-15.
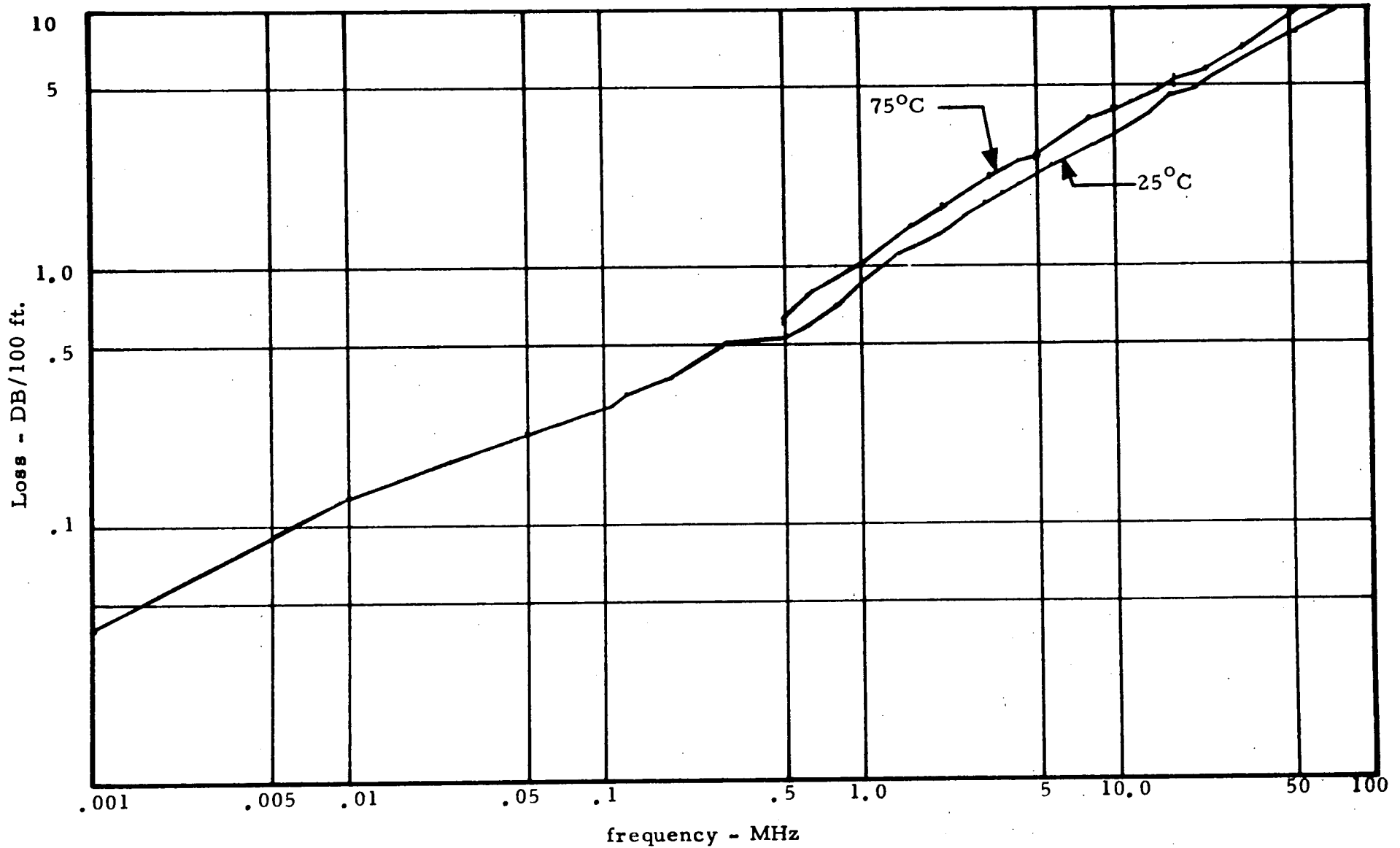
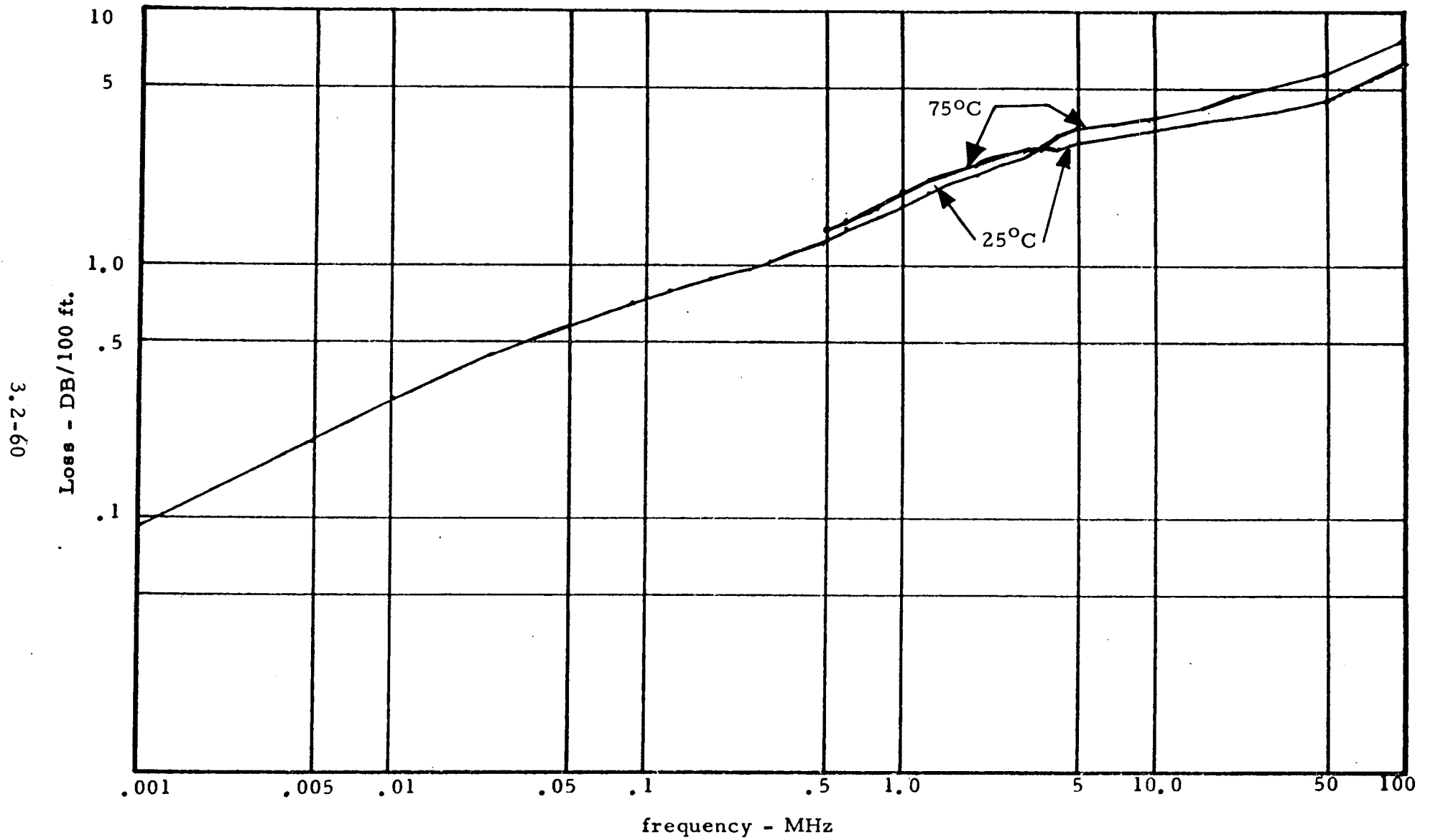FIGURE 3.2-14 LOSS, α, VS. FREQUENCY TSP NO. 22 AWG

FIGURE 3.2-15   LOSS, α, VS. FREQUENCY RG-180 COAXIAL

It was seen that the change in attenuation did not increase quite at the rate predicted. However, there was a degree of error in the test, such that it was recommended that the change in cable loss be calculated based on the change in the resistivity of the conductor.

The conclusions are that the added loss incurred at high temperatures must be accounted for in the data bus design, and that changes in characteristic impedance and phase shift may be ignored when a fluorocarbon insulation (TFE, FEP Teflon or Kapton) is used.

3.2.8   Interrelated Factors

During the course of the study of Transmission Media, an attempt was made to treat the topics in a manner that was independent of the other efforts of the Multiplex Data Bus Techniques Study for the Space Shuttle. There are interrelated factors which must be considered, however. The relationship of the transmission medium to the modulation and detection process is obvious. In the following paragraphs some of the major considerations are noted.

Low Frequency Distortion

In the Phase I Report it was stated that low frequency distortion might be a serious problem in transmission of baseband data because at low frequencies the propagation constant, γ and characteristic impedance, Z_0, are complex functions of frequency. This was also verified in the cable test of Section 3.2.3. This was demonstrated very well when a particular waveform is transmitted over a cable, and "eye" patterns are observed at the receiving end. The use of eye patterns as an evaluation technique, and an example of several different modulation techniques are shown in two Technical Notes. Eye patterns are the wave-

forms which are observed when random data is transmitted over a medium and the oscilloscope is in synchronism with the bit rate clock. Every possible state and transition is seen superimposed, with the result that the clear area, the "eyes", represent the usable signal to the detector.

While observing eye patterns of waveforms that have a large low frequency component, it was noted that a serious distortion results which is proportional to the bit rate transmitted. The distortion is inversely proportional to the frequency of the total word length. Some waveforms have been shown in transmit data at rates several times higher than waveforms with low frequency components, even though the total spectral occupancy of the former waveform is greater than the latter.

Signal Distortion Due to Reflections

In Section 3.2.4, some operational modes were shown which produced mismatches. The effect of reflections resulting from mismatches are not the same on all modulation and detection techniques. It was proposed that at some later date an experiment be conducted to show to what degree candidate modulation and detection techniques can tolerate reflections.

Effect of Filtering at the Receiver

The results of the interference test indicate that a form of low pass filtering is necessary to reduce the effect of impulsive EMI. The ideal form of filtering is developed in the Signal Design and Detection studies. Filtering also has an effect upon the amount of reflection caused distortion that can be tolerated. The effect of cable distortion combined with filtering must be analyzed for a particular type of modulation.

Methods of Driving Cable

Driving with a low impedance transmitter has been shown to perform well experimentally. Transmitters can be constructed fairly easily for use with bilevel modulation waveforms. It was found that waveforms of three levels must also maintain a low impedance in all three signal states. Transmitters for bilevel waveforms resemble inverter circuits in that while one transistor is driven into saturation, the other transistor is turned off. A highly efficient transmitter can be designed using this method. When multiple level signals are generated, it is more difficult to drive in this fashion.

Transmission Line versus System Operation

In choosing the network that is appropriate for a data bus it is apparent that the choice of the basic operating mode is interrelated with other aspects of the system. As the number of terminals and the length of the transmission line increases, it would seem that the operating method chosen should be one in which less transmission line losses are involved. Eventually the designer must consider the probability that the line will become faulted, so that perhaps redundant transmission lines become necessary. The designer's task now is to determine whether it is more cost-effective to transmit more power with lossy networks or to include more complexity in remote terminals for selecting and/or voting lines.

The use of stubs and branches will further complicate the problem of network selection, as will the method of modulation and signal detection.

3.3   SIGNAL DESIGN AND DETECTION STUDIES

3.3.1   <u>Introduction and Summary</u>

This section presents a summary description of the Signal Design and Detection Study performed during the Multiplex Data Bus Techniques Study for the Space Shuttle. The Signal Design and Detection Study was concerned primarily with the analysis and practical application of the seven signaling methods selected during Phase I as candidates for use in the SSV data bus. These seven signaling methods are referred to as the recommended signal set. Each member of this set was described in detail in the Phase II Report, Volume II (including a plot of the power spectrum of each), and recommended methods using conventional logic to generate each signal were presented. Next, the significant elements of the data bus affecting signal transmission were identified as (1) filters, (2) the transmission medium, and (3) coupling transformers, and the effects of each were described. Optimum and suboptimum techniques for detecting the selected signals were then described and analyzed. The description of signal detection included a treatment of transmitting and receiving filters since the effects of filtering cannot be divorced from the detection process. Also included under signal detection were definitions of mathematical models of the noise expected on the data bus, because this information was needed in order to make meaningful estimates of a detector's bit error ratio. The analysis of signal detection techniques was followed by a comparison of signaling methods based on evaluation criteria which included predicted performance in the presence of noise as well as suitability to specific applications.

Items of secondary importance were (1) redundant coding, (2) message formatting, and (3) interactive aspects. Studies of redundant coding were limited to determination of throughput and probability of undetected error for simple parity, conventional block parity, and repetition coding.

3.3.2   Investigations

3.3.2.1   Signal Descriptions and Spectra

The recommended signal set consists of the following baseband signaling schemes:

- Unipolar NRZ-Level
- Polar NRZ-Level
- Polar RZ
- Biphase-Level

- Bipolar NRZ
- Delay Modulation
- Duobinary

Figure 3.3-1 illustrates the fundamental approach used to generate each signal, depicts the resulting waveform produced by the data message 1110010, and illustrates the power spectrum of each signaling scheme when transmitting stationary uniformly distributed random data. Also included with each sketch of the power spectrum is its equation, as well as an indication of the minimum transmission bandwidth required. Minimum transmission bandwidth is expressed in terms of the signaling rate, fs, in bits per second, and was defined as the highest frequency which must be passed by a channel in order to assure that the message can theoretically be removed at the receiver.

3.3.2.2   Signal Generation

All members of the recommended signal set can be easily and precisely generated under the following conditions:

- Use standard digital techniques and proven standard computer logic design practices.

- Employ standard gated clock pulse logic —commercially available integrated circuits.

Figures 3.3-2 through 3.3-6 illustrate logic circuits, accompanied by waveform diagrams, for the process of generating each of the following baseband modulation forms:

- Delay Modulation (Miller Code)
- Duobinary
- Bipolar NRZ

- Polar RZ
- Biphase-Level

3.3-2

Signaling Methods	Method of Generation	Time Waveform	Power Spectrum

Data

| 1 | 1 | 1 | 0 | 0 | 1 | 0 |

Unipolar NRZ-Level — A + level represents a "1", Zero level represents "0".

Polar NRZ-Level — Same as Unipolar NRZ-Level except waveform is symmetrical about zero.

$S(f)$

Note: Unipolar NRZ has a line at 0 Hz Polar NRZ does not.

$$S(\omega) = 2\left(\frac{\sin \omega T/2}{\omega}\right)^2$$

$$B = f_s/2$$

Frequency in Hz: $\frac{1}{T}$, $\frac{2}{T}$, $\frac{3}{T}$, $\frac{4}{T}$

Polar RZ — A "1" represented by +V Pulse and "0" by -V pulse. Pulses are 1/2 bit wide.

$S(f)$

$$S(\omega) = 8\left(\frac{\sin \omega T/4}{\omega}\right)^2$$

$$B = f_s$$

Frequency In Hz: 1/T, 2/T, 3/T, 4/T

Bipolar NRZ — "1's" are alternately +V or -V pulse 1 bit wide zero level represents "0".

$S(f)$

$$S(\omega) = 8\left(\frac{\sin \omega T/4 \, \sin \omega T/2}{\omega}\right)^2$$

$$B = f_s/2$$
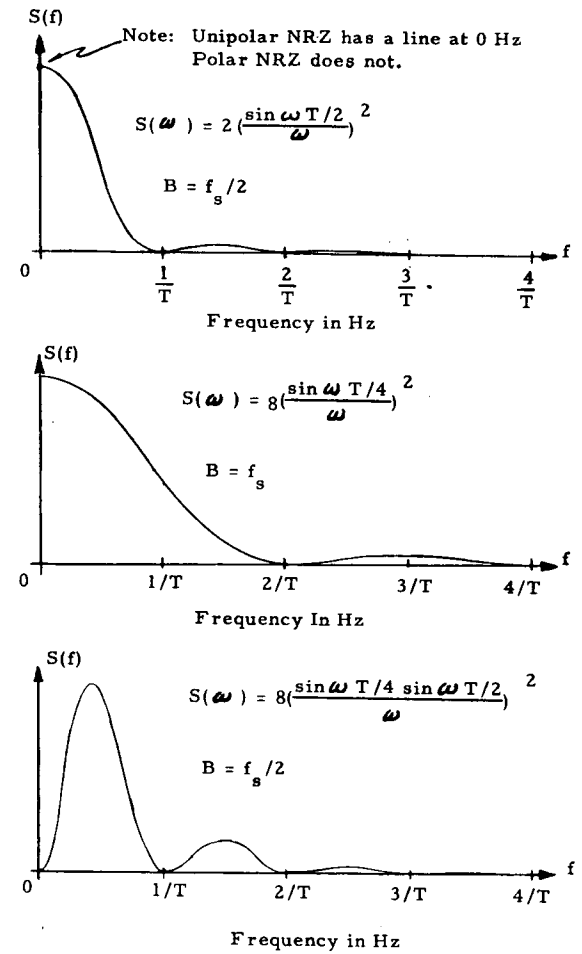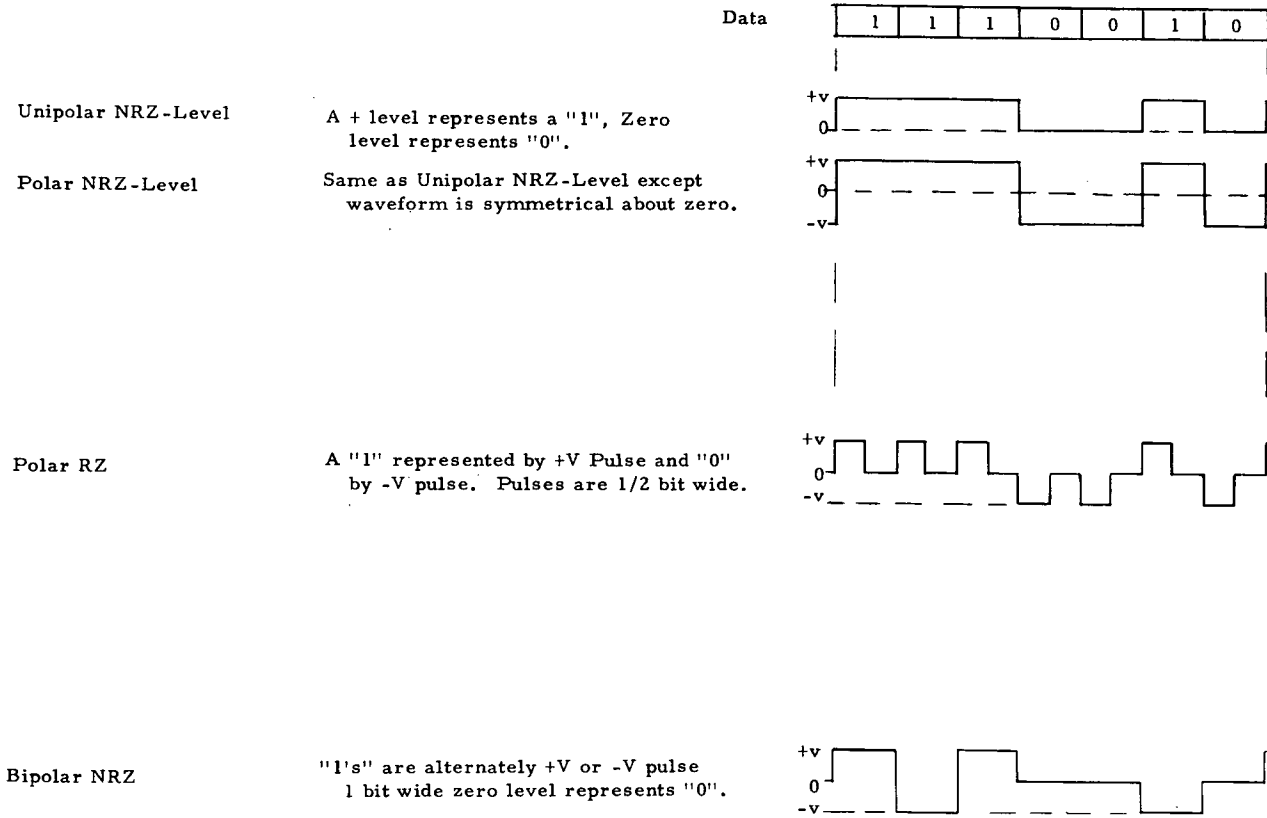
Frequency in Hz: 1/T, 2/T, 3/T, 4/T

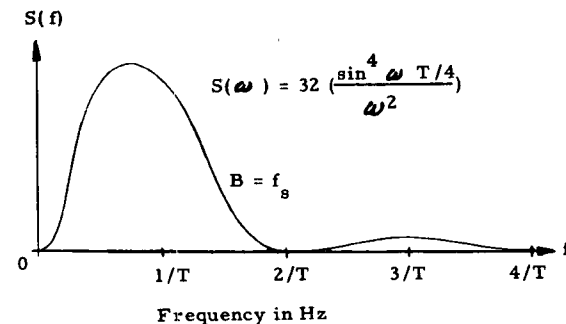FIGURE 3.3-1   DESCRIPTION OF RECOMMENDED SIGNAL SET

Signaling Method	Method of Generation	Time Waveform	Power Spectrum

Biphase-Level

"1" represented by ⊓⌐, "0" by its inverse.

Time waveform bits: | 1 | 1 | 1 | 0 | 0 | 1 | 0 |

$+v$
0
$-v$

$S(f)$

$S(\omega) = 32 \left(\dfrac{\sin^4 \omega T/4}{\omega^2}\right)$

$B = f_s$

0 — 1/T — 2/T — 3/T — 4/T — f

Frequency in Hz

Duobinary

"1" is zero level. "0" is either +V or -V, the polarity being reversed each time a "0" is preceded by an odd number of consecutive "1's".

$+v$
0
$-v$

$S(f)$

$S(\omega) = \left(\dfrac{\sin \omega T}{2\omega}\right)^2$

$B = f_s/4$

0 — 1/T — 2/T — 3/T — 4/T — f

Frequency in Hz
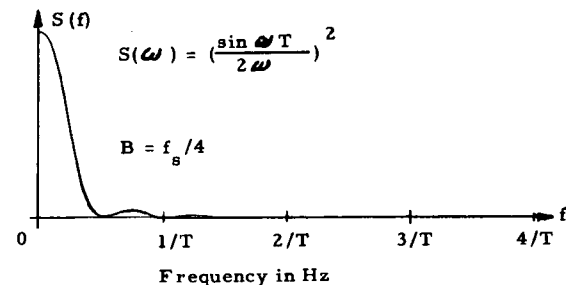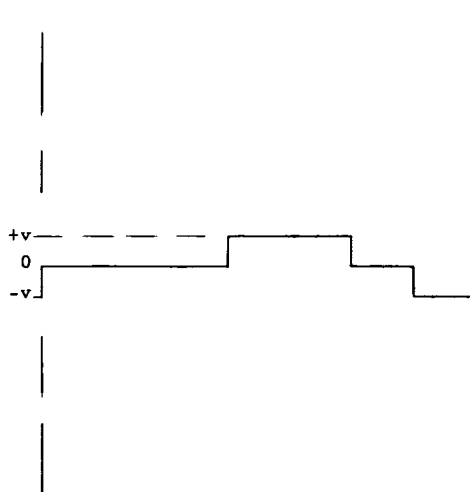
Delay Modulation (Miller Code)

"1" causes transition in middle of bit interval. "0" has no transition except at end of bit interval between adjacent "0's".

$+v$
0
$-v$

$S(f)$

$S(\omega) = \dfrac{2}{\omega^2 T(17+8\cos 4\omega T)}[23 - 2\cos\left(\dfrac{\omega T}{2}\right)$
$-22\cos \omega T - 12\cos^3 \omega T + 5\cos 2\omega T + 12\cos\dfrac{5}{2}\omega$
$+2\cos 3\omega T - 8\cos\dfrac{7}{2}\omega T + 2\cos 4\omega T]$

$B = f_s/2$

1/T — 2/T — 3/T — 4/T — f
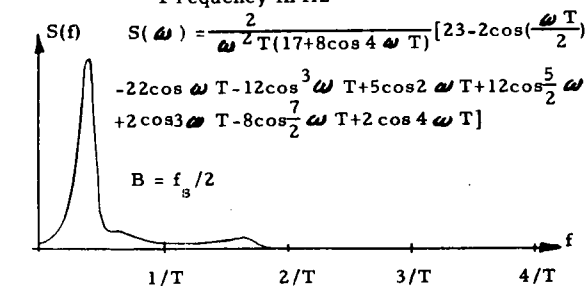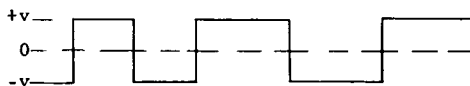
FIGURE 3.3-1   DESCRIPTION OF RECOMMENDED SIGNAL SET (CONTINUED)
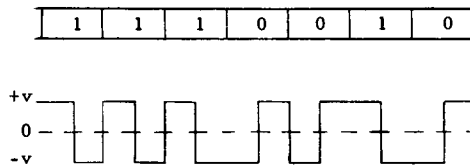
| 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |

Clock

x2 Clock

NRZ Data In

NRZ Data Delayed

A · $\overline{C}$

$\overline{A}$ · $\overline{B}$ · C

Miller Code Output
(Delayed by 1/2 Bit)
(Unipolar-Conver-
sion to Polar Form
Requires Only a Shift in
DC Level)

3.3-5

x2 Clock Source

÷ 2

Clock to NRZ Data Source

1 Bit Delay

NRZ Data In

$\overline{x2 \text{ Clock}}$

Flip Flop

Miller Code Output
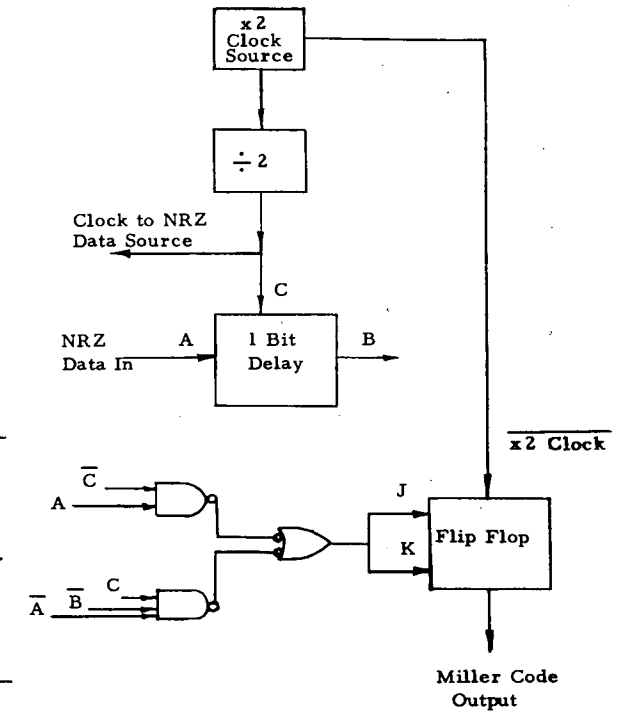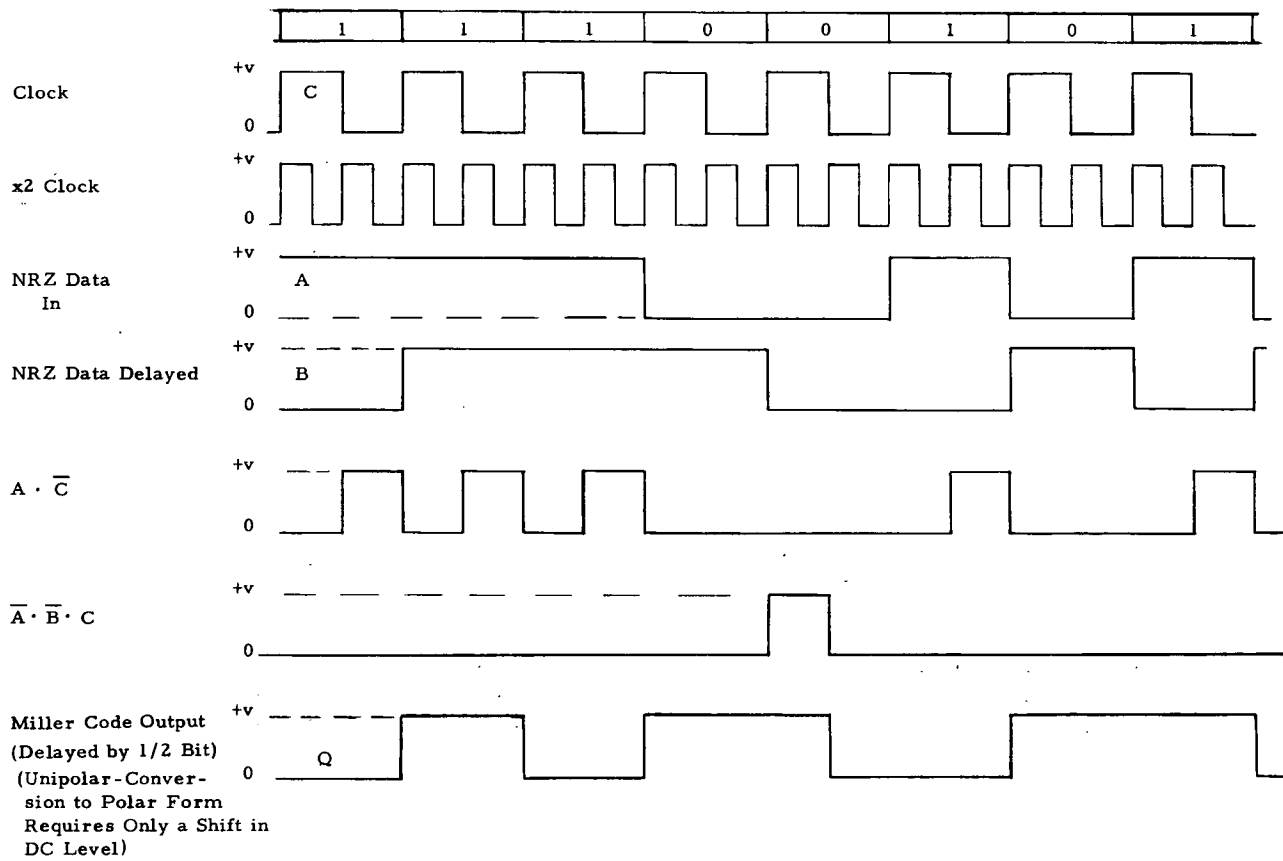
FIGURE 3.3-2   MILLER CODE MODULATION
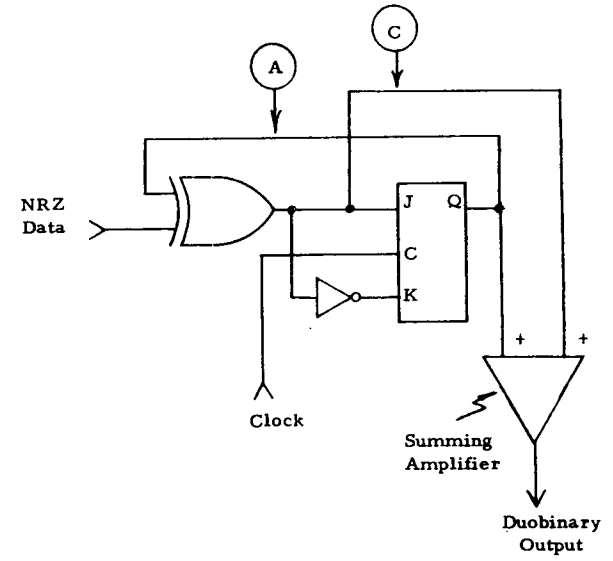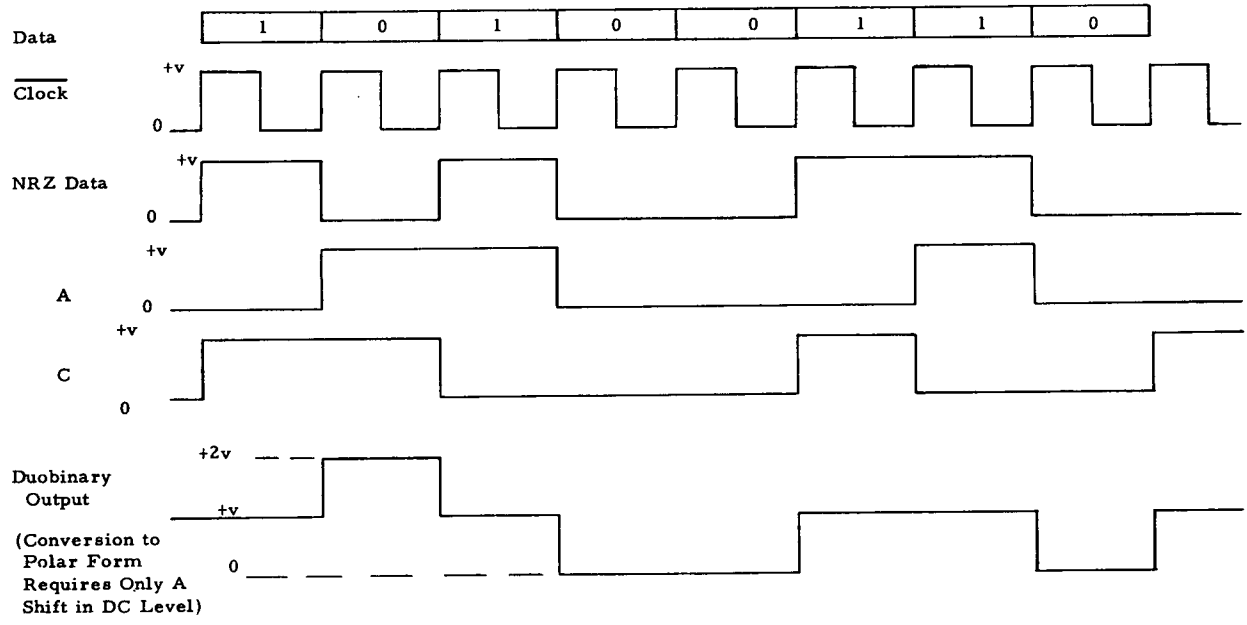
FIGURE 3.3-3   DUOBINARY MODULATION

3.3-6

Data	1	1	0	1	0	0	1	1

NRZ Data

Clock

Flip Flop Q

+ Input to Amp

- Input to Amp

Bipolar NRZ Output

NRZ Data Input

Difference Amplifier

Clock

J
C
K

Flip Flop

Q

Q̄

+

−

Bipolar NRZ Output
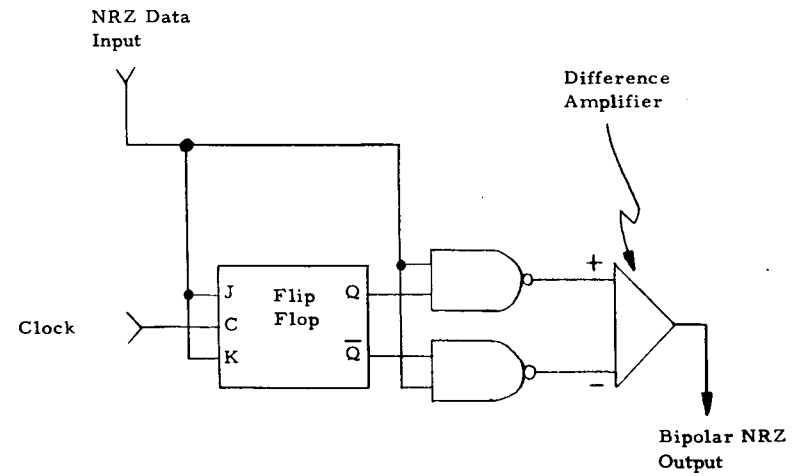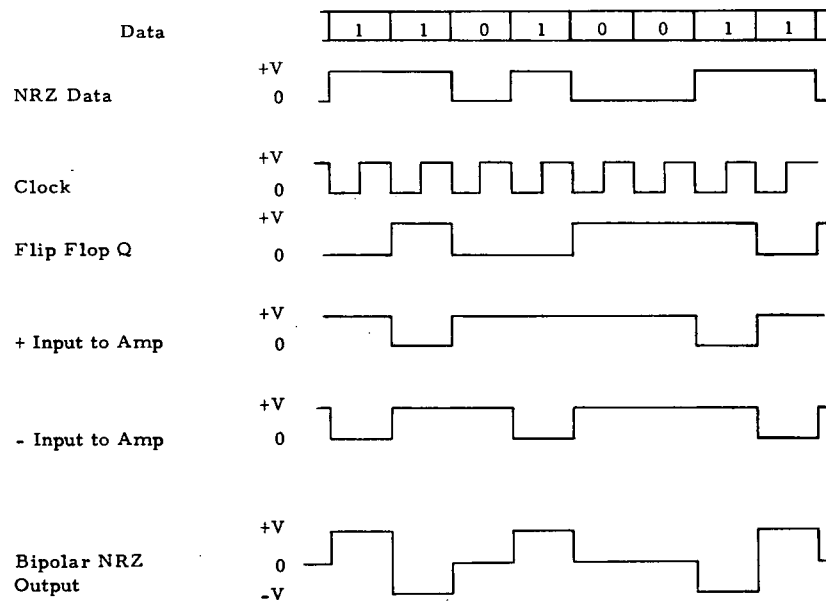
FIGURE 3.3-4   BIPOLAR NRZ MODULATION
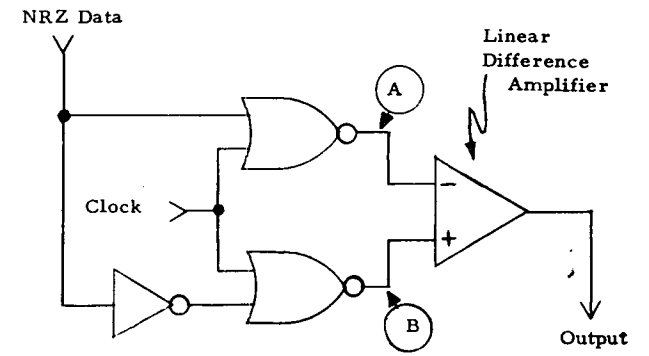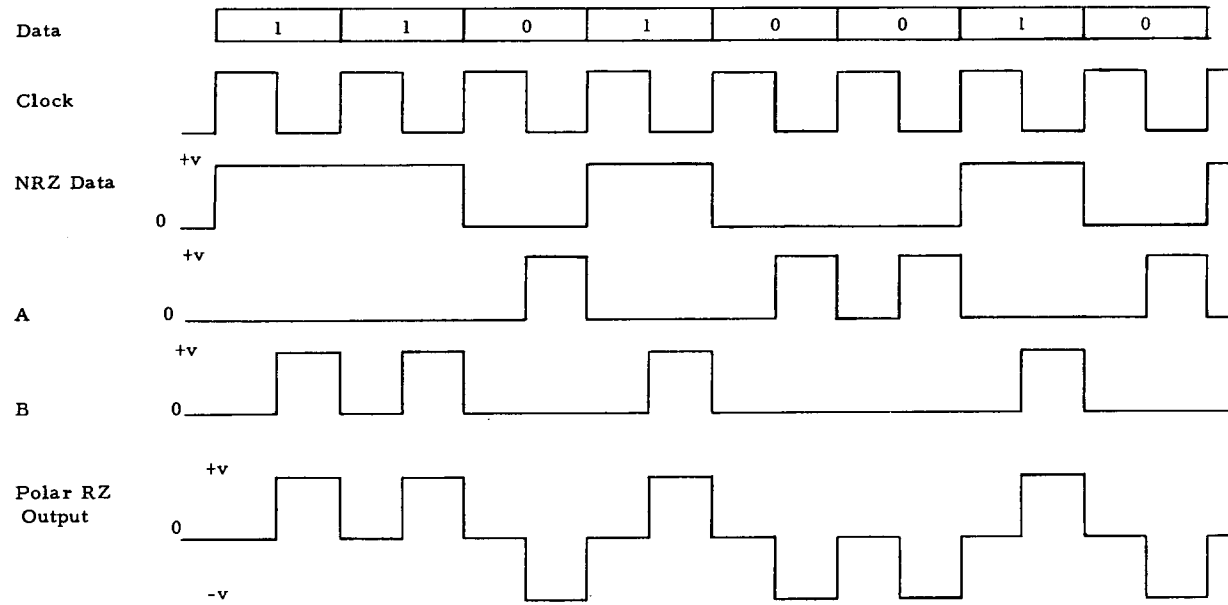
FIGURE 3.3-5   POLAR RZ MODULATION
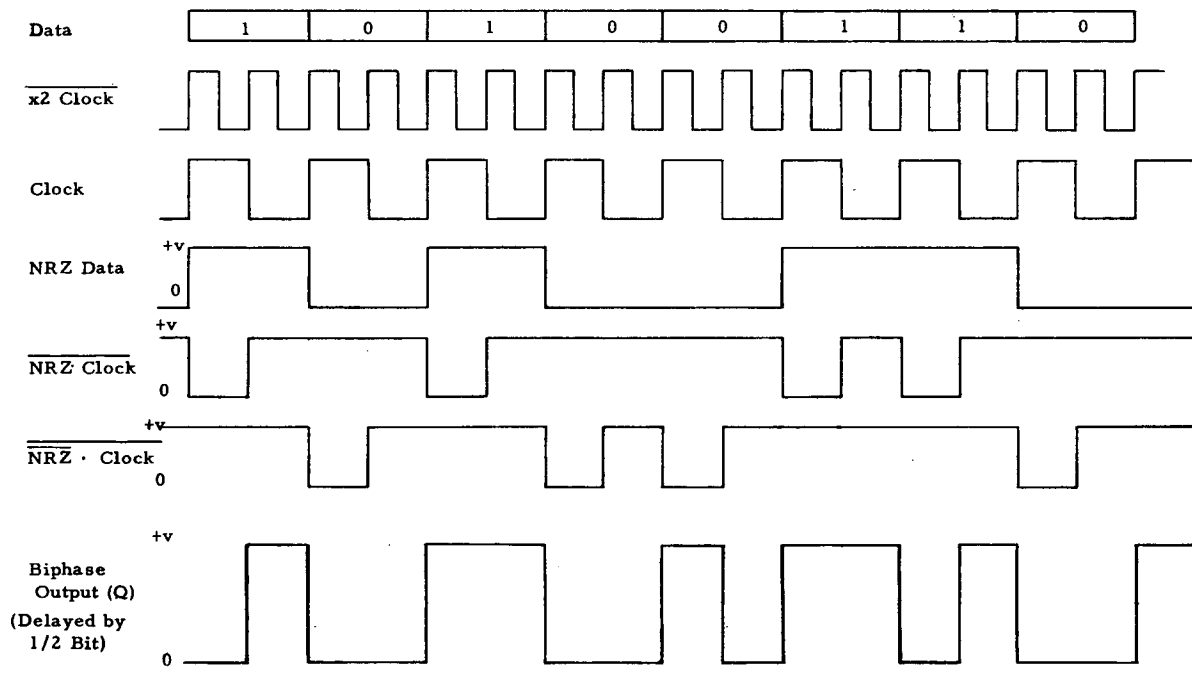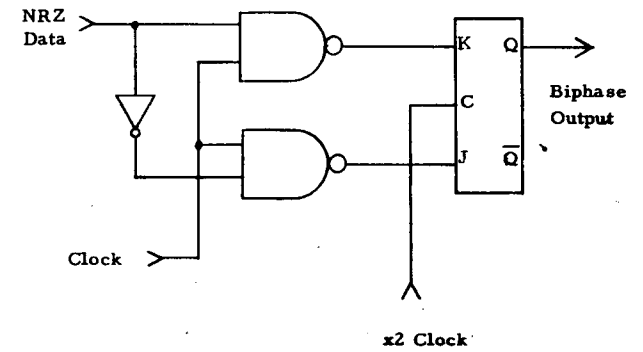
FIGURE 3.3-6 BIPHASE-LEVEL MODULATION

3.3-9

All the logic circuits described in the figures accept Unipolar NRZ-Level as their input. Circuits for generating Unipolar NRZ-Level and Polar NRZ-Level have not been included, as these are generally the forms in which the raw data originally exists.

3.3.2.3 Data Bus Element Effects

The most important element effects imposed on the transmission of the selected signal designs are those caused by:

- Linear Filters
- The Linear Transmission Medium
- Coupling Transformers

Linear filters may be employed to suppress unwanted Electromagnetic Interference at the transmitter and to enhance the predetection signal-to-noise ratio at the receiver. The transmission medium may in all cases be treated as a linear network, since the anticipated losses do not justify the use of repeaters. Transformer coupling was recommended for the following reasons:

- Maintain isolation.
- Help achieve high common mode rejection.
- Not extremely lossy.
- Relatively inexpensive.
- Ease of interfacing to various impedances.

Its importance warranted it receiving considerable attention.

3.3.2.3.1 Filtering

Filters may be cascaded with the transmission medium for two purposes: (1) to prevent radiated electromagnetic interference, and (2) to reduce noise at the receiver input.

Filters in general introduce a bandwidth restriction, which affects the nature of the received signal. Bennett and Davey (reference 1, chapter 5, pp. 49-82) discuss the effects of restricted bandwidth, and show the specific conditions that must be met in order to reliably transmit data through filters without introducing excessive intersymbol interference.

3.3.2.3.2 Transmission Medium

The two significant types of transmission impairments which arise directly as a result of the transmission medium are amplitude-frequency distortion and phase-frequency distortion. Nonlinear distortion does not occur in the SSV data bus transmission media since the cables themselves are linear, and repeaters are not required.[*] Noise and interference are not directly a result of the medium, and so their effects are treated elsewhere.[**]

It was much easier to measure amplitude and phase responses of the cables directly than to make analytical determinations. Direct observation of "eye" patterns provided a useful means for evaluating the overall effects of a given cable on each specific signal design. "Eye" patterns are displays of received waveforms produced by random data when presented on an oscilloscope that is synchronized with the bit timing clock of the transmitted data. By this means, all possible level transitions are superimposed in a manner which is clearly observable. Cable distortion decreases the eye opening near the decision level (a closing of the eye). A decrease in the open area of the eyes results in less margin against noise and intersymbol interference. It is the total area of the eye openings which is of interest;

[*] Repeaters are not required because the cable losses are not appreciable for cable lengths in the range of 0 - 1000 feet.

[**] Reference Noise Model Definition.

thus, a three-level waveform could be compared with a bilevel waveform, even though the times between transitions and the number of amplitude levels differed.

To ascertain the effects of selected transmission media on each member of the recommended signal set, eye patterns were observed for a data rate of 1 Mbps, and a cable length of 500 feet. The transmission media used were (1) twisted-shielded pair (TSP) of #22 wire size, insulated with Kapton, and (2) a twin-axial cable type Trompeter TWC-78-2. The cables were terminated at each end by their characteristic impedance. Representative waveforms for each member of the recommended signal set were generated by appropriate logic circuitry. Figure 3.3-7 illustrates the test set-up and Figure 3.3-8 illustrates a photograph of the resulting eye patterns. From these photos it was concluded that intersymbol interference is not serious enough to prevent reliable detection of any of the signal designs by conventional means, and that the twin-axial cable introduces less inter-symbol interference than the TSP-22 cable in all cases except Biphase-Level and Bipolar NRZ, which have about the same intersymbol interference regardless of which cable type is used.

3.3.2.3.3 Transformer Coupling

An analysis of the effects of passing various baseband modulation waveforms through a transformer was performed in order to establish which signals are most compatible with this method of coupling. This analysis led to the following conclusions.

Bipolar NRZ and Biphase-Level were found to be best suited to transformer coupling shcemes. All other modulation techniques introduce "baseline wander", although in the case of Delay Modulation, baseline wander may be removed and does not pose as severe a problem. Therefore, only Bipolar

Pseudo-Random Sequence Generator (Period = 1023 bits) → Signal Generation Circuitry → Line Amp. Bal. Output — $Z_0/2$ / $Z_0/2$ — 500 feet of TSP Cable — Z_0 — Differential Input Oscilloscope
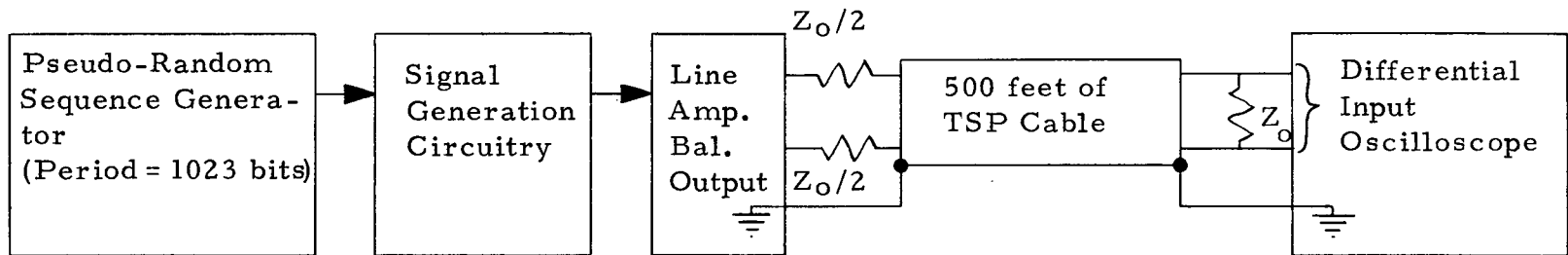
FIGURE 3.3-7 TEST SET-UP FOR OBSERVATION OF EYE PATTERNS

FIGURE 3.3-8a

BIPHASE — 1 Mbps

TWINAXIAL CABLE
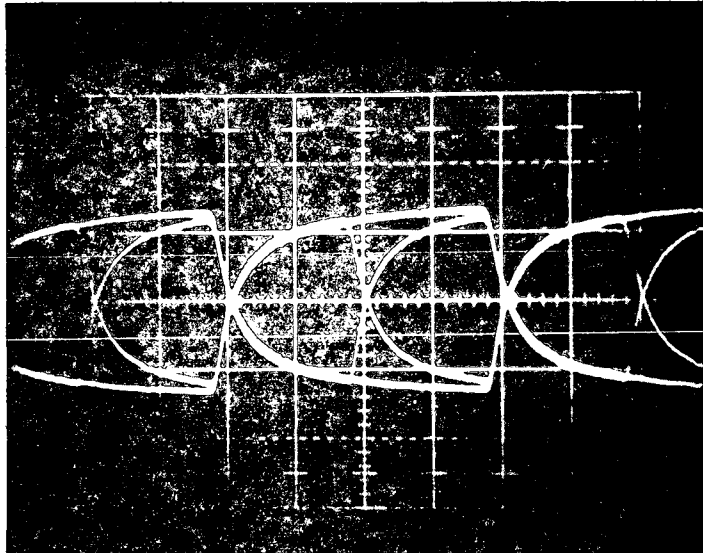
Horizontal Scale - 0.25 μsec/Div.

FIGURE 3.3-8b

BIPHASE — 1 Mbps

KAPTON TSP-22
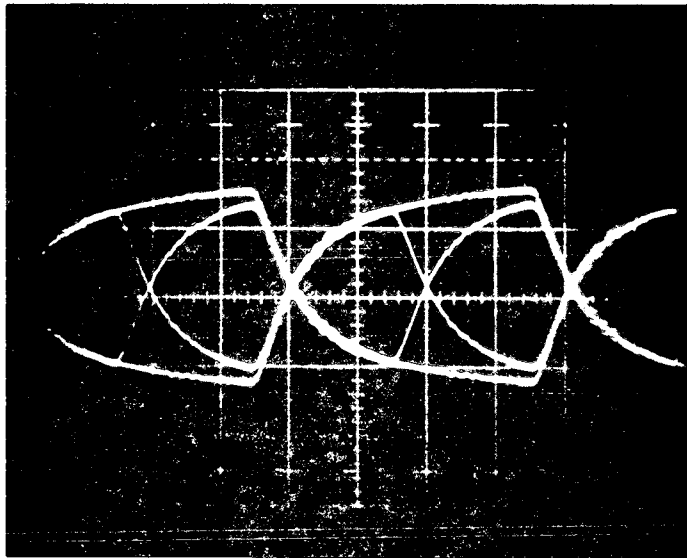
Horizontal Scale - 0.25 μsec/Div.

NRZ, Biphase-Level and Delay were found to be compatible with transformer coupling.

Baseline Wander
==============

Baseline Wander (reference 1, pp. 59-60) arises because all practical transformers fail to pass DC. Its effect on each member of the recommended signal set is illustrated in Figure 3.3-9, and a representative photo, Figure 3.3-10, shows NRZ DC coupled and AC coupled. From Figure 3.3-9 it is clear that the following modulation schemes exhibit a wandering zero base:

- Unipolar NRZ
- Polar NRZ
- Polar RZ
- Delay Modulation
- Duobinary

The consequences of this phenomenon are that it complicates the receiver design, and may altogether prevent reliable reception. Normally, level changes are sensed at the receiver by "slicing", but baseline wander prevents the direct use of this technique in all the above cases except delay modulation. While it might at first appear that a differentiation ahead of the slicer could provide a suitable means for detecting level transitions, this is the case only if the rise time is short compared to the duration of a bit interval. In a practical situation, level transitions at the detector do not generally occur abruptly, but are much more likely to exhibit rise times that are a significant fraction of a bit interval. This lengthening of the rise time comes about due to the practical bandwidth limitations of the transmission medium as well as any filters which are in cascade with the channel. Baseline wander therefore prevents reception by normal means

Data	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0

Unipolar NRZ

Transformer Output

Polar NRZ

Transformer Output

Polar RZ

Transformer Output

Bipolar NRZ

Transformer Output
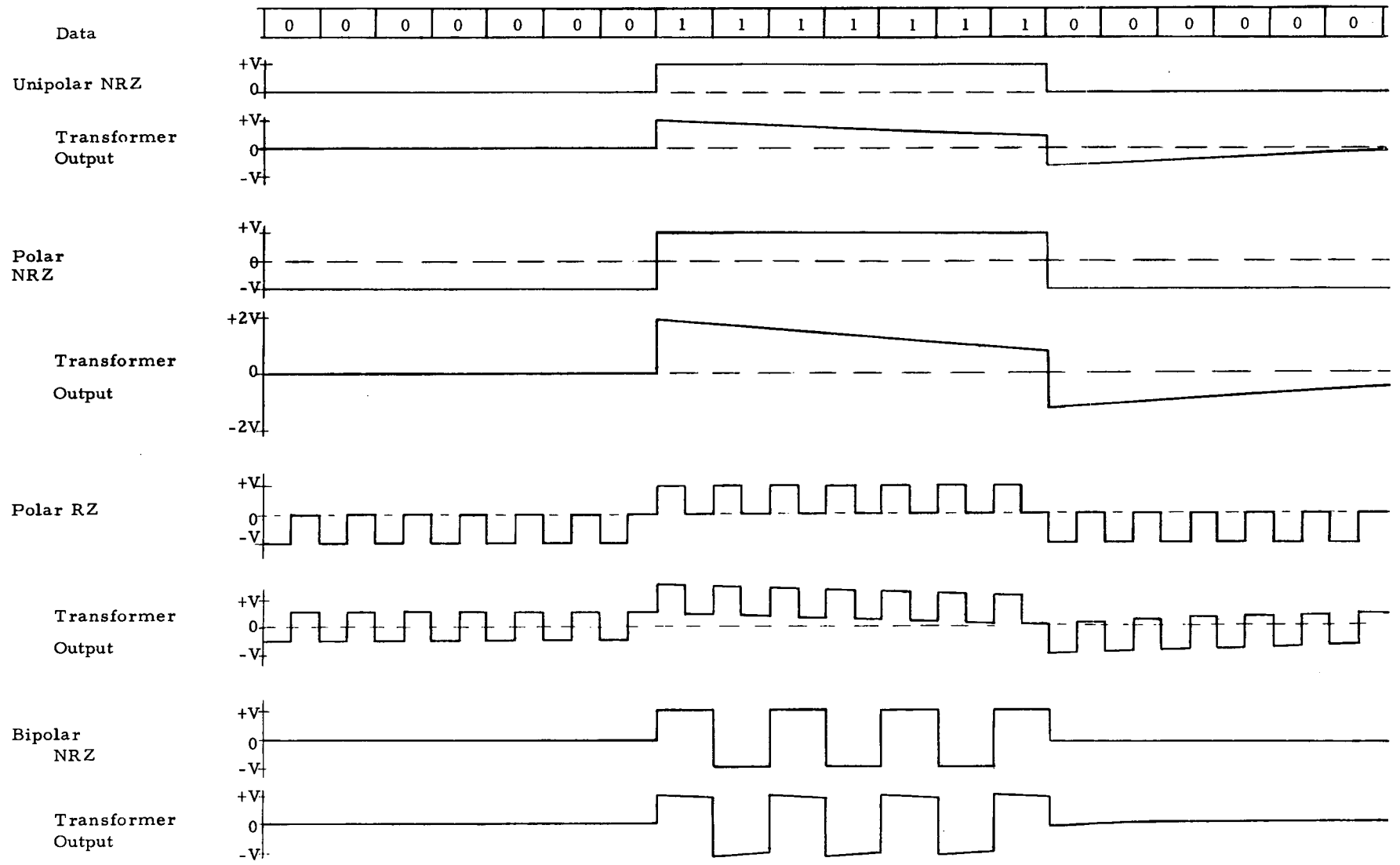
FIGURE 3.3-9a   EFFECTS OF TRANSFORMER COUPLING (I)

Data

| 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |

Biphase Level

+V
0
-V

Transformer
Output

+V
0
-V

Delay Modulation
(Miller Code)

+V
0
-V

Transformer
Output

+2V/3
0
-4V/3

Data

| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Duobinary

+2V
+V
0

Transformer
Output

+2V
+V
0
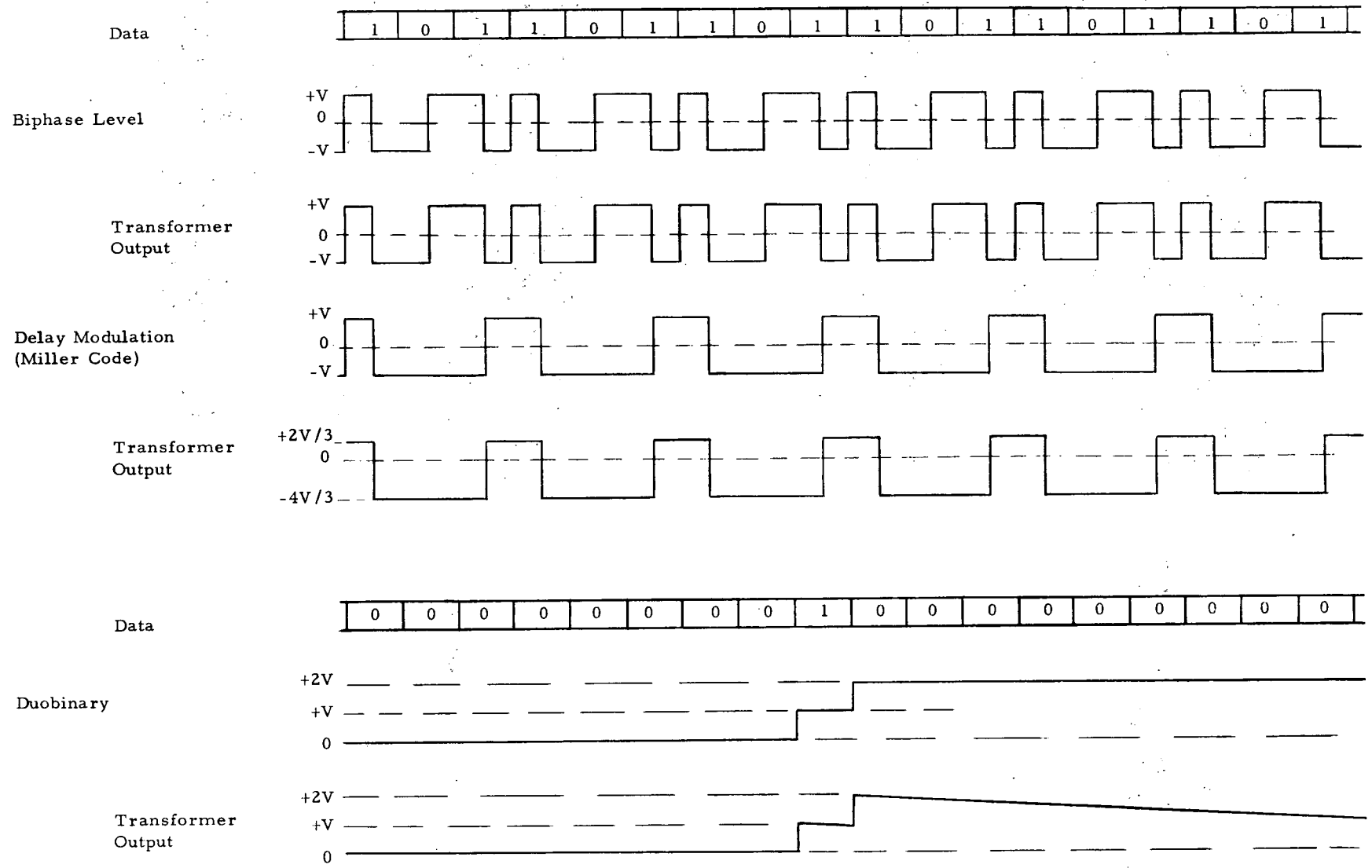
FIGURE 3.3-9b   EFFECTS OF TRANSFORMER COUPLING (II)

Figure 3.3-10a

NRZ, 1 Mbps, Direct Coupled
through 500 ft. of Twinaxial Cable
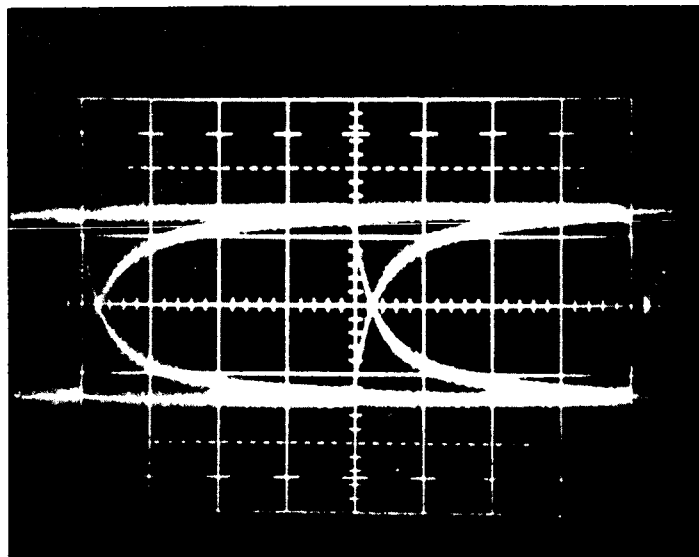
Horizontal Scale - 0.25 us/Div.

Figure 3.3-10b

NRZ, 1 Mbps, AC Coupled
through 500 ft. of Twinaxial Cable
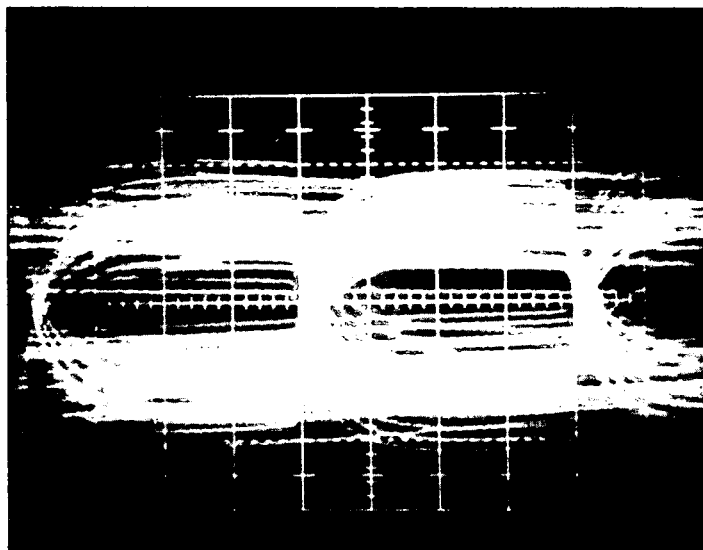
Horizontal Scale - 0.25 usec/Div.

of Unipolar NRZ, Polar NRZ, Polar RZ, and Duobinary; and complicates the design of detectors for Delay Modulation, when transformer coupling of signals is used.

Removal of Baseline Wander by Means of Quantized Feedback

Baseline wander may be overcome in some cases by equalization using "quantized feedback" in each receiver (reference 1, pp. 274). However, a detailed examination of the technique revealed that it is only effective with signals having a known constant amplitude, which is not the case for SSV. In some cases a given receiver may be required to receive signals having different amplitudes from several different transmitters located at different physical locations. For this reason, it may not be possible to achieve correct equalization by a single adjustment at the receiver. In any case, such an adjustment is likely to be tedious and undesirable. Normalization of the input signal to a fixed amplitude by means of hard limiting is not effective because the baseline of the signal input to the limiter wanders as a result of its having been passed through a transformer.

Removal of Baseline Wander from Delay Modulation

Baseline wander may be removed from Delay Modulation by means of another technique, because a level change always occurs at least once every two bit intervals. The original zero baseline can be recovered completely by means of an AGC amplifier followed by a DC restorer (clamp circuit) as illustrated in Figure 3.3-11. The primary disadvantage of this technique is that its AGC circuit may not be able to respond sufficiently fast. This becomes a problem if the amplitude of the received signal is subject to sizable and rapid changes, as might be the case if the receiver must accept messages from several different transmitters located along the data bus at widely different distances from the receiver. However, this
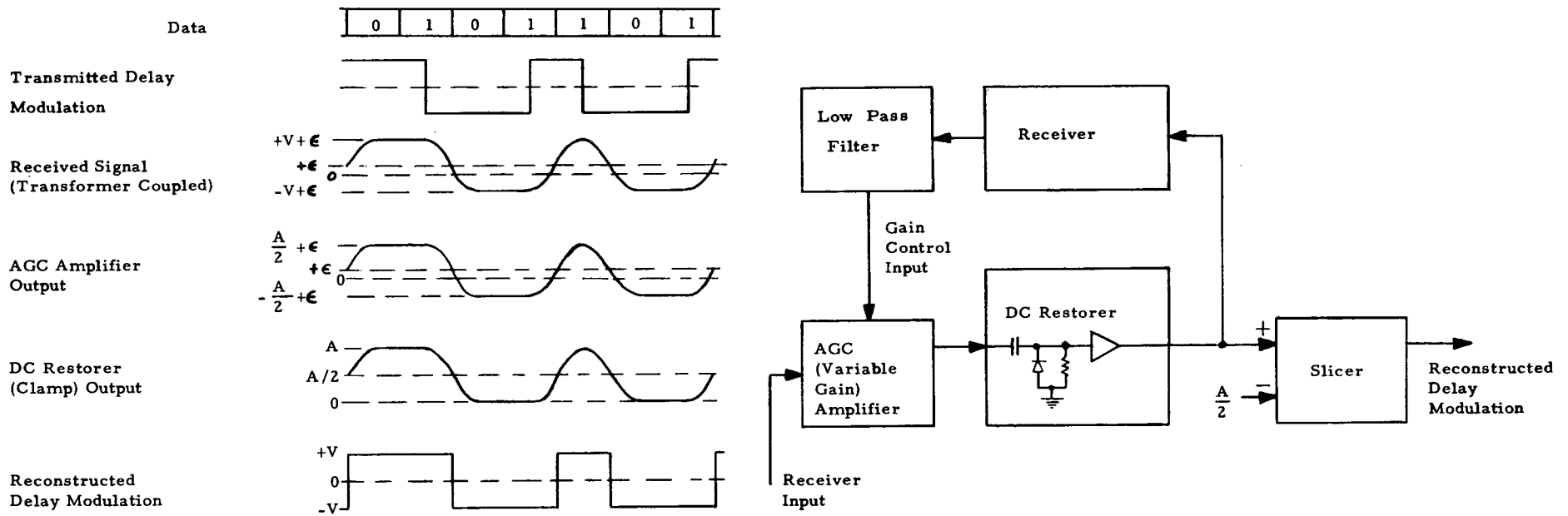
FIGURE 3.3-11   REMOVAL OF BASELINE WANDER FROM DELAY MODULATION

problem only arises in systems wherein the receiver must accept information from numerous different transmitters. The technique may therefore be useful in a centralized system in which all messages on the bus are originated by a single transmitter.

3.3.2.4   Signal Detection

Signal detection is concerned with specific detection, filtering and synchronization techniques, and was broken down into four topics.

- Detection Techniques
- Transmitting and Receiving Filters
- Noise Model Definition
- Synchronization Techniques

It is believed that the fundamental detection methods covered were reasonably and sufficiently simple and effective in the performance of their intended functions. An analysis of transmitting and receiving filters has led to the conclusion that the only filtering necessary for enhancement of the predetection signal to noise ratio should be between the receiver and the data bus. Mathematical models for the noise on the SSV data bus and specific synchronization techniques were presented including general problems and solutions encountered in providing bit and word synchronization.

3.3.2.4.1   Detection Techniques

Detection techniques were described for each member of the recommended signal set with the exception of Duobinary which was ruled out.

Synchronous detection requires the synchronization of a receiver's local clock with the incoming information. For this reason synchronization circuits employing phase locked loops were described for those signal

forms which contain adequate synchronization information, e.g. Polar RZ, Biphase-Level and Delay Modulation. In all these cases a phase locked loop was shown as the recommended method of smoothing axis crossing data to generate a steady clock signal. Bandpass filters could just as well have been used to perform this function, but phase locked loops were used in the circuits shown because they may be caused to smooth the synchronization information over a much longer period of time and thus provide a more stable bit timing reference.

Unipolar and Polar NRZ

Polar and Unipolar NRZ are similar, except that Unipolar NRZ contains a constant DC component that is not present in Polar NRZ. Neither Polar NRZ nor Unipolar NRZ contains adequate bit synchronization information and therefore must be detected synchronously by a separately derived clock. Another disadvantage is that neither is amenable to transformer coupling. For these reasons, Unipolar and Polar NRZ are appropriate for use only in direct coupled bus applications wherein bit synchronization is conveyed by some other means such as via a separate channel.

Detection Technique

Figure 3.3-12 is a waveform and logic diagram that shows the conventional method of detecting Polar and Unipolar NRZ.

Performance in AWG Noise

The minimum achievable bit error ratio when using Polar NRZ or Unipolar NRZ in the presence of Additive White Gaussian (AWG) noise has been shown to be (references 1, 2, chapter 4, pp. 54-56).

Data

Transmitted
Polar NRZ

Transmitted
Unipolar NRZ

Filtered
Polar NRZ

Filtered
Unipolar NRZ

Slicer
Output

Clock

NRZ
Output   -Q

Filter Polar NRZ or
Unipolar NRZ input

Slicer — Threshold
        Voltage

= 0 for Polar

= A/2 for Unipolar

D
Flip-Flop — Clock
            Input

NRZ Data
Output
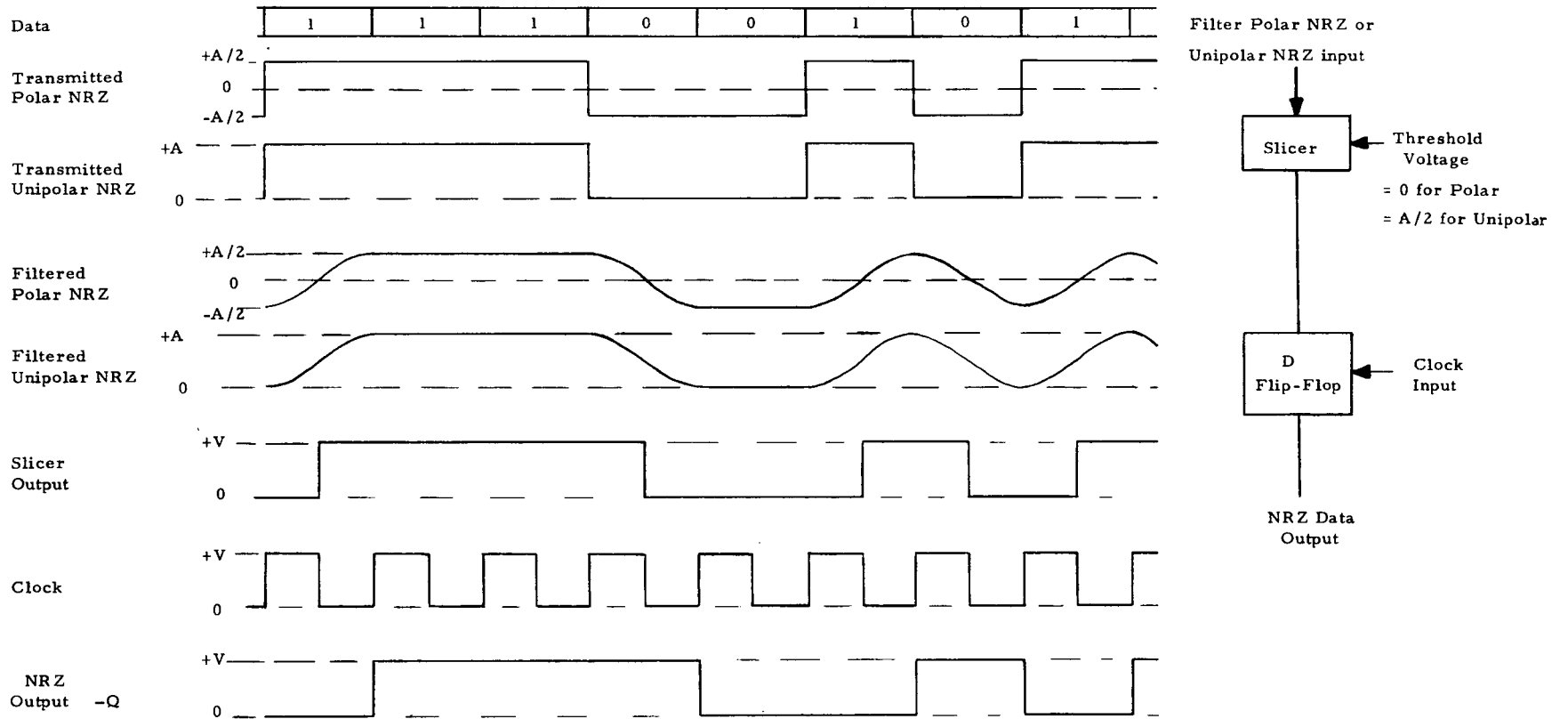
FIGURE 3.3-12   WAVEFORM AND CIRCUIT DIAGRAM OF RECEIVER FOR
                POLAR NRZ OR UNIPOLAR NRZ

Polar NRZ: $\qquad$ $P = 0.5 \text{ cerf } \dfrac{S}{N}$

Unipolar NRZ: $\qquad$ $P = 0.5 \text{ cerf } \dfrac{S}{2N}$

where "cerf" is the co-error function, S is the average signal power (assuming that ONES and ZEROS occur with equal probability), and N is the noise power measured in a bandwidth equal to the bit rate.

Polar RZ

Polar RZ is most appropriate for use on short direct-coupled local buses wherein bit synchronization information must be contained in the basic signaling waveform. This section describes two asynchronous detectors and one synchronous detector for Polar RZ. The bit error ratio as a function of signal to noise ratio is determined for synchronously detected Polar RZ, primarily to provide a basis for comparing the performance of Polar RZ with other signaling forms in the presence of Additive White Gaussian (AWG) noise.

Simple Asynchronous Polar RZ Detector

For short direct coupled local buses wherein very little noise is encountered, the simple asynchronous detector of Figure 3.3-13 may be adequate.

Simple Asynchronous Polar RZ Detector with Filtering

To provide more immunity to high frequency noise, the asynchronous detector of Figure 3.3-13 may be preceded by a low pass filter. The filter parameters should be adjusted to produce the raised cosine response to a unit step as illustrated in Figure 3.3-14a.
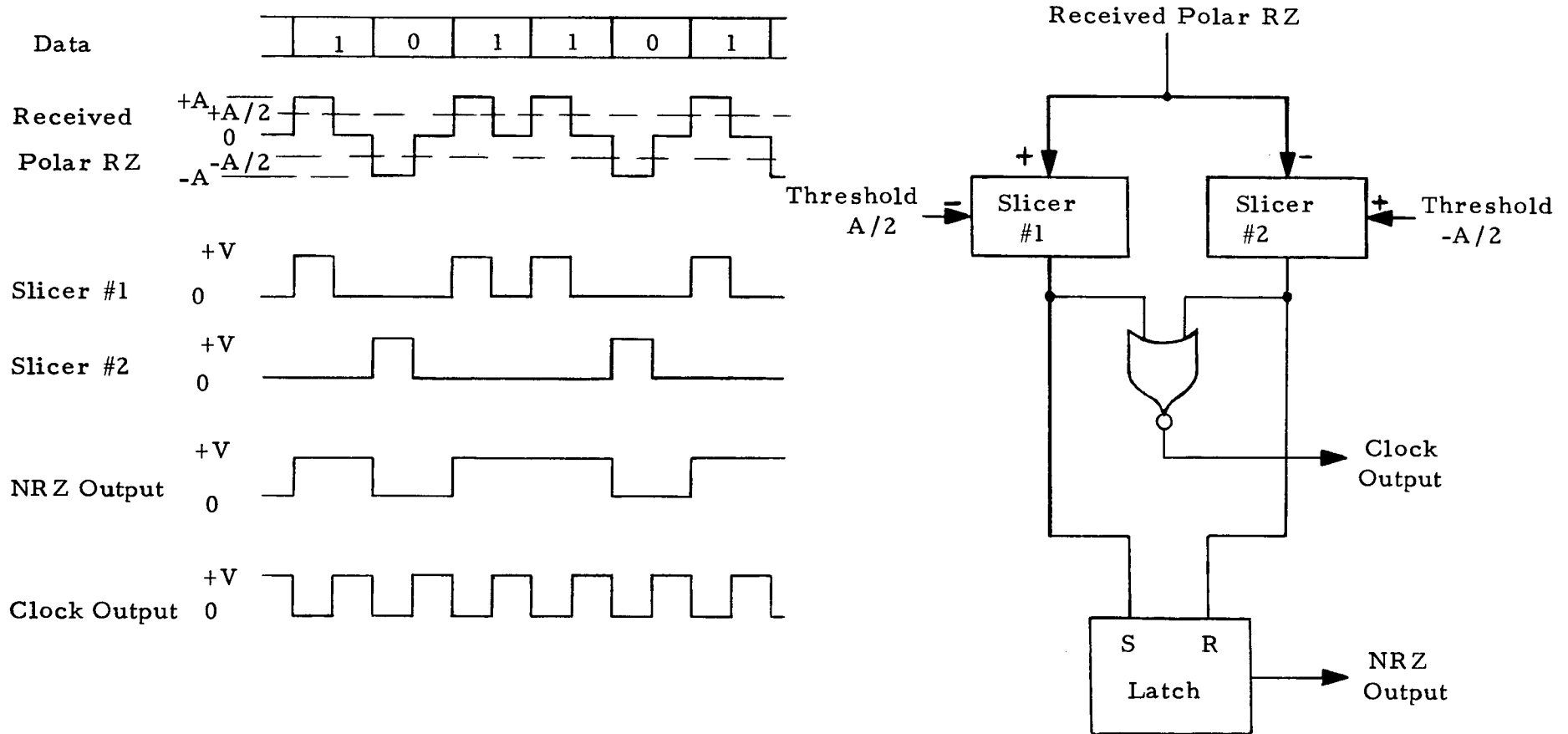
FIGURE 3.3-13   SIMPLE ASYNCHRONOUS POLAR RZ DETECTOR

Time in Bit Intervals
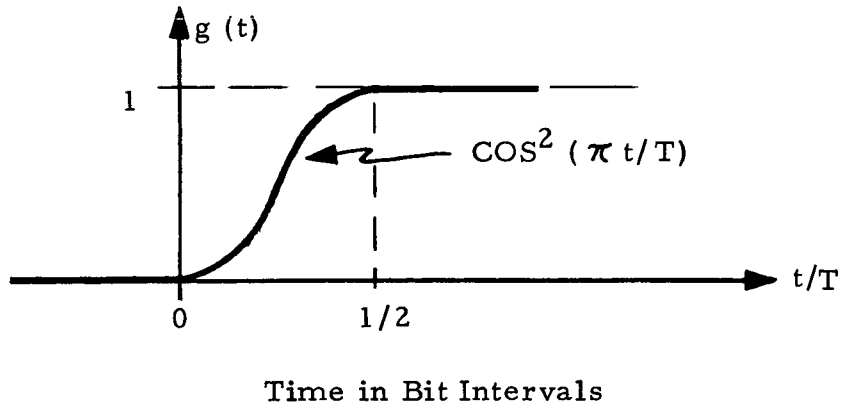
FIGURE 3.3-14a   FILTER STEP RESPONSE
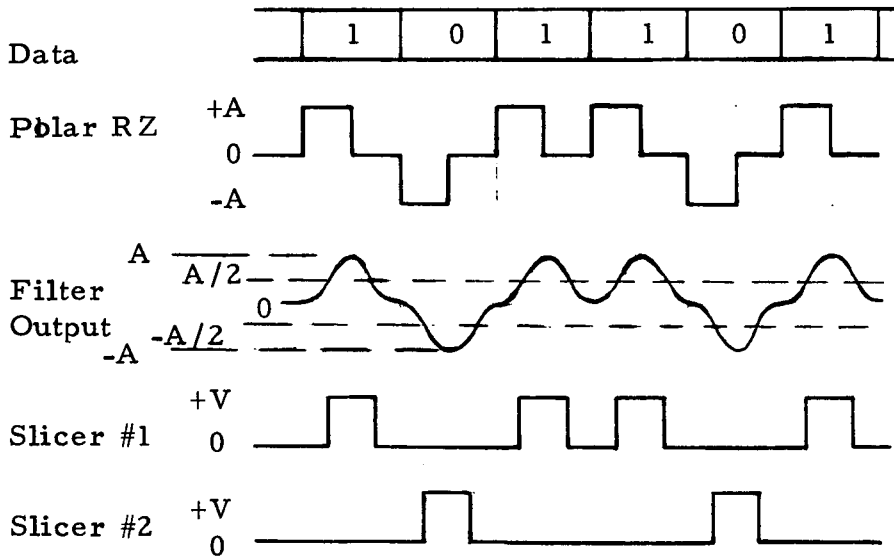
FIGURE 3.3-14b   RESULT OF FILTERING AND SLICING POLAR RZ

Synchronous Polar RZ Detector

Figure 3.3-15 illustrates a synchronous detector for Polar RZ which is optimum in the presence of Additive White Gaussian Noise. The bit error ratio vs. signal noise ratio for this detector in the presence of white gaussian noise is:

$$P = 0.5 \text{ cerf } \frac{S}{N} \qquad \text{(ref. 1, Chapt. 18, pp. 312)}$$

where S is the average signal power, and N is the average noise power in a bandwidth equal to the signaling frequency.

Biphase-Level

Biphase-Level is a baseband modulation technique that has two significant properties which make it attractive for use in the primary transmission medium of the SSV data bus:

1. The signal has no DC component, which makes it highly amenable to transformer coupling.

2. It provides truly "self-clocking" synchronization information since a transition always occurs in the middle of each bit interval, which makes asynchronous detection possible.

The primary disadvantage of Biphase-Level is that it requires a transmission bandwidth equal in Hz to the signaling frequency in bps. This is approximately double the bandwidth requirements of both Bipolar NRZ and Delay Modulation.

Three techniques for detecting Biphase-Level follow:

3.3-27

C3
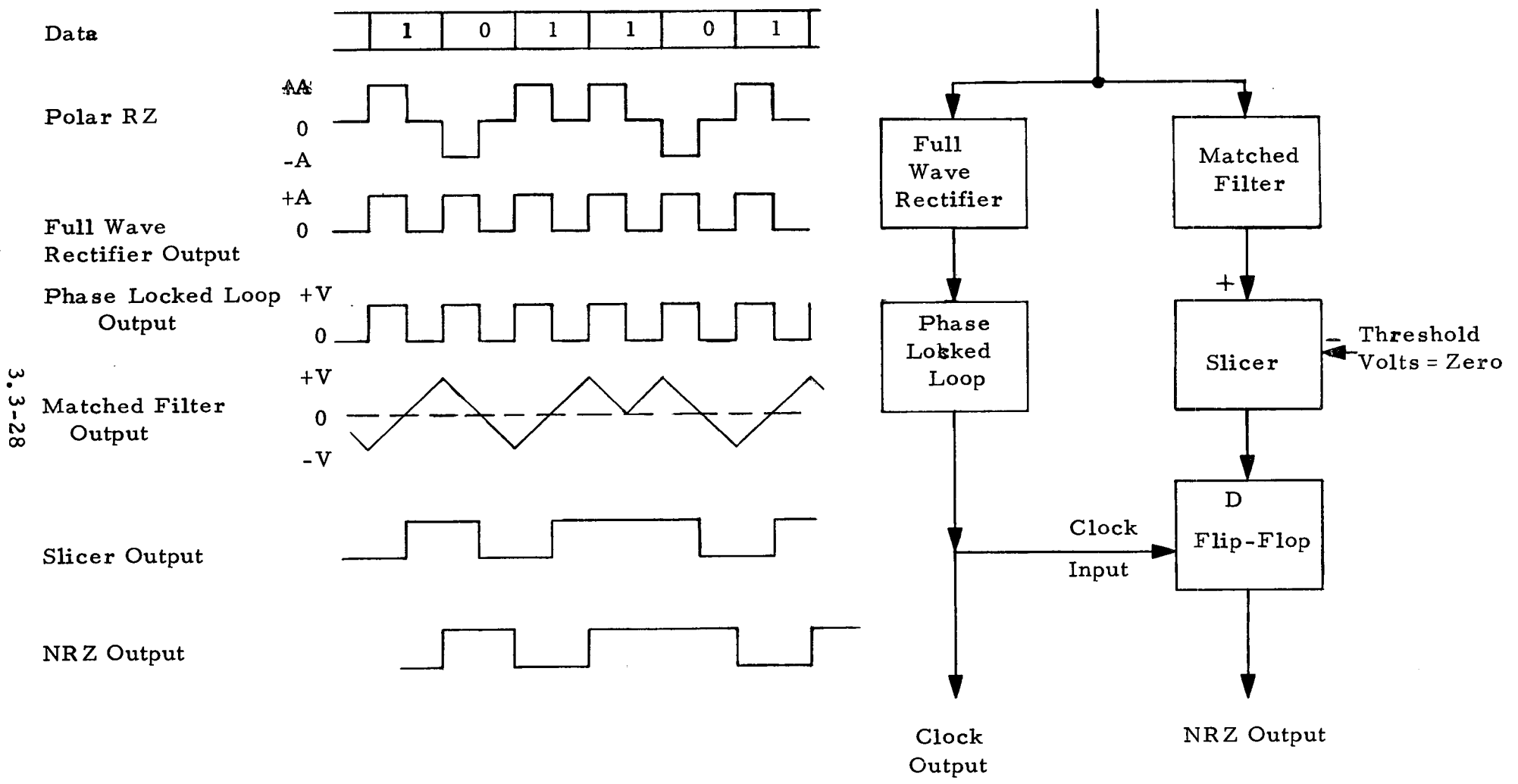
FIGURE 3.3-15   SYNCHRONOUS POLAR RZ DETECTOR

- **A Simple Asynchronous Detection Technique**

Asynchronous Biphase-Level detection techniques are in general less immune to noise induced errors than synchronous techniques, but have the advantage that they can be simpler and require less hardware. Figure 3.3-16 illustrates an asynchronous biphase receiver which converts Biphase-Level to NRZ, and in addition supplies on output clock.

- **A Synchronous Detection Technique**

Figure 3.3-17 is a waveform and block diagram illustrating a method synchronously detecting Biphase-Level modulation. It assumes the existence of a clock having a frequency and phase which are in proper synchronism with the received signal. A means for achieving proper synchronization is illustrated in Figure 3.3-18.

- **Performance Under Noisy Conditions**

Determining the bit error probability of the simple asynchronous biphase receiver shown here appeared to be a very difficult mathematical problem. Fortunately, even without a rigorous mathematical treatment it was readily apparent that the mistiming of a single pulse from the differentiator output could seriously affect the error rate. If noise causes the 3/4 bit one shot to fail to be triggered off near the middle of a bit interval (within $\pm$ 0.25 bit period) then the phase of the clock reverses. This causes a steady stream of errors until such time as a data transition (01 or 10) occurs in the data pattern. Because of this unreliability in the clock, the error rate of this asynchronous receiver in the presence of noise would definitely exceed that of a synchronous Biphase-Level receiver.
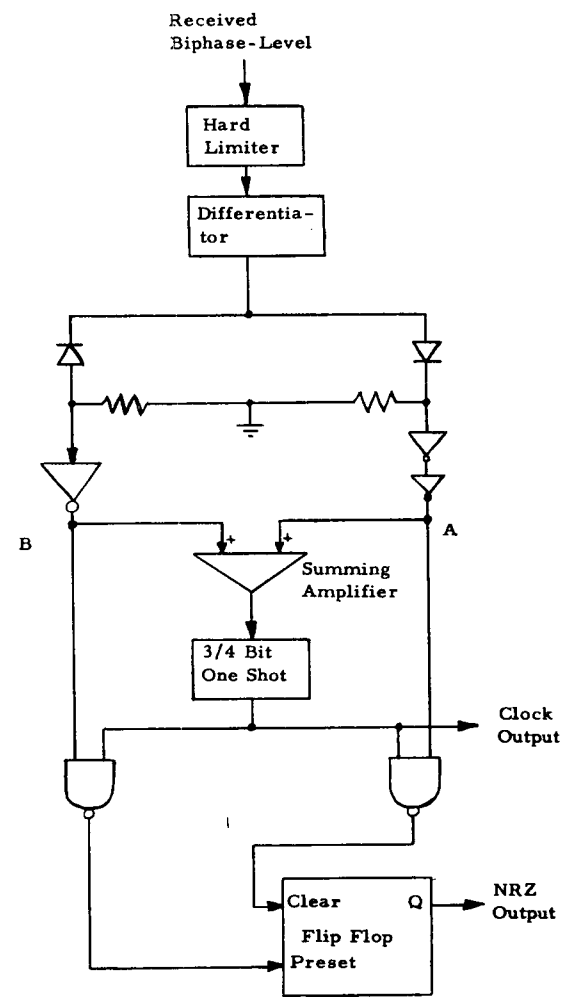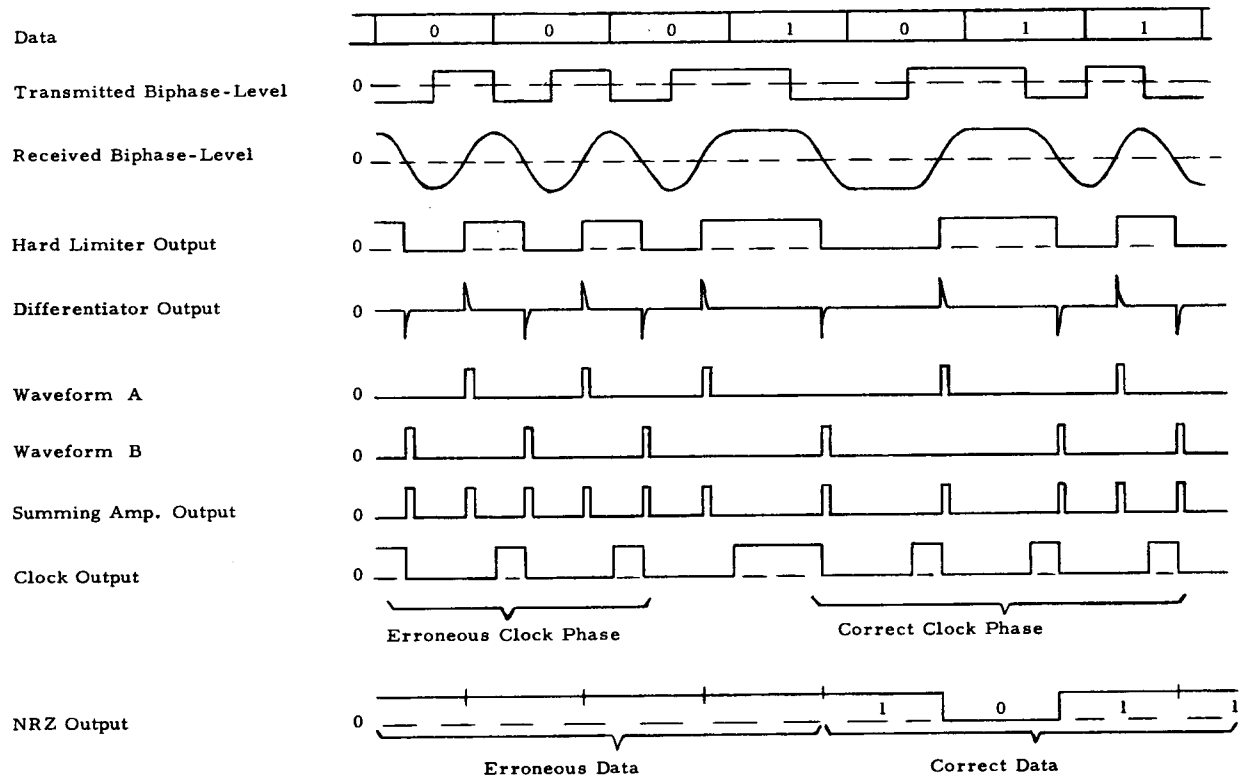
FIGURE 3.3-16   ASYNCHRONOUS BIPHASE RECEIVER

Data

Transmitted
Biphase-Level

Received Signal
Plus Noise

Hard Limiter Output

Clock Input

Exclusive or Output

Flip Flop Output Q

Integrator #2 Output

Integrator #1 Output

Summing Amp. Output

Slicer Output

NRZ Otuput
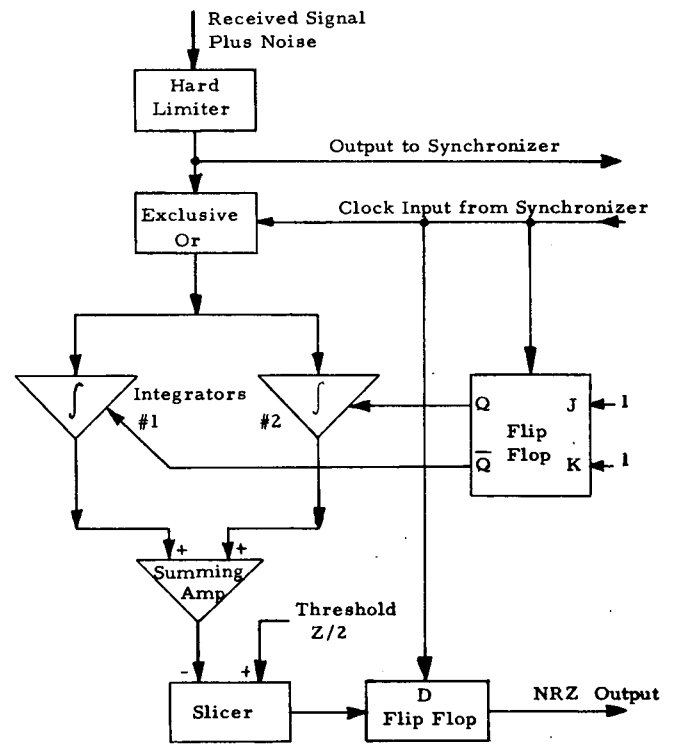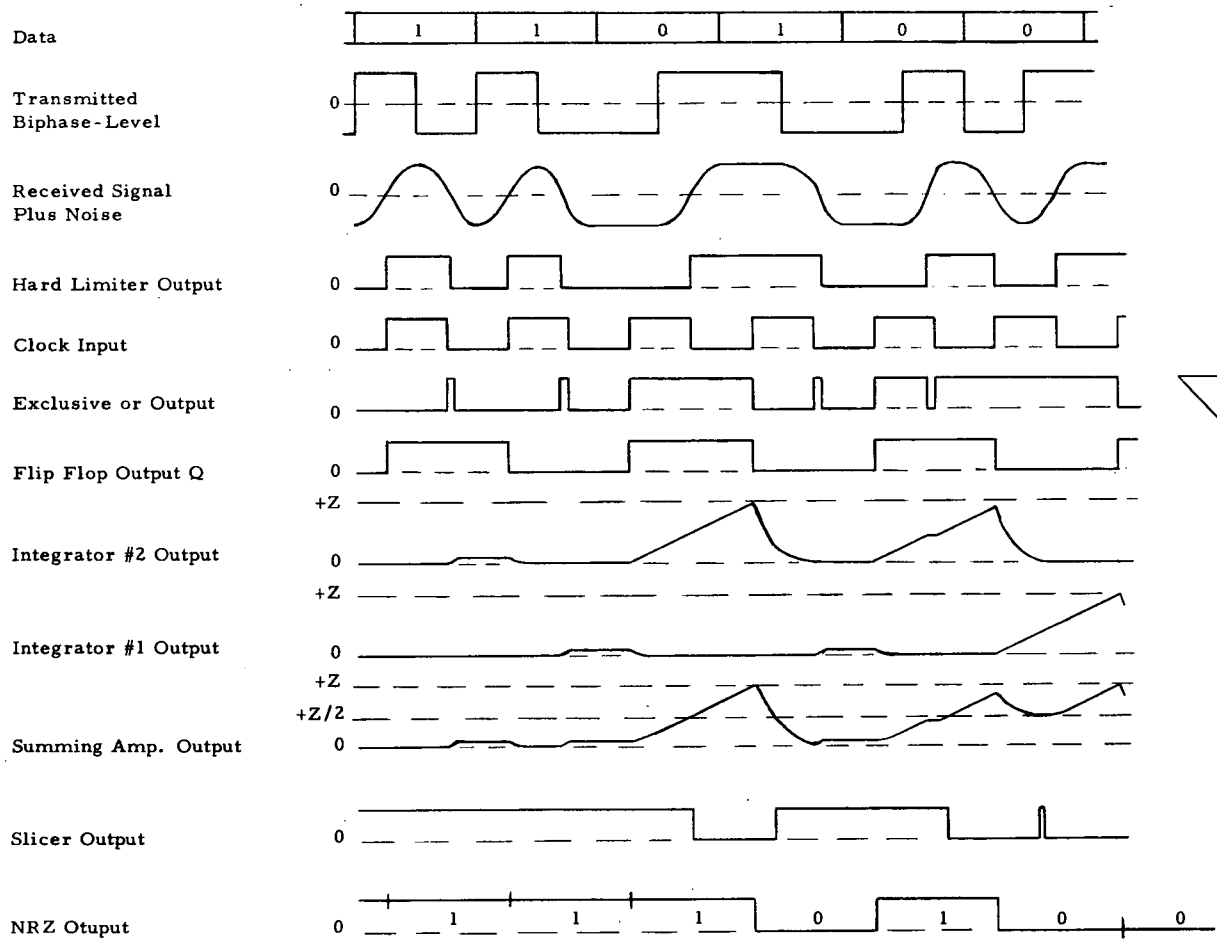
FIGURE 3.3-17   SYNCHRONOUS RECEIVER FOR BIPHASE-LEVEL

A synchronous biphase receiver can be designed to have a highly reliable clock which is far less susceptible to noise than is the case in an asynchronouse receiver. This superior performance is achieved by providing adequate smoothing of the measured phase error in the loop filter of a phase locked loop which is effective so long as there is not a sudden gross change in the phase of the received data.

Determining the bit error ratio of the synchronous biphase receiver is less difficult than in the asynchronous case, and for the case of AWG noise, has been found to be:

$$P = 0.5 \, \text{cerf} \, \frac{S}{n_o B}$$

where cerf is the co-error function, S is the average power of the received signal power in volts^2, n_o is the one-sided noise power density in volts^2/Hz, and B is the bit rate in bps. This is identical to the bit error ratio for synchronously detected PSK or DSBSC, as one might naturally expect.

● Asynchronous Integrating Biphase (AIB)

The detection technique is superior to the simple asynchronous detection technique presented above. The asynchronous detection technique previously described relies on a one-shot multivibrator for the extraction of clock information, and has the additional disadvantage that its performance in the presence of noise is extremely difficult to analyze. The improved method uses as integration technique to measure the times between axis crossings with a precision that cannot be achieved using one-shot multivibrators. Its decision rule consists of comparing measured pulse durations with those expected from valid biphase signals.

Data

Transmitted Biphase-
Level Waveform

Received Signal
Plus Noise

Input from
Hard Limiter

Differentiator Output

Full Wave Rectifier
Output

3/4 Bit One Shot

Sampling Pulse Train

VCO Output

Flip Flop Output

Sawtooth
Generator Output

Sampler Output
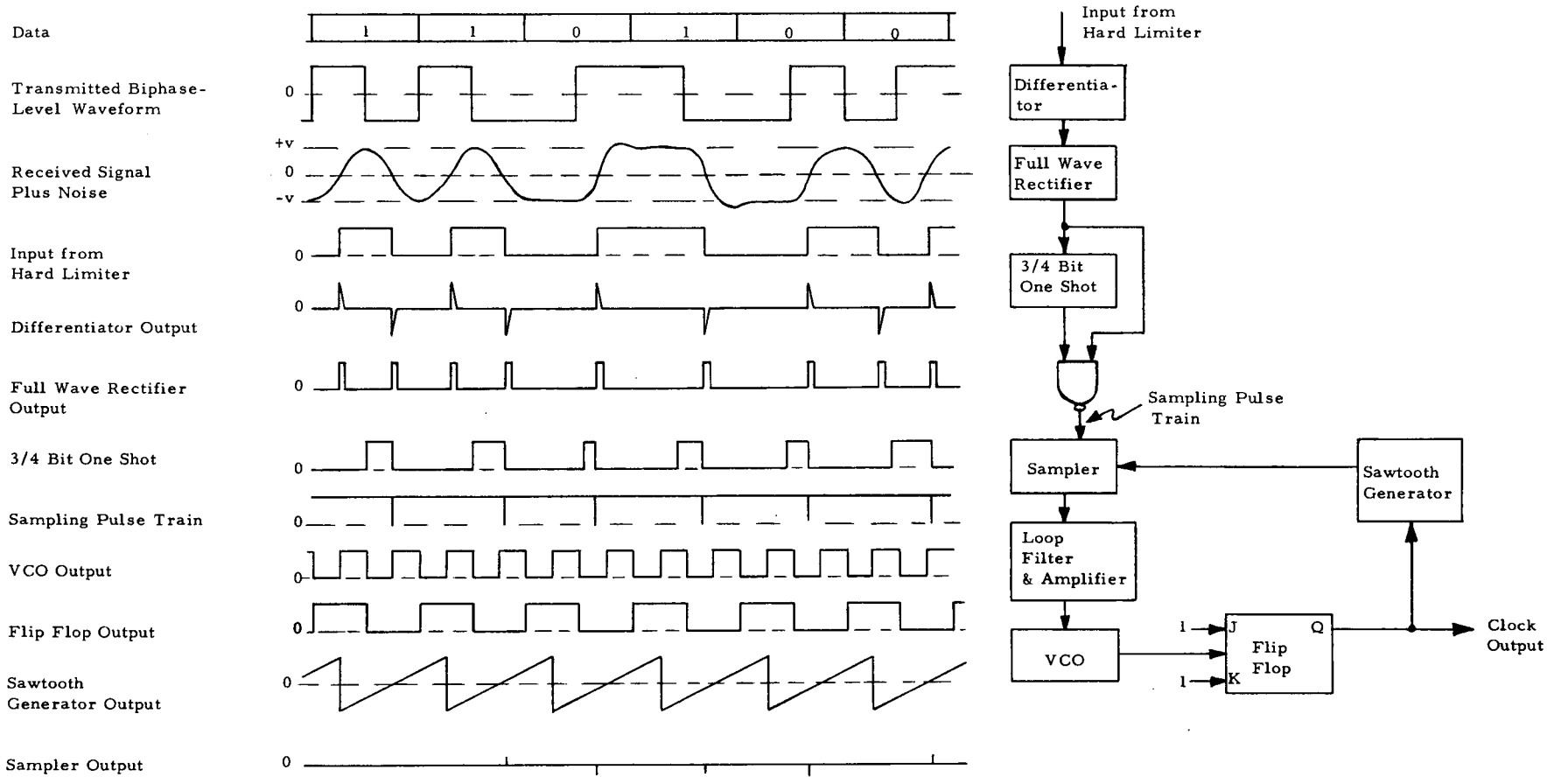
FIGURE 3.3-18   SYNCHRONIZER FOR BIPHASE-LEVEL RECEIVER
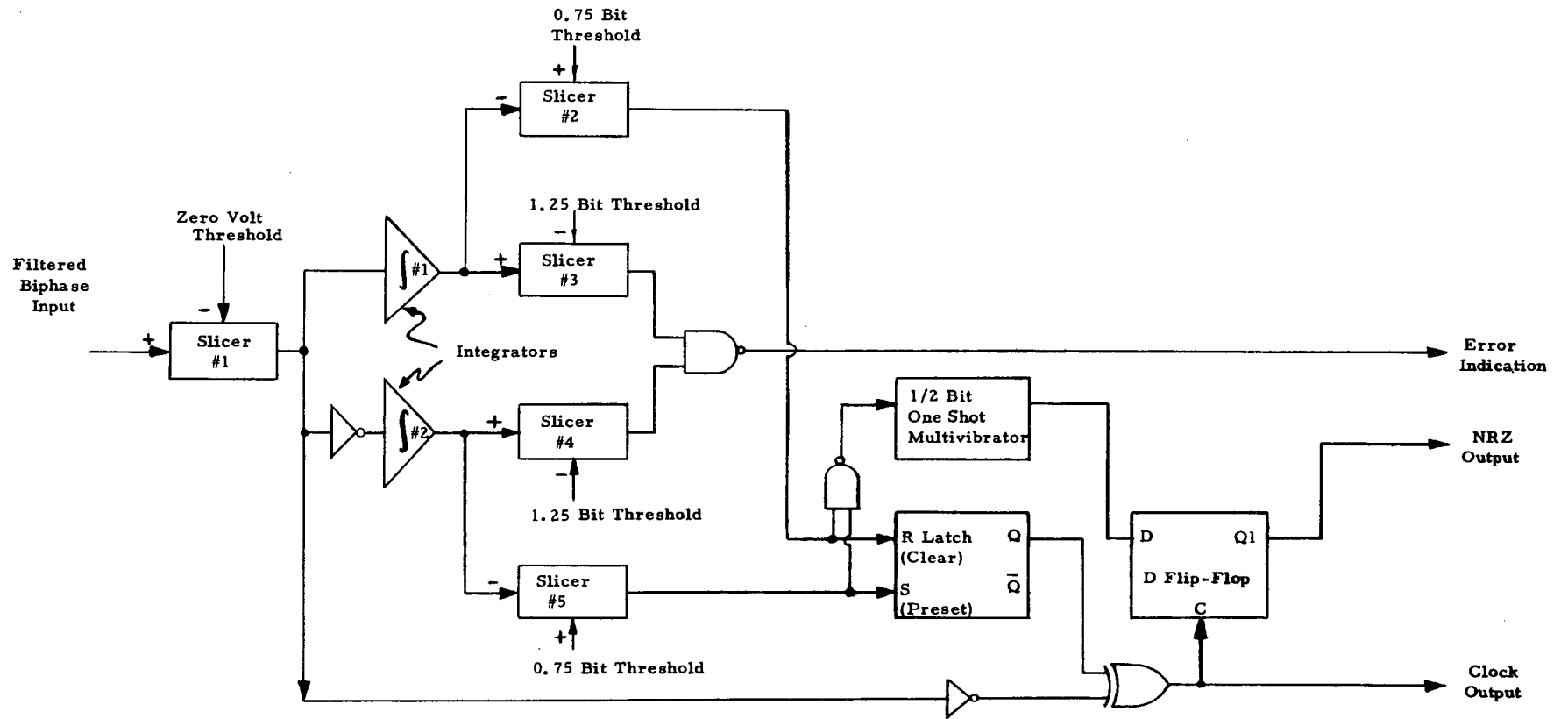
FIGURE 3.3-19   BLOCK DIAGRAM OF AIB RECEIVER
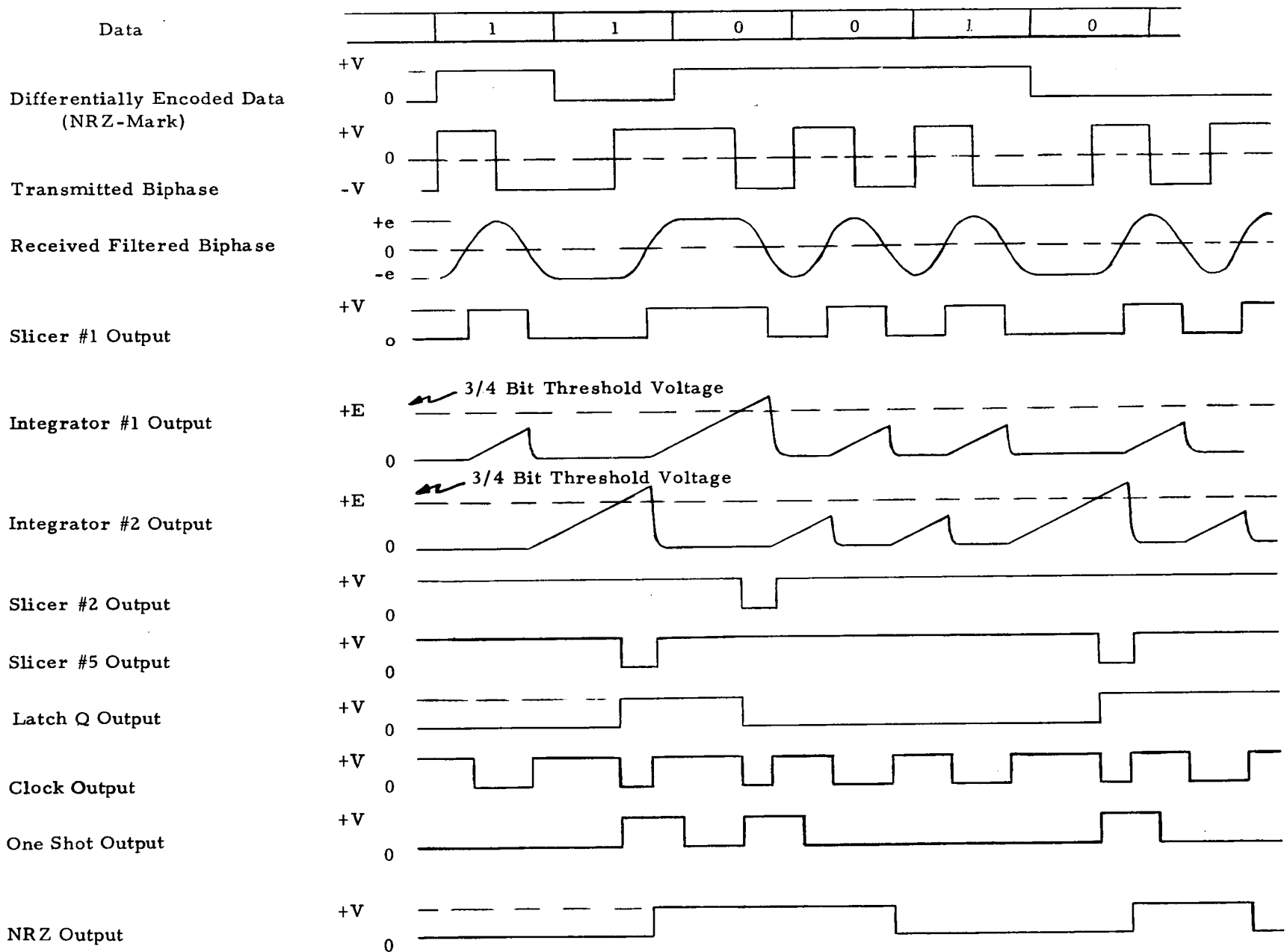
FIGURE 3.3-20 WAVEFORM DIAGRAM DESCRIBING AIB RECEIVER OPERATION

Figure 3.3-19 is a block diagram of a receiver which uses the AIB technique and Figure 3.3-20 is a waveform diagram that describes its operation. Note that the transmitted signal is differentially encoded biphase as illustrated in Figure 3.3-20. This is necessary in order to prevent errors at the receiver from propagating into successive bit intervals as a consequence of the detection method.

An additional feature of the receiver shown in Figure 3.3-20 is that it detects certain invalid signaling waveforms. It accomplishes this by means of slicers #3 and #4, which sense when the time between successive axis crossings exceeds 1.25 bit interval. These slicer outputs are "nanded" to produce an error indication which is normally high, but falls to logic level zero upon the occurrence of the prescribed error condition.

●   Performance Under Noisy Conditions

It is a most difficult mathematical problem to determine the performance of the AIB receiver in the presence of the types of noise expected in the SSV data bus, and time did not permit an investigation of this problem. However, it was possible to make a reasonable estimate of bit error ratio vs. Signal-to-Noise Ratio (SNR) for the case of AWG noise when the SNR is greater than 10. Under these conditions bit error ratio has been found to be approximately:

$$P = e^{-\frac{4}{\pi^2}\left(\frac{S}{N}\right)}$$
(3.3.2.4-1)

where S is the transmitted signal power, and N is the noise power in a bandwidth equal to the signaling rate. This approximation is excellent when the signal to noise ratio is large ($S/N \gtrsim 10$). In deriving this equation it was assumed that the receiver was preceded by an input filter having a raised cosine step response as shown in Figure 3.3.14a. Figure 3.3-21 is a plot of equation (3.3.2.4-1).
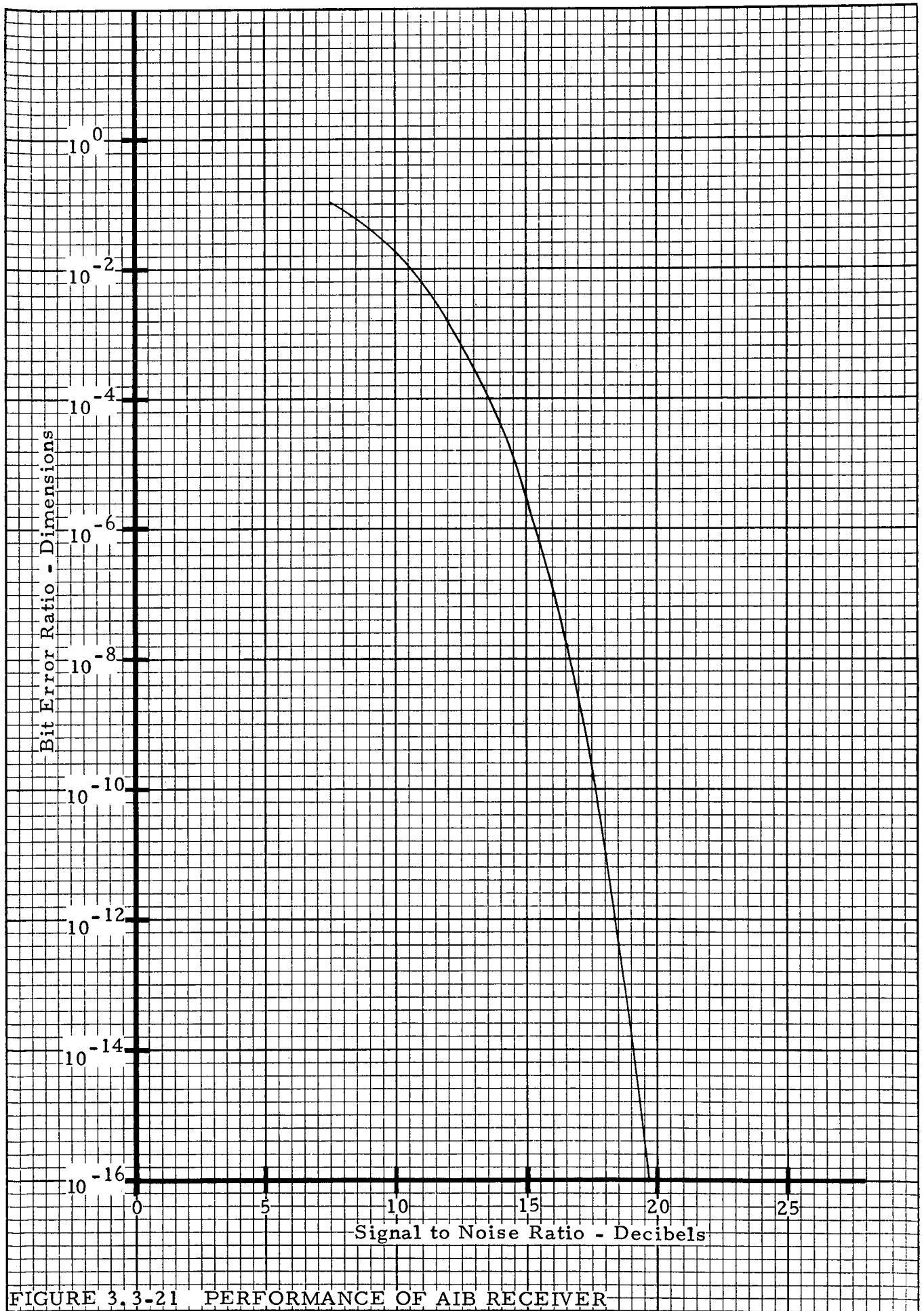
FIGURE 3.3-21   PERFORMANCE OF AIB RECEIVER

The phase error θ is related to the axis crossing time jitter by:

$$\theta = 2\pi \frac{t}{T} \qquad (3.3.2.4-2)$$

where t is the error in the time of an axis crossing, and T is the time duration of a bit.

Bipolar NRZ

Bipolar NRZ is a baseband modulation technique that has three significant properties which make it attractive for use in the primary transmission medium of the SSV data bus:

1. The signal has no DC component provided the number of "ones" transmitted in a word is even (use even parity per word). This makes it amenable to transformer coupling.

2. It requires a transmission bandwidth equal in Hz to one-half the signaling rate in bps, whereas Biphase-Level requires a bandwidth equal to the bit rate.

3. It has a built-in error detecting capability, which allows all single bit errors and many multiple error combinations to be detected when the alternating property of the pulses in the scheme is violated.

Bipolar NRZ has two significant disadvantages:

1. It does not contain adequate synchronization information for detection without an auxiliary timing source. For example a long sequence of "zero's" contains no level transitions from which to derive bit sync. In this regard both Biphase-Level and Delay Modulation may be advantageous, since each provides a steady flow of axis crossing

3.3-38

information, regardless of the data pattern being transmitted. For detection of Bipolar NRZ, synchronization must be provided by external means such as separate channel.

2.   To achieve optimum performance regardless of signal amplitude, the decision threshold must be varied as a function of the signal amplitude. This is an added complication in the receiver design which does not occur with Biphase-Level. It involves measurement of the signal amplitude, or power, then generation of the proper threshold level via a special device such as a nonlinear circuit. If the threshold is not varied in this manner, but is held at a fixed value which is optimum for the weakest expected signal level, then the bit error probability cannot diminish significantly below the value encountered at the optimum threshold level, regardless of the strength of the received signal. This arises because the commission error probability of Bipolar NRZ is a function only of the threshold setting and the standard deviation of the noise, and is independent of signal power, since no signal power is transmitted during a "zero".

The following summarizes a simple synchronous detection technique for converting Bipolar NRZ to Unipolar NRZ and describes receiver performance under noisy conditions for the case of Additive White Gaussian (AWG) noise.

●   A Simple Synchronous Detection Technique for Bipolar NRZ

Figure 3.3-22 is a waveform and block diagram illustrating a simple and effective method for synchronously detecting Bipolar NRZ modulation. It assumes the existence of a clock signal having a frequency and phase which are in proper synchronism with the received signal.

The illustrated receiver input waveform is first sliced about threshold levels +E and -E. The two slicer outputs drive a half adder (exclusive or) circuit, the output of which is inverted then sampled by the clock signal to produce the desired NRZ output. To make use of the built-in error detecting property of Bipolar NRZ, the two slicer outputs are routed to the error detection logic illustrated in Figure 3.3-23.

● Performance Under Noisy Conditions

A solution of the bit error ratio as a function of signal-to-noise ratio for the receiver described in Figure 3.3-22 under the influence of AWG noise has been found to be:

$$P = \frac{1}{2} \operatorname{cerf}\left(\frac{E}{\sqrt{2N}}\right) + \frac{1}{2}\left[\operatorname{erf}\left(\sqrt{\frac{S}{N}} + \frac{E}{\sqrt{2N}}\right) - \operatorname{erf}\left(\sqrt{\frac{S}{N}} - \frac{E}{\sqrt{2N}}\right)\right] \qquad (3.3.2.4-3)$$

where "cerf" is the co-error function, "erf" is the error function, E is the threshold setting in volts, N is the noise power in volts^2, and S is the average signal power in volts^2 when a continuous sequence of "ones" is received.

As would be expected, the bit error ratio is strongly affected by the magnitude of the slicer threshold levels, E. The optimum threshold setting is that which minimizes the bit error ratio and is a function of the signal and noise power. The derivation shows that this function for the optimum threshold setting is:

$$E_{opt} = \sqrt{\frac{S}{2}}\left\{\frac{\cosh^{-1}(e^{S/N})}{S/N}\right\} \qquad (3.3.2.4-4)$$

Figure 3.3-24 is a plot of this optimum threshold setting (normalized to the signal amplitude) as a function of signal-to-noise ratio.

B
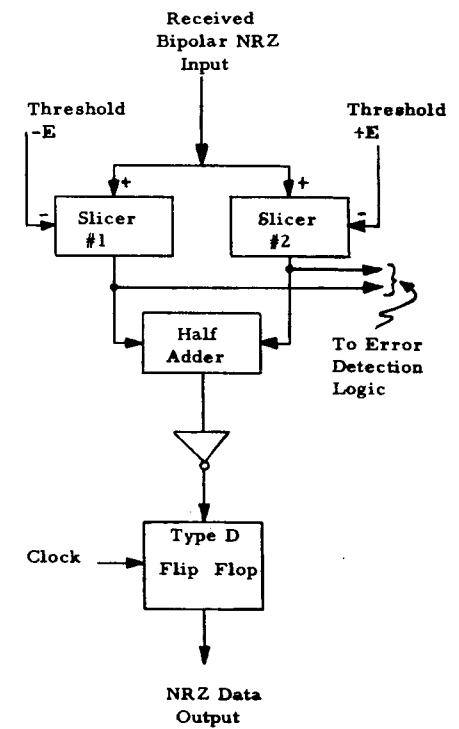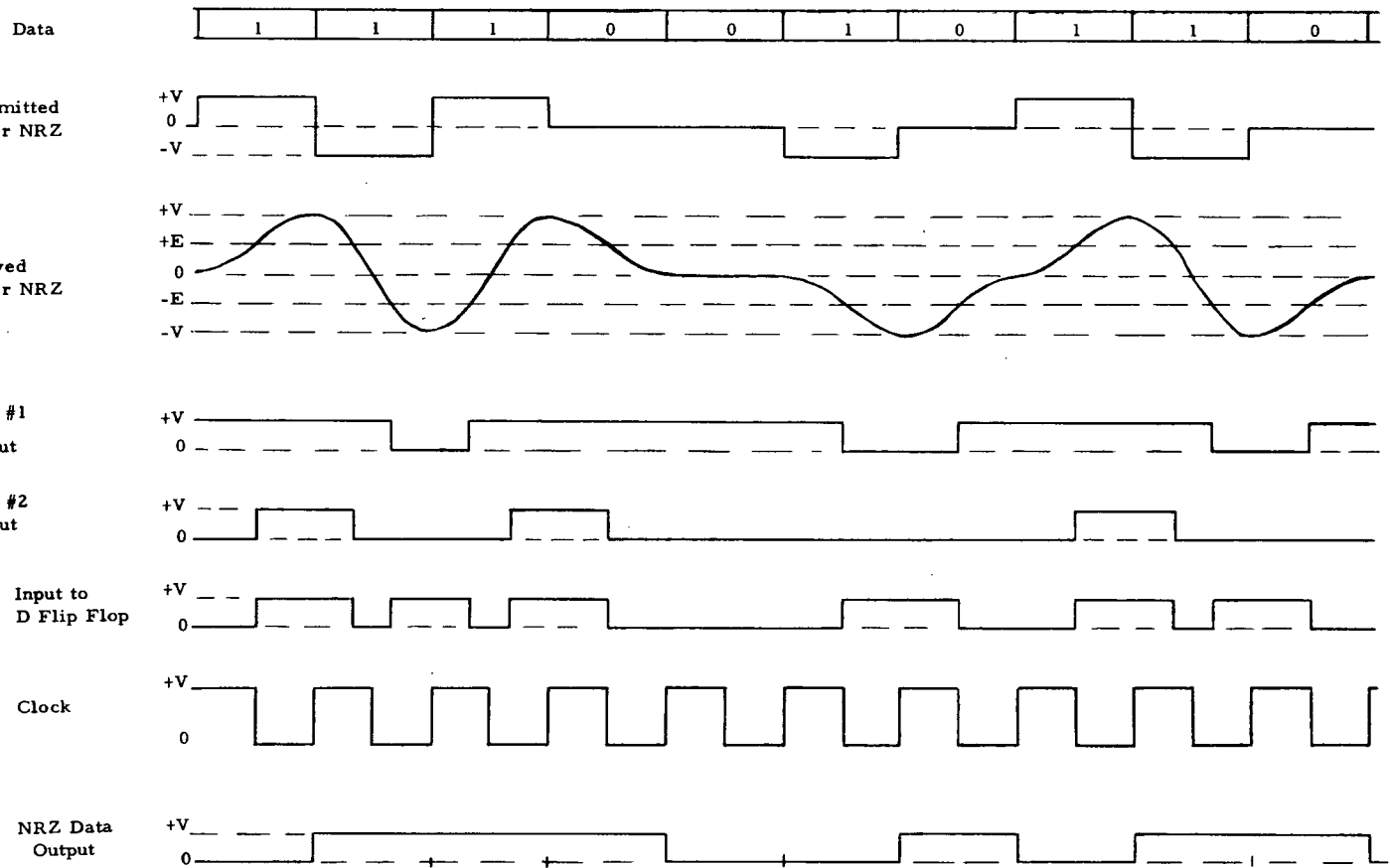
FIGURE 3.3-22   SYNCHRONOUS DETECTION OF BIPOLAR NRZ

3.3-41

Data

| | 1 | 1 | 1 | 0 | 0 | 1 | 0 |

Transmitted
Bipolar NRZ

+v
0
-v

Received
Bipolar NRZ

+v
+E
0
-E
-v

Effects of Noise Transient

Input from Slicer #1

+v
0

Input from Slicer #2

+v
0

Clock Signal

+v
0

Flip Flop Q

+v
0

Output Error
Indication

+v
0

Input from Slicer #1

Clock

J   JK   Q
     Flip Flop
K   Q̄

Input from Slicer #2

Data
Input

Clock Input

Clear Input

D
Flip Flop

Output Error
Indication
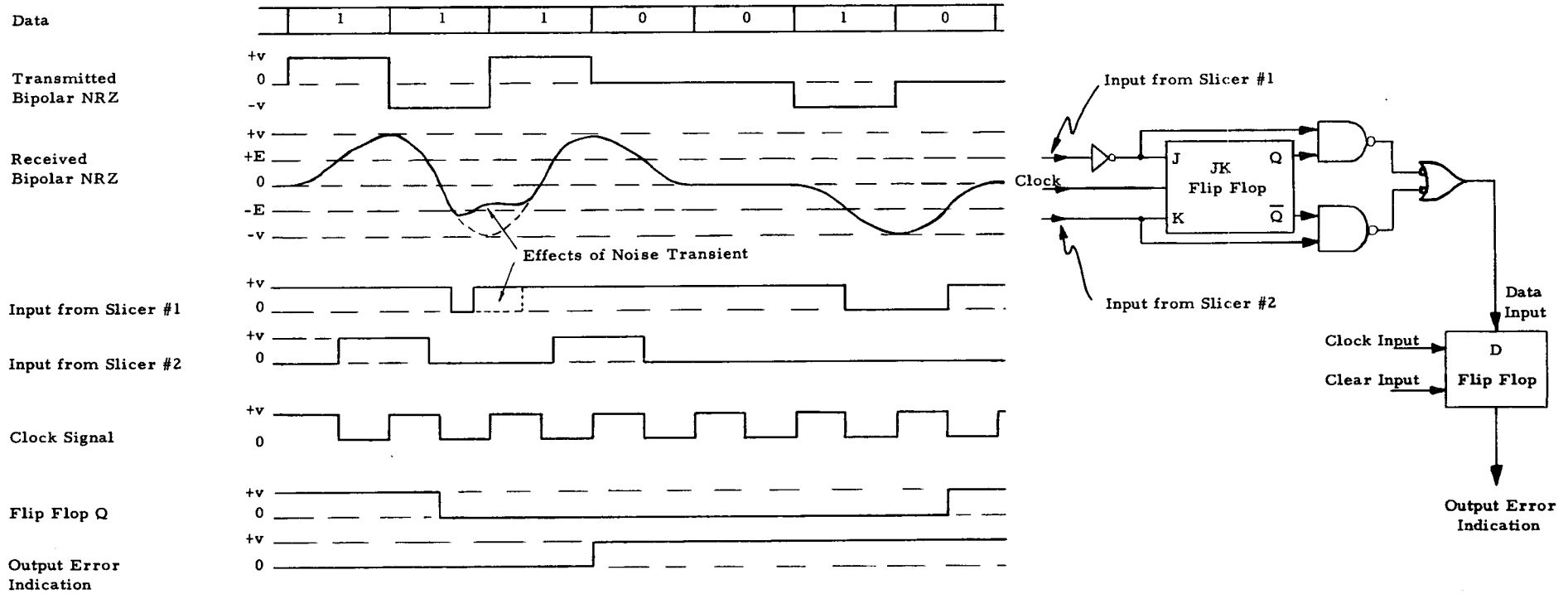
FIGURE 3.3-23   BIPOLAR NRZ ERROR DETECTION LOGIC

FIGURE 3.3-24.   OPTIMUM THRESHOLD VS. SIGNAL TO NOISE RATIO

$$t = \frac{1}{2}\left\{\frac{cosh^{-1}\left(e^{\rho}\right)}{\rho}\right\}$$

$t = \frac{E}{A}$

Normalized Threshold Setting
Dimensionless

Signal to Noise Ratio-Decibels

$\rho = \frac{S}{N}$
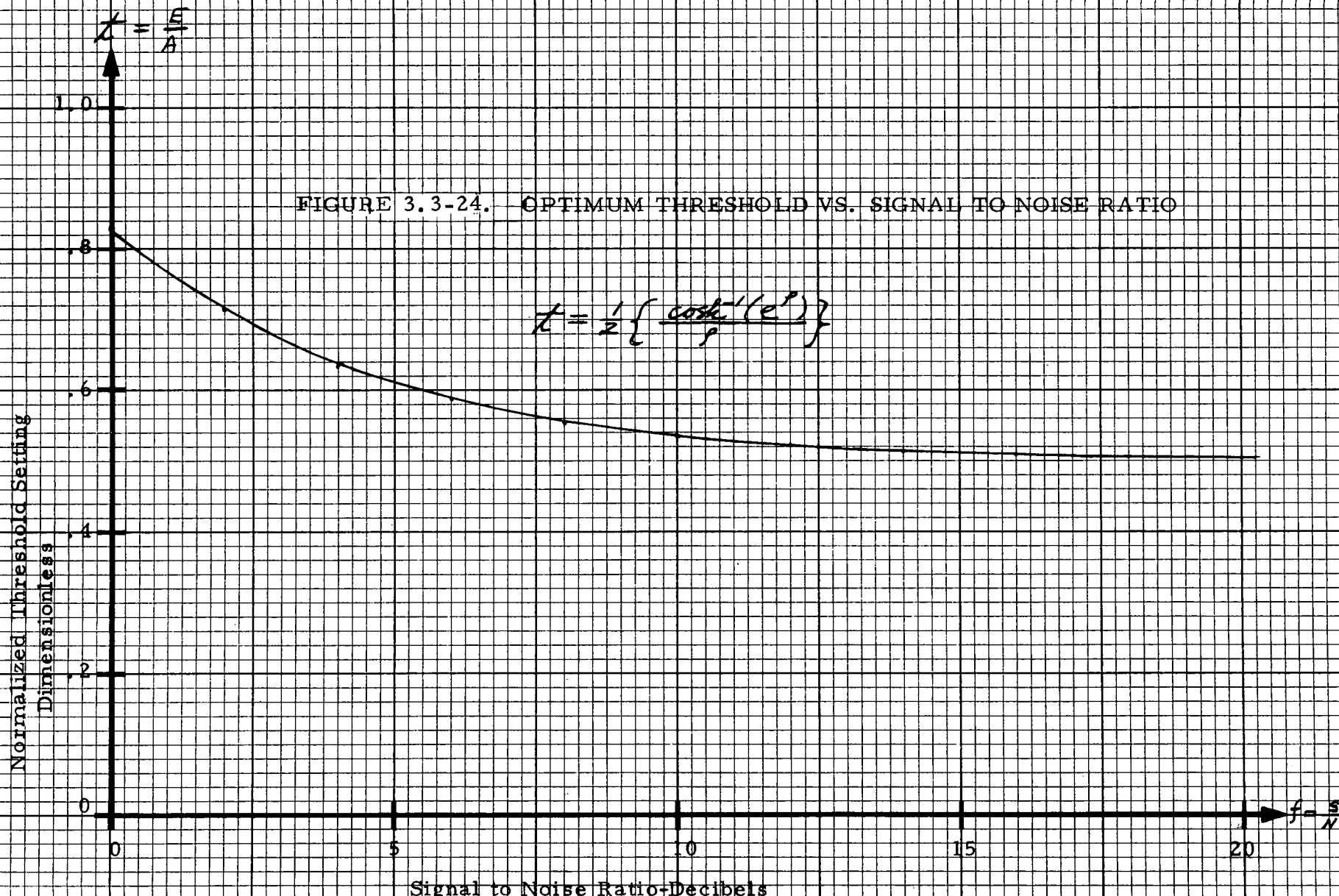
Clearly, if the received signal power is allowed to vary, then for optimum receiver performance (minimum bit error rate) the signal power or signal amplitude must be measured and the result of this measurement used to control the threshold setting in accordance with equation (3.3.2.4-4). If this is done, then the bit error ratio becomes strictly a function of signal-to-noise ratio, since substitution of (3.3.2.4-4) into (3.3.2.4-3) yields:

$$P = \frac{1}{2} \left\{ \text{cerf}\left[\frac{1}{2} \cosh^{-1}(e^{S/N})\right] + \frac{1}{2} \left[\text{erf}\left[\right.\right.\right.$$

$$\left.\left.\left. \sqrt{\frac{S}{N}} \left(1 + \frac{1}{2} \cosh^{-1}(e^{S/N})\right)\right] - \text{erf}\left[\sqrt{\frac{S}{N}} \left(1 - \frac{1}{2} \cosh^{-1}(e^{S/N})\right)\right]\right]\right\} \qquad (3.3.2.4-5)$$

This result is plotted in Figure 3.3-25, which shows the minimum achievable bit error probability as a function of signal-to-noise ratio.

It should be remembered that the minimum achievable bit error probability shown in Figure 3.3-25 can only be attained if the threshold setting is a controlled function of signal power in accordance with equation (3.3.2.4-4). A fixed threshold cannot yield optimum performance (minimum error rate) unless the signal power is also fixed. In fact, equation (3.3.2.4-3) shows that with a fixed threshold the error rate can never be less than

$$P_{min} = \frac{1}{2} \text{cerf}\left(\frac{E}{\sqrt{2N}}\right) \qquad (3.3.2.4-6)$$

even if the signal-to-noise ratio is infinite.

Figure 3.3-26 illustrates this at the optimum value for a specified signal-to-noise ratio (curve A). If the signal-to-noise ratio is less than the value for which the threshold is optimum, then the bit error probability will be greater than the value shown on curve B. If SNR is greater than the value for which the threshold setting is optimum, then the bit error probability will be

FIGURE 3.3-25. BIT ERROR PROBABILITY VS. SNR OF BIPOLAR NRZ
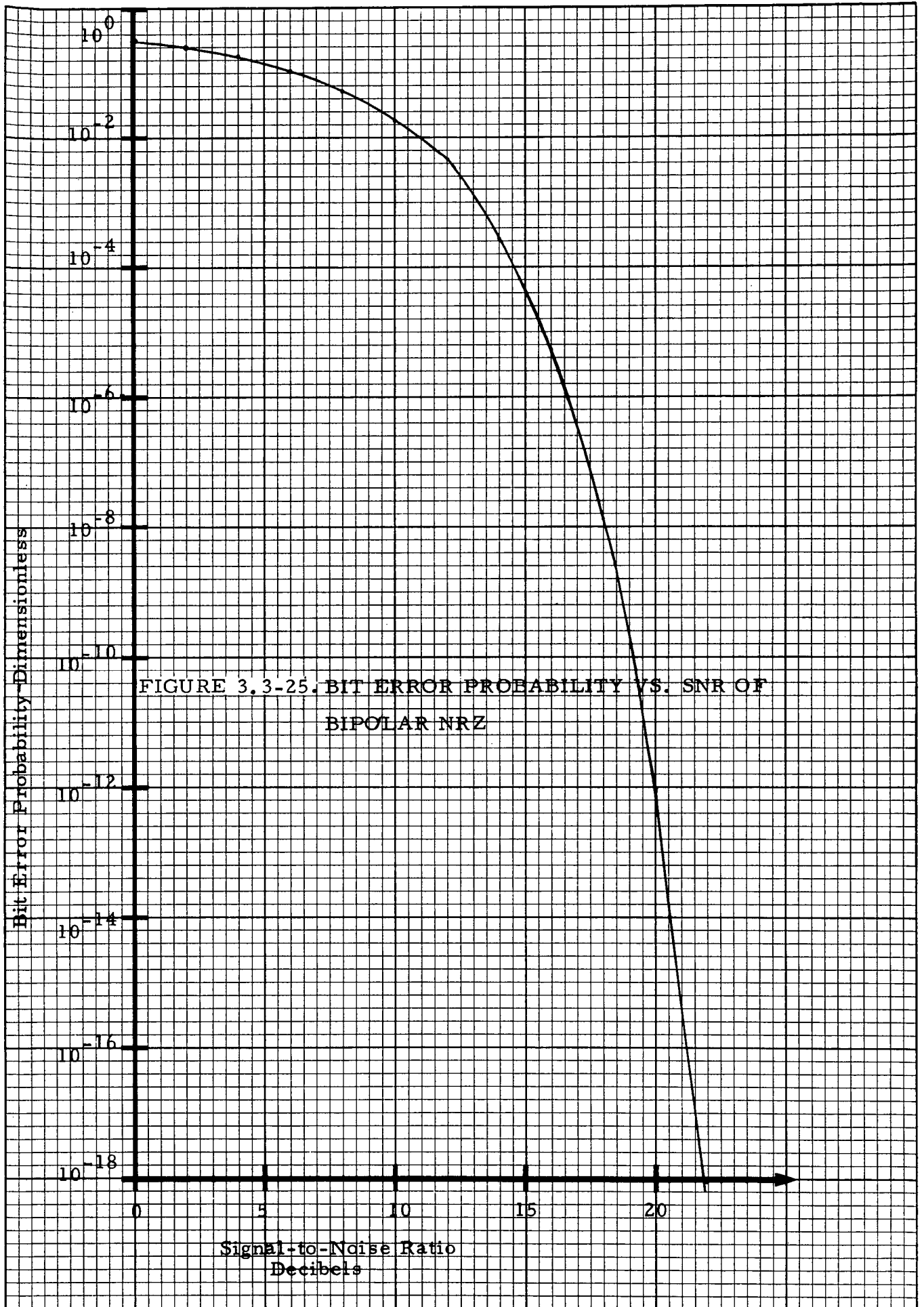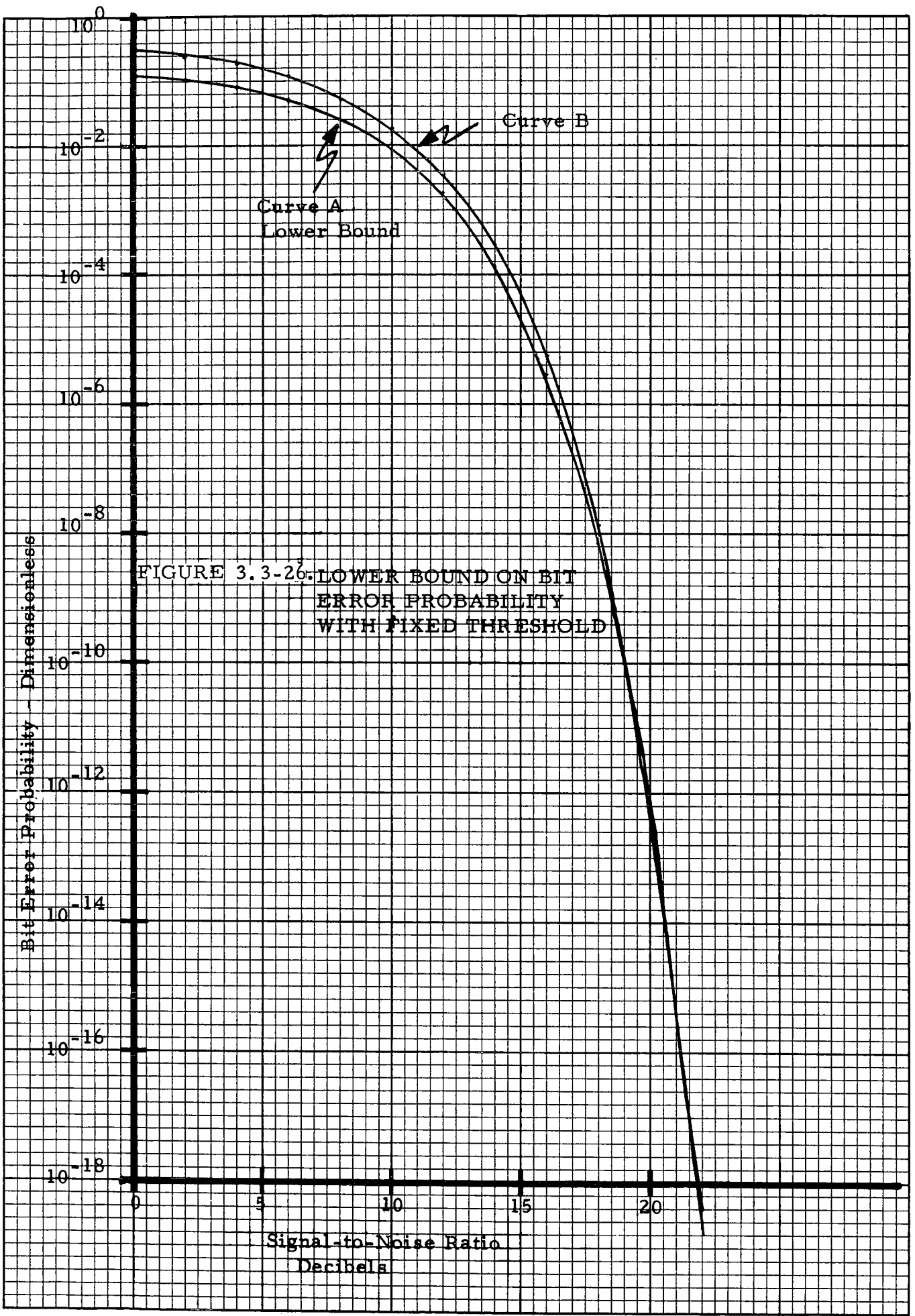
FIGURE 3.3-26. LOWER BOUND ON BIT
ERROR PROBABILITY
WITH FIXED THRESHOLD

Curve B

Curve A
Lower Bound

Bit Error Probability – Dimensionless

Signal-to-Noise Ratio
Decibels

less than that shown on curve B, but can never fall below the value shown on curve A, regardless of how large the SNR is.

Delay Modulation

Delay modulation (Miller Code) is a baseband modulation technique that has three useful properties which make it worth considering for application in the primary transmission medium of the SSV data bus:

1. The signal has only a small DC component, which makes it amenable to transformer coupling.

2. It has an advantage over Bipolar NRZ in that it provides a steady flow of synchronization information, since transitions in signal level occur at least as frequently as once every two bit intervals.

3. It offers an advantage over Biphase-Level in that it requires a transmission bandwidth of approximately one-half the bit rate, whereas Biphase-Level requires a bandwidth approximately equal to the bit rate.

Delay Modulation has the following primary disadvantages:

1. Unlike Biphase-Level and Bipolar NRZ, upon passage through a transformer, Delay Modulation produces a "wandering baseline" shift. The value of this shift varies with the data pattern being transmitted, but its absolute value is always less than one-sixth of the peak-to-peak signal amplitude. This makes the signal more difficult to detect correctly in the presence of noise.

2. Detection of Delay Modulation requires the use of a clock which is in proper synchronism with the received signal. Delay Modulation

is not truly "self-clocking" since it does not always contain transitions occurring repeatedly at a known position during each bit interval. Consequently a "fly-wheeling" reference clock must be generated which is in synchronism with the transitions occurring in the received data.

- A Simple Delay Modulation Detector

Figure 3.3-27 is a waveform and circuit diagram illustrating a method for detecting Delay Modulation. It assumes the existence of a clock having a frequency and phase which are in proper synchronism with the received signal. A means for achieving synchronization is illustrated in Figure 3.3-28.

- Effects of Baseline Wander on the Simple Delay Modulation Detector

The effects of baseline wander may be readily observed in the hard limiter and integrator output waveforms of the figure. Baseline wander causes the times of occurrence of axis crossings to vary, thus causing a variation in the output levels reached by an integrator at the end of its integration period. The maximum amplitude of the error caused by baseline wander in the time of occurrence of an axis crossing is approximately:

$$t_{max}/T = \frac{\sin^{-1}(1/3)}{\pi} \qquad (3.3.2.4-7)$$

$$= 0.11 \text{ bit period} \qquad (3.3.2.4-8)$$

This can cause an error in the integrator output of up to 22% of its maximum output. For this reason, the value of the threshold amplitude should lie within the range

$$.22Z < E < .78Z \qquad (3.3.2.4-9)$$

where Z is the maximum possible output of the integrator.

• Synchronization

Referring to Figure 3.3-28, the clock input of the synchronizer is derived by dividing the X2 output of the VCO by 2. This is accomplished by the flip flop labeled Q. To assure that the phase of the clock output is correct, Q is reset to the proper phase each time the data pattern 101 is received. The pattern is recognized with the aid of a 3 bit shift register and appropriate gates. This circuitry recognizes the presence of an "all-high" or "all-low" condition at the limiter output for 2 successive bit intervals. This should occur only when the 101 data pattern is received. Hence to achieve proper bit synchronization, the data pattern 101 should be transmitted at the beginning of a message.

• Performance in Noise

Classical computation of bit error ratio vs. signal to noise ratio for this receiver requires a determination of the distribution of zero crossings for hard limited signal plus Gaussian noise. As recently as 1960, Middleton (reference 3, pp. 426) stated that distribution problems of this nature remain largely unsolved. A more recent reference (reference 2, pp. 222) also states that the problem of the error analysis of the zero-crossing detector is unsolved.

A Delay Modulation Receiver with Baseline Wander Removal

An improved method of detecting delay modulation utilizes baseline wander removal and is superior to that described above. It is not affected by baseline wander, and exhibits the same theoretical bit error ratio performance in white gaussian noise as Bipolar NRZ.

A chief disadvantage of this technique is that in order to achieve optimum performance regardless of signal amplitude the decision threshold must

be varied as a function of the signal amplitude. This involves measurement of the signal amplitude or power (such as may be provided by an AGC voltage), then generation of the proper threshold level via a special device such as a nonlinear circuit. It has the disadvantage that it requires Automatic Gain Control (AGC). This may lead to considerable difficulty if the level of the received signal is subject to sizable and rapid changes, as might be the case if the receiver must accept messages originating from several different transmitters located along the bus as widely different distances from the receiver. However, for applications wherein all messages are originated by a single transmitter whose position is fixed relative to the receiver, it should demonstrate performance which is markedly superior to that of the technique previously described.

Technique Description

The basic principle of the technique is to first normalize the receiving input waveform with an AGC and Clamp Circuit to remove baseline wander. Next, transitions occurring during the middle of a bit are detected by means of two slicers whose outputs are sampled by a synchronous square-wave clock signal. Figure 3.3-29 is a waveform and circuit diagram illustrating the detection technique.

Performance Under Noisy Conditions

The bit error ratio for the case of Additive White Gaussian (AWG) noise is identically the same as that previously described for Bipolar NRZ.

3.3.2.4.2 Transmitting and Receiving Filters

As pointed out earlier, filters may be cascaded with the transmission medium for two purposes: (1) to prevent excessive Electromagnetic
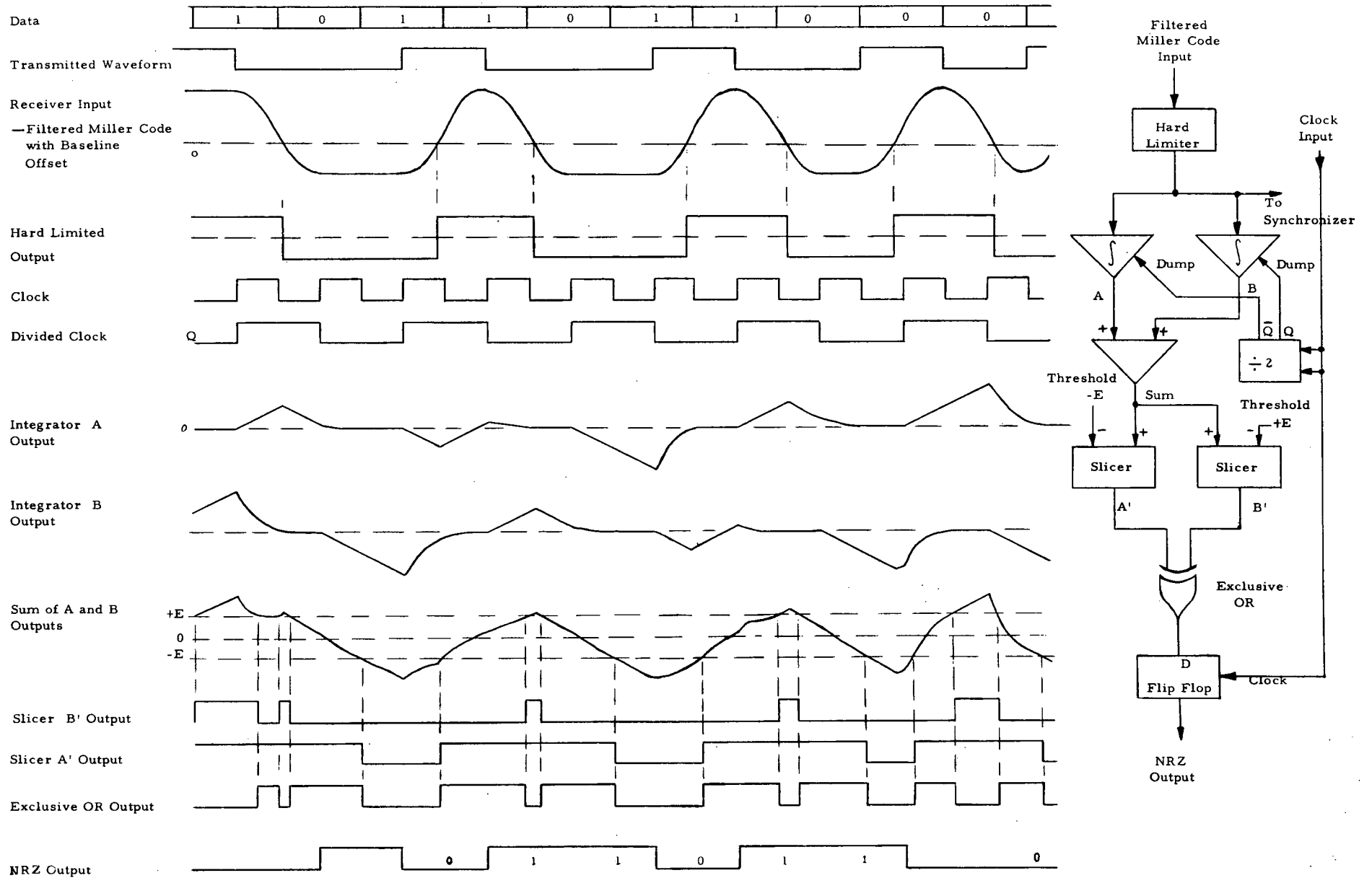
FIGURE 3.3-27   MILLER CODE DETECTION PROCESS

Data

Transmitted Waveform

Receiver Input
   -Filtered, with Offset

Input from Hard Limiter

Waveform

VCO Output

Sawtooth Gen. Output

Waveform

Shift
Register
Outputs

Clock Reset

Clock Output
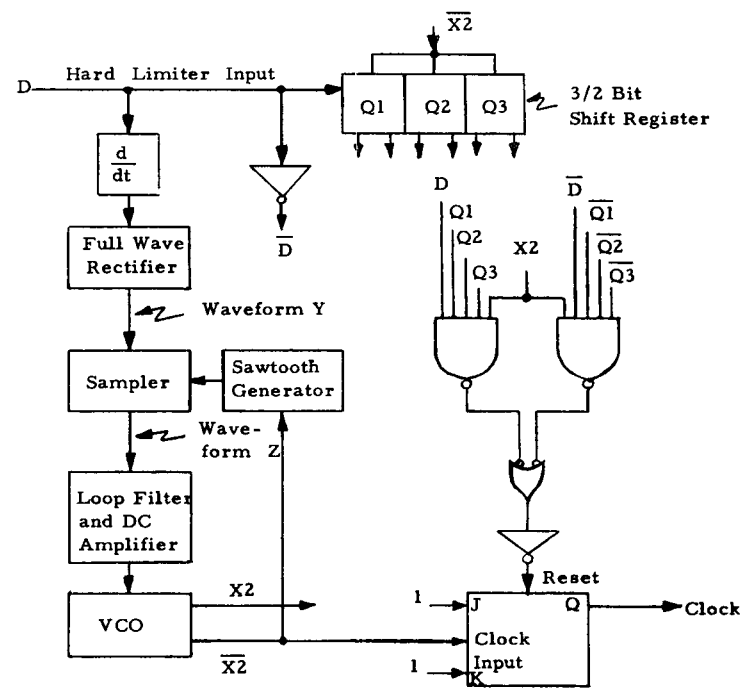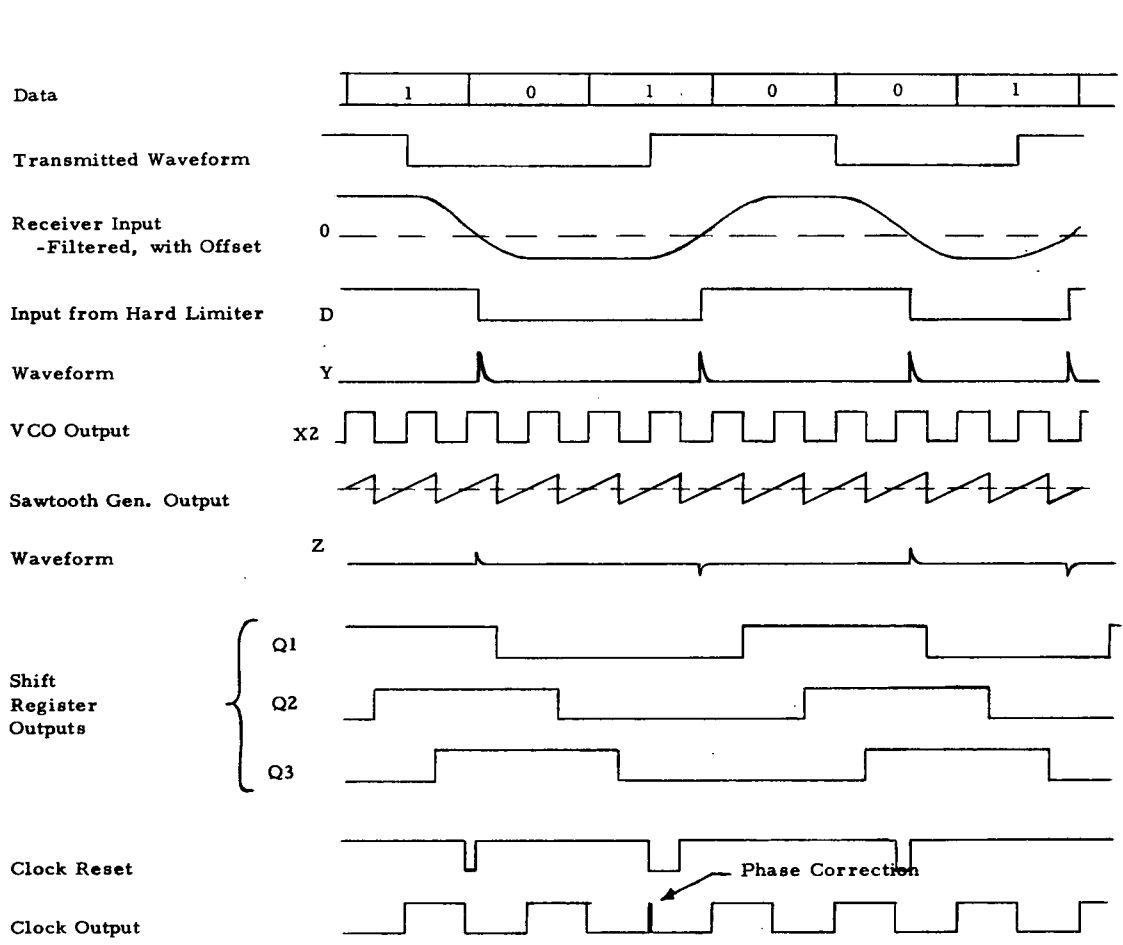
Miller Code Synchronizer

FIGURE 3.3-28   MILLER CODE SYNCHRONIZATION PROCESS
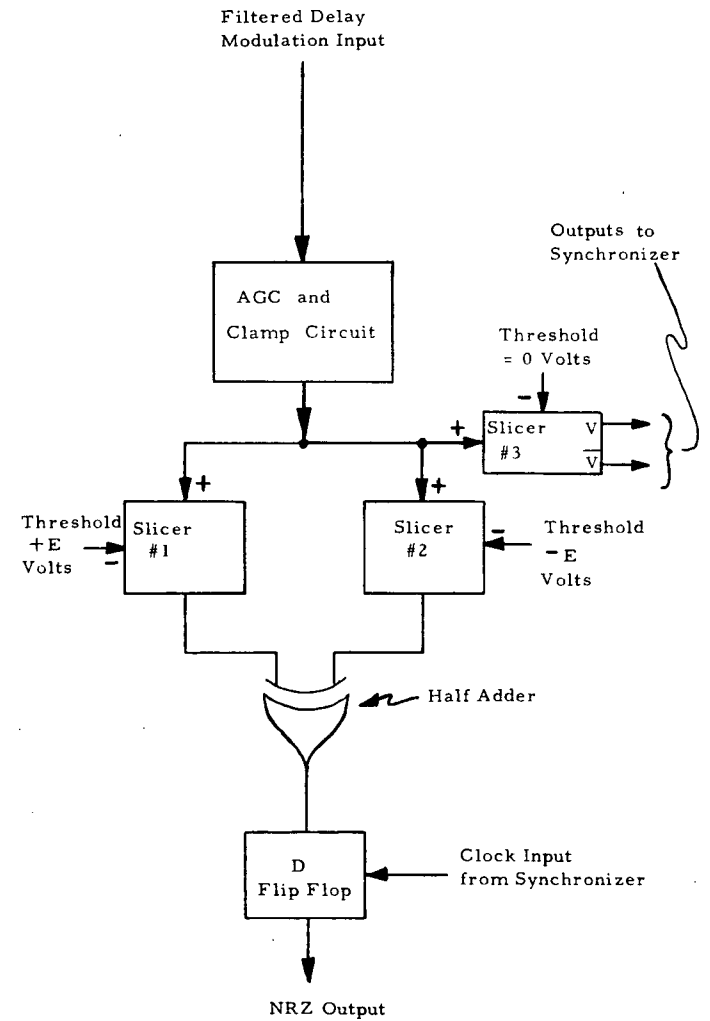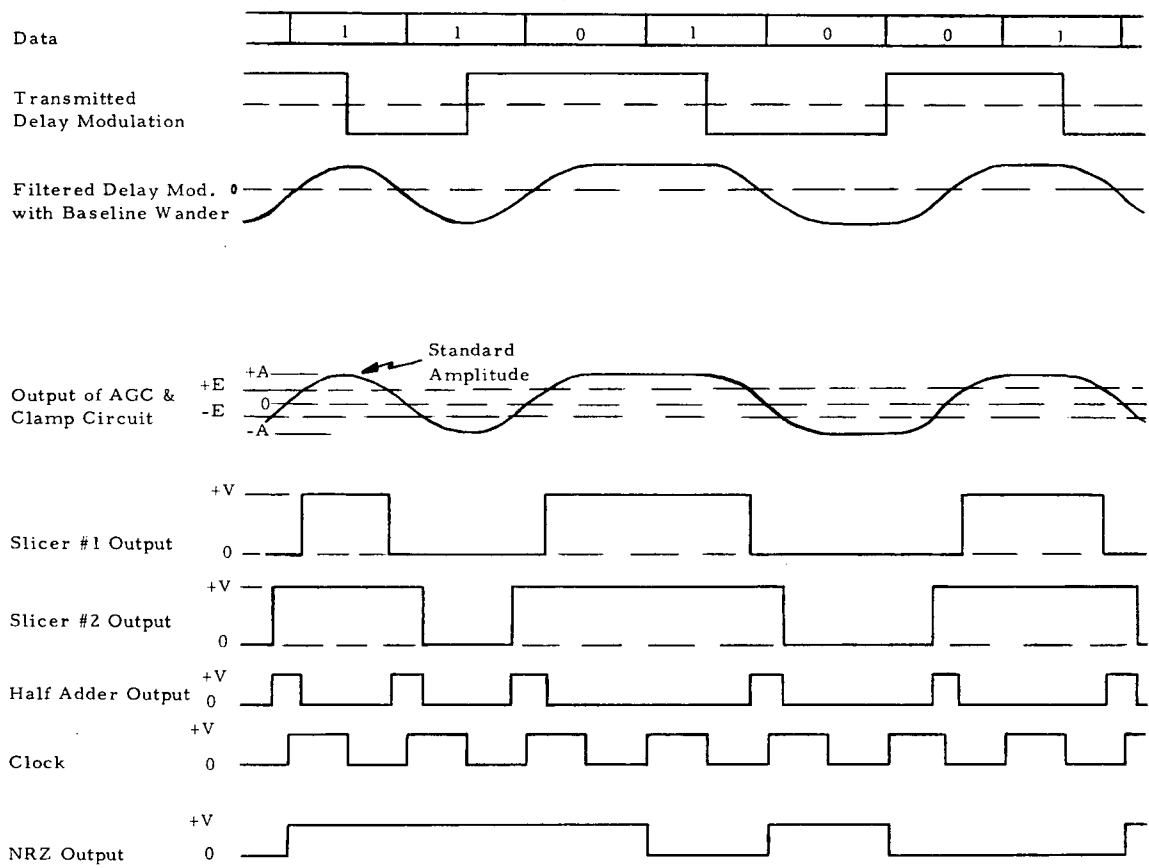
FIGURE 3.3-29   WAVEFORM AND CIRCUIT DIAGRAM OF IMPROVED DELAY MODULATION RECEIVER

characteristic, which is discussed by Bennett (ref. 1, Chapts. 5 and 7) and Lucky (ref. 2, Chap. 4), et al. It actually consists of two filters: one at the transmitter and one at the receiver. The transfer function of the transmission medium is assumed to be unity at all frequencies. The product of the two filter transfer functions yields a "raised cosine" amplitude spectrum $|G(j\omega)|$ at the receiver filter output which is plotted in Figure 3.3-32. The time interval T is one bit duration—the time interval between the PAM delta functions.

The required transfer function of the receiver filter can thus be determined if the transfer function of the filter at the transmitter is known. For example, a transmitter filter which converts PAM delta functions to NRZ data on the transmission medium would have a time response to a unit impulse as illustrated in Figure 3.3-33.

The Fourier transform of this waveform is:

$$G_T(j\omega) = \frac{2e^{-j\omega\frac{T}{2}} \sin(\omega\frac{T}{2})}{\omega}$$

A satisfactory transfer function for the receiver filter should therefore be:

$$G_R(j\omega) = \frac{[1 - \cos(\frac{\omega T}{2})]}{4 \sin(\frac{\omega T}{2})} \qquad (3.3.2.4-10)$$

since the product of $G_R(j\omega)$ and $G_T(j\omega)$ yields an overall raised cosine frequency response. Under these conditions the intersymbol interference at the output of the receiver filter is zero (reference 1, Chapt. 5, pp. 56, Figure 5-11). Figure 3.3-34 shows a practical result.

C

Figure 3.3-35 illustrates how well this filter provides the desired raised cosine frequency response characteristic when driven by NRZ data. Figure 3.3-36 is a schematic diagram of the synthesized filter circuit, with parameter values shown as a function of the NRZ signaling rate of f_s bps.

Transmitter Output Filtering

Filtering between a transmitter and the primary transmission medium of the SSV data bus for the purpose of lowering electromagnetic interference or for improved performance in the presence of noise does not appear to be necessary or desirable. EMI tests described in paragraph 6.4 of Vol. I clearly demonstrated that no transmitter filtering is necessary for reducing Electromagnetic Interference. The transmission of NRZ data in the presence of Additive White Gaussian (AWG) noise was considered. Bennett and Davey's optimum transmitter and receiver filtering scheme was compared with that described above, which requires no filter at the NRZ transmitter. It was shown that Bennett and Davey's method requires 3 db more transmitter power than is required when no filtering is provided at the transmitter and a filter of the type described above is provided at the receiver. Reference Vol. IV, paragraph 3.4.2.2 for a detailed analysis.

Figure 3.3-37 illustrates the recommended filtering arrangement, as described earlier, which employs no filtering at the transmitter.

Practical Applications of the Receiver Filter

The synthesized filter was applied to the selected signal designs which are most appropriate for use on the primary transmission medium: Bipolar NRZ, Biphase-Level and Delay Modulation. No change in the filter as shown in Figure 3.3-35 was required for Bipolar NRZ or Delay Modulation. Biphase-Level low pass filter was adjusted such to pass 2 Mbps NRZ, which also would accommodate 1 Mbps Biphase-Level.

Interference (EMI) from being radiated by the transmitter, and (2) to boost the predetection signal-to-noise ratio at the receiver. The problem of filtering for signal-to-noise ratio enhancement was analyzed, and the results summarized. On the basis of available information concerning the spectrum of the expected noise, a practical receiver input filter was designed. In addition, it was concluded that a filter between the transmitter and the transmission medium for the purpose of boosting the predetection signal to noise ratio at the receiver is neither necessary not desirable.

Receiver Input Filtering

The essential purpose of predetection filtering is to reduce the bit error ratio at the receiver output by boosting the predetection signal to noise ratio. To gain an insight into the kind of filtering required, it was useful to view the noise spectrum. Figure 3.3-30 is a recorded plot of the power spectrum produced by the impulsive noise source described in paragraph 6.2 of Volume I. However, additional tests of the impulsive noise source revealed the noise spectrum illustrated in Figure 3.3-31. The spectrum of Figure 3.3-30 shows a large concentration of noise power above 1.5 MHz, and very little noise power below this frequency, whereas Figure 3.3-31 shows a significant amount of noise power below 2 MHz. At the same time, however, this photograph shows a large concentration of noise power at high frequencies extending all the way up to about 40 MHz. From these observations, it was apparent that a filter was required which rejects high frequency noise, yet passes the useful signal without introducing excessive intersymbol interference or signal attenuation.

A conventional approach to the design of a filter which restricts the bandwidth of PAM data as much as possible without introducing excessive intersymbol interference is based on the so-called "raised cosine" frequency
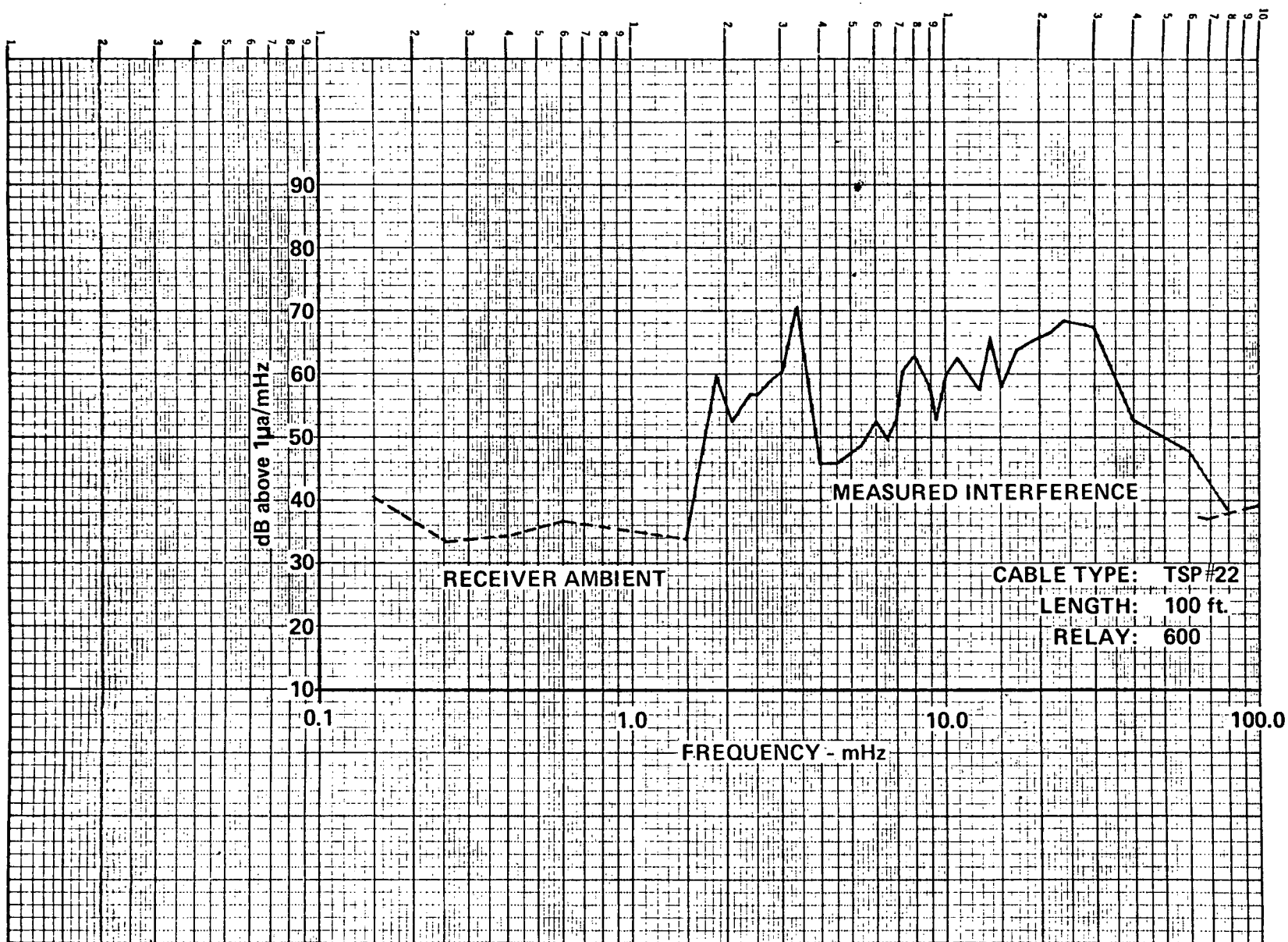
FIGURE 3.3-30 IMPULSIVE INTERFERENCE LEVEL MEASURED ON TRANSMISSION LINE
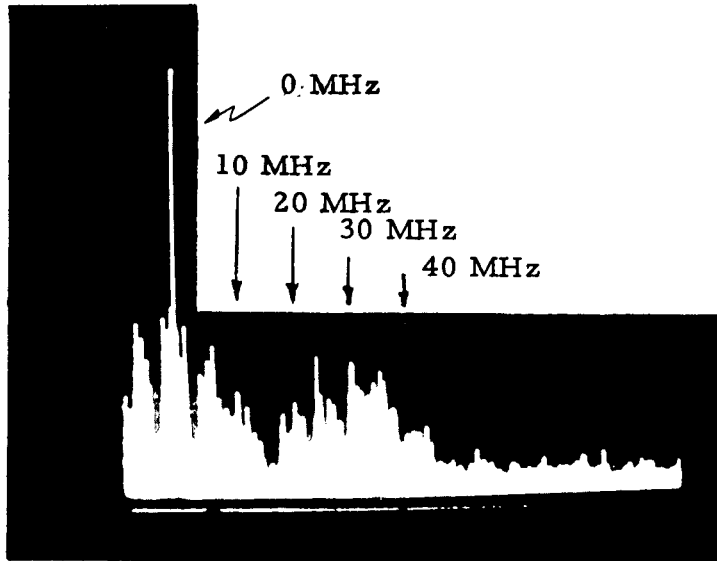
FIGURE 3.3-31   MEASURED SPECTRUM OF IMPULSIVE NOISE SOURCE
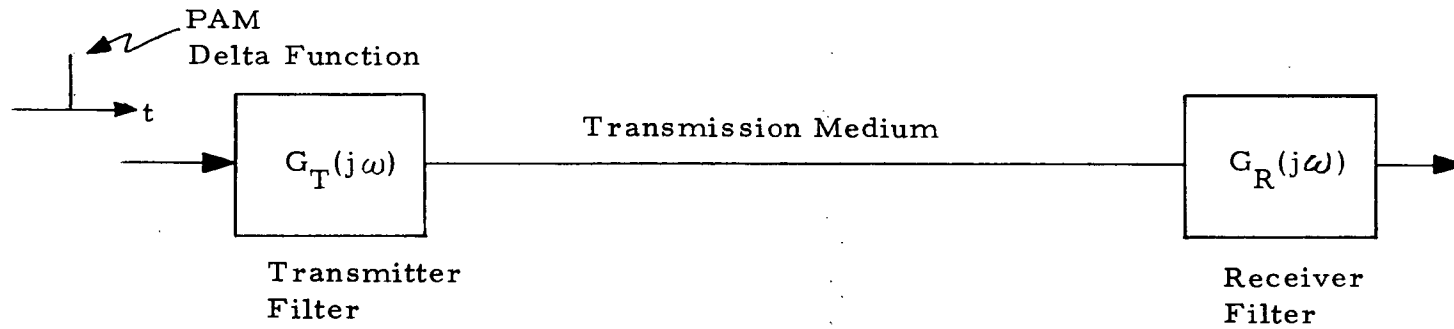
FIGURE 3.3-32a.   TRANSMITTER AND RECEIVER FILTER ARRANGEMENT
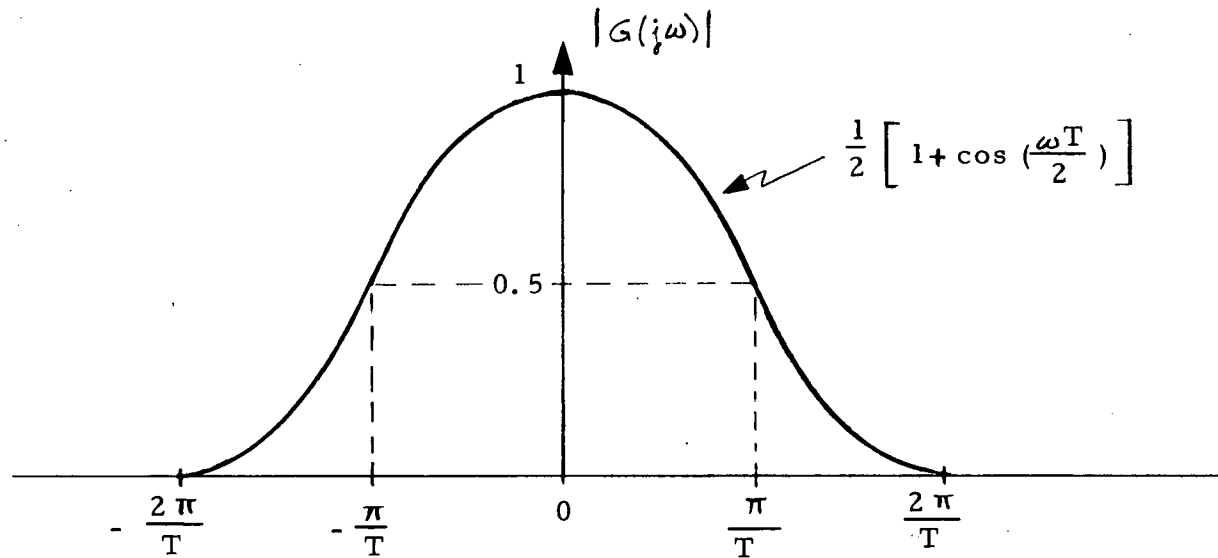
FIGURE 3.3-32b.   RAISED COSINE AMPLITUDE SPECTRUM
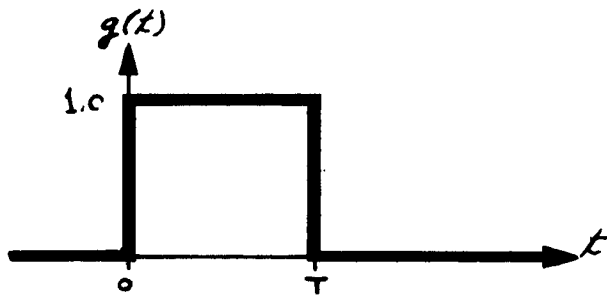
FIGURE 3.3-33   IMPULSIVE RESPONSE OF FILTER PRODUCING NRZ DATA
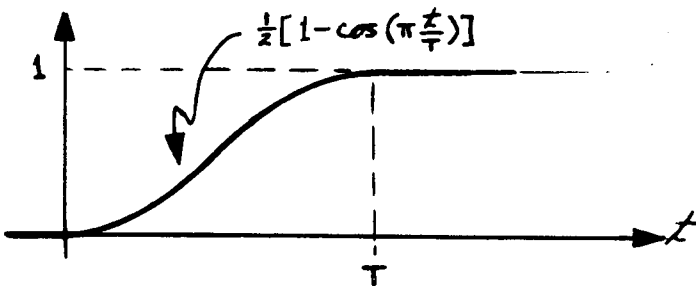
FIGURE 3.3-34   APPROXIMATE STEP RESPONSE OF
PRACTICAL RECEIVER FILTER
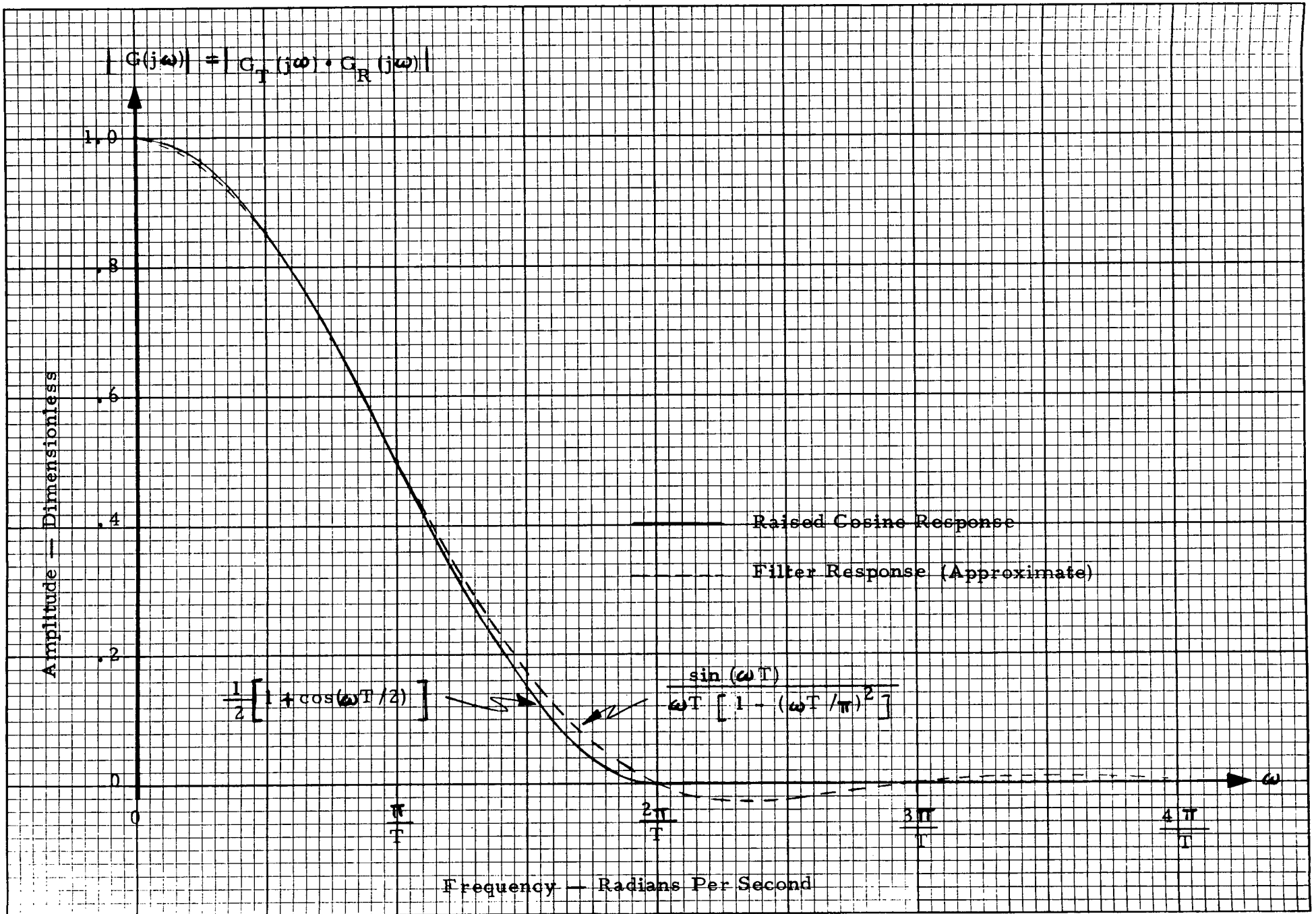
FIGURE 3.3-35   DESIRED AND APPROXIMATE FILTER RESPONSE

The diagram shows a synthesized filter with:

Top row: resistor R, then an inductor labeled $\frac{R}{4f_s}$

Shunt branches: inductors labeled $\frac{R}{4f_s}$ in series with capacitors C_1, C_2, C_3; capacitors C_0 and C_4.
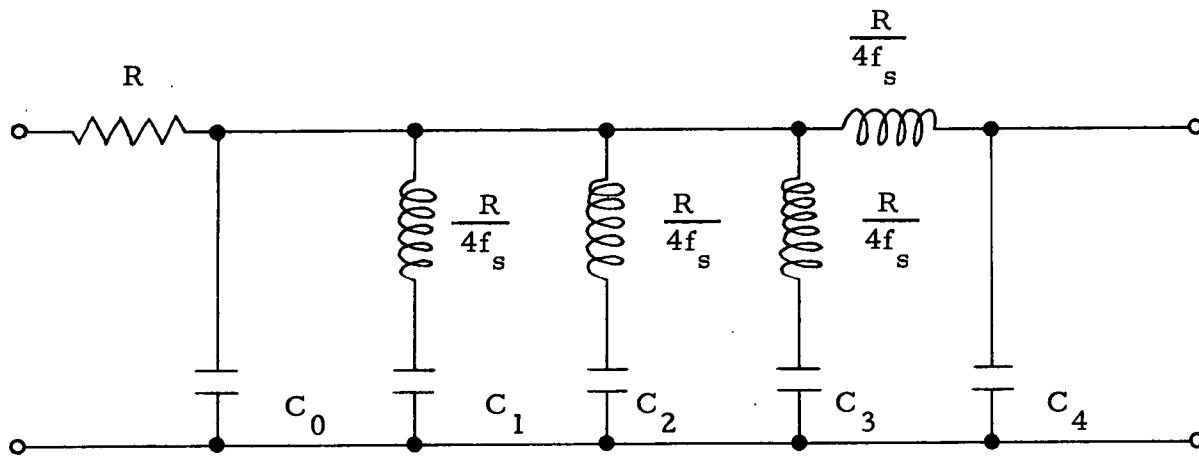
$$C_0 = 4/(14.5\ \pi^2 Rf_s)$$
$$C_1 = 4/(49\ \pi^2\ Rf_s)$$
$$C_2 = 4/(25\ \pi^2\ Rf_s)$$
$$C_3 = 4/(9\ \pi^2\ Rf_s)$$
$$C_4 = 4/(\ \pi^2\ Rf_s)$$

FIGURE 3.3-36   SCHEMATIC DIAGRAM OF SYNTHESIZED FILTER

NRZ Output

Transmitter

Transmission Medium

$F(j\omega)$

f

1/T

Receiver

Receiving Filter

Approximate
Raised Cosine
Spectrum
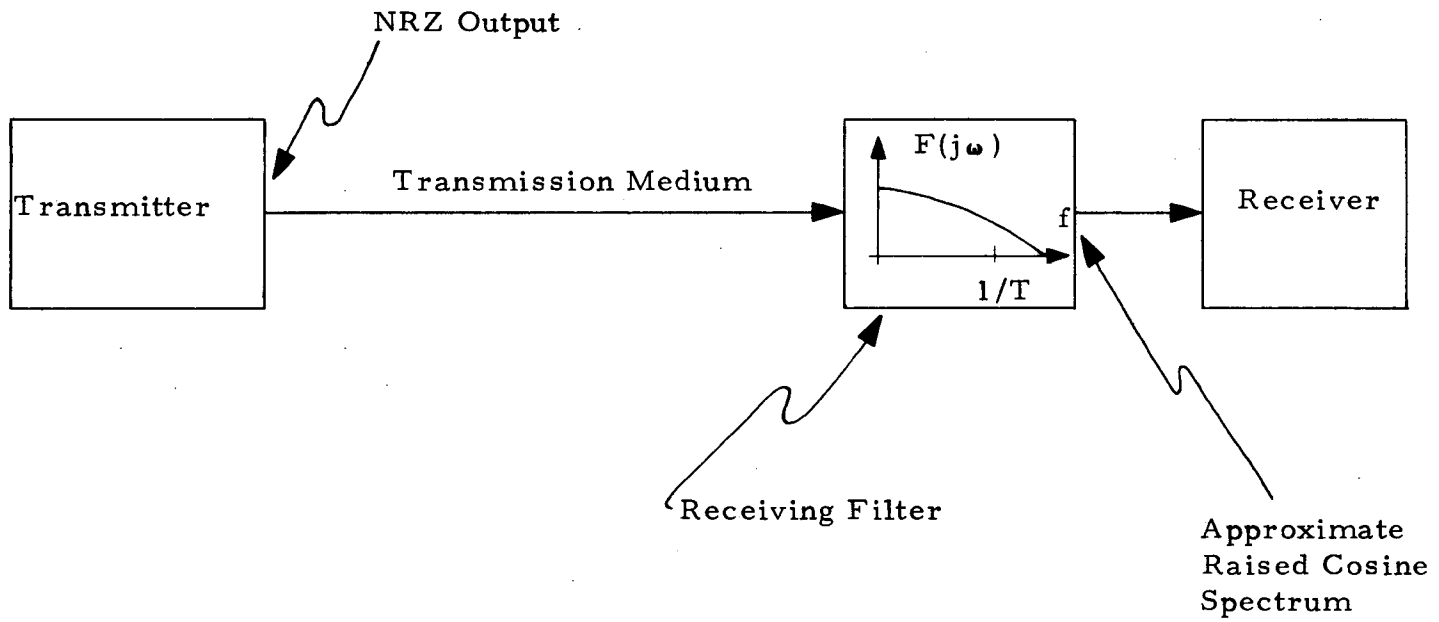
FIGURE 3.3-37   RECOMMENDED FILTERING ARRANGEMENT

Each signal modulation was transmitted at a 1 Mbps rate through 500 feet of #22 Kapton twisted shielded pair prior to filtering. The results are shown in Figure 3.3-38 through 3.3-43. The Bipolar NRZ data demonstrated negligible intersymbol interference at the sampling times (sampling time is the time at which the signal amplitude is maximum or minimum). Biphase-Level data showed negligible intersymbol interference through the filter, but a noticeable amount in Figure 3.3-41. However, its effect on the bit error ratio can be negligible by slicing the filter output about zero volts. Delay Modulation showed no intersymbol interference at the sampling time in Figure 3.3-42, and only slight interference in Figure 3.3-43. It is acceptable, however, because the original waveform can be reconstructed after removal of baseline wander by slicing the filtered output about zero volts.

3.3.2.4.3 Noise Model Definition

Paragraph 6.0 of Volume I points out that impulse noise is the only significant type of noise which is of any concern in the SSV data bus. About the subject of developing a mathematical model for the type of noise, Lucky, et al say:

> "The difficulty in measuring and mathematically characterizing this particular type of noise has prevented any significant analytical work in this area, except with practically atypical isolated identical impulses..."

The experimental work conducted in this area at SCI has partially confirmed Lucky's findings, although significant inroads have been made by Houts and Moore[4] in determining performance for the family of impulsive noise transients expected on the SSV data bus. The greatest problem encountered in formulating an equation for impulsive noise transients is
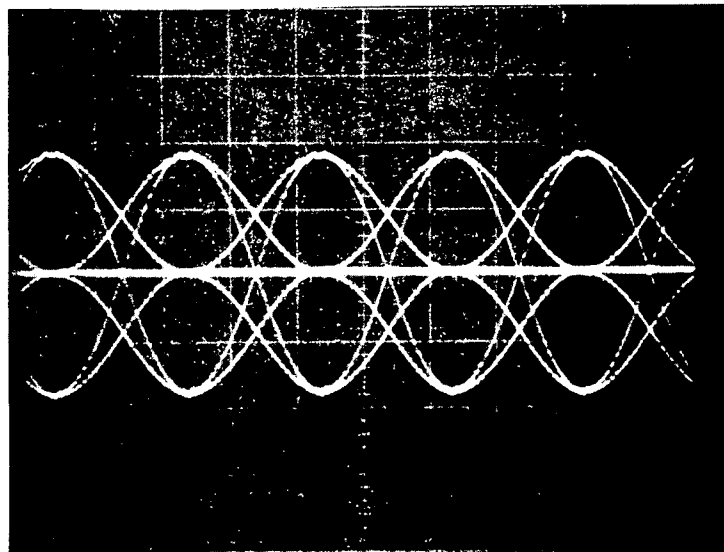
FIGURE 3.3-38   EYE PATTERN OF FILTERED BIPOLAR NRZ
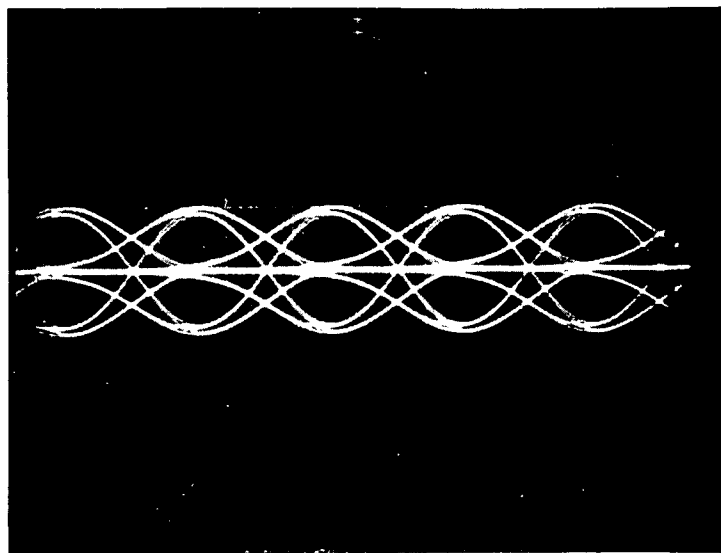
FIGURE 3.3-39   EYE PATTERN OF FILTERED BIPOLAR NRZ AFTER

PASSAGE THROUGH 500 FEET OF CABLE

3.3-65
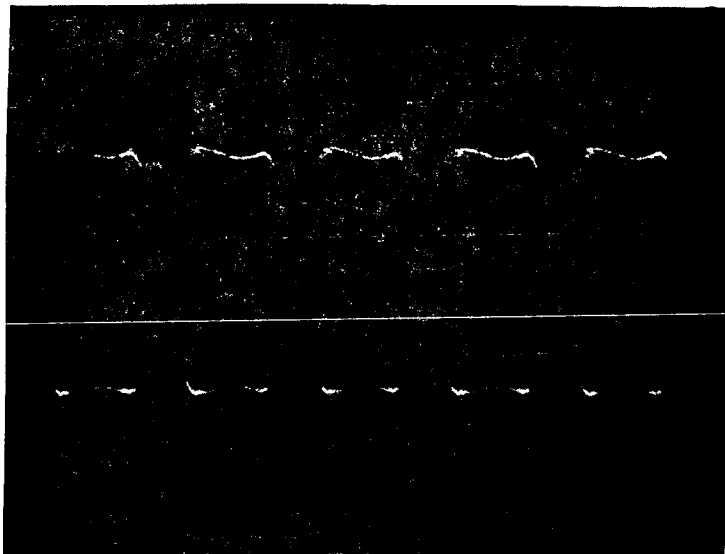
FIGURE 3.3-40   EYE PATTERN OF FILTERED BIPHASE-LEVEL
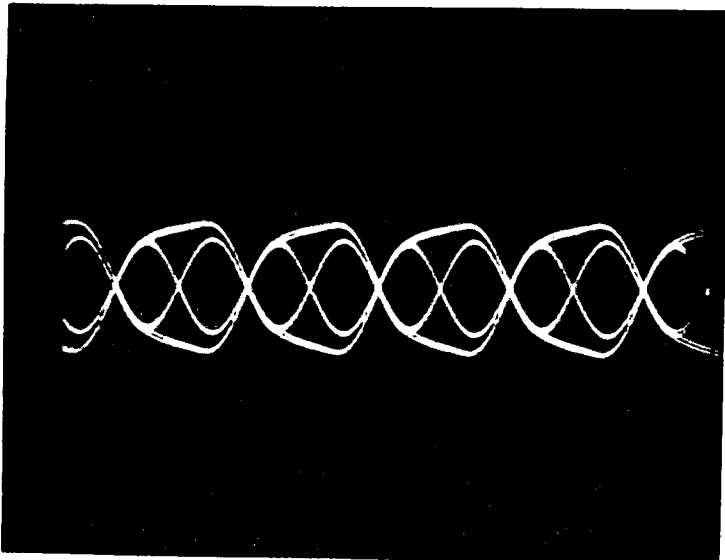
FIGURE 3.3-41   EYE PATTERN OF FILTERED BIPHASE-LEVEL AFTER
PASSAGE THROUGH 500 FEET OF CABLE
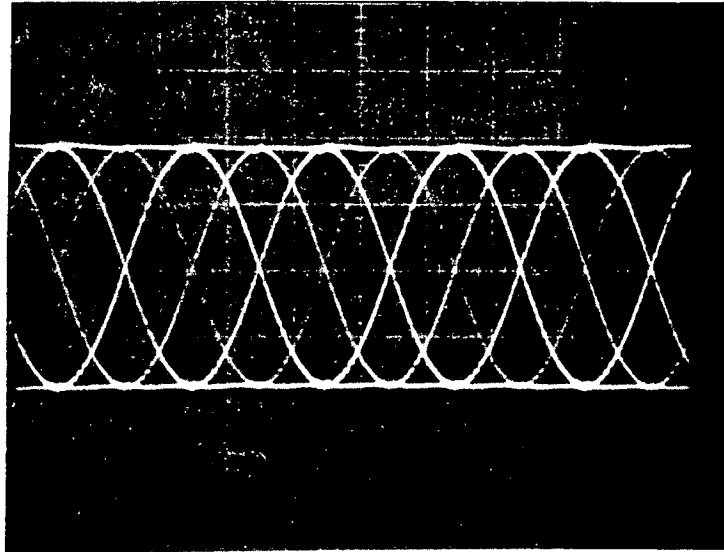
FIGURE 3.3-42   EYE PATTERN OF FILTERED DELAY MODULATION
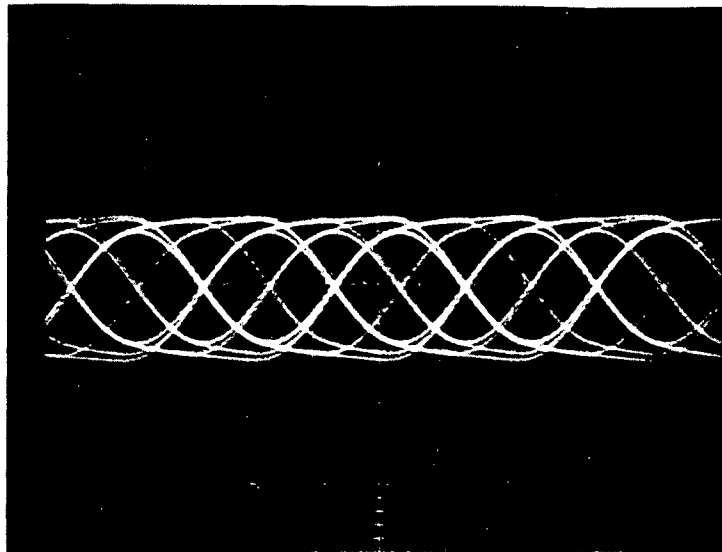
FIGURE 3.3-43   EYE PATTERN OF FILTERED BIPHASE-LEVEL AFTER
                     PASSAGE THROUGH 500 FEET OF CABLE

that certain parameters of the equation are functions of many unknown factors. Some of these factors cannot be determined until the data bus is actually installed in the SSV along with all the other avionics equipment and even then it may be extremely difficult to instrument. While it is possible to characterize the unknown parameters (of the general equation for noise transients) as random variables having assumed distributions based on judgment and experience, the mathematical treatment required to then produce meaningful results from this stochastic model is very apt to be prohibitively difficult.

Recognizing the difficulties of treating a model noise transient having random parameters, it was decided that a "worst case" noise transient should be developed, and its properties used to define a unique waveform model. The results of this effort follow.

Figure 3.3-44 is a circuit diagram of the impulsive model test set up. A screen room separated the relay noise source and cable from the filters and measuring devices to prevent the noise from coupling to the instruments through any path other than the twisted shielded pair, and in order to produce a steady flow of impulsive transients the relay was wired to cause a semiperiodic opening and closing of its contacts in the manner of a buzzer.

Photographs taken of the resulting transients and their power spectra were measured:

● Directly at the output of the twisted shielded pair (Figures 3.3-45,-46), strong frequency components seen at 0.4 and 1.9 MHz, with maximum peak amplitude of the noise transients of about 700 mv.
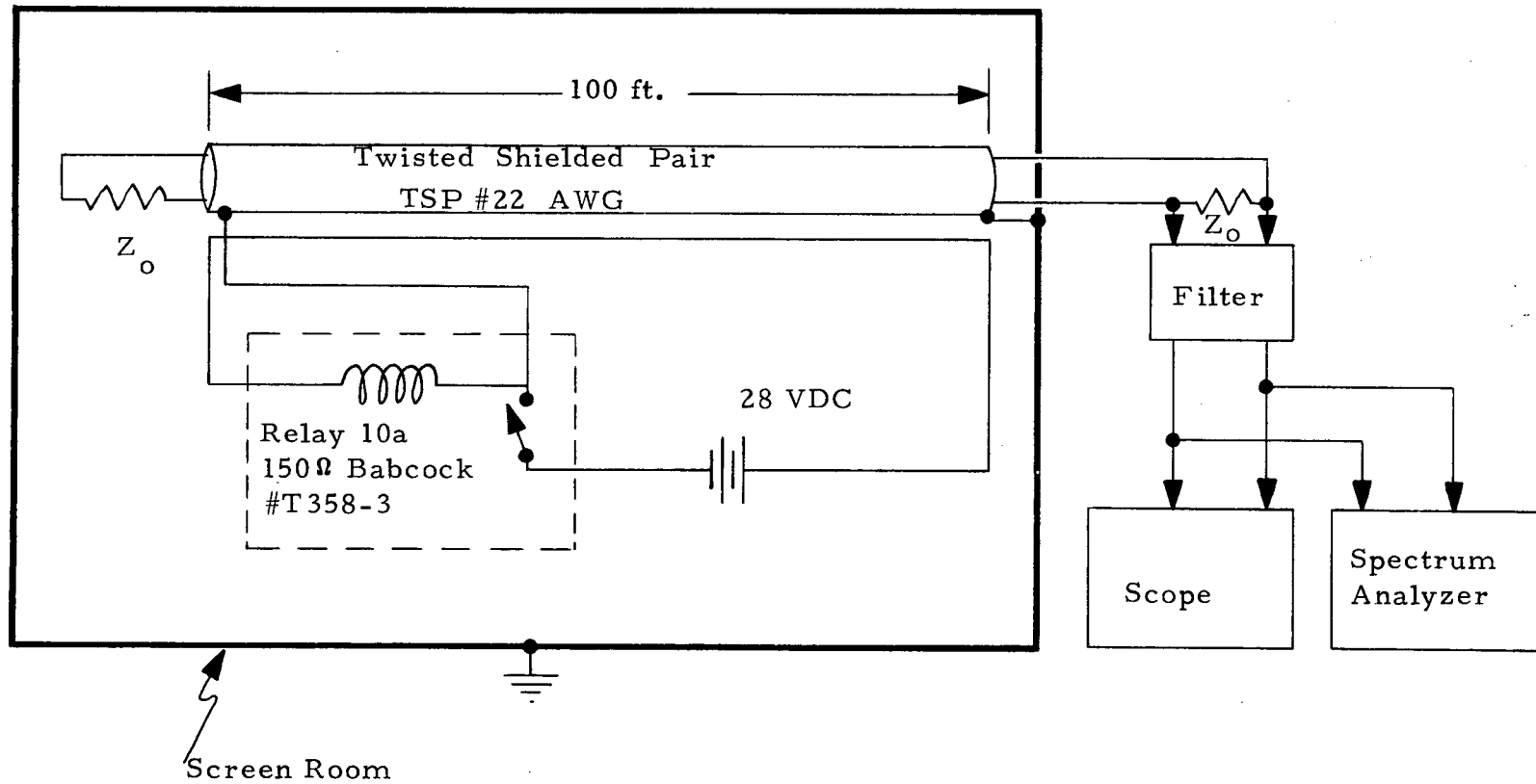
FIGURE 3.3-44   CIRCUIT DIAGRAM OF THE INTERFERENCE MODEL AND
ASSOCIATED INSTRUMENTATION

Vertical Scale:

200 MV /DN

Horizontal Scale:
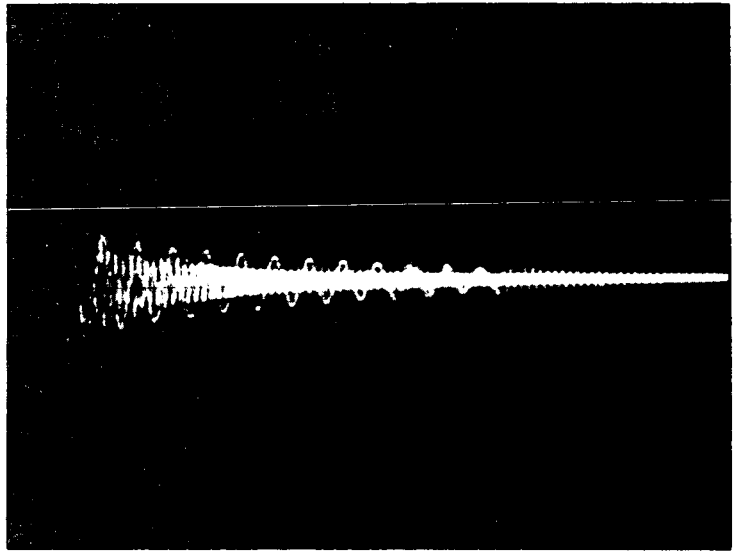
5 Microsec. /Div.

FIGURE 3.3-45   UNFILTERED NOISE TRANSIENTS

Vertical Scale:

10 db/div.

0.0 MHz

0.4 MHz

1.9 MHz
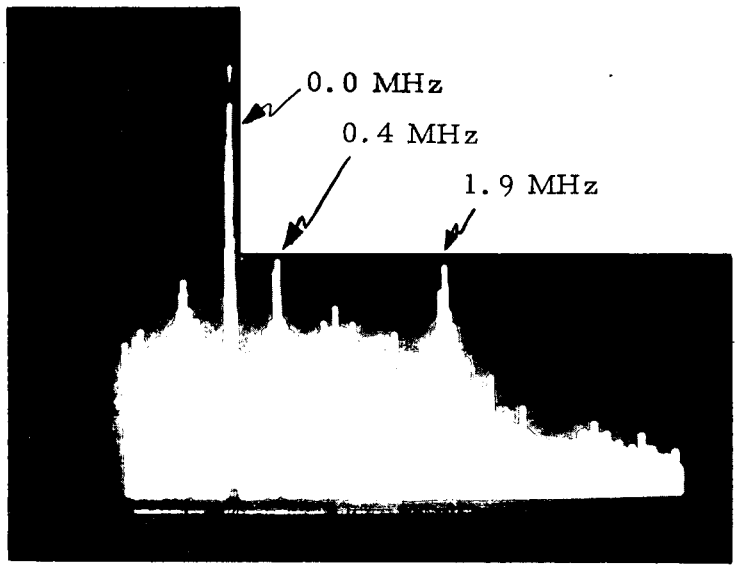
FIGURE 3.3-46   UNFILTERED NOISE SPECTRUM

Vertical Scale:

    100 mv/Div.

Horizontal Scale:

    5 Microsec./Div.
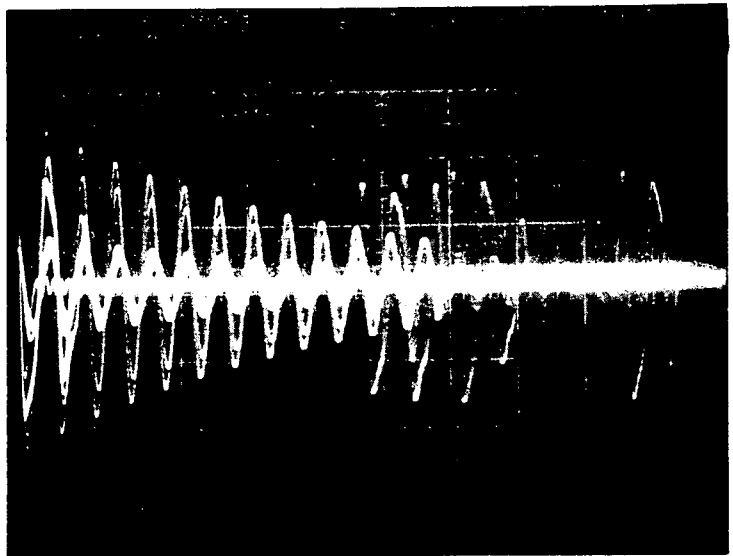
FIGURE 3.3-47   NOISE TRANSIENTS AT OUTPUT OF
1 Mbps BIPOLAR NRZ FILTER

Vertical Scale:

    10 db/Div.

0.0 MHz

0.4 MHz

1.9 MHz
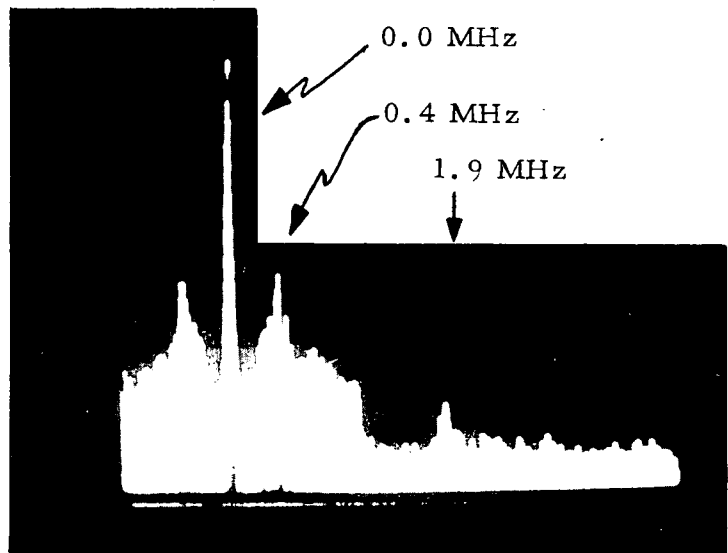
FIGURE 3.3-48   NOISE SPECTRUM AT OUTPUT OF
1 Mbps BIPOLAR NRZ FILTER

Vertical Scale:

    100 mv/Div.

Horizontal Scale:

    5 Microsec./Div.
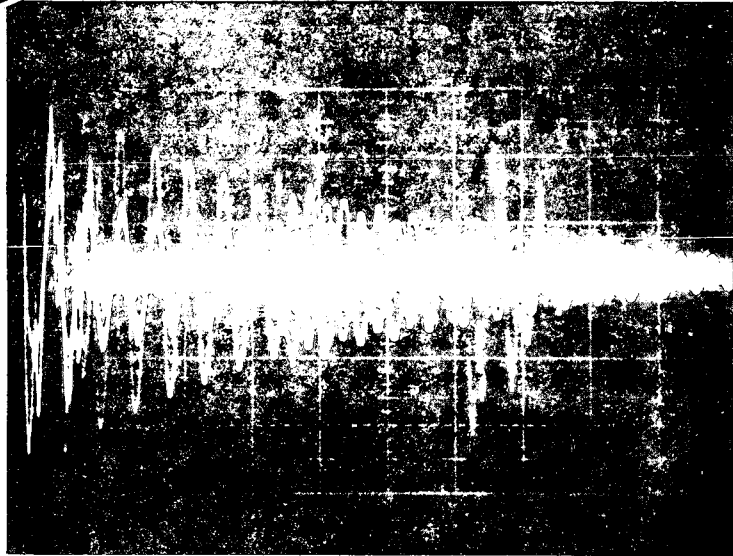
FIGURE 3.3-49   NOISE TRANSIENTS AT OUTPUT

                            OF 1 Mbps BIPHASE FILTER

Vertical Scale:

    10 db/Div.

0.0 MHz
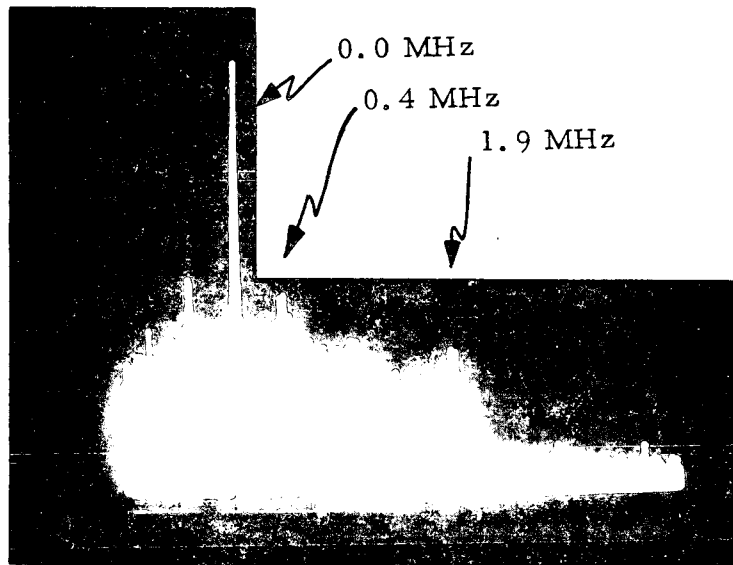
0.4 MHz

1.9 MHz

FIGURE 3.3-50   NOISE SPECTRUM AT OUTPUT

                            OF 1 Mbps BIPHASE FILTER

- At the output of a filter designed for reception of 1 Mbps Bipolar NRZ (Figures 3.3-47, -48)—filter rejects the 1.9 MHz frequency component, but passes the 0.4 MHz damped sine wave. 250 mv maximum peak amplitude seen.

- At the output of a filter deigned for reception of 1 Mbps Biphase-Level (Figures 3.3-49, -50)—The transient is the same damped sinusoid observed in Figure 3.3-47, but with a noticeable amount of energy above 0.4 MHz.

Conclusions and Definition of Noise Model

From experimental evidence of the model tested, it is clear that the observed noise bursts may be well-approximated mathematically by the GIN (Unique Waveform) model described by Houts and Moore[4]. In particular, they treat the case of an exponentially decaying sinusoid in considerable detail, and much of this work is thus directly applicable to the characterization of the noise actually observed in the laboratory.

It should be recognized that the amplitude, frequency and damping factor of the observed noise transients are functions of cable type, cable length, length of interfering wire, distance between the interfering wire and the twisted shielded pair, relay type, switch contacts and possibly other variables. In addition, the frequency of occurrence of noise bursts and the number of noise transients occurring with each burst are also functions of many factors which in general are not well-defined.

With the above facts in mind, a specific mathematical model of this impulsive noise based on experimental evidence may nonetheless be defined as follows:

General Nature of Unique Waveform	Damped Sine Wave
Frequency of Damped Sine Wave	0.4 MHz
Time Constant of Damped Sine Wave	10 μsec
Duration of the Burst Interval	1.5 ms
Average Number of Unique Waveforms/ Burst Interval	10
Distribution of Initial Amplitude of Unique Waveform	Gaussian with Zero Mean
Standard Deviation of Initial Amplitude:	
Out of 1 Mbps Bipolar NRZ Filter	125 mv
Out of 1 Mbps Biphase Filter	200 mv

Using these data, together with an estimate of the average number of noise bursts per unit time, it should be possible to determine Bit Error Ratio vs. the Energy to Noise Parameter (ENP) defined by Houts and Moore. However, the effort required to perform such an analysis is of such a magnitude and the results so questionable (due to the unknown nature of the true noise sources) that the value of such an endeavor does not appear to justify its pursuit, at least for the purposes of this study.

Worst Case Gaussian Noise Model

Because of the difficulty of determining bit error ratio as a function of ENP using the impulsive noise model just described, a worst case Gaussian model was formulated. The bit error ratio resulting from this Gaussian noise model should far exceed that due to the impulsive model because of the conservative assumptions on which it is based.

For worst case bit error ratio calculations, it was decided that stationary Additive White Gaussian noise would be assumed. The mean value of this noise should be zero, since the mean value of all measured noise transients

was zero. The standard deviation of the Gaussian noise has been assumed to be one-half the peak amplitude of the largest noise transient measured in the tests previously described. This was a very overly-conservative assumption since maximum amplitude noise bursts actually occur very infrequently compared to the frequency with which the Gaussian model reaches values exceeding twice its standard deviation. For this reason, the bit error ratios for the case of the impulsive noise described before should be well below estimates of those which are based on this worst case Gaussian noise model.

3.3.2.4.4 Synchronization

Some of the problems concerned with the generation and reception of bit and word synchronization information are directly associated with signal design and detection methods. For this reason, techniques for extracting bit timing information from received signals and two classes of word synchronization techniques most applicable to the SSV data bus were examined.

Bit Synchronization

Bit synchronization information is referred to by Bennett and Davey (ref. 1 Chapt. 14, pp. 260-267) as "symbol timing" information whose detection at a receiver is often called "clock extraction". Bennett and Davey describe the two basic clock extraction techniques based on the detection of the time of occurrence of level transitions, followed by:

- Smoothing of level transition information by a passive filter.
- Smoothing of level transition information by a phase locked loop.

The latter form of smoothing can be made more reliable in the presence of noise because it allows one to smooth timing information over a much

greater period of time. Neither of these techniques is effective unless level transitions in the transmitted signal occur with sufficient frequency. This condition can be assured by coding the transmitted signal to provide a regular flow of level transitions, as is the case with Delay Modulation, Biphase-Level and Polar RZ (only Biphase-Level and Polar RZ are truly "self-clocking" signaling forms). In all the remaining signaling forms of the recommended signal set, with the bit sync methods cited by Bennett and Davey, there would then be a distinct possibility that sync would be lost.

In both Polar RZ and Biphase-Level, a level transition always occurs in the middle of each bit interval, making it possible to extract clock information directly. Consequently, the phase of the individual clock pulses that are detected in this manner, as well as the phases of the bit trains in successive words are free to vary. However, while direct extraction of clock information is simpler (no smoothing required) and affords greater versatility (possibility of either centralized or distributed timing between all transmitters and receivers), it is inherently less reliable in the presence of noise.

Delay Modulation is not a truly self-clocking signaling form, since transitions may not occur during a time interval as great as two bit periods. However, it does provide a steady flow of symbol timing information, and therefore appears to be appropriate for those applications wherein continuous bit synchronization between a transmitter and receiver is desirable or necessary.

Word Synchronization

In a centralized (synchronous) system in which words are made up of a fixed number of bits, Bennett and Davey (ref. 1, Chapt. 14, pp. 260-267)

have pointed out that word timing pulses can be obtained by dividing the bit clock. Each word timing pulse must begin at a known bit position within a word. Once the correct phase of the word timing pulse train has been established, no additional word synchronization information is required at the receiver, provided no errors subsequently occur in the bit timing clock. To prevent the loss of more than a single word due to a single error in the bit timing clock, a special word synchronization pattern is customarily sent at the beginning of each word. For the same reason, a special word synchronization pattern is customarily sent at the beginning of every word in a distributed (asynchronous) system.

Lucky, et al (ref. 2, Chapt. 11, pp. 361-368) discuss several sophisticated word synchronization techniques based on redundant coding using cyclic codes and coset codes. However, due to the greater hardware complexity introduced by block encoding and decoding for error control, these approaches appeared to be less appropriate for the SSV than the more conventional technique of transmitting and detecting a special synchronization pattern at the beginning of each word.

Of the many possible types of synchronization patterns which might be transmitted, it was convenient to group them into two classes: 1) bit patterns and 2) unique waveforms.

A bit pattern was defined as a fixed number of binary digits corresponding to a specific binary number. These bits for all intents and purposes appear to be the same as data bits, and differ from data only by their position in the word format. Customarily, they are all grouped together at the beginning of a word. Figure 3.3-51 illustrates the transmitted waveform which results when a word synchronization bit pattern of 111 is followed by the data sequence 01101 and the resulting wavetrain is coded to produce Biphase-Level.

If the synchronization bit pattern is unique, it cannot be confused with the data sequence bit patterns. Considerable complexity results from such coding, and more often a bit sync pattern is used that is not unique.

Figure 3.3-52 contains an example of a synchronization pattern belonging to the unique waveform class. The unique waveform of the synchronization pattern is wholly different from that which contains the data, and can therefore be used to rephase the word timing whenever it is recognized. The unique synchronization waveform is normally detected separately from the data by special circuits designed to recognize its presence.

The choice of specific word synchronization patterns for the SSV data bus is governed not only by the complexity of the circuits required to generate and detect them, but also by the amount of overhead bits available for this function and the amount of noise immunity required. This interrelates very strongly with the overall system problems encountered in the study of synchronization, timing and control (reference Section 3.4).

3.3.2.5   Comparison of Techniques

In order to compare the different siganling techniques, it was first necessary to establish appropriate evaluation criteria. Among the more significant evaluation criteria was the predicted performance of each signaling technique in the presence of noise. Therefore, the performance of each technique in the presence of Additive White Gaussian (AWG) noise was determined.

The final comparison of all techniques in terms of all the evaluation criteria is provided in the applications summary. Here it was concluded that the best all around signaling schemes for use on the primary transmission medium are Biphase-Level and Bipolar NRZ. Delay Modulation was found

Word Contents

Prior to Coding
by Transmitter

| 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |

Sync Bits   Data Bits

Transmitted
Biphase-Level

+v
0
-v
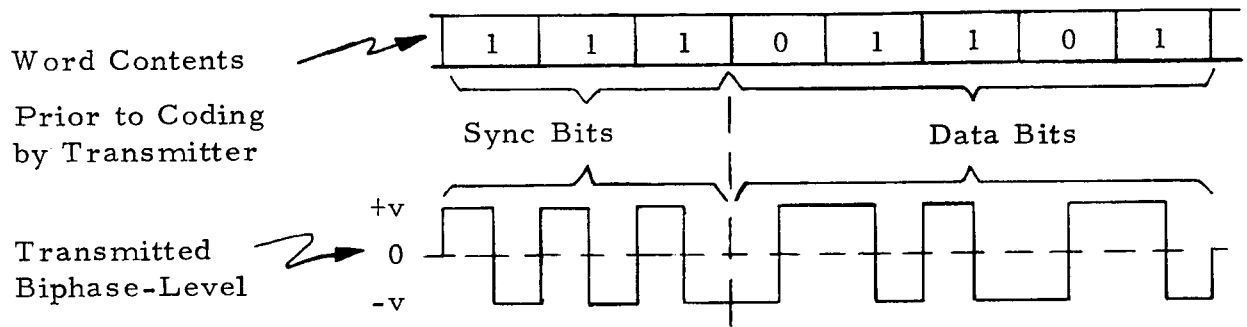
FIGURE 3.3-51.   EXAMPLE OF A WORD SYNCHRONIZATION TECHNIQUE
BASED ON A SPECIAL BIT PATTERN

Unique
Word Sync
Waveform

Biphase
Data

+2v
+v
0
-v
-2v
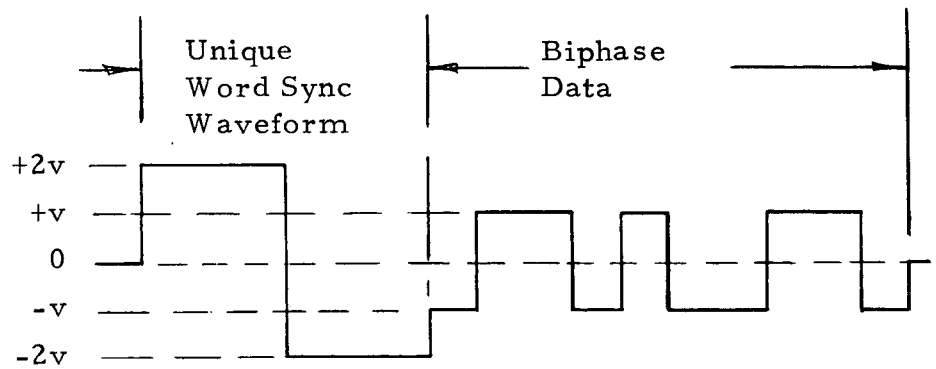
FIGURE 3.3-52.   EXAMPLE OF A WORD SYNCHRONIZATION TECHNIQUE
BASED ON A SPECIAL UNIQUE WAVEFORM

to be less desirable for this application because of its greater complexity. Polar RZ appeared to be best for use in short direct coupled local buses because it contains bit synchronization information, and at the same time was simpler than any other forms except Unipolar and Polar NRZ. Polar NRZ is recommended only for applications in the internal digital logic of individual terminal equipment.

Evaluation Criteria

In deciding which signal design was most appropriate for a given application the following evaluation criteria were significant considerations.

- Error Detection Capabilities

Some of the signal designs have built-in redundancy which make it possible for logic in the receiver to detect bit errors. This may prove useful, especially in those applications where the addition of special parity bits for this purpose is not appropriate. Even in systems employing parity bits, the additional error detection capability inherent in some signal designs may be desirable in order to improve the operational reliability of a system by lowering the probability of undetected errors.

- Hardware Complexity

The complexity of hardware required to generate and receive each signal is a most important consideration, not only because of physical weight and space considerations, but also because hardware simplicity leads to greater operational reliability.

- Required Transmission Bandwidth

The bandwidth restriction caused by the transmission medium is not severe enough to cause significant intersymbol interference for any of the signal

designs being considered. Hence transmission bandwidth does not appear to be as significant a factor as other evaluation criteria.

● Compatibility with Transformer Coupling

Paragraph 5.2 of Volume I points out the desirability of using transformer coupling between all data terminals and the primary transmission medium. However, some of the selected signal designs simply cannot be received after passage through a transformer. Hence, compatibility with transformer coupling really determines whether a signal design is suitable for use in the primary transmission medium.

● Presence of Sufficient Synchronization Data

Some of the signal designs do not alone contain sufficient synchronization data in themselves to allow reliable reception. In these cases, synchronization information must be provided by some other means such as via a separate channel. In some cases, such a provision may be unacceptable or less desirable than using for example a signal design which is self-clocking.

● Complexity of Bit Synchronization Circuitry

This criterion need only be considered for those members of the recommended signal set which provide adequate synchronization information. In these cases, the same considerations listed above under "Hardware Complexity" apply.

● Required Signal-to-Noise Ratio

This criterion was important because it allows one to compare the relative transmitter power required with each signal design in order to yield com-

parable performance. Here for convenience we assumed optimum synchro-
nous detection for each member of the recommended signal set in the pre-
sence of Additive White Gaussian (AWG) noise. While it is true that
AWG noise does not in general yield the same performance as impulsive
noise, Bennett and Davey[1] and Lucky, Salz and Weldon[2] both claim
that the _relative_ bit error ratios can be determined for nearly all noise
environments by comparing performances in the presence of AWG noise.
More recent work by Houts and Moore[4] tends to confirm this hypothesis,
although a major exception was noted in a comparison of On-Off, Binary
Antipodal, and Orthogonal signaling methods.

It was also recognized that the actual performance using practical
detection techniques in general differ from that of the optimum achievable
by a correlation receiver in the presence of AWG noise. In the presence
of AWG noise practical receivers are usually less efficient, and Houts and
Moore[4] have shown that it is possible to design practical receivers which
are more effective than correlation receivers in the presence of certain
types of impulsive noise. In general, when pre-detection filtering is used
with a non-optimum detector (as is recommended earlier in this report)
a performance penalty proportional to the square root of the signal band-
width occupancy may result. This means, for example, that the variation
in performance between such a detector and an optimum correlation
detection will be 3 db greater for a signal, such as Bi-$\emptyset$-L, whose spectral
occupancy is equal to the bit rate than for a signal of bandwidth $f_s/2$ such as
polar NRZ. An example of this variation is shown in Figure 3.3-55, which
shows a difference of approximately 5 db between the performance of a
correlation detector and an AIB detector for a biphase level signal. None-
theless, because it is less difficult to determine and also because it has been
standard practice in the past, the various signaling schemes will be compared
assuming optimum correlation detection in the presence of AWG noise.

Optimum Performance in Additive White Gaussian (AWG) Noise

Figures 3.3-53 and 3.3-54 show the optimum theoretical performance of each member of the recommended signal set in the presence of Additive White Gaussian noise. Figure 3.3-53 contains plots of bit error ratio vs. the ratio of average transmitted signal power to average noise power on the data bus, where the noise power is that measured in a bandwidth equal to the bit rate. The curves of Figure 3.3-54 show bit error ratio vs. the ratio of peak transmitted signal power to average noise power on the data bus in a bandwidth equal to the bit rate.

When viewing the curves of Figures 3.3-53 and 3.3-54 it should be borne in mind that the results are valid only for the case of synchronous detection by means of a correlation receiver. A practical receiver will produce different results. For example, the performance of the Asynchronous Integrating Biphase (AIB) receiver is nonoptimum, as is clearly illustrated in Figure 3.3-55. Here it may be observed that the AIB receiver is about 5 db less effective than the Optimum Synchronous Biphase receiver, but is about 1 db better than Optimum Synchronous Delay Modulation or Bipolar NRZ.

From the example just shown it is clear that the curves of Figures 3.3-53 and 3.3-54 should not be used to estimate attainable performance. The reason for this is that there are several conditions that must be met in order to achieve optimum performance using a correlation receiver which are not in general satisfied by the kind of receiver one would prefer to use in the SSV data bus application. For example, optimum synchronous detection by a correlation receiver assumes that:
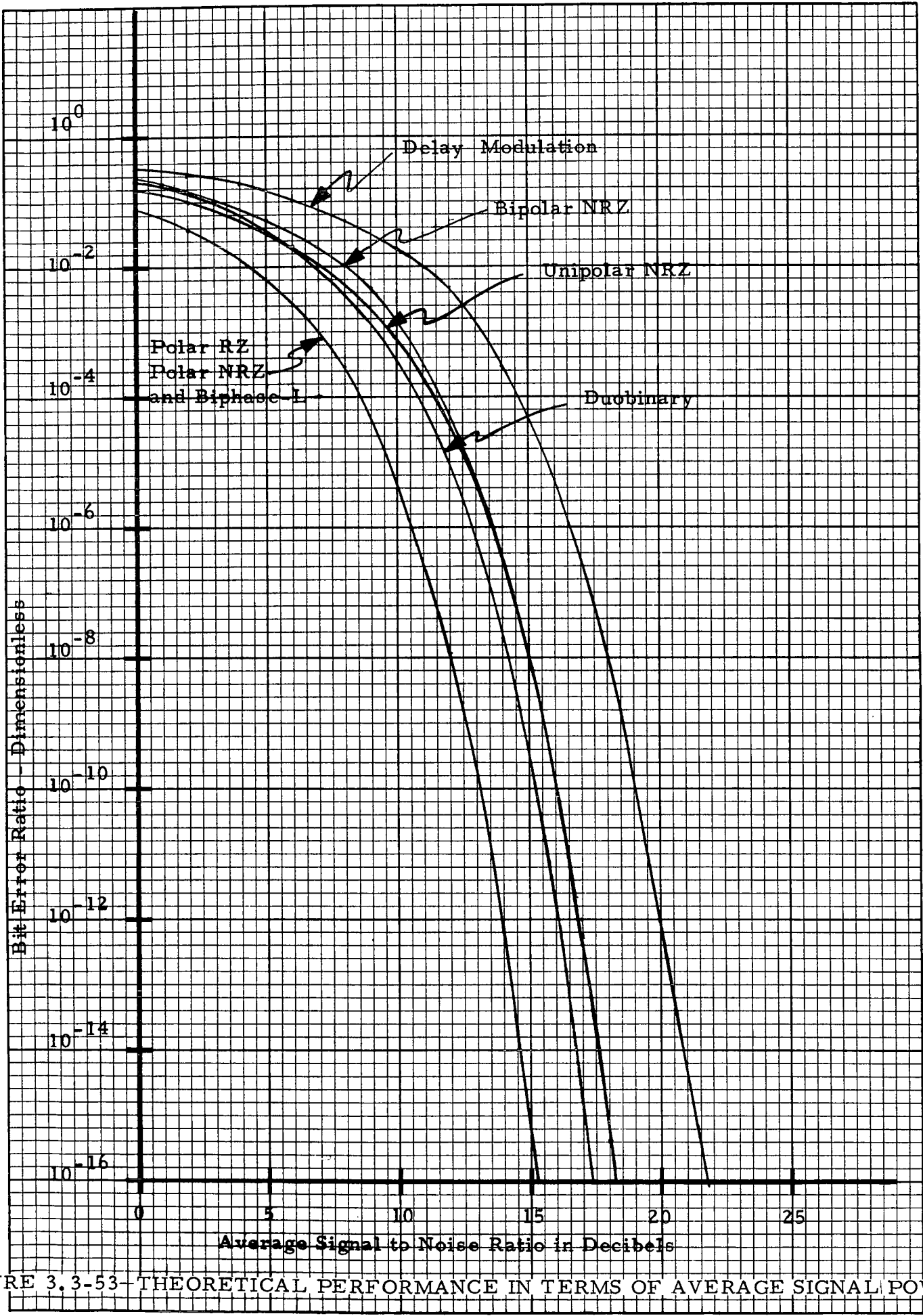
FIGURE 3.3-53- THEORETICAL PERFORMANCE IN TERMS OF AVERAGE SIGNAL POWER
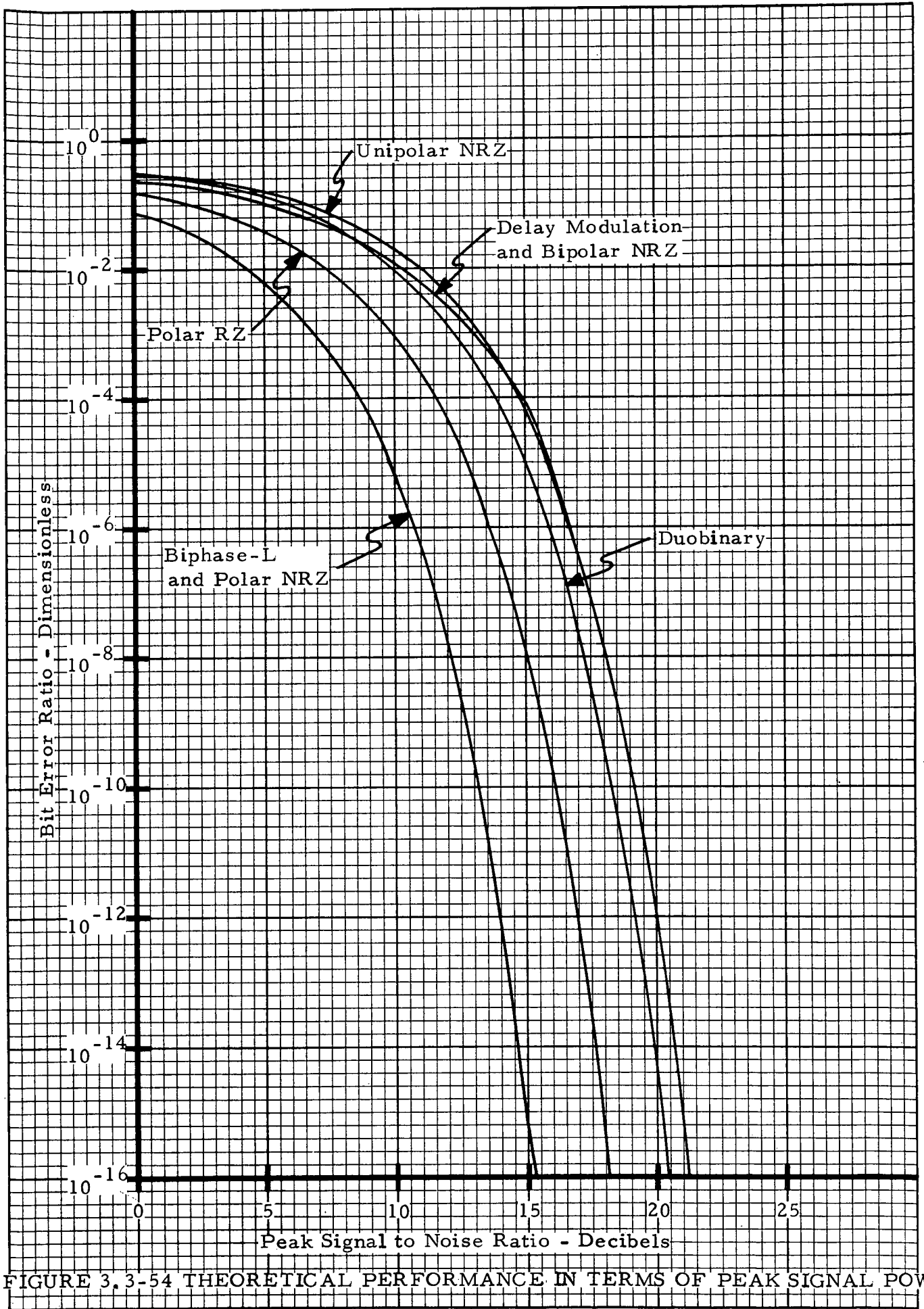
FIGURE 3.3-54 THEORETICAL PERFORMANCE IN TERMS OF PEAK SIGNAL POWER
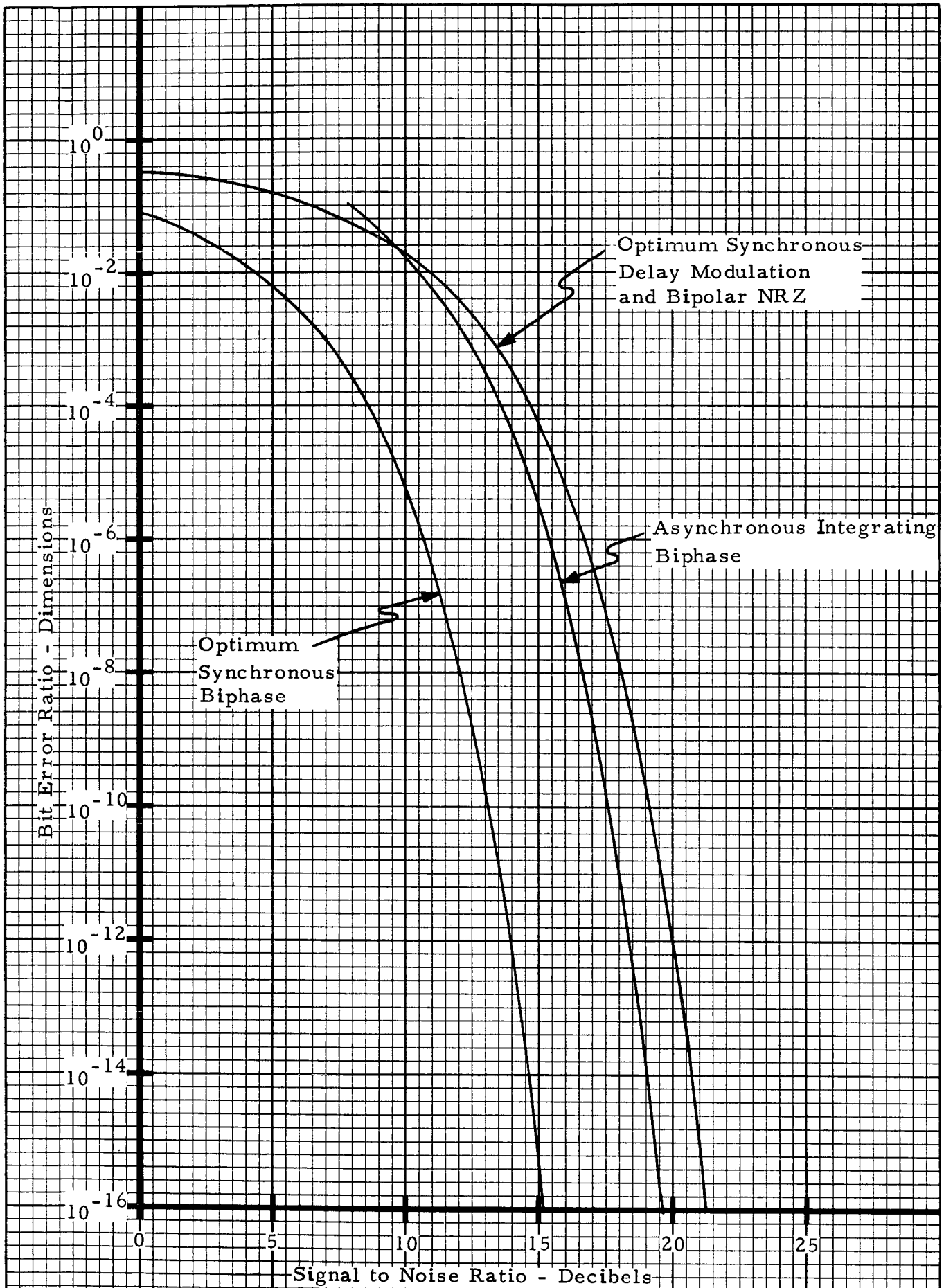
FIGURE 3.3-55   PERFORMANCE COMPARISON OF SIGNALING METHODS

- The reference waveform at the receiver must be perfectly synchronized with the received waveform.

- The received waveform in the absence of noise must be matched perfectly by the locally generated reference waveform.

- Noise must be white and gaussian distributed.

- No nonlinear operations occur ahead of the multiplier.

- No band-limiting occurs ahead of the integrator.

- The multiplier is linear.

In a practical receiver for the SSV data bus, the following exceptions to the above assumptions arise:

- While near-perfect synchronization can be achieved, asynchronous detection may be desirable (ex: the AIB receiver).

- Distortion by the transmission medium in general prohibits perfect matching of received and reference waveforms.

- Impulsive noise rather than white gaussian is expected on the SSV data bus.

- Nonlinear operations such as limiting or slicing ahead of the multiplier are often desirable in a practical receiver.

- A band-limiting filter is desirable at the receiver input for reasons already mentioned in paragraph 3.3.2.4.2.

- Nonlinear multiplier such as an exclusive or circuit may be desirable for hardware simplicity.

Table 3.3-1 can be used for a quick comparison of optimum synchronous detection techniques keeping the above considerations in mind. This table

lists the average and peak signal-to-noise ratio required by yield a bit error ratio of 10^{-6} for each of the seven selected baseband modulation schemes.

Signaling Scheme	Required SN (db for BER of 10^{-6})	
	Average	Peak
Unipolar NRZ	13.6	16.6
Polar NRZ	10.6	10.6
Polar RZ	10.6	13.6
Biphase-Level	10.6	10.6
Bipolar NRZ	13.6	16.6
Delay Modulation	16.6	16.6
Duobinary	12.7	15.7

TABLE 3.3-1   PERFORMANCE COMPARISON OF
RECOMMENDED SIGNAL SET

If there is a limit on the amount of peak power (rather than average power) that the transmitter can generate, then the curves relating performance to peak signal to noise power ratio in Figure 3.3-54 are appropriate for comparing signaling schemes. Otherwise, the curves of Figure 3.3-53 should be used.

Applications Summary

Table 3.3-2 summarizes the significant features of each signal design.

Appropriate applications for each of the signal designs are summarized in the following paragraphs.

● Unipolar NRZ

Unipolar NRZ is the inherent form in which data are customarily expressed in logic circuits. Because it is not compatible with transformer coupling, it is not suitable for use on the primary transmission medium of the data

	Unipolar NRZ	Polar NRZ	Polar RZ	Biphase-Level	Bipolar NRZ	Delay Modulation	Duobinary
Inherent Error Detection Capability	No	No	Yes	Yes	Yes	Yes	Yes
Hardware Complexity (0 to 5)	0	1	2	3	4	5	5
Required Transmission Bandwidth/ bps	0.5	0.5	1.0	1.0	0.5	0.5	0.25
Compatible with Transformer Coupling?	No	No	No	Yes	Yes	Yes	No
Sufficient Bit Synchronization Data Present?	No	No	Yes	Yes	No	Yes	No
Complexity of Bit Sync Circuitry (0 to 5)	N/A	N/A	1	3	N/A	5	N/A
Required SNR (db for BER of 10^{-6}) - Peak Signal Power/Noise Power	16.6	10.6	13.6	10.6	16.6	16.6	15.7

TABLE 3.3-2 SUMMARY COMPARISON OF RECOMMENDED
SIGNAL SET MODULATION TECHNIQUES

bus. And because it requires twice as much signal power for a given peak-to-peak signal excursion as Polar NRZ, it is less attractive for use on short direct-coupled local buses than Polar NRZ, which otherwise has identical properties.

In conclusion, because of its inherent simplicity, and because it is less appropriate for applications involving transmission media than the other modulation forms, Unipolar NRZ appears to be best suited for use in the internal logic circuitry of individual units.

Polar NRZ

Polar NRZ is easily generated from Unipolar NRZ by subtracting out its DC level. For this reason, it is less suited for internal logic operations than Unipolar NRZ. It is better suited for applications on short direct-coupled local buses than Unipolar NRZ since it requires only half as much signal power for the same peak-to-peak signal excursion. It is not well-suited for use on the primary transmission medium because it is not compatible with transformer coupling. Since Polar NRZ does not contain adequate bit synchronization information, it is useful on direct-coupled short local buses only in those applications where bit synchronization is conveyed by some other means such as via a separate channel. In this case, it is superior to Polar RZ because it is less complex and requires only half the transmission bandwidth. It is also superior to Duobinary because it is far simpler, and because bandwidth conservation is not a serious problem when the cable length is short. Otherwise if bit synchronization is not provided by other means, then Polar NRZ will not work, and is therefore less suitable than Polar RZ.

In conclusion, Polar NRZ appears to be most appropriate for use on short

direct-coupled local buses wherein bit synchronization is conveyed by other means, such as by a separate channel.

Polar RZ

Polar RZ is superior to Duobinary and Unipolar or Polar NRZ in direct-coupled local bus applications which require that bit synchronization information be contained in the basic signaling waveform. While Biphase-Level and Delay Modulation could also be used in this application, they are more complex, and therefore less appropriate. Polar RZ is not appropriate for use on the primary transmission medium because it is not compatible with transformer coupling.

In conclusion, Polar RZ appears to be most appropriate for use on short direct-coupled local buses which require a self-clocking waveform.

Biphase-Level

Like Polar RZ, Biphase-Level consists of a self-clocking waveform and is well-suited to applications in which bit synchronization cannot be conveyed by other means. Unlike Polar RZ, Biphase-Level is compatible with transformer coupling, and may therefore be used to convey data via the primary transmission medium. In this capacity it is superior to Bipolar NRZ for cases where synchronization information cannot be conveyed by a separate channel. Because of its greater complexity, Biphase-Level is less appropriate than Polar RZ for short direct-coupled local buses which require a self-clocking waveform. However, for local buses which require transformer coupling and a self-clocking waveform, Biphase-Level is markedly superior to Delay Modulation which is more complex, and requires more signal power.

In conclusion, Biphase-Level is most appropriate for use on short trans-former coupled local buses, or on the transformer-coupled primary trans-mission medium (which may be long— $\sim$ 500 feet.) provided bit synchroni-zation information must be conveyed by the signaling waveform, and cannot be provided via a separate channel.

Bipolar NRZ

Bipolar NRZ, because of its greater complexity, is less appropriate than Polar NRZ on short direct-coupled local buses. It is, of course, inappro-priate on short direct-coupled buses which require that synchronization information be conveyed as an integral part of the signaling waveform. Bipolar NRZ may be more appropriate than Biphase-Level on the primary transmission medium in cases where a separate clock channel is available and bandwidth is a significant factor and/or the error detection capability of Bipolar NRZ can be effectively utilized.

In conclusion, Bipolar NRZ is best suited for use on the transformer-coupled primary transmission medium where synchronization information is supplied by a separate channel, and bandwidth utilization or error con-trol considerations provide sufficient advantages over Biphase-Level to compensate for a small increase in complexity.

Delay Modulation

Delay Modulation, because of its greater complexity, is less appropriate than Polar NRZ on short direct-coupled local buses that do not require that clock information be extracted from the signaling waveform. Short direct-coupled local buses that require a self-clocking waveform are better served by Polar RZ than by Delay Modulation, since it is also less com-plex. Short transformer-coupled local buses are better accommodated by

Biphase-Level because of its greater simplicity and because there is no significant bandwidth restriction if the transmission medium is short. Because of its greater complexity, Delay Modulation is less suitable for use on the primary transmission medium than Bipolar NRZ (only for applications that do not require a self-clocking waveform). For applications requiring the extraction of clock information from the signaling waveform, Delay Modulation is superior to Biphase-Level only if the transmission medium has a bandwidth restriction which prevents effective reception of Biphase-Level.

In conclusion, Delay Modulation is best suited for use on the transformer-coupled primary transmission medium wherein (1) clock information must be extracted from the signaling waveform, (2) there is insufficient transmission bandwidth to accommodate Biphase-Level.

Duobinary

Duobinary is not appropriate for applications which require transformer coupling, and hence is not appropriate for use on the primary transmission medium. It is more appropriate for applications which employ direct coupling in which there is a bandwidth restriction which prevents the use of Polar NRZ. This situation does not occur on short local buses.

In conclusion, Duobinary does not appear to be well-suited for any application in the SSV data bus when compared with the other more appropriate signaling schemes.

3.3.2.6   Redundant Coding

Phase II studies of redundant coding consisted of consideration and/or analysis of the following error protection schemes:

- Simple Parity
- Bipolar NRZ
- Horizontal and Vertical (Block) Parity
- Repetition Coding
- Simple Parity and Repetition Coding Combined

Throughput efficiency here was defined as the ratio of the number of information bits to the total number of bits transmitted in a word or block of data. This should not be confused with the overall throughput of the SSV data bus, which is a function of many other factors. Throughput efficiency here indicates only the coding efficiency of a redundant code.

Various block codes such as the Bose-Chaudhuri-Hocquenghen (BCH) codes are potentially applicable to data bus applications. However, because they have received exhaustive coverage in readily available technical literature it was decided that available efforts under this contract would be applied more effectively to other aspects of the signaling problem.

Studies of the first four selected redundant coding methods were limited to a comparison of their throughput efficiency and error detection capabilities. The error detection capability of each method is expressed in terms of the probability of occurrence of undetected errors. In order to estimate the probability of undetected errors associated with each scheme some simplifying assumptions were necessary. Because these assumptions are not representative of the true state of affairs expected in the SSV data bus, caution should be exercised in order to avoid drawing premature conclusions which are not generally true.

Simplifying Assumptions

Two important simplifying assumptions were necessary in order to make possible a reasonable estimate of probability of undetected errors for the purpose of comparing the selected coding methods. They are as follows:

- Individual bit errors are assumed to be statistically independent.

- The bit error ratio is assumed to be 10^{-6}, regardless of the detection technique employed or the prevailing signal-to-noise ratio on the bus.

Evaluation of Simple Parity

It is a well-known fact that the throughput achievable with any redundant coding scheme decreases monotonically with increasing error detection capability. This is a natural consequence of the fact that in order to reduce the probability that terrors in a message go undetected it is necessary to increase the number of redundant bits in the message. While simple parity has a high throughput, it has the poorest error detection capability of the five schemes considered.

Probability of Undetected Errors

For the conditions previously assumed, and with certain well-shown approximations (ref. Vol. II, $\emptyset$2), the probability of undetected errors occurring in a message containing I information bits is:

$$P \doteq \frac{I}{n - 1} \binom{n}{2} p^2 \qquad (3.3.2.6-1)$$

since n-1 is the number of information bits per word, and I/(n-1) is therefore the number of words required to send I information bits. (n = total number

of bits in a word and p = the bit error ratio.)

Throughput efficiency of simple parity is

$$\tau = \frac{n-1}{n} \text{ X } 100\%$$
(3.3.2.6-2)

Evaluation of Bipolar NRZ

Due to its alternating property of binary ones, Bipolar NRZ has a built-in error detecting capability which allows all single bit errors and many multiple error combinations to be detected. The errors most likely to go undetected are of four types as follows:

- Two successive (but not necessarily adjacent) "ones" are mistakenly called "zeros".

- A commission error occurs which has a sign opposite to that of the last available "one", and is followed by another commission error having a sign opposite to that of the first erroneous bit. No "ones" occur between these two commission errors.

- An omission error occurs, and is followed by a commission error having a sign equal to that of the preceding "one" which was mistakenly called a "zero".

- A commission error having a sign opposite to that of the last available "one" occurs and is followed by an omission error on the next available "one".

Erroneous words having more than two bits in error occur with a probability that is far less than the probability of occurrence of words having pairs of errors provided $p \ll 1$, where p is the bit error ratio. For this

reason the probability of failure to detect an erroneous word containing two errors is an excellent approximation to the overall probability of failure to detect any erroneous word. This probability has been found to be:

$$P \doteq 2(n - 2 + 2 \times 2^{-n})p^2 \tag{3.3.2.6-3}$$

where n and p are as previously defined. The probability of undetected errors occurring in a message containing I information bits is therefore:

$$P \doteq \frac{2I}{n-1}(n - 2 + 2 \cdot 2^{-n})p^2 \tag{3.3.2.6-4}$$

This assumes that an even parity bit is contained in each word, which is necessary in order to prevent baseline wander.

The throughput efficiency of Bipolar NRZ is the same as that of simple parity:

$$\tau = \frac{n-1}{n} \times 100\% \tag{3.3.2.6-5}$$

Evaluation of Horizontal and Vertical (Block) Parity

Two dimensional block parity coding, sometimes referred to as "horizontal and vertical parity", requires that the last bit of each column and row be a parity bit.

Consider a block of data having m columns and n rows. The mth column and the nth row contain parity bits. All other columns contain data bits. Block parity fails to detect sets of four errors occurring in the following bit positions:

Column No.	Row No.
i	j
i	r
k	j
k	r

where $1 \leq i \leq m$, $1 \leq k \leq m$, $1 \leq j \leq n$, $1 \leq r \leq n$, $i \neq k$, and $j \neq r$.

Assuming that individual bit errors are independent the probability that four and only four errors will occur in one of these sets of positions is:

$$P = \binom{m}{2} \cdot \binom{n}{2} p^4 (1-p)^{mn-4} \qquad (3.3.2.6-6)$$

where p is the Bit Error Ratio of a symmetric binary channel. This is very nearly equal to the probability of failure to recognize an erroenous block.

Block parity also fails to detect certain other combinations of errors occurring in more than 4 bit positions. For example, Figure 3.3-56 is an example wherein eight errors would be undetected. This is the next largest number of errors that can go undetected.

```
-   x   x   -   -   -
-   x   x   x   x   -
-   -   -   -   -   -
-   -   -   x   x   -
```

Figure 3.3-56. Example of Eight Errors

It should be noted, however, that the probability of more than four errors in a block going undetected is negligible in comparison to the probability that four errors go undetected.

The probability of undetected errors occurring in a message containing I information bits is obtained by observing that

$$m = \frac{I}{n - 1} \qquad\qquad (3.3.2.6-7)$$

Substitution of this result into (3.3.2.6-6) yields

$$P = \binom{\frac{I}{n-1}}{2} \binom{n}{2} p^4 (1-p)^{\frac{In}{n-1} - 4} \qquad\qquad (3.3.2.6-8)$$

The throughput efficiency of horizontal and vertical parity is clearly

$$\tau = \frac{(m-1)(n-1)}{mn} \times 100\% \qquad\qquad (3.3.2.6-9)$$

Substitution of (3.3.2.6-7) into (3.3.2.6-9) yields throughput efficiency as a function of n and I as follows:

$$\tau = \frac{n-1}{n} - \frac{(n-1)^2}{In} \qquad\qquad (3.3.2.6-10)$$

Repetition Coding

Repetition coding consists of repeating a word or message r times, then comparing all received words or messages in order to correct errors or sense an error condition.

Comparison of the received messages may be performed in a number of ways. One of the more promising message comparison techniques identified during Phase I is "bit voting" (reference paragraph 3.6.3 of the Phase I Report), and this is the method selected for analysis.

The probability that a voted bit is in error in the case of repetition coding is:

$$P_B \doteq \binom{r}{\left[\frac{r}{2}\right]} p^{\left[\frac{r}{2}\right]}$$

(3.3.2.6-11)

where the function $[x]$ connotes "the smallest integer greater than "x". Therefore, the probability of an uncorrected and/or undetected error occurring at the voter output for a message containing I information bits is:

$$P \doteq I \binom{r}{\left[\frac{r}{2}\right]} p^{\left[\frac{r}{2}\right]}$$

(3.3.2.6-12)

Where the "cost" of an error is much greater than the cost of a message rejection, message repetition can also be used in an error detection mode. In this case complete agreement in all bit positions is necessary for message acceptance. The resulting approximate probability of undetected error is:

$$P \doteq I p^{r}$$

(3.3.2.6-13)

The throughput efficiency is clearly inversely proportional to the number of times the message is repeated. Hence:

$$= 100\%/r$$

(3.3.2.6-14)

Simple Parity and Repetition Coding Combined

This coding method consists of bit voting repeated words (or identical words received via r independent channels) which contain a parity bit at the end of each word. In addition to the information bits in the redundant words, the parity bits are voted as well. The result appears to offer a significant improvement in transmission reliability over that which can be achieved using simple parity or repetition coding alone.

Because this technique also offers protection against errors caused by hardware malfunctions it was covered in detail under the operational reliability study task, reported in Volume 4 of the Phase II report.

3.3.2.7 Message Formatting

As was pointed out during Phase I, message formatting arrangements are best described in terms of message contents. A message generally contains some combination of the following:

- Synchronization information such as:
  - bit synchronization pulses,
  - special signal symbols or bit patterns signifying the beginning and/or end of a group of bits (ex: byte sync, word sync, or frame sync).

- Supervisory instructions which may designate:
  - addresses of information sources and sinks (user subsystem designations),
  - quantity of data to be transferred (ex: number of bytes),
  - when to begin a specified data transfer,
  - when to stop a specified data transfer,
  - time reference information indicating when a specified source may transmit to one or more specified receivers.

- The message data to be transferred.

- Error control information such as a simple parity check bit at the end of each word.

The design of an optimum formatting arrangement is highly interactive with the basic data bus configuration as well as the methods employed for syn-

chronization, timing and control. For this reason, detailed formatting arrangements were treated in studies of synchronization, timing and control and candidate system designs.

3.3.2.8   Interactive Aspects

Signal design and detection techniques interact most strongly with transmission media (3.2), synchronization, timing and control (3.4), and operational reliability (3.6).

3.3.3   Conclusions and Recommendations

Key conclusions and recommendations influencing the SSV data bus design are as follows:

- Either Biphase-Level, Bipolar NRZ or both should be used on the primary transformer-coupled transmission medium. Delay Modulation should not be used here because it is more complex and offers no significant compensating advantages over Biphase-Level.

- Polar RZ should be used on short direct-coupled local buses because of its simplicity and its self-clocking capability.

- Biphase-Level should be used on short transformer-coupled local buses because of its simplicity and its self-clocking capability.

- An Asynchronous Integrating Biphase (AIB) receiver of the type described in paragraph 3.3.2.4 should be used to receive Biphase-Level transmissions via the transformer coupled primary transmission medium in those applications requiring distributed (asynchronous) system timing.

- A Synchronous Biphase receiver of the type described in paragraph 3.3.2.4 should be used to receive Biphase-Level transmissions via the transformer-coupled primary transmission medium in those applications requiring centralized (synchronous) system timing.

- A Synchronous Bipolar NRZ receiver of the type described in paragraph 3.3.2.4 should be used to receive Bipolar NRZ transmissions via the transformer-coupled primary transmission medium wherein a synchronous clock signal is supplied by some other means such as via a separate channel.

- A simple asynchronous receiver of the type described in paragraph 3.3.2.4 should be used to receive Biphase-Level transmissions via short transformer-coupled local buses.

- Simple parity provides adequate redundant coding for error control and requires the least number of overhead bits per word (one).

- No filtering between a transmitter and the primary transmission medium is desirable or necessary.

- Appropriate filters similar to the type described in paragraph 3.3.2.3 should be inserted between the primary transmission medium and each receiver for improved performance in the presence of noise.

- The primary transmission media recommended in Volume I do not cause significant frequency distortion for data rates of 1 Mbps or less.

- Impulsive noise may be characterized by the mathematical model described.

- For the purpose of making conservative estimates of bit error ratio, the worst case Gaussian noise model may be used.

3.4   SYNCHRONIZATION, TIMING AND CONTROL

This section of the Final Report summarizes the work accomplished during Phases I and II. Investigations and comparisons are reviewed in sections 3.4.1 and 3.4.2, and results, conclusions and recommendations are presented in section 2.2.4.

3.4.1   Investigations

During Phase II, the following six major functional categories were investigated:

- Timing and Synchronization
- Bus Access Control
- Message Formatting including Function and Message Identification.
- Message Routing
- Channeling Methods
- Programming Considerations

The paragraphs which follow provide a brief review of each of the six (6) problem areas listed above.

3.4.1.1   Timing and Synchronization

Studies of the timing and synchronization problems in the SSV data bus during Phase II were limited to a consideration of means for achieving bit and word synchronization. Byte and frame timing need not be conveyed explicitly in each message. Instead, byte timing may be achieved implicitly by the choice of a suitable format, and frame timing may be conveniently conveyed by a special message often referred to as a framing pattern. For these reasons, only bit and word synchronization techniques were studied during Phase II.

Bit Synchronization

Numerous techniques for achieving bit synchronization were treated in detail in Volume II of the Phase II report on Signal Design and Detection. Section 3.3 includes a review of this subject.

Word (Message) Synchronization

This section describes and evaluates the word synchronization waveforms used in conjunction with Biphase-Level Modulation signals of four candidate systems. These candidate systems have been under consideration by the Phase B contractors, NASA/MSC and NASA/MSFC. The relative effectiveness of their word synchronization waveforms was assessed with regard to noise immunity and number of overhead bits.

- ### Description of Waveforms

Figure 3.4-1 illustrates the word synchronization waveforms of the four candidate systems, and also indicates (1) their relative ranking with regard to noise immunity, and (2) the bit overhead requirements of each. The word synchronization waveform for System B might be more aptly called a message synchronization waveform, since it prefaces words having anywhere from 9 to 315 bits. All the other waveforms shown are truly word synchronization waveforms which preface words having lengths in the neighborhood of 15 to 33 bits.

- ### Immunity to Noise

System B is by far the weakest of the four systems with regard to noise immunity. Here, no power is transmitted for two bit intervals to signify the beginning of a word. During this time, noise pulses can either cause the system to fail to sense the beginning of a word, or cause the system to signal the beginning of a word at the wrong time. Systems C and D are
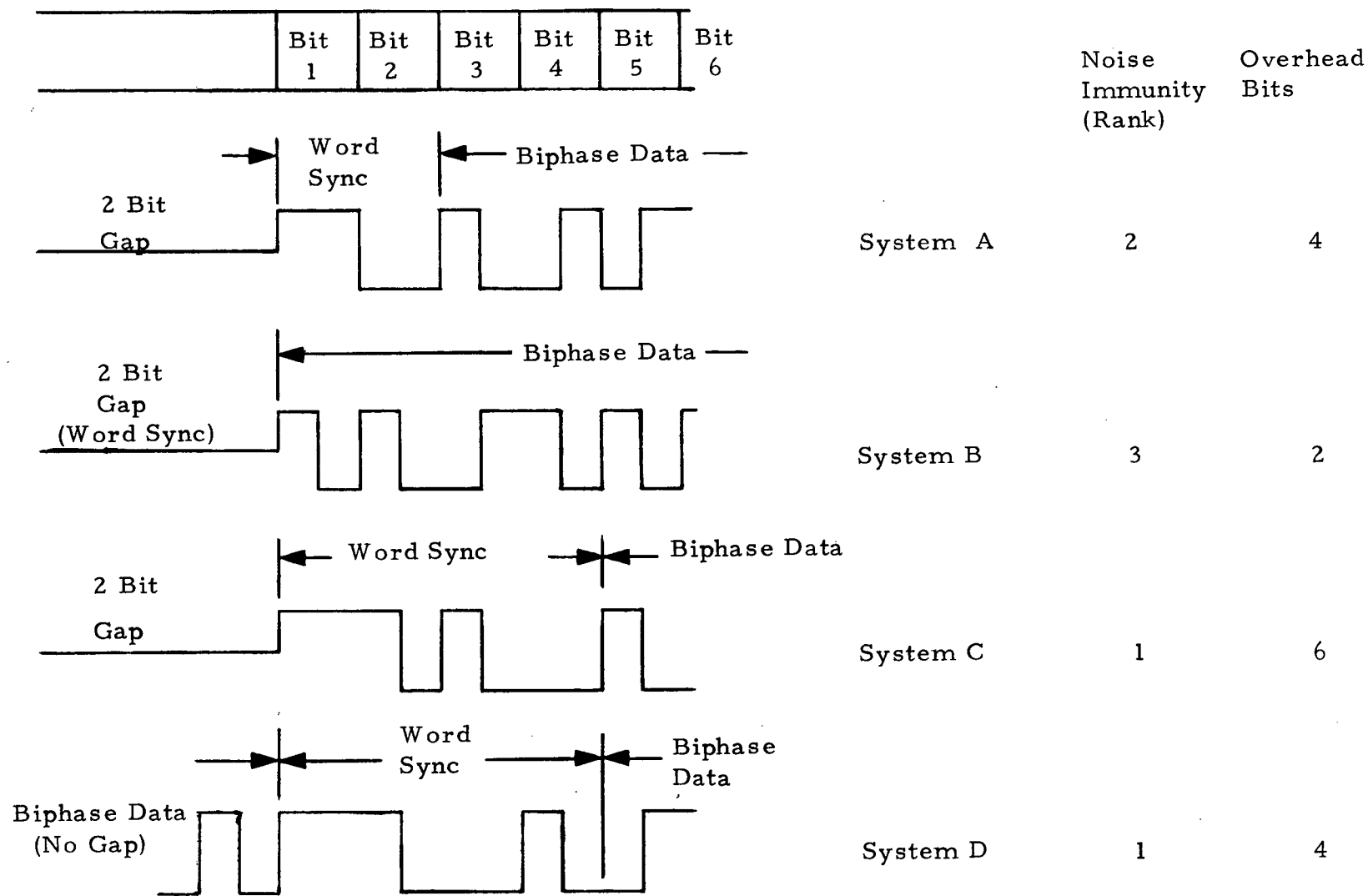
FIGURE 3.4-1.   DESCRIPTION OF WORD SYNCHRONIZATION WAVEFORMS

the most effective schemes with regard to noise immunity because they use the greatest amount of signaling energy to signify the beginning of a word. They are ranked equally in effectiveness against noise because they both use the same amount of signaling energy. Systems A and B are ranked second and third in effectiveness against noise because they contain correspondingly less signaling energy than systems C and D.

● <u>Comparison of Systems</u>

Systems C and D are ranked at the top of the list with regard to noise immunity but system C has the greatest number of overhead bits per word and systems A and D rank second in this regard. System B has the lowest number of overhead bits, but the least immunity against noise. System A lies in between these two extremes. Systems A, B, and C are all somewhat unconventional, whereas system D is an accepted waveform for word synchronization in conjunction with Biphase-Level Modulation. This waveform has been specified in the Navy's General Requirements Document AR-63 concerning Multiple Interior Communications Systems (MINCOMS) dated 2 March 1970. This same waveform has been designated by the Aircraft Multiplexing Committee (A2K) of the Society of Automotive Engineers in their Aerospace Information Report #1183 for use in the multiplexing systems of commercial aircraft. A waveform virtually the same as that shown for system C is to be used in the Air Force's CITS system for the B1 bomber. The only distinction between the B1's CITS waveform and that of system D is that CITS also uses the inverse of the system D waveform as a word sync pattern. The polarity of the word sync pattern in the B1 CITS system is thus used to indicate the direction in which messages are to flow over a shared half-duplex transmission medium.

Because the word synchronization pattern of System D is conventional (whereas the others are not) and because of its greater noise immunity when compared with System A and B, it is recommended for use in Biphase-Level channels of the SSV data bus.

3.4.1.2   Bus Access Control

The following four bus access control schemes were classified, and are listed below with attendant features:

a)   Centralized Control - Time Reference

- each subsystem data point assigned a unique time slot
- central clock source provides bit, words per frame, frame and subframe timing for all terminals.
- each terminal counts, decodes and responds per its time slot.

b)   Centralized Control - Command-Response

- central controls activation of data terminal
- terminal recognizes one or more addresses
- programming flexible - fixed or variable sequence

c)   Distributed Control - Handover

- control function resides in terminal
- control passed from terminal to terminal, based upon completion of transmission-to-next operator.
- readily adaptable to small number of highly intelligent terminals.

d)   Distributed Control - Contention

- central source supplies clock signal to all terminals
- upon terminal operation completion, clock line is contended for by terminals.
- "capture" possibility best near central and poorest down toward end of line.

These four techniques are further evaluated and graded, as shown in Table 3.4-1, in an accepted [*] semi-quantitative manner. The centralized command-response method far outscored the other methods. A brief on each feature follows.

- Hardware Simplicity

Both centralized approaches ranked high because of simplicity of hardware, with the contention method close behind. Hardware complexity handicapped the handover methods scoring.

- Program Flexibility

Data bus equipment response to changes in data flow requirements is implemented by either software or hardware programming, with the former inherently more flexible. For this reason, the command-response method rated very high. The time reference method was marked down because once a frame is initiated, it cannot reasonably be altered.

The distributed handover method rated high by virtue of its ability to redirect to the next terminal after each point transmission.

[*] Churchman, C. W., Ackoff, R. L. and Arnoff E. L., Introduction to Operations Research, Chapt. V, John Wiley and Sons, Inc. 1963.

3.4-6

● <u>Programming Centralization</u>

Only the centralized command-response technique permits all programming to be performed at one terminal — namely at the central bus control unit. All other methods require that programming be provided at each terminal. This is obvious for the case of distributed techniques since in this case the centralized time-reference approach also requires programming at each terminal in the form of decoding logic used to recognize the proper time slots in which data from the terminal is granted access to the bus. However, the whole subject of programming centralization was down-graded upon the consideration that when program changes are being made, quite likely changes would be made in the terminals. These instances lessen the centralization effectiveness with respect to reprogramming.

● <u>Economy of Channel Bandwidth</u>

Three of the approaches rank equally good because they cause about the same amount of traffic flow per data exchanged. The contention method requires an extra cable for conveyance of clock information, making it the least efficient of the four.

● <u>Ease of Synchronization</u>

Synchronization is easiest with the centralized command-response and distributed hand-over schemes, which only require bit and word synch to achieve bus access. The time-reference approach requires frame and/or subframe synchronization <u>plus</u> bit and word sync.

3.4.1.3   Message Formatting

Each individual message is a string of symbols (in binary digits, except for sync) used to convey one or more of the following types of information:

Desirable Features	Bus Access Control Techniques				Weight
	Centralized		Distributed		
	Time-Reference	Command-Response	Hand Over	Contention	
Hardware Simplicity	9	10	3	8	5
Programming Flexibility	5	10	10	5	4
Economy of Bandwidth	10	10	10	6	3
Ease of Synchronization	7	10	10	9	2
Total Weighted Score	109	140	105	96	

TABLE 3.4-1.   COMPARISON OF BUS ACCESS CONTROL TECHNIQUES

- Synchronization information such as

  . Bit synchronization

  . Byte synchronization

  . Word (or message) synchronization

  . Frame Synchronization

- Supervisory instructions which may designate

  . Addresses of information sources and sinks (user subsystem designations).

  . Function identification of data to be transferred.

  . Quantity of data to be transferred

  . When to begin and when to stop a specified data transfer.

  . Time reference information indicating when a specified source may transmit to one or more specified receivers.

- The basic message data to be transferred

- Error control information such as a simple parity check bit at the end of a word.

All the four types of information listed above may be contained in a single message, or they may be sent separately by different messages. The appropriate arrangements of the four basic types of information to be conveyed are influenced by the message routing techniques and channeling arrangements employed. In all cases, however, it is convenient to consider separately the formatting of supervisory and data words, which may either be merged in sequence to form one message or may be sent separately.

The following paragraphs summarize various means of formatting data and supervisory information and their relation to word length.

Data Packing

The contention as to whether or not data should be packed and if so, in what increments is addressed here.

Settling on a fixed word length simplifies hardware and avoids the necessity of having to transmit additional information in order to specify the number of bits in each word.

It was clear from the analysis of the data flow model that certain losses in throughput efficiency arose because the data in its original form cannot always be made to conform to the selected word length. From Volume III, note that the maximum raw data word is 11 bits, and that peak data rate is 0.422 mbs. The latter equates to perfect packing.

The following packing arrangements were used for this examination:

(1) No packing at all.

(2) Packing of discrete data (periodic discretes and aperiodic discrete monitor signals).

(3) Packing of discrete data and multiple bytes having a common number of bits.

Case (1) does not really involve packing. Case (2) posed the more interesting problem of determining what discrete signals may be packed. The rules decided upon were as follows:

Rule 1A   All discrete signals except aperiodic commands may be packed in accordance with the following rules:

Rule 2A   The signals must share a common set of mission phases.

Rule 3A   They must originate from the same physical location.

Rule 4A   They must have a common sampling rate.

The packing rules selected for case (3) are as follow:

Rule 1B   Discretes and multiple bit data bytes may <u>not</u> be packed in the same word.

Rule 2B   All discretes must be packed in accordance with the same rules used in case (2).

Rule 3B   All bytes packed in a word must contain the same number of bits.

Rule 4B   All bytes packed together must share a common set of mission phases.

Rule 5B   All bytes packed together must originate from the same physical location.

Rule 6B   All bytes packed together must have the same sampling rate.

Rule 7B   If the word length is less than the number of bits per byte, then multiple words are sent until all the bits of a byte have been transmitted.

Data Rate Evaluation

The required data rates for the case of perfect packing as well as for the three cases cited have been determined through computer-aided analysis of the SSV data flow model. The results are summarized in Table 3.4-2.

As would be expected, the highest data rate per word length occurs when no data whatever is packed. Data rate nulls are seen at 6, 11 and 24 bits per word. The latter two are more attractive because they would not require the splitting of data words.

		Word Length in Bits					
		6	8	11	12	16	24
Peak Data Rate in MBPS	Case (1): No Packing at All	0.533	0.687	0.637	0.695	——	——
	Case (2): Rules 1A through 4A	0.486	0.620	0.541	0.590	0.784	——
	Case (3): Rules 1B through 7B	0.486	0.612	0.467	0.492	0.596	0.503
	Perfect Packing (Theoretical)	0.423					

TABLE 3.4-2. PEAK DATA RATE VS. WORD LENGTH FOR VARIOUS PACKING TECHNIQUES

From Table 3.4-2, it is evident that the loss in throughput efficiency for the practical packing techniques indicated is never less than 9% nor greater than 46% for the word lengths considered.

Data Blocking

When a large number of signals originate from the same general physical location and at the same time have a common sampling rate, it is often convenient to send these data in blocks made up of multiple words. The reason data blocking may be attractive is that less supervisory information is required to specify the origin and/or destination of the data.

The number of words in a block can be fixed or it may be variable. Because the SSV data bus has a highly variable number of words which may conveniently blocked together, only variable length blocking was considered.

The effectiveness of data blocking technique has been evaluated as a function of word length, message routing technique, channeling technique and packing technique for comparison with comparable schemes that do not employ data blocking. These results are described in paragraphs 3.4.2 and 2.2.4.

Supervisory Word Formatting

For the purposes of this study, it was assumed that the supervisory word must as a minimum convey word synchronization data and address information. The four bit word synchronization pattern selected in paragraph 3.4.2.1 was assumed for the purposes of all data rate calculations. In addition to these four bits, a supervisory word containing either one or two addresses to specify message routing, and one or two parity bits for error control was assumed.

The address portion of the supervisory word was determined from the user subsystem interface requirements, which suggested that the total number of data terminals (SIU's) should be no greater than 16, the maximum number of SIA's is 8, and the maximum number of channels per SIA is 128. Thus, the minimum number of bits required to address one data channel at a user subsystem interface is 14. It is therefore reasonable to assume that a supervisory word will require no more than 20 bits as follows:

Bits 1 - 4:	Word Synchronization
Bits 5 - 8:	SIU Address
Bits 9 - 11:	SIA Address
Bits 12 - 18:	SIA Channel Address
Bit 19:	1 Parity Bit
Bit 20:	Spare (May provide a gap)

For the case where the supervisory word must specify the addresses of both a source and a destination, the following format has been assumed in all data rate calculations:

Bits 1 - 4:	Word Sync
Bits 5 - 18:	Sink Channel Address
Bits 19 - 32:	Source Channel Address
Bit 33:	Parity Bit
Bit 34:	Spare (May provide a gap)

3.4.1.4   Message Routing

Altogether five different message routing techniques which fall into three basic categories were examined during Phase II, as follows:

a)   Routing without terminal-to-terminal (TTT) transfers.

b) Routing with indirect terminal-to-terminal transfers.

c) Routing with direct terminal-to-terminal transfers, with

- Source terminal address supplied by a central bus controller and sink terminal address supplied by the transmitting terminal.

- Sink and source channel addresses both supplied by a central bus controller.

- Source address supplied by central bus controller with sink address implicitly derived from source address.

The first type of message routing (a) has been ruled out because the SSV signal listings in Volume III clearly indicate that much of the data must flow from terminal to terminal.

The second type of message routing (b) permits terminal-to-terminal transfers but only indirectly via a central unit. This method is feasible in the SSV data bus, but requires a considerably higher data rate than the following methods and does not accommodate multiple destination transfers. For the latter reason, it is ruled out.

The third type of message routing (c) accommodates terminal-to-terminal transfers in a direct manner providing a higher throughput efficiency than the second method because the data portion of a message need not be repeated. Of the three major subcategories examined, the first has been ruled out because it requires considerable complexity in each data terminal to perform this function.

The second direct routing subcategory in which both sink and source channel addresses are supplied by central has a lower throughput efficiency than the other two subcategories, but has less hardware complexity.

The third direct routing subcategory is functionally similar to source terminals, but sink decoding requirements differ. The intended sink terminal must receive the source address and decode it per predetermined definition. This technique becomes more complex when a particular terminal must receive from various other terminals, and usually would require a ROM (read-only-memory). This technique has a high throughput efficiency and is also useful as a means of stripping data from the bus.

For purposes of comparison, the routing techniques selected for further examination have been numbered as follows:

R1:   Indirect terminal-to-terminal transfers via central.

R2:   Direct terminal-to-terminal transfers with source and
        sink addresses supplied by central.

R3:   Direct terminal-to-terminal transfers with sink
        address implicitly derived from the source address via
        a memory.

These techniques are compared, along with data packing, data blocking, and channeling techniques as a function of word length in paragraph 3.4.2.

3.4.1.5   Channeling Methods

The following channeling methods were studied during Phase II (see Figure 3.4-2).

a)   Single half-duplex cable
b)   Separate supervisory and data cables
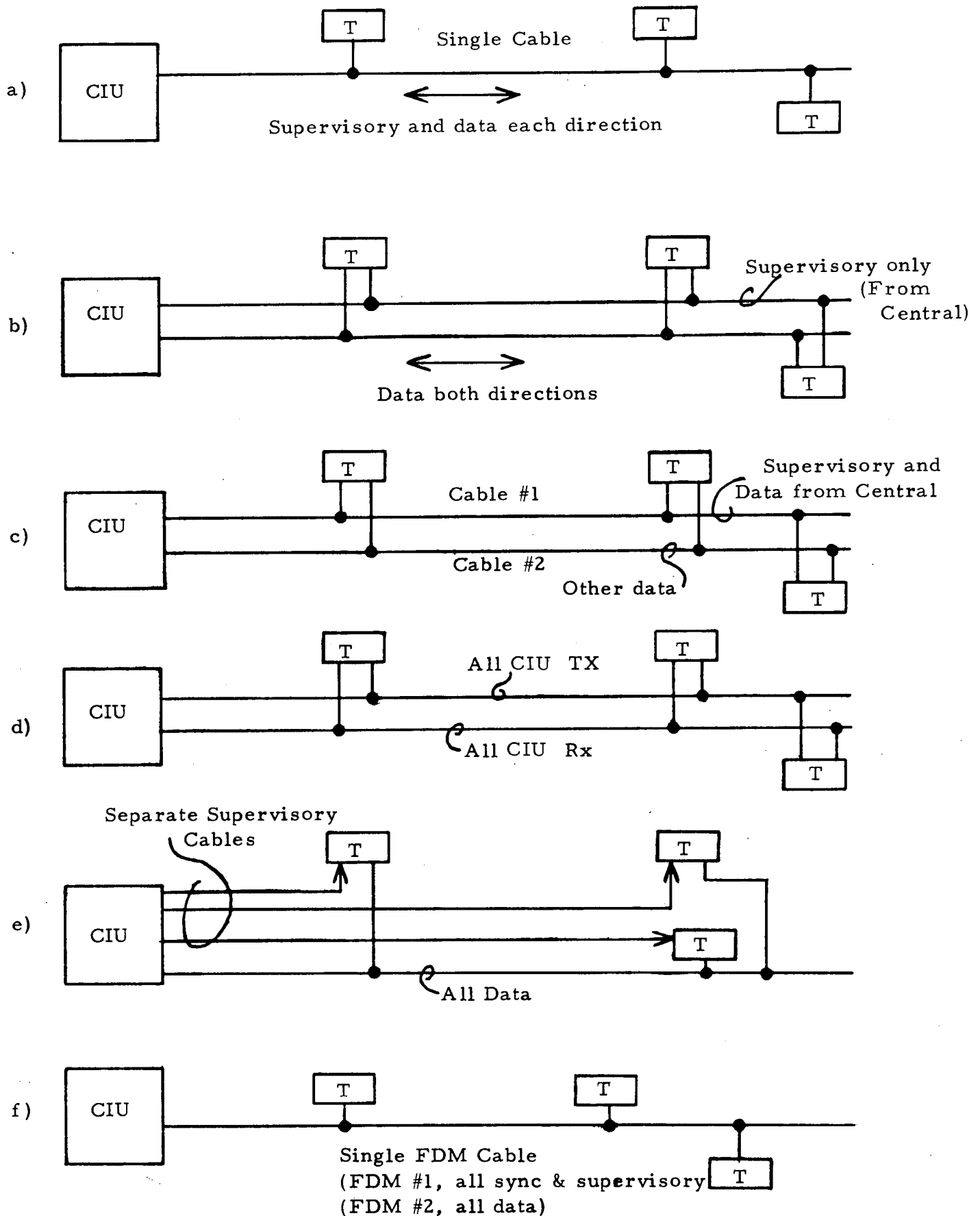
FIGURE 3.4.2 DIAGRAM OF CHANNELING METHODS

3.4-17

c)   Supervisory and centrally originated data sent via Cable #1 and other data sent via Cable #2 (TTT permitted over data cable).

d)   Separate transmit and receive cables with transmission through central (no direct TTT link).

e)   Separate supervisory cables to various multiple destinations, with data on a single cable which goes to all destinations.

f)   Single hybrid TDM-FDM cable. Supervisory and synchronization information sent via one FDM channel, and data sent via a second FDM channel.

The chief advantage of the first and last methods is that they require less cable than the rest. Their chief disadvantage is that they both require greater bandwidth. The single cable hybrid TDM-FDM approach is more complex and at the same time less efficient of bandwidth than the single half-duplex cable approach, and has therefore been ruled out.

The third method (c) was not considered further in the comparison because this method is similar to method two and requires additional routing to data registers. Method two also provides better distribution of traffic between two cables. All the four remaining methods were considered and numbered as follows:

C1:   Single half-duplex cable

C2:   Separate supervisory and data cables

C3:   Separate "transmit" and "receive" cables with transmission through central.

C4:   Separate supervisory cables to multiple destinations with data on another cable which goes to all destinations.

3.4.1.6 Programming Considerations

The programming arrangement required at the data terminals and the user subsystems relate to recognition of the applicable transmit commands, receive commands, and function tags and the generation of appropriate responses to each.

Programming considerations strongly influence the choice of appropriate blocking, routing, and channeling techniques. If the system is to remain flexible and easily alterable to accommodate changing data flow requirements, programming is required at one or more of the following places:

- Within the central bus control element.
- Within a data terminal.
- Within certain user subsystems.

An additional programming requirement in the SSV involves the editing necessary to select sets of data to be routed to alternate data paths. Possible destinations for these data sets include:

- A telemetry link.
- An on-board tape recorder.
- A ground-based GSE data bus (during ground-based operations only).
- A ground-based computer (during ground-based operations only).
- The other SSV stage (during prelaunch and boost).

It was considered more desirable to place all data bus related programming within the central bus control element because it appeared to be less difficult than being performed at each data terminal. In addition, distributed programming generally results in a lower efficiency in utilization of the memory and logic associated with programming.

Programming is highly interactive with other significant properties of the data bus as a whole, particularly the combined packing, blocking, channeling, and message routing scheme selected. The summary comparison of techniques in paragraph 3.4.2 which follows attempts to show the relation of programming considerations in the selection of appropriate combinations of design alternatives.

3.4.2 Summary Comparison of Techniques

Certain specific timing and synchronization and bus access control techniques were selected for further investigation, and several reasonable design alternatives were identified in the areas of message formatting, message routing, and channeling methods. Also, the potential desirability of centralized rather than distributed programming was recognized.

The alternatives noted in the areas of message formatting, message routing, and channeling methods interact. Therefore, the effectiveness of each combination of alternatives was assessed on an individual basis. This was done for all reasonable combinations of message formatting, message routing, and channeling methods, using data rate as a yardstick for comparison.

Besides data rate, programming centralization was taken as a prime consideration strongly affecting the choice of a suitable combination of formatting, routing, and channeling techniques. A subjective evaluation

C4

of hardware complexity and programming centralization was included in the final selection of candidate synchronization, timing and control techniques.

3.4.2.1   Design Alternatives

In accordance with previous conclusions, the following design alternatives were selected for determining the data rate:

- Data Packing

  - P1: Pack only discretes which are not aperiodic commands.
  - P2: Pack all data except aperiodic commands.

- Data Blocking

  - B1: No blocking.
  - B2: Block all data except aperiodic commands.

- Channeling Methods

  - C1: Single half-duplex cable.
  - C2: Separate supervisory and data cables.
  - C3: Separate transmit and receive cables (through central).
  - C4: Separate supervisory cables to multiple destinations with data on another cable which goes to all destinations.

- Message Routing

  - R1: Indirect terminal-to-terminal transfers via central.
  - R2: Direct terminal-to-terminal transfers with source and sink addresses supplied by central.
  - R3: Direct terminal-to-terminal transfers with sink address implicitly derived from the source address.

- Word Lengths

    - 6 Bits

    - 8 Bits

    - 11 Bits

    - 12 Bits

    - 16 Bits

    - 24 Bits

Certain combinations of the preceding alternatives were incompatible such as:

- C3 and R2 or R3:   C3 is by definition only compatible with indirect terminal-to-terminal routing.

- C4 and R1:   C4 is by definition only compatible with direct terminal-to-terminal routing and hence does not go with R1.

- C4 and R3:   C4 is not compatible with R3 because with C4 the source and sink addresses are supplied simultaneously by separate cables from central.

These combinations were labeled NA (Not Applicable) in the summary of data rates.

Another set of alternatives which were omitted from the list was the set of word lengths greater than 11 for the case of packing alternative P1, because for packing arrangement P1 the data rate increases monotonically with word length when the word length exceeds 11 bits per word. Cases which yield higher data rates are of little interest.

A third set of alternatives omitted was the case of P2 packing with B2 blocking, because data blocking per se was ruled out, as shown in subsequent discussion. The P1-B2 case was presented here only to show the great reduction in required data provided by data blocking, for purposes of comparison with schemes which do not employ blocking.

3.4.2.2   Summary of Required Data Rates

Table 3.4.3 summarizes the minimum required data rates for each of the design alternatives considered. These rates include the effects of the supervisory words including word synchronization, address, and parity bits where applicable. Each supervisory word has been structured in accordance with the appropriate format specifications outlined previously. For the case of data blocking, appropriate supervisory word or words were assumed at the beginning of each block, preceded by one 20-bit word to specify the number of words in the block.

Comparison of Alternatives

Some of the foremost considerations which should be used in the choice of the best combination of the alternatives listed in Table 3.4.3 are as follows:

- Economy of channel bandwidth
- Flexibility-programming centralization
- Economy of hardware

Economy of channel bandwidth can be determined directly from Table 3.4.3 in terms of the minimum data rate required to convey information. It presently appears that data rates above 1.5 Mbps over a single cable become increasingly difficult to realize with simple hardware, while data rates below this value are easier to obtain without resorting to special high-speed logic with resultant higher power consumption.

TABLE 3.4.3

SUMMARY COMPARISON OF COMBINATIONS OF ALTERNATIVES

P1 - Packing, Periodic Discretes which are not aperiodic commands

B1 - No Blocking

C1 - Single Half-Duplex Cable

Routing	Word Length (Bits)	Data Rate (Mbps)
R1	6	4.22
	8	5.32
	11	4.71
R2	6	3.25
	8	4.34
	11	4.07
R3	6	2.11
	8	2.89
	11	2.80

C2 - Separate Supervisory and Data Cables

Routing	Word Length (Bits)	Supervisory Cable	Data Cable
R1	6	3.24	1.30
	8	3.10	1.55
	11	1.97	1.28
R2	6	2.75	0.65
	8	2.64	0.77
	11	1.67	0.64
R3	6	1.62	0.65
	8	1.55	0.77
	11	0.99	0.64

C3 - Separate Transmit and Receive Cables

Routing	Word Length (Bits)	Data Rate (Mbps)
R1	6	2.11
	8	2.17
	11	1.52 *
R2	NA	NA
R3	NA	NA

Table 3.4.3 (Continued)

$$\begin{pmatrix} \text{P1} - \\ \text{B1} - \end{pmatrix} \text{Continued}$$

C4 - Separate Supervisory Cables to Multiple Destinations — Data Cable
to ALL

		Data Rate (Mbps)	
Routing	Word Length (Bits)	Supervisory Cables	Data Cables
R1	NA	NA	NA
R2	6	1.62	0.65
	8	1.55	0.77
	11	0.98 *	0.64
R3	NA	NA	NA

P2 - Packing ALL data except aperiodic commands

B1 - No Blocking

C1 - Single Half-Duplex Cable

Routing	Word Length (Bits)	Data Rate (Mbps)
R1	6	4.20
	8	4.29
	11	2.63
	12	2.63
	16	2.68
	24	1.84
R2	6	3.24
	8	3.22
	11	1.91
	12	1.89
	16	1.86
	24	1.24
R3	6	2.10
	8	2.14
	11	1.33
	12	1.31
	16	1.34
	24	0.92 *

Table 3.4.3 (Continued)

$$\left(\begin{array}{l} \text{P2 -} \\ \text{B1 -} \end{array} \text{(Continued)}\right)$$

C2 - <u>Separate Supervisory and Data Cables</u>

		Data Rate (Mbps)	
<u>Routing</u>	<u>Word Length (Bits)</u>	<u>Supervisory Cable</u>	<u>Data Cable</u>
R1	6	3.24	1.30
	8	3.06	1.53
	11	1.69	1.10
	12	1.64	1.15
	16	1.49	1.34
	24	0.84	1.09
R2	6	2.75	0.65
	8	2.61	0.77
	11	1.44	0.55
	12	1.40	0.58
	16	1.27	0.67
	24	0.71	0.54
R3	6	1.62	0.65
	8	1.54	0.77
	11	0.85	0.55
	12	0.82	0.58
	16	0.75	0.67
	24	0.42	0.54 *

C3 - <u>Separate Transmit and Receive Cables</u>

<u>Routing</u>	<u>Word Length (Bits)</u>	<u>Data Rate per Cable (Mbps)</u>
R1	6	2.11
	8	2.13
	11	1.31
	12	1.31
	16	1.34
	24	0.92 *
R2	NA	NA
R3	NA	NA

Table 3.4.3 (Continued)

$$\begin{pmatrix} P2 - \\ B1 - \end{pmatrix} \text{(Continued)}$$

C4 - <u>Separate Supervisory Cables to Various Multiple Destinations</u>
<u>With Data on a Single Cable to All</u>

		Data Rate (Mbps)	
Routing	Word Length (Bits)	Supervisory Cables	Data Cable
R1	NA	NA	NA
R2	6	1.59	0.65
	8	1.54	0.77
	11	0.85	0.55
	12	0.82	0.57
	16	0.74	0.67
	24	0.42	0.53 *
R3	NA	NA	NA

> P1 - Packing, Periodic Discretes
>
> B2 - Blocking

(for example only)

C1 - <u>Single Half-Duplex Cable</u>

Routing	Word Length (Bits)	Data Rate (Mbps)
R1	6	1.06
	8	1.33
	11	1.18 *
R2	6	0.74
	8	0.86
	11	0.73
R3	6	0.74
	8	0.86
	11	0.73

Table 3.4.3 (Continued)

$$\begin{pmatrix} \text{P1 -} & \\ & \text{(Continued)} \\ \text{B2 -} & \end{pmatrix}$$

C2 - <u>Separate Supervisory and Data Cables</u>

		Data Rate (Mbps)	
Routing	Word Length (Bits)	Supervisory Cable	Data Cable
R1	6	0.18	1.30
	8	0.18	1.54
	11	0.18	1.28
R2	6	0.09	0.65
	8	0.09	0.77
	11	0.09	0.64
R3	6	0.05	0.65
	8	0.05	0.77
	11	0.05	0.64

C3 - <u>Separate Transmit and Receive Cables</u>

Routing	Word Length (Bits)	Data Rate Per Cable (Mbps)
R1	6	0.58
	8	0.71
	11	0.63
R2	NA	NA
R3	NA	NA

C4 - <u>Separate Supervisory Cables to Multiple Destinations with Data on</u>
<u>a Separate Cable to all Destinations</u>

		Data Rate (Mbps)	
Routing	Word Length (Bits)	Supervisory Cables	Data Cable
R1	NA	NA	NA
R2	NA	NA	NA
R3	6	0.09	0.65
	8	0.09	0.77
	11	0.09	0.64

Adaptability to multiple users is a measure of flexibility of operation, in which distribution of a certain message or command to a number of users is simplified.

Economy of hardware implies lower costs, less weight and size, and greater long term reliability by virtue of using fewer parts to perform the given operations.

3.5   USER SUBSYSTEM INTERFACE

The user subsystem interface (USI) of the data bus is that element of the
data bus system which allows various users of the system to interface
with the data bus system such that their signals may be transmitted or
received over the data bus to or from the various points on the vehicle.
The user subsystem may be signal generating devices such as transducers,
a data sink, or a computer I/O. The purpose of this section of the study
has been to

1.   Define the functional requirements of the interface between
the user subsystems and the data bus transmission medium
(3.5.1).

2.   Identify constraints relating to the interface (3.5.2).

3.   Identify electronic operations (3.5.3).

4.   Make further analyses and examine areas of trades and alterna-
tives (3.5.4).

5.   Summarize recommended approaches (2.2.5).

Examples and test cases were employed in many instances because of the
interdependent nature of the many choices. The information herein is
summarized from the Volume IV report, which should be referred to
for details.

3.5.1   Functional Requirements

Before addressing the functional requirements and characteristics of
the user/data bus interface, several terms used in this study are defined:

- The <u>Remote Terminal</u> (RT) is that element of the data bus system which performs the interface function between the user subsystem and the data bus transmission medium. The relationship of the RT to the data bus system and user subsystem are shown in Figure 3.5-1.

- The RT is composed of a <u>Standard Interface Unit</u> (SIU) which performs most of the bus interface functions, and the <u>Subsystem Interface Adapter</u> (SIA) which performs the interfacing to the user subsystems.

- The <u>I/O Module</u> is defined as a grouping of input or output signals. The concept of an I/O module does not necessarily denote a physical module, rather it is a convenient method of grouping signals in some of the discussions to follow.

- <u>Data Access Time</u> - The access time of data is defined as the time that is required for the central processor of a data bus system to acquire data from a specific RT. It is measured from the time the bus controller begins to transmit the command word to the time that the entire response (with the data requested) is received back from the RT.

- <u>Interrogation Time</u> - The time available for a specific analog channel to be sampled and digitized in the RT.

- <u>Utilization Factor</u> - A measure of how well all the RT input/output channels are utilized. The ratio of the utilized inputs and outputs to the total number of input and output channels available.

Central
Computer
(CR)

Bus
Controller
(BC)

Data Bus Transmission Media

Remote
Terminal
(RT)

User
Subsystem
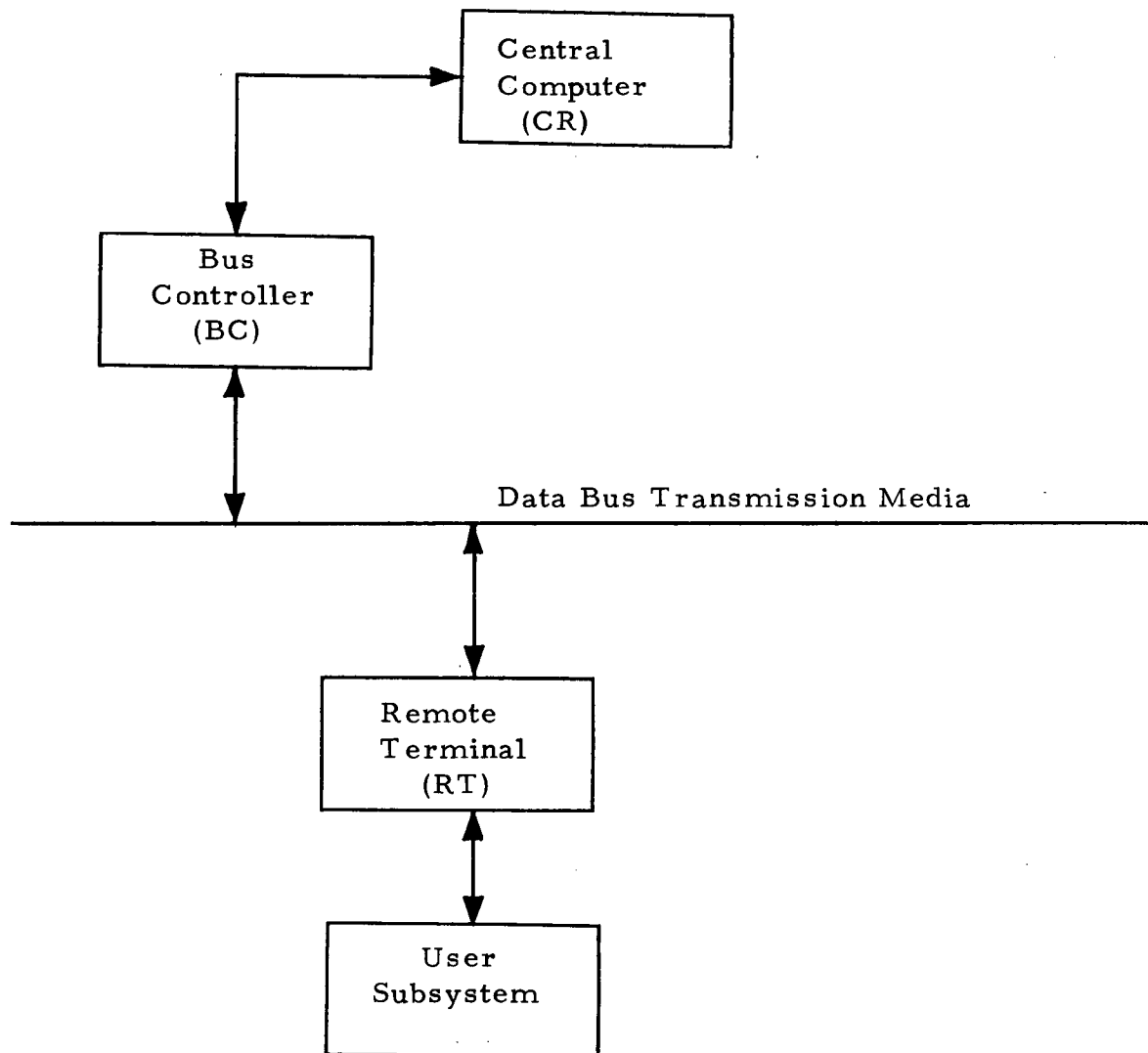
FIGURE 3.5-1.   THE GENERAL DATA BUS SYSTEM

3.5.1.1 Functions of the RT

The functions which must be performed by the RT are shown in Figure 3.5-2. The three columns of functions in this figure represent (1) the functions which must definitely be performed by the SIU, (2) the functions which may be performed either by the SIU or the SIA, and (3) definite functions of the SIA. Figure 3.5-2 does not necessarily reflect the configuration or packaging of the RT, but is intended to clarify the functions performed. The RT may eventually be composed of several elements in a modular form. A group of functions not shown would be those interface functions required if the RT was configured such that part(s) of the RT are designed for remote location and operation. The primary task of this section of the study is to select the appropriate functions identified in Figure 3.5-2 and to group them into either the SIU, SIA or elsewhere. Modularity weighs heavily in these considerations.

3.5.1.2 Modularity of RT

The rationale for selecting whether the RT should be fixed or modular is based on the face that the single unit is less costly to design, develop and build than several. However, the modular system is more cost effective in a growth and vehicle reconfiguration environment.

The rationale for modularizing functions are listed below:

- Modularization leads to flexibility in RT configurations.

- Test and diagnostics are easily performed on a modular basis.

- The standardization of modules allows the use of MSI-LSI techniques to be cost-effective, which leads to a reduction in size and weight.

REMOTE TERMINAL

Data Bus Trans- mission Media

User Subsystem

3.5-5

────── SIU ──────   ─ ─ ─ ─ ─   ────── SIA ──────

Definite Functions	Possible Functions	Definite Functions
• Converts NRZ Data to the appropriate form (BIØ, etc.)	• Recognition of RT Address	• Input Multiplexing
• Transmits Chosen Waveform	• Decodes Command Words (Function Code)	• A/D Conversion
		• Signal Conditioning
• Applies Word Sync Pattern	• Determination of Failure Condition & Reconfigure Control	• Demultiplexing
• Applies Chosen Method of Redundancy		• D/A Conversion
• Provides Isolation to Transmission Medium	• Serial to Parallel Conversion	• Generation of Enable Gates (For Serial-Digital Inputs or Outputs)
• Receives, Filters, De-modulates Signals from Bus	• Buffering of Data Words	• Filtering of Signals
	• Generation of Timing & Control Signals	• Channel Decoding
• Obtains Bit Sync, Generates Clock	• Word Formatting	• Output Latches for Discrete Signals
	• Storage of Data Words	
• Destaggers or Deskews Data	• Storage of Test Words, Status	• Power Output (Relay Drivers, etc.)
• Error Checking, Voting, Other Validity Checking	• Control of Power	• Generation of Interface Control Signals (Data Ready, Send Data, etc.)
• Compensates for Trans-mission Delay	• Storage of Command Signals	
• Applies Compensation for Transmission Media		

FIGURE 3.5-2.   FUNCTIONS OF THE REMOTE TERMINAL

It is obvious that the criteria used for modularizing functions of the RT
should lead to the system which is most cost effective for a wide variety
of applications on board the SSV. However, modularization if carried
to an extreme leads to a system in which the electronic packaging density
suffers, i.e. more weight and volume is devoted to connectors and
enclosure material as the modules become less complex or smaller.
Alternate methods of achieving modularity are described below.

System 1   An RT composed of one SIU and variable number of
            SIA's, each SIA containing a definite, fixed mixture
            of I/O modules.

System 2   An RT using a fixed SIA, but with the number and
            type of I/O modules variable.

System 3   An RT in which both the number of SIA's is variable,
            and the number and type of I/O modules are variable.

The general arrangement of SIU, SIA and I/O modules in the modular RT
is as shown below in Figure 3.5-3. This figure shows three functional
blocks within the RT.
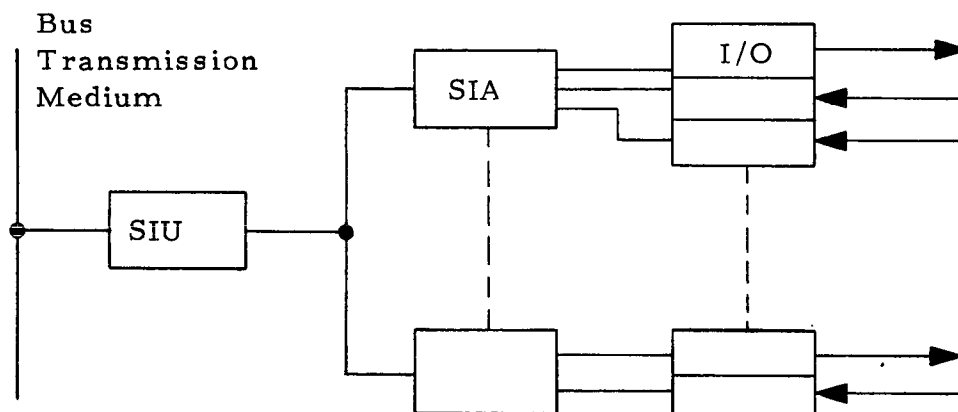
Figure 3.5-3   The Modular RT Configuration

The next logical extention of the Figure 3.5-3 arrangement is to give the SIA remote capability. Some alternate methods of achieving this are given in Figure 3.5-4. Figure 3.5-4a is the nonremote configuration, where the SIA is an integral part of the RT. Figure 3.5-4b is a configuration where the SIA is located remotely from the SIU using dedicated circuits, (c) where the SIA is interfaced to the SIU through a serial data bus, and (d) where the interface is by a parallel bus arrangement.

If the SIA is to be made remotable, then a number of other possible alternatives must be considered concerning the SIU/SIA interface as listed below:

- Number of lines (2 wire duplex, 3 wire duplex, half duplex) on local bus.
- Isolated versus non-isolated.
- Maximum distances.
- Signal design and detection method.
- Method of driving cable.
- Sync and timing method.
- Error checking or voting.
- Type of cable to be used.

As may be noted many considerations in the SIU/SIA interface (with a local bus) are similar to those considered in the study for the main data bus but on a smaller scale. The choices made concerning SIU, SIA and I/O modules can be found in paragraph 3.5-4, Trades. As would be expected, the mix per location of the various signals contributed significantly toward the resultants.

Data Bus Transmission Media
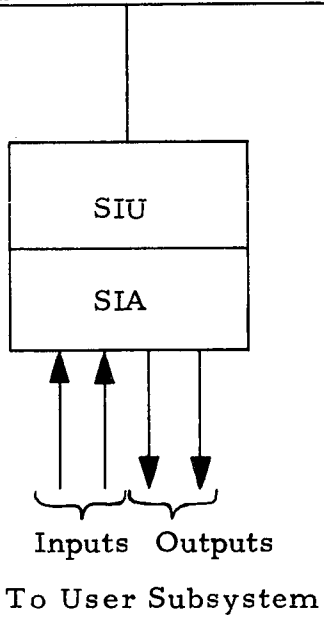
(a) Nonremote SIA
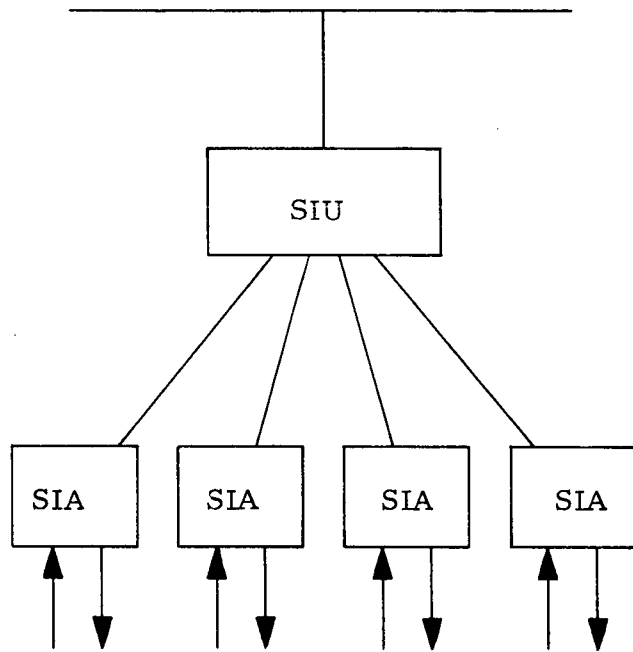
(b) Dedicated SIA/SIU Interface
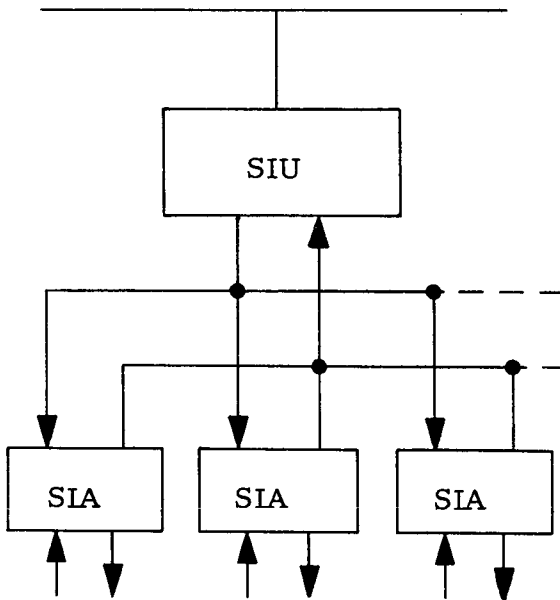
(c) Serial Data Bus
    SIU/SIA Interface
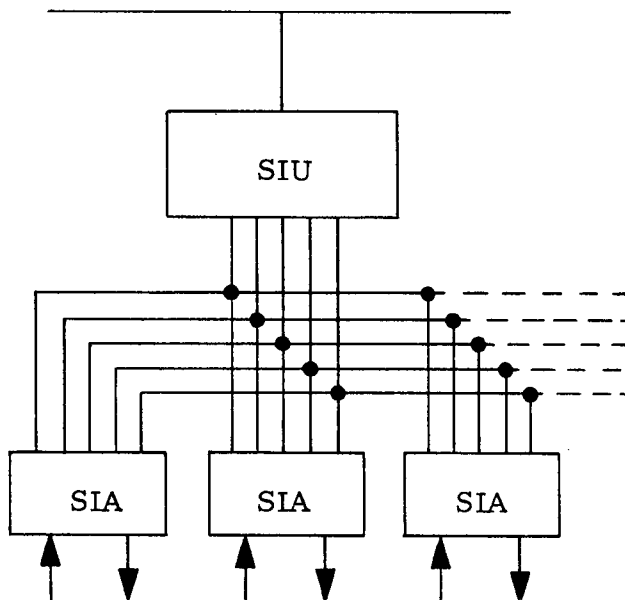
(d) Parallel Data Bus
    SIU/SIA Interface

FIGURE 3.5-4   BASIC RT CONFIGURATIONS

3.5.1.3   Candidate RT Configurations

It is appropriate at this point to present four candidate RT configurations advocated by Phase B contractors and NASA, illustrating their divergent views as to the functions and configurations of the data bus system and the RT.

Figure 3.5-5 shows the functions attributed to each of the four candidate RT's, and Table 3.5-1 lists the essential characteristics of the candidates.

In some cases, assumptions are made because certain system details were not reported. It will be recognized that many of the functions listed under the various candidates are identical functionally to those of other candidate systems, but different terminology is used. The nomenclature and terminology of the originator is preserved in each candidate system.

Some of the significant differences which are relevant to the USI study are pointed out below:

- All but one system provides some flexibility in the overall configuration by using some form of modularity. System B, however, proposes three different RT's to meet varying subsystem needs of the SSV. System A proposes modular submultiplexers to vary the user subsystem interface, but this only allows a greater number of inputs if they are at a correspondingly lower data rate.

- Only System B recognizes the need for providing signal conditioning to some of the raw signals. Again, only System B provides enable gates and clocks to a user subsystem for inputting or outputting serial digital data. One of the System B configurations also provides a number of power discrete outputs (relay drivers).

FIGURE 3-5-5

CANDIDATE SYSTEMS REMOTE TERMINAL CONFIGURATIONS

3.5-10

SYSTEM A

LCU

Address Program Plug

Act
- T/R Switching
- XMT
- Receive
- I/O Registers
- Control & Timing
- Channel Address & Sequences
- A/D
- Parity Check
- MUX
- DEMUX

(Submux)

(Latch & D/A)

User I/O

Input Modules

Output Modules

Inputs

Outputs

- Analog
- Bilevel

(Variable Mix)

SYSTEM A
(One of Two Types)

SYSTEM B

Clock (Optional)

Bus

A P P

Area DIU
- Modem
- Line Transponder
- Control Logic
- Power Control
- Basic I/O
- Parity Check
- Read Only Memory
- Signal Conditioner
- A/D
- D/A
- MUX/DEMUX

Inputs   Outputs

- Analog
- Bilevel
- Ser.-Dig.
- Raw Signals
- Transducer Excitation
- Enable Gates
- Clock

SYSTEM B
(One of Three Types)

SYSTEM C

Data

Control

A P P

SIU
- XMT
- RCV
- BCH Decoding
- BCH Encoding
- Control & Timing
- Reply Formatting
- EIU Interface
- Parity Check

XMT   XMT   RCV

1   8   1   8   1   8

EIU
- Rec./XMT
- Parity Check
- Channel Decode
- MUX/DEMUX
- A/D
- D/A

Output   Input

- Analog
- Bilevel
- Output Signal Gates

SYSTEM C

SYSTEM D

Control

Data

Destaggered Data From Other Units

Destaggered Control From Other Units

To Other Units

APP

DT

Stagger Taps

- XMT
- Receive
- Destagger
- Stagger
- Vote
- Parity Check
- Decoder/Control/Timing
- Scratch Pad Memory
- Mode A/B Select & Control
- MDM Interface

- Failure Det.
- I/O Registers

XMT   XMT   Rec.

(Local Bus)

M/DM
- Receive
- Parity Check
- XMT
- M/DM Decoding
- Channel Decoding
- A/D
- D/A

- Vote

Outputs   Inputs

- Analog
- Bilevel

SYSTEM D

TABLE 3.5-1

COMPARISON OF CANDIDATE USER SUBSYSTEM INTERFACE

	SYSTEM A	SYSTEM B	SYSTEM C	SYSTEM D
● Elements of Data Bus System	Transmission Line (TL) Bus Controller Unit (BCU) Line Coupling Unit (LCU) Acquisition Control & Test (ACT)	(TL) IOCU (BCU) Digital Interface Unit (DIU)	(TL) (BCU) Standard Interface Unit (SIU)	(TL) (BCU) Data Terminal (DT)

● Bus Interface/Mode
- Modulation
- Total Lines of System
- Connections per
    Remote Terminal
- Method of Error & Failure Det.
	Duplex
	Biphase
	  5 (1 XMT, 1 RCV, 3 Spare)
	
	5
	
	Echo Check, Parity, ACT Address
	True 8 Complement
		Half-Duplex
		Biphase
		  4
		1
		
		H & V Parity, Echo Check
			Duplex
			Biphase
			8 (4 XMT, 4 RCV)
			
			2
			Echo Check, Error Det.
			  Code
				Duplex
				Biphase & Bipolar NRZ (on Data Line)
				8 (4 XMT, 4 RCV)
				
				2
				Voting, Parity Check, + Staggered
				Transmission of Data

● Data Routing	Through BCU (ACT/Select Buffer May Xmit to another ACT/Select Buffer)	Through BCU	Through BCU	Through BCU & DT to DT Using Primary/Secondary Addressing Technique
● Method of Bus Control	Command Response (CR)	CR	CR	CR
● Method of Data Transfer - Data Byte Size - Word Size	"Byte" Addressable or Blocks 8 Bit	Blocks - Locally Stored Sequence 9 Bits (8 Data & Parity) 19 Bytes Receive/35 Bytes Transmit	Byte Addressable o Blocks 8 Bit 33 Bit Words/Contains 1 or 2 Data	Byte Addressable 8 Bits 20 Bits/Contains 2 Data Bytes
● Components of User Subsystem Interface	LCU, ACT & User I/O Interface (Modular)	DIU	SIU Electronic Interface Unit (EIU)	DT MUX/DEMUX (M/DM)

● Types of User Sub. Interface
Variation of I/O Mix/Method
- Method of Interface
- Modulation
- Remote User Interface/No. of Cables
- Error Check at MUX
	(2) 1. ACT 2. ACT/Select Buffer
	Yes/Modular I/O Units/Parallel
	Digital
	  NRZ
	  No/None
	None
		(3) 1. Area 2. IMU 3. Crew
		  No
		
		  No/None
		
		    None
			(1) SIU
			YES/Up to 32 EIU
			Serial Digital
			Biphase
			Yes/3 per EIU
			Parity
				(1) DT
				Yes/Up to 16 M/DM
				Serial Digital
				(Remote) Polar RZ
				Yes/3 (Local Bus)
				Voting & Parity

● Input Channels	31 Each May be Submultiplexed.	Area Crew IMU 24 Analog 16 8 4 S-D 2 16 64 Dis. 24 64 4 Raw 0 0	32 Analog 256 Discrete } per EIU	32 Analog 32 Discretes } per M/DM

TABLE 3.5-1 (Continued)

	SYSTEM A	SYSTEM B			SYSTEM C	SYSTEM D
● Output Channels	31 Each May Be Sub/Demultiplexed (#32 Reserved for Loop Test)	Area 8 Analog 4 S-D 56 Dis.	Crew 16An 2S-D 32D 20D (Power)	IMU 0 An 8S-D 32 D	8 Analog 64 Discretes } per EIU	32 Analog 32 Discretes } per M/DM
		[+ Clock, Word Gates, Data Present, etc.]				
● Data Acquisition Time for 1 mbs Rate on Bus (Time for Computer to Acquire One Byte of Data)	Timing Not Defined	Not Defined			2 Words x 33 Bits/Word = 66 usecond	4.75 words x 20 Bits/word = 95 usecond
● Interrogation Time (Time to Sample and Digitize)	Not Defined	Not Defined			25 us	26 us
● Memory/Function/Size	None	Stores Sampling Sequence, Gain, and Calibration			None	Stores Data and Special Test Word 64 Words x 17 Bits
● Signal Conditioning Capabilities	None	Programmable Gain & Calibration Area DIU Accepts 4 Raw Signal—Does Req'd Conditioning —Will Take Some Incrementals (Pulse Rate) —Provides Transducer Excitation for 4 Raws			None	None
● Power Control/Power Consumption	Power Strobed/1. Stdby 1.5w 2. ON 25w	Power Strobed/1. Stdby 2. Receive, 3. Transmit 4. Transpond			------	--------

- Both Systems A and B are vague as regards system timing. It was therefore not possible to estimate data accessibility or interrogation time. As will be shown later, this is an important consideration in acquiring signals.

- The interface with the data bus may not be clear from the accompanying diagram. System A interfaces with all five of the transmission lines, one of which is used as a control line from the bus controller, and the other used as a party line to transmit data back to the bus controller. The other three lines are spare and may be used for either prupose if either of the first two lines should fail. Systems B and C are fully independent of the other elements of the redundant system. It is assumed that the user subsystem has the capability to select from the four independent strings of the data to be used. In System D the received words of one pair of lines are destaggered in each RT and the destaggered words are passed back to the other three units for voting. In addition each RT may determine that a failure has occurred and generates a signal to the other units so that reconfiguration is possible.

- It is noted that only Systems B and D employ a memory of any significant size (they all employ registers in inputting or formatting data). The use of the memories are quite different, however. System B uses the memory to store instructions for blocking of data or for providing a special sampling sequence. In addition, its memory is used to store gain (and perhaps offset) instructions for some analog channels, and special raw data signal conditioning instructions. In System D, the memory (scratch pad) is used to store digital data as an intermediate step in the data acquisition process. It is assumed that both memories may be used for test or status reporting purposes.

3.5.1.4 Data Acquisition Mode

The basic mode of operation of the data bus, i.e. whether it is full or half duplex, command or contention, etc. is largely determined by consideration of subjects treated elsewhere in the study. However, the configuration and functions required of the user subsystem interface are impacted to some degree by the choice of basic operating mode, such that some particular aspects of the data acquisition mode are discussed in this paragraph. The alternatives discussed are:

- "Byte" addressing of data.
- "Blocking" of data.
- Intermediate storage of data in a scratch pad memory.
- Delayed response of data.

The essential characteristics of "byte" and "blocks" of data are described in Section 3.4, Synchronization, Timing and Control. The concern in this section is the impact upon the hardware of the RT. First, if a data word or block of data words contains more than one data byte, it is obvious that the input or output channels associated with the bytes must be of like sampling rate, and located in the same RT. When several data bytes are transmitted in one data word ("packing") or several words are transmitted, a channel address becomes associated with more than one I/O channel. In either case additional circuits and control are necessary in the RT to sample and assemble the bytes in the right order. Blocking of data would invariably lead to more complexity at the RT because to be efficient the length of the block should be variable. The sampling sequence could be stored in a memory located at the RT. The decision as to whether a system should be designed to transfer bytes, packed words, or blocks of data words depends on the nature and distribution of the data sources/sinks, and other system requirements such as overall system flexibility.

A method of data acquisition where a scratch pad memory is used to store data in an intermediate step at the RT has been identified. The sequence of operation is as follows: as soon as the SIU recognizes a valid request for data from a particular channel, data from a memory location associated with that address is read out and is available for transmission on the data bus, then the input channel is sampled and digitized, and used to refresh the data held in memory. This technique allows the RT to respond quickly with data, but the data could have a degree of "staleness". Another method of operation is to merely provide a fixed delay between the time that a data "byte" or block is requested and the time that it is transmitted over the bus transmission medium. The delay must be of sufficient time to allow all the data acquisition circuits to respond.

The best choice of the two techniques described above depend upon a number of considerations. These considerations will be discussed in greater detail in paragraph 3.5.4.4, Interrogation Time vs. Data Accessibility, where some of the characteristics of data acquisition circuits are discussed in detail.

3.5.2   Interface Related Constraints and Limiting Factors

The previous paragraphs summarized functions and system approaches possible and characteristics associated with accomplishing these functions. The next paragraphs will summarize electronic operations, areas of trades, and analysis and recommendations. Between what is desired, paragraph 3.5.1, and the following implementation oriented sections, it is appropriate to briefly define restrictions, constraints and limiting factors.

- Temperature extremes to be experienced aboard SSV's have great impact upon avionics. The need for cold rails or plates restricts placement of avionics to certain defined areas or bays, effecting signal mix, modularity, signal conditioning and physical size, to name some.

- The physical size of the RT package is limited by such constraints as the need to fit cold rails or plates, or to be easily installed into the environmentally conditioned area.

- The total number of RT's should be limited because of the loading effect on the transmission medium. The number used in the transmission media study was 100 or less.

- Constraints imposed upon the RT configuration by the techniques selected in the areas of synchronization timing and control and in the methods insuring operational reliability.

- Quality of RT based upon severity and conditions of use and environment (reference Vol. III for more detail).

- Flexibility - to accommodate all TDM type signals aboard the SSV's.

3.5.3   Electronic Operations

This section reviews various electronic aspects associated with the implementation of a viable RT for Space Shuttle Vehicles. Significant elements of the design are performance, signals accommodation, size, weight and power consumed.

3.5.3.1 Signal Conditioning, Transducer Elements, and Calibration Techniques

A list of the transducers, signal conditioning methods, important terms and definitions, and calibration techniques which are applicable to the SSV were compiled. The methods given are believed to represent more than 90% of all measurements to be made. The transducer elements covered include:

- Strain Gauges
- Resistance Temperature Elements (RTE)
- Thermocouple
- Variable Reluctance Devices
- Linear Variable Differential Transformers (LVDT)
- Piezo-Electric Devices

The characteristics of the above elements, their range of measurement, and detail signal conditioning and calibration circuits are given in Vol. III and Vol. IV.

The signal conditioning circuits most often used are some form of bridge circuit, excited by either a constant voltage or a constant current supply. The bridge circuit used for strain gauges and RTE's are somewhat similar, and the advantages of using a constant current source in both cases are pointed out in Vol. IV.

Thermocouples require a particular circuit in which a reference junction is employed in some manner. Alternate circuits and their characteristics are given in Vol. IV.

All the circuits using some form of bridge, and the thermocouple circuits have some things in common: they all require calibration, or their gain and offset must be compensated for in some manner to produce meaningful measurements. An alternative method is to program the input amplifiers in some manner to compensate for gain and offset.

3.5.3.2   Distribution of Measurements Aboard the SSV

The data compiled in the RI & A study, Volume III of the Phase II Report was used to establish the quantity and type of measurements in each of the equipment bays of the Booster vehicle. The results are given in Table 3.5-2. There appears to be several types of signals which are sufficiently concentrated to warrant an investigation into the feasibility of providing special signal conditioning techniques to reduce the complexity of equipment at these points. Included in the table are 1942 discrete signals and digital words, whose conditioning are relatively simple.

It can be envisaged that on large aerospace vehicles there will be found many opportunities to use techniques that allow signal conditioning and multiplexing techniques to be used in a cost-effective method. One such technique is the time sharing of signal conditioners.

3.5.3.3   Time Sharing of Signal Conditioners

Time sharing (or multiplexing) of the signal conditioners is divided into two general classes; 1) sharing between signals which are only used during certain mission phases, or for short periods, and 2) a continuous, periodic sharing. In either case the objective is to reduce the total amount of cost, size, power and weight required to perform the signal conditioning function.

TABLE 3.5-2

BOOSTER MEASUREMENTS

TYPE SIGNALS AT LOCATION

| Type | Nose | Location (Equipment Bay) | | | AFT | Total |
		Crew	Mid.	APU		
(A)	--	4	2	--	156	162
(L)	--	1	1	1	2	5
(F)	--	4	6	24	---	34
(V)	--	2	16	103	6	127
(T)	11	102	122	131	268	624
(S)	8	18	57	12	16	111
(P)	4	171	46	223	550	994
(Y)	22	381	145	176	582	1306
(E)	5	1427	--	321	842	2595
(I)	5	24	32	50	72	183
(Q)	--	28	46	16	16	106
(R)	--	9	6	52	96	163
(G)	--	2	11	--	--	13
(H)	--	5	--	--	--	5
(N)	--	--	--	12	--	12
TOTAL	45	2178	494	1121	2606	6444

LEGEND TO TABLE 3.5-2

SYMBOL	MEASUREMENT	TRANSDUCER/METHOD
(A)	Acceleration	Force Balance
(E)	Voltage	Direct, Voltage Transformer
(F)	Flow	Impeller-Magnetic Pickup, differential pressure
(G)	Gas Analysis	Special Purpose
(H)	Frequency	Counter
(I)	Current	Shunt (Direct), current transformer
(L)	Accoustic	Piezoelectric, ferroelectric, etc.
(N)	Lube Oil	Light Intensity
(P)	Pressure	Strain Gauge, potentiometer, differential transformer
(Q)	Quantity	Capacitive sensors, level sensors
(R)	Rate	Impeller, fan rotation, magnetic pickup, etc.
(S)	Strain	Strain guage, bridge
(T)	Temperature	RTE, thermocouple
(V)	Vibration	Piezoelectric
(Y)	Position	LVDT, variable reluctance Discrete (limit switches)

In order to implement time sharing of signal conditioners it is necessary that the signals be located in the same general area, i.e. to be affixed to a common RT or SIA. Secondly, the signals must be of the same type. From the distribution of measurement signals presented previously, it does appear that there is an opportunity for time sharing at certain locations. The effectiveness of time sharing signal conditioners depends upon whether one or more of the following criteria is met:

- The signal conditioning circuit is expensive, or complex.

- The power consumption of individual transducers or signal conditioners is high.

- The transducers or conditioning circuits do not require continuous excitation, or integration over long periods of time.

- The insertion of switches in the conditioning circuit does not introduce significant error.

Circuits which are well suited to time sharing include those which employ constant current excitation (e.g. strain gauge bridges and RTE's), and thermocouple circuits because of the rather expensive and cumbersome reference junction.

3.5.3.4 Switching Time of Signal Conditioners

The main concern here is how fast the circuit may be switched. Figure 3.5-6 shows an equivalent network for a signal conditioner comprised of an exciting voltage and a resistive network such as a bridge completion circuit, the effective line capacitance C, and the L & R of the transducer.

The solution to the network, applying the step function ($\frac{1}{S}$), is as follows:

$$E_o(S) = \frac{E}{S} \cdot \frac{R_2 + L_S}{R_1 L C S^2 + (R_1 R_2 C + L)S + R_1 + R_2}$$

Typical network values:

$R_1 = 500 \qquad C = 2400$ pf

$R_2 = 100 \qquad L = .1$ mh

50 ft. of TSP
#22 Kapton

To test if the circuit is underdamped or overdamped, insert values in the following expression -

Overdamped if (1) > (2);

Underdamped if (1) < (2)

$$\begin{array}{cc} (1) & (2) \\ \left(\dfrac{R_1 R_2 C + L}{2 R_1 L C}\right)^2 & \dfrac{2 R_2}{L C} \end{array}$$
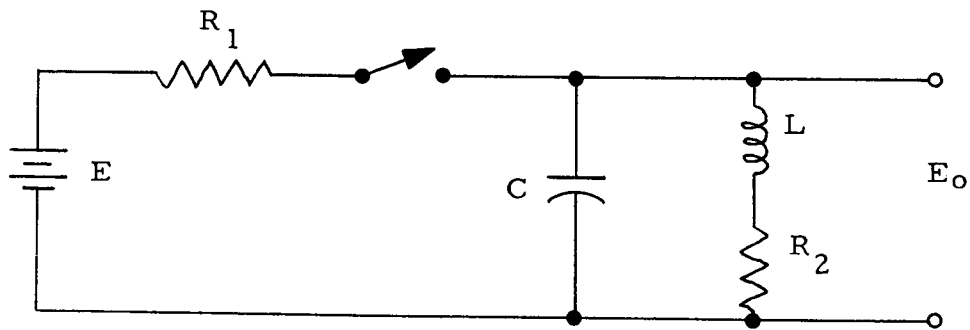
Figure 3.5-6   Equivalent Signal Conditioning and Transducer

For 0.1% accuracy (10 bit), about 15 to 20 microseconds would be required. This then is not a major concern in signal conditioning when the multiplexing is applied properly, i.e. in tiers.

Time sharing methods must also account for temperature effects which are caused by excitation current. This is a relatively long term problem, which can be solved by the use of low excitation current and providing an adequately low duty cycle.

3.5.3.5   Signal Conditioning Modularization

Signal conditioning time sharing is feasible in many cases. A recommended set of modules which include multiplexing, demultiplexing, and signal conditioning is given below.

- Hi Level Analog Input Multiplexer
- Low Level Analog Input Multiplexer
- Bilevel and Serial Digital Multiplexer
- Analog Demultiplexer and Output
- Bilevel and Serial Digital Output
- Combinations of Analog and Digital Output
- Thermocouple Signal Conditioning/Multiplexer
- Constant Current Signal Conditioner/Multiplexer (for RTE's, etc.)
- Piezo-Electric/Charge Amplifier/Multiplexer
- Bridge Completion and Power Supply/Multiplexer
- LVDT Excitation and Demodulator/Multiplexer
- Frequency Counting Module
- Synchro/Digital Converter

The above modules would be designed to interface directly with an analog/digital converter or with a digital combiner if the output is already digital.

A standard module size of about 60 in^3 volume is chosen for an example. Two examples that demonstrate a modular concept to signal conditioning/ multiplexing and empty time sharing of signal conditioning elements follow:

- **Thermocouple Multiplexer Unit**

  Signal conditioning, multiplexing, decoding of the multiplexer command, and automatic offset compensation of the amplifier are accomplished in one unit. This unit was designed using discrete components and IC amplifier circuits (not MSI) with the result that 16 channels are accommodated in 8" x 5" x 1.5" module. Using MSI circuits, the module could be expanded to 32 channels.

  In this design the temperature of the reference junctions is measured periodically using an RTE, bridge, and a precision voltage source. When the amplifiers are connected to the RTE circuit, a circuit automatically changes the offset of the amplifier to produce zero voltage at the amplifier output. Therefore, the reference junctions are calibrated and the offset of the amplifiers corrected without external command.

- **Analog Resistance Multiplexer**

  Using constant current methods of signal conditioning applied to resistive sensing elements and MSI techniques, a preliminary design and breadboard has resulted in an 8" x 5" x 1.5" module containing 64 channels. The module includes channel address decoding, has a test current accuracy of .1%, and an input impedance to the analog voltage multiplexer of approximately 100 megohms.

Presampling Filtering

The use of presampling filtering (PSF) on analog channels is classified into two cases:

1. When the entire signal is of interest,
2. When unwanted signal components are present (interference).

In case one, PSF may be used to eliminate problems due to aliasing - when the signal spectrum overlaps the sampled spectrum. Because of the great number of channels and the large bulk of hardware that would be required, PSF is not recommended for SSV, except in special cases. The alternative of assigning an adequate sampling rate to the analog channel is suggested.

In case two, interference on board the SSV is expected, and a small amount of filtering is suggested at each channel input in the form of an RC or LC circuit. Large resistance values should be avoided because of the increase in mux settling times. A conservative suggestion is that the filter cut-off frequency be several times the data cut-off frequency, in order to prevent inaccuracies due to the filter.

3.5.3.6   Multiplexing

Multiplexers are used to connect one of several signal inputs to a common point so that circuits may be shared and signals put into a TDM format. The most commonly used multiplex switches in present day aerospace designs are the junction field-effect transistor (JFET) and the metal-oxide field-effect transistor (MOSFET). These switches provide the following features:

- excellent DC isolation, switch driver to analog signal path
- zero offset voltage

- low leakage current
- high off/on impedance ratio
- low cost, size, weight and power consumption
- readily available as discrete, integrated circuit, MSI and LSI packages.

Multiplexing speed is of prime importance to data accessibility. This and configurations are covered, as well as remarks about dedicated amplifiers per channel.

Basic Mux Configurations

Figures 3.5-7 and 3.5-8 show two-wire, three-wire and guarded substrate techniques, which are usually preferred to single-ended switching by virtue of their improved noise rejection.

Figure 3.5-9 shows multitiering techniques which lend to modularization and faster data through-put speed.

Following the switching section is the common amplifier. Small size and weight are achieved by an IC type amplifier, but performance specs on linearity, slew rate, offset and gain must be apprised. The amplifier output connects to an analog-to-digital (A/D) converter.

Figure 3.5-10 shows the MOSFET and JFET circuits. Notice that the MOSFET device requires no feedback, gives better isolation between channels, and is generally used in most modern analog multiplexers.
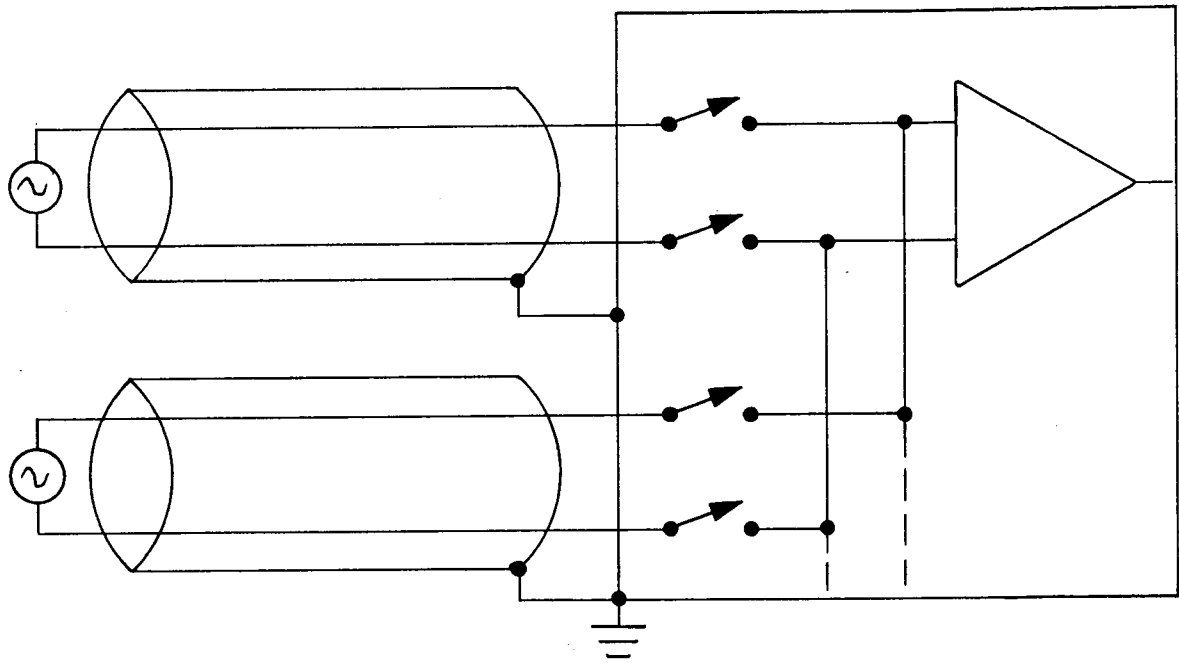
(a)   Two Wire Differential Multiplexer
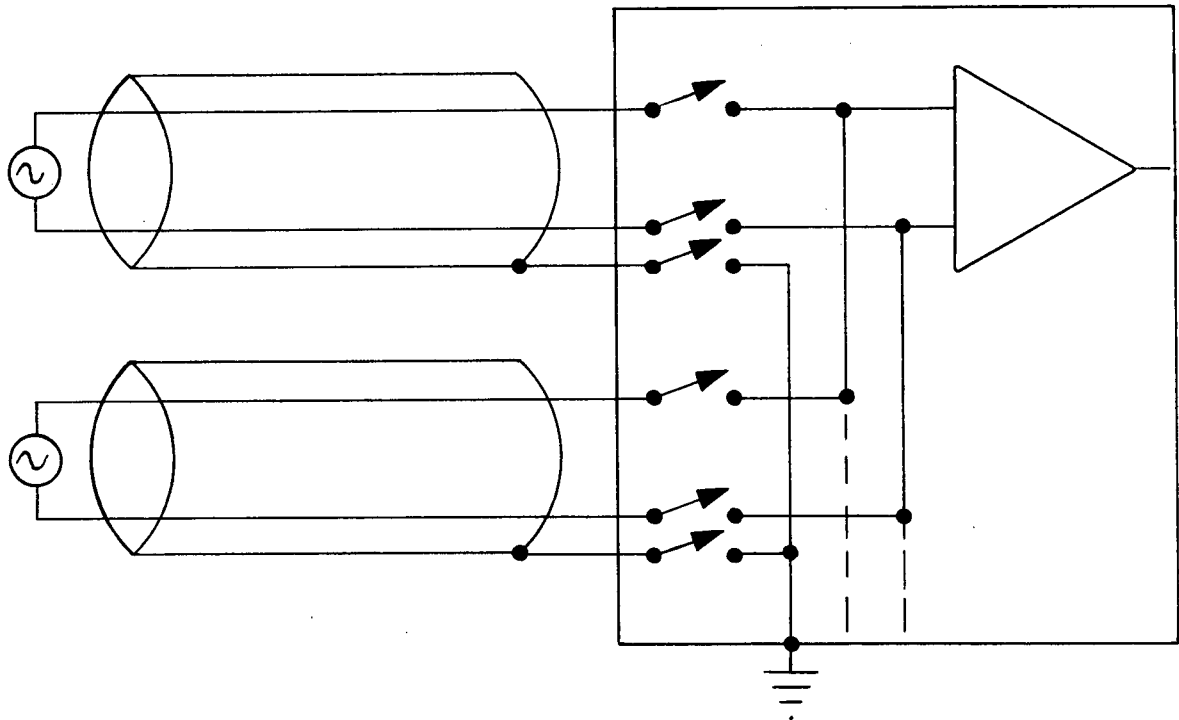
(b)   Three Wire Differential Multiplexer

FIGURE 3.5-7   BASIC DIFFERENTIAL MULTIPLEXER
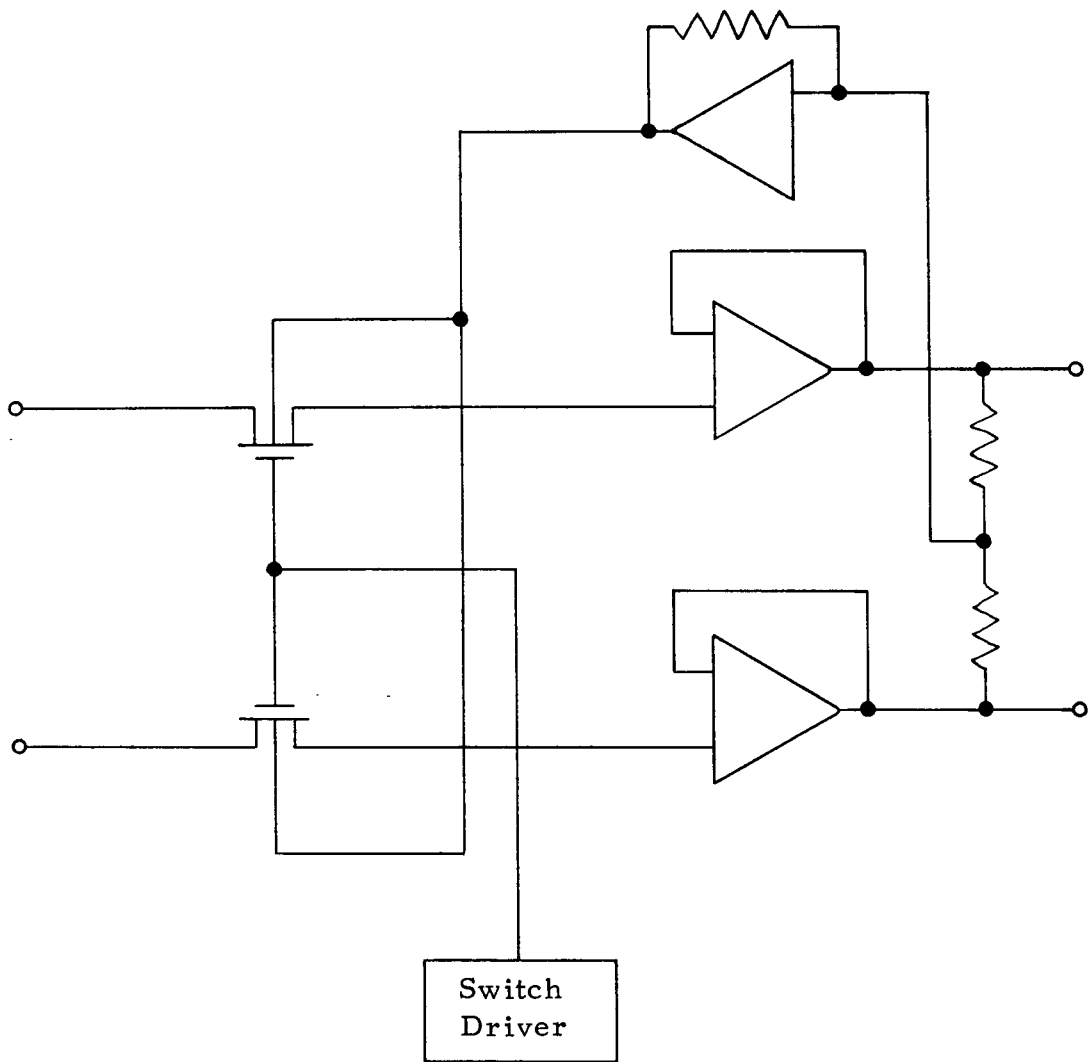
FIGURE 3.5-8   METHOD OF GUARDING THE MOSFET SUBSTRATE
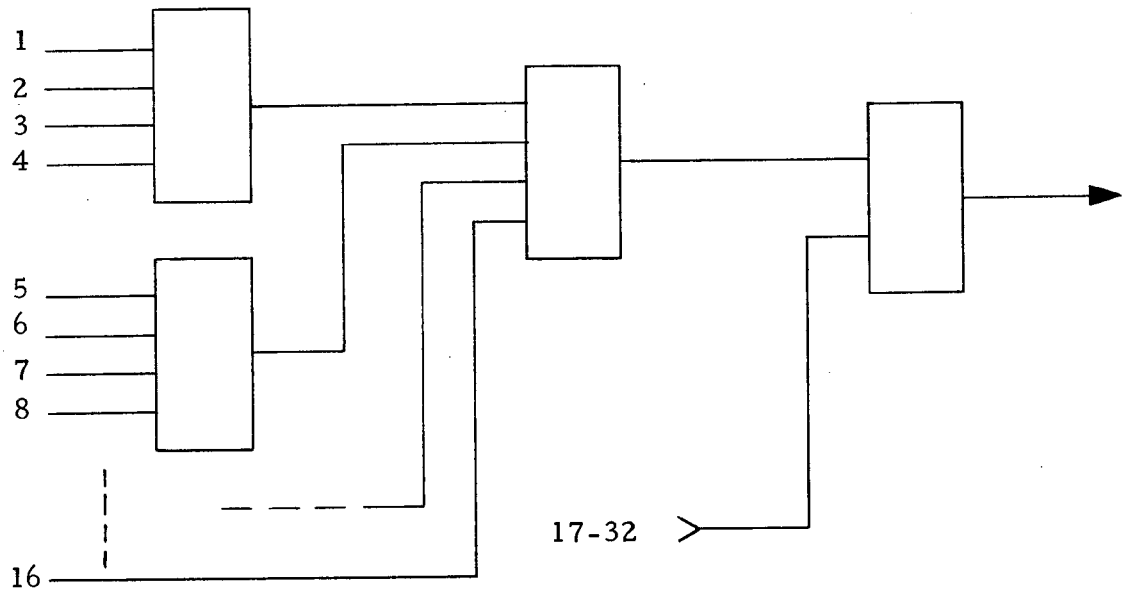
3-Level Tier, 32 Inputs
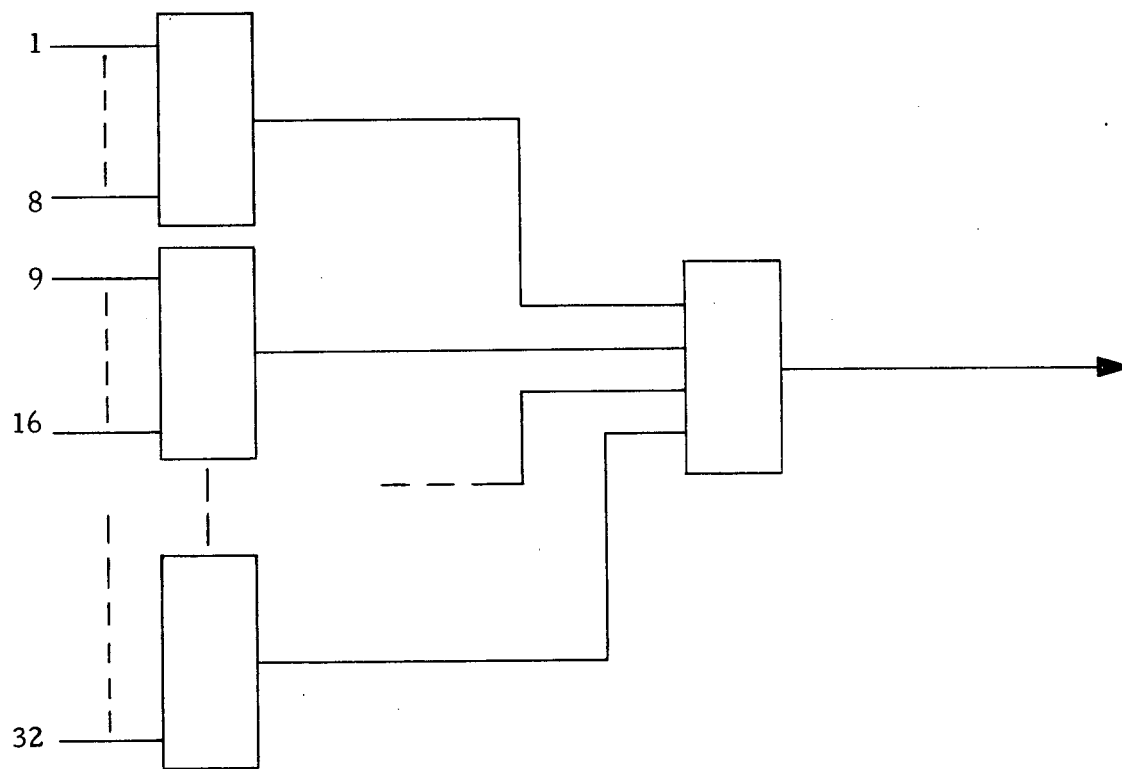
2-Level Tier, 32 Inputs

FIGURE 3.5-9   EXAMPLES OF MULTIPLEXER TIERING

Signal (± 10V)

N-Channel
(Depletion Mode)

PAM

"ON" = +15V

+15

"OFF" = -15V

-15

Switch Driver
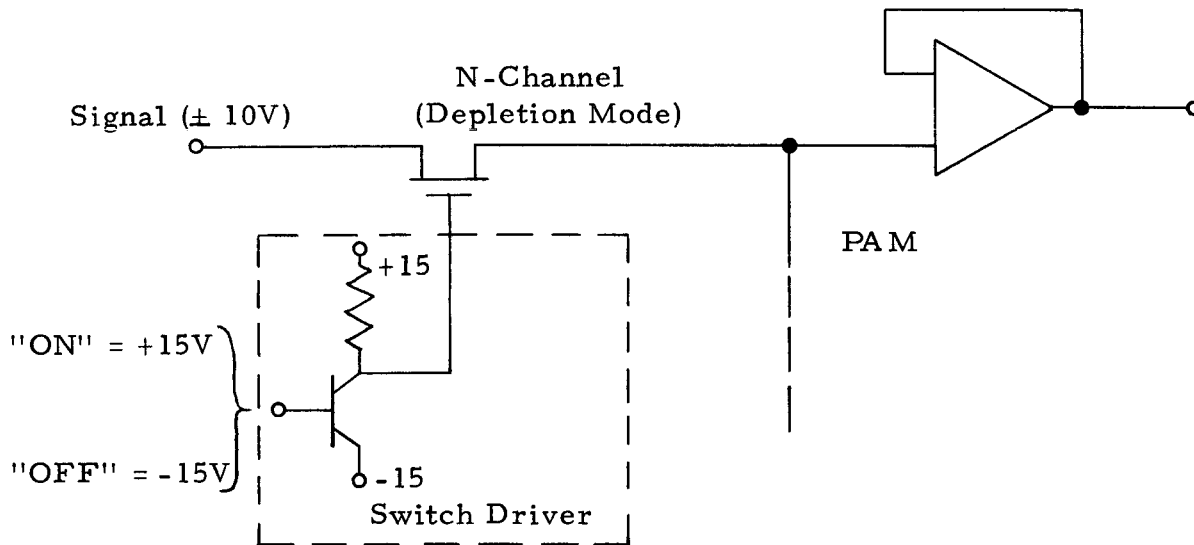
(a) Circuit Using MOSFET Transistor Switch

Signal

N-Channel

R_B
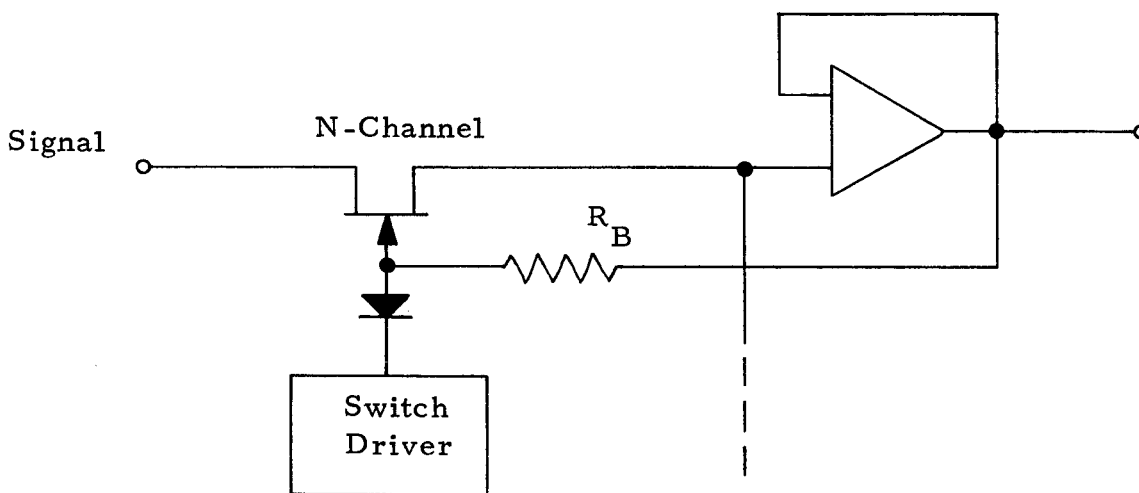
Switch
Driver

(b) Circuit Using JFET Transistor Switch

FIGURE 3.5-10   MOSFET AND JFET CIRCUITS

Multiplexer Rate

The rate at which signals may be multiplexed is determined by the settling time of the multiplexer and amplifiers, and the conversion time of the A/D. The main factor in multiplexer settling time is the RC time constant, which is composed of the source and FET resistances and the FET switch capacitances, stray capacitance, and amplifier input capacitance. The capacitance associated with FET switches are the drain-to-gate, the source-to-gate, drain-to-source, drain-to-body (or substrate), and source-to-body. The body (substrate) capacitance is seldom given in manufacturers specifications, but it is significant. The drain-to-gate and body capacitance in a multiplexer is proportional to the number of switches.

Other factors which increase the settling time is the complex impedance the transmission line between the transducer and switch, and the gate driver feedthrough.

The effect of the transmission line is to introduce a delay between the signal source and the multiplexer such that there is an effective RC time constant greater than what is expected from circuit parameters. A rule of thumb is that for a .1% accuracy about 7 or 8 RC time constants are required, while for .01% about 10 RC time constants are required. The capacitance is the total drain-to-body and drain-to-gate capacitance, and the R is the sum of the sensor, line, and switch resistances.

Methods for reducing capacitance and allowing faster multiplexing are multitiering and not sampling successively on the same input group. The practice of substrate guarding is also used to reduce the capacitance to the substrate (body). The amplifier slew rate then becomes a limiting factor.

Two examples of operational multiplexing systems are given. The first example is a 64 channel multiplexer using tiering with the basic number of switches in a group limited to 16. The MOSFET switches used are Siliconix devices, with 5 switches on each flat pack. The multiplexer is grouped into groups of four flat packs, and each group with its own programmable gain amplifier. Thus, each group is actually a 16 channel multiplexer. With a 500 ohm low level source, the settling time to 10 bit accuracy is 16 μsec. The guarded substrate technique is used, and overvoltage protection is provided (source current limited to 1 mA during overvoltage).

A second example is a 32 channel device using about the same technique, but with a source impedance of 10 K. There is also some resistance in the input circuits and in the feedback path from the guard amplifier to the substrate. The settling time to 8 bit accuracy is 31 μseconds. There are other differences in the two examples, but the former example represents the present state-of-the-art when speed is a major consideration, while the latter example reflects some compromise (cost, size, and higher source impedance).

The two approaches above represent a good compromise, and indicate that the settling time should not exceed about 20 μseconds.

Alternate Multiplexing Method

The multiplexer problems discussed are greatly alleviated if each signal input fed into a dedicated separate amplifier, whose output could be multiplexed. Such an approach would be very expensive, and would consume a large amount of space and power. However, the multiplexer settling time using this device would only be a few useconds.

3.5.3.7   Digitizing

The time required to digitize an analog signal level into a digital word is another factor which increases the total interrogation time required.

An excellent description of almost every conceivable type of A/D converter is given by Schmid[1]. The following is a list of the basic types, as categorized by Schmid.

- Parallel Feedback Types
    - Servo Type
    - Successive Approximation

- Serial or Feedback Types
    - Circulation Type
    - Charge Equalizing Type

- Indirect Types
    - Single Ramp Conversion
    - Precision Ramp Conversion
    - Up/Down Integration
    - Precision Type without Precision Components

- High Speed Types
    - Cascade Analog to Binary
    - Cascade Analog to Gray
    - Variable Reference Cascade
    - Multi-Threshold Type
    - Partially Cascaded

1.   "A/D Conversion", by Herman Schmid, Electronic Design, December 5, 1968, December 19, 1968 and January 4, 1969.

- Ultra-High Speed

    - All Serial
    - All Parallel
    - Serial-Parallel
    - Propagation
        - using shift registers
        - using delay lines

In addition to the above there is an SCI proprietary technique known as "differential approximation encoding" which contains about twice as many components as the comparable successive approximation encoder, but the digitizing rate is about 10 times as fast.

Of the types listed above, the successive approximation type is the prime candidate, because of its fast slewing rate and moderate number of components. The performance of the converter shown in Figure 3.5-11 is greatly dependent upon analog comparator offset and D/A ladder accuracy and drift.
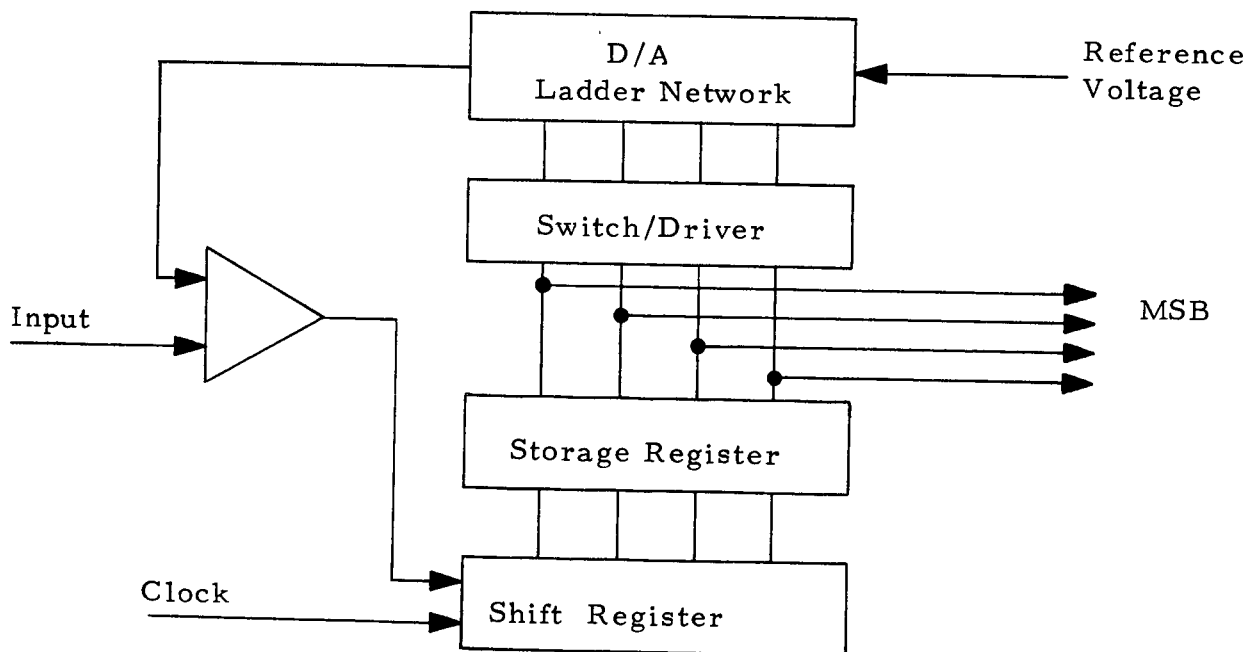
Figure 3.5-11 Successive Approximation A/D

Performance versus price comparatives are given in Table 3.5-3.

Total Time Required

The total time for multiplexing and digitizing is presented here for three different approaches.

(1)   The total time required for a dedicated amplifier multiplexer and a high speed A/D is less than 6 μseconds.

(2)   Using state of the art techniques, MOSFET multiplexer and a moderate speed A/D, the total time could be within 22 μseconds. (18 μs for muxing and 4 μs for A/D).

(3)   Using the same approach as in (2), but with a programmable offset and gain amplifier the total time is about 30 microseconds.

3.5.3.8   The Use of Memory in the RT

Data may be maintained for rapid access by use of a scratch pad memory, i.e.:

(1)   data is kept in RT memory, and is updated only for the requested channel after interrogation.

(2)   Write new data into memory asynchronously, on a non-interference basis with bus transfers.

The semiconductor type scratch pad memory is preferred to plated wire and core memories because of size, speed and compatibility with interfacing circuits. Random Access Memories (RAM) are available comprised of bipolar or MOS semiconductors. Bipolars enjoy a speed advantage, but MOS excell in bit density, less power and lower cost.

TABLE 3.5-3

A/D CONVERTER PERFORMANCE

AS ADVERTISED BY MANUFACTURER

Resolution (Bits)	Conversion	STABILITY		Price
		Gain T.C. (PPM/°C)	PSRR PPM/ %	
8	12 us	± 50	± 150	$195.00
10	18 us	± 40	± 150	225.00
8	16 us	± 5	± 20	250.00
10	25 us	± 5	± 20	280.00
12	25 us	± 5	± 20	305.00
8	4 us	± 20	± 500	495.00
10	6 us	± 20	± 500	725.00
12	10 us	± 20	± 500	775.00
8	.8 us	± 50	± 1500	1680.00
10	1.0 us	± 50	± 1500	1990.00

Memory Requirements

In the following discussion some applications in which the use of the scratch pad memory is useful are pointed out, and some of its limitations are noted. As a reference a data bus system is envisaged for the SSV, i. e. , one in which the word length is from 20 to 24 μseconds.

- For the RT whose role is primarily one of data acquisition, there appears to be no necessity for the memory if the data access time can be on the order of 75 microseconds. There appears to be adequate time on the data bus to sample, digitize, and transmit back data. The multiplexing/digitizing equipment is not elaborate. There may be certain restrictions placed upon the sampling sequence. The data words could be transmitted back one or two word times after the control word requesting the data.

- It is conceivable that the software or the organization of the main bus controller computers may require that data be received immediately after it is requested. In this case a scratch pad memory is definitely required, as not even the high speed multiplexer/converter could respond quickly enough.

- Certain software operations may require two or more data bytes to have been made simultaneously for time correlation, in which case the scratch pad memory would prove useful.

- For the system which employs staggered transmission of data as a means of achieving immunity to burst noise, the degree of stagger allows less time for the multiplexing and digitizing process such that the use of a scratch pad memory becomes

essential. This is also true of certain other coding schemes which in effect spread the message out in time.

- The memory at the DT may be used to store information other than data, such as test and status information, channel multiplexing sequencing, offset and gain instructions for programmable amplifiers or signal conditioners, and limits. By limits, what is implied is that the information desired regarding an analog channel is merely whether it exceeded some limit (which is programmable by the bus controller). It would be more efficient to transmit back one bit signifying whether the limit was exceeded than the entire value for instance.

- An intermediate interfacing action, such as the serial transmission between SIU and SIA may lengthen the interrogation time to an unacceptable degree, such that a scratch pad memory becomes mandatory.

- The user subsystem interface, required to output a large number of analog signals has certain complex problems that, while not formidable, must be considered. One method of implementing analog outputs is by converting the digital word from a demultiplexer to an analog level, storing the analog word on the D/A ladder, and buffering the output until another word is received for that channel. While this technique is straight-forward, it does not utilize hardware efficiently. Another approach is to time share the D/A converter with several channels, storing levels on a capacitor, and buffering the outputs. The capacitor must eventually be recharged, which can be achieved by some logic circuitry and a memory to store the digital words. Thus, one more use of the memory at the RT is identified.

3.5.4   <u>Analyses, Trades and Approaches</u>

Certain examinations have been made in previous sections. They have included the following:

- RT functions to be performed, and possible approaches.
- Modularization aspects of the RT.
- Data acquisition methods.
- Constraints and limiting factors.
- Signal conditioning considerations, including time sharing.
- Distribution of SSV measurements.
- Filtering, multiplexing and data conversion aspects.
- Use of memory in RT's.

Further examinations covering the RT and its sizing, and interrogation time in data acquisition follow.

3.5.4.1   <u>Special Purpose vs. General Purpose RT</u>

It is pertinent to point out the type of systems which may be included and special provisions that must be included at the RT for them.

- Eavesdropping Mode - Several subsystems have been identified which require access to much of the data transversing the data bus system, but do not generate data. Such subsystems include the telemetry system, tape recorders, the orbiter/booster interface, the GSE interface and the OFI/DFI interface. One possible method for stripping data needed for these subsystems is an "eavesdropping" mode, where supervisory words are monitored so that data concerned with certain channels may be fed into the eavesdropping RT without having to perturb the central computer. Addressing methods include the following:

1) RT primary and secondary address recognition - as pre-
determined within the RT. This may require address
translation, which certainly would require a memory.

2) RT primary and secondary address recognition - as
received from central over the supervisory line.

3) Bus controller handles all traffic, re-distributing it.

- Distributed vs. Localized User Subsystems - In the Phase I Report
two broad categories of user subsystem signals were identified:
(1) Interface Oriented Signals and (2) Distributed Signals. The sub-
systems themselves were further categorized into the distributed
versus localized concepts, and examples were given of each. It is
pointed out here only because one of the candidate subsystems pre-
sented incorporated a memory for checking limits and for storing
gain and calibration data at the local level. These features may
alleviate some of the data rate requirements between the central
computer and the subsystem on board the SSV, but generate an array
of problems in overall data management system design and software.

- The BC and CIU - the bus controller and/or computer interface unit
are considered to be special cases of a remote terminal, and they
should be designed as special purpose units which interface with the
bus transmission medium.

3.5.4.2   Signals Mix Analysis

A trade area identified previously is in the RT size, i.e., the number of input or output channels which the RT or SIA may accommodate. As has been previously defined, the I/O module is defined as the lowest increment of input or output channels which may be grouped effectively. Reference Table 3.5-4 for a listing of signals per SSV locations.

The constraints on the number of channels, or the module increment (MI) per I/O module are:

1.   That MI = 2^n, n = a positive integer, so that addressing of channels may occur using binary numbers.

2.   That MI be as large as possible, since the cost per channel, etc., decreases as function of the number of channels.

3.   That the utilization factor of the I/O module does not drop below some level.

In this approach, the module increment (MI) was divided into the quantity of each signal category of each location per SSV. Categories are as follows:

1)   Booster Measurement Analog - BMA

2)   Booster Measurement Discrete/Digital - BMD

3)   Booster Control Analog - BCA

4)   Booster Control Discrete/Digital - BCD

5)   Orbiter Measurement Analog - OMA

6)   Orbiter Measurement Discrete/Digital - OMD

7)   Orbiter Control Analog - OCA

8)   Orbiter Control Discrete/Digital - OCD

TABLE 3.5-4

OPERATIONAL (OFI)

SIGNAL MIX PER LOCATIONS

FOR BOOSTER AND ORBITER

BOOSTER LOCATIONS	MEASURE		CONTROL	
	ANALOG	DISCRETE /DIGITAL	ANALOG	DISCRETE/DIGITAL
Nose Bay (2)	39	18	0	22
Crew Sta. (2)	1127	1132	66	1421
Midbay (2)	333	156	1	85
APU (2)	872	304	12	382
Aft (1)	2284	332	280	683
	4655	1942	359	2593

ORBITER LOCATIONS	MEASURE		CONTROL	
	ANALOG	DISCRETE/DIGITAL	ANALOG	DISCRETE/DIGITAL
Nose Bay (2)	136	166	2	32
Nav. & Crew Bay (2)	589	423	94	553
FWD. Bay (2)	260	602	2	72
Wheelwell Bay (2)	234	166	8	102
Aft Bay (2)	806	645	81	363
	2025	2002	187	1122

The unused channels for each category were added up, then subtracted from the base amount for that particular category. A ratio of used-to-total channels per category was taken, which became the "% Utilization Factor".

Based on an approximate 90% U.F. criteria of acceptability, the following I/O module increments were suggested.

TABLE 3.5-5.   MODULE INCREMENTS VS. SIGNAL CATEGORIES

Categories   Module Increments, MI

	8	16	32	64
BMA, OMA				X
BMD, OMD				X
BCA, OCA	X			
BCD, OCD			X	

The resulting complement of modules assigned to each area is shown in Table 3.5-6.

Sizing of SIA per SIU was tested using the booster modules requirements found in Table 3.5-6, and a System I (reference 3.5.1.1) configuration. The following mixture was used:

Type	Modules/SIA	I/O Channel per SIA
BMA	2	128
BMD	2	128
BCA	1	8
BCD	5	160

TABLE 3.5-6

MODULES REQUIRED

CATEGORIES	LOCATIONS					
BOOSTER	NOSE	CREW	MID	APU	AFT	TOTAL
BMA	1	18	6	14	36	75
BMD	1	18	3	5	6	33
BCA	0	9	1	2	35	47
BCD	1	45	3	12	22	83
Booster Totals	3	90	13	33	99	238
ORBITER	NOSE	CREW	FWD	WHEELWELL	AFT	TOTAL
OMA	3	10	5	4	13	35
OMD	3	7	10	3	11	34
OCA	1	12	1	1	11	26
OCD	1	18	3	4	12	38
Orbiter Totals	8	47	19	12	47	133

A 59% overall U.F. resulted. The poor results suggested that a System I type arrangement cannot meet the degree of modularity needed in SSV's. Further testing led to the conclusion that the only configurations suitable for use on the SSV is either a modular configuration in which both the number of SIA and input/output mix of channels are variable (System 2) or to build a number of fixed units, each of which has been optimized for a particular location.

As an example of how the RT might be configured, the following description is given of the RT capabilities:

- The number of I/O modules per SIA is from 1 to 4.
- The total number of SIA channels cannot exceed 128.
- The RT consists of one SIU and from 1 to 8 SIA's.
- The number of channels per I/O module (as defined previously) is:

  - Analog input   = 64
  - Digital Input   = 64
  - Analog Output   = 8
  - Digital Output   = 32

Using the module requirements of the Booster, Table 3.5-6, the number of SIA's and RT's are estimated for various locations as given below:

Location	SIA's	RT's
Nose	2	1
Crew	30	4
Mid	5	1
APU	13	2
Aft	29	4
TOTAL	79	12

3.5.4.3 SIU/SIA Interconnect

Parallel versus serial SIU-to-SIA interconnect was examined. It was determined that the choice of method depends primarily on the transmission distance, serial being preferred for longer paths. In general, for bit rates on the order of 1 Mbs, the crossover point is about 30 to 40 feet.

3.5.4.4 Interrogation Time Vs. Data Accessibility

The factors which affect the interrogation and data access time depend on several things, many of which are dependent on the basic operation of the data bus system, and on methods which may be used to insure operational reliability, synchronization, and control, etc. A list of some of the more significant factors is given below.

- Decoding the supervisory word requires time. Usually one word time is used to shift the information into a register, then the word is decoded in parallel.

- Error checking takes some time. If simple parity is used, this is but one bit time. A more sophisticated code could take longer. However, some codes, BCH for example, are used by sending information bits first followed by the check bits, thus the processing of the word can start before the error detector determines whether an error was present. Bit by bit voting requires no additional time.

- Staggering of redundant words to decorrelate errors due to interference requires time to destagger the words at the RT and to stagger data for transmission.

- Transmission of data between SIU and SIA in a serial mode could require additional time, especially if the SIU/SIA interface is a local bus.

- Transmission line delay, while small (1.8 microseconds for round trip delay over a 500 ft. bus) may compound the bit skew problem. The circuits needed to overcome the bit skew could introduce more delay.

- The basic word and message structure may have an effect on interrogation time.

- The response of the multiplexer, the time required for the sampled signal to settle to the required accuracy is perhaps the greatest factor. The time required for digitizing the analog sample is probably the second greatest factor. Both of these factors will be discussed in greater depth in the paragraphs to follow.

An example of a message format is given in Figure 3.5-12 to demonstrate the concept of interrogation time.
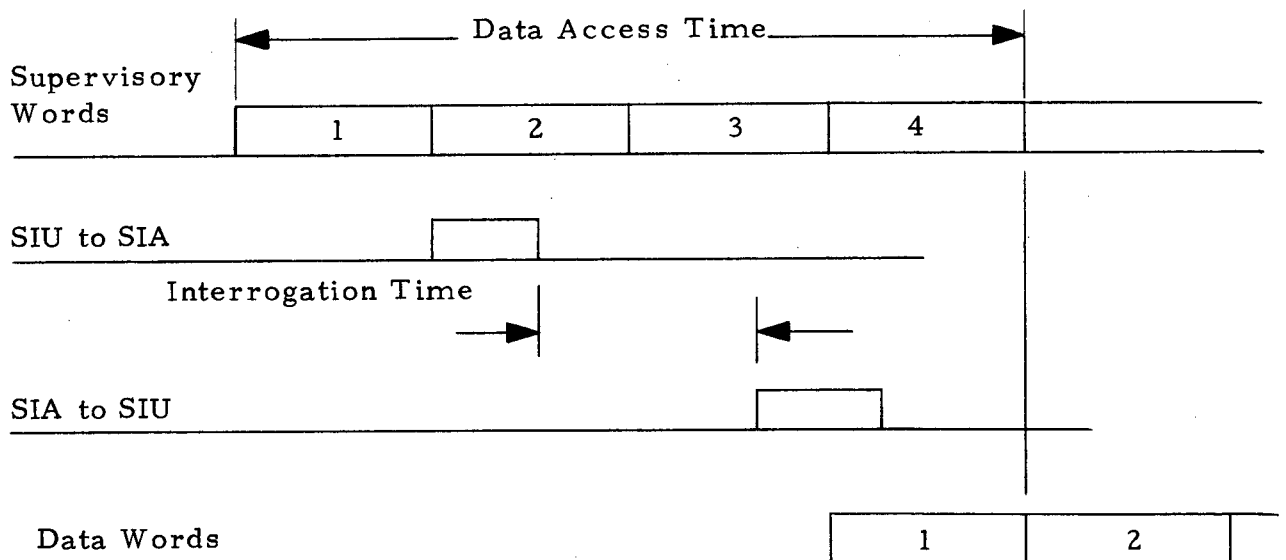
Figure 3.5-12 Typical Message Format

Other factors affecting the interrogation time are multiplexing/digitizing associated operations such as programmable gain and offset control. For example, a 4 bit (16 gains) programmable amplifier may take 8 useconds to settle to within 0.1%. Delay due to offset control might be averted by performing the operation during the sampling process.

3.6   OPERATIONAL RELIABILITY

Operational Reliability was treated in detail in Volume IV, Phase 2 Report of this study, and is the basic document used in compiling this summary report. Consequently, many proofs, the appendices, and details have been omitted from the Volume IV report in order to present here a more concise treatment of the subject.

Volume IV introduced the subject by a recognition that reliability prediction is the essence of reliability analysis, followed by examples to back up this contention. References cited (refer to Appendix III-F) were 25, 26, 27 and 28.

Reliability problems and needs of the SSV Data Bus were cited as follows:

- design, reliability and fault tolerance are inseparable features of a data bus.

- fault tolerance fail operational - fail operational - fail operational (FO-FO-FO) of a given design can be routinely analyzed, but synthesis for a minimal design is not routine.

- There is an acute requirement to clarify the relationship between good fault-tolerant designs and good reliability for the Space Shuttle Data Bus.

- The reliability/design relationship needs clarification on relative merits of 1) standby redundancy, 2) masking redundancy, 3) hybrid redundancy (voting/sparing combination), and 4) a list of critical parameters.

- hardware reliability and transmission reliability are combined into a new concept of "total reliability" needed to access the best Data Bus configuration.

Summary of Contents

Phase I results are recounted.

Phase II study of Operational Reliability is given in detail in Volume IV, including proofs in the appendices. Given here are those subjects in summary form, concluding with conclusions and recommendations. Subjects are:

- critical parameters and characteristics of systems with standby redundancy.

- critical parameters and characteristics of systems with Masking and Hybrid systems.

- "total Unreliability", a novel concept containing both hardware reliability and transmission reliability is synthesized.

- proposals A, B, C and D, known and unknown critical parameters, with recommendations for an improvement.

- recommended designs for power supplies, clocks, voters and monitors, at least near minimal designs for FO^3 fault tolerance.

- conclusions and recommendations.

Section 3.6.1 is a review of Phase 1 results. Section 3.6.2 contains Phase 2 results. Section 3.6.2.1 establishes critical parameters and characteristics of systems with Standby redundancy; section 3.6.2.2 does likewise for masking systems and hybrid systems. Section 3.6.2.3 synthesizes a novel concept of "total unreliability" which contains both hardware reliability and transmission reliability.

Section 3.6.2.4 details the unknown critical parameters of proposals A, B, C and D. Section 2.2.6 makes recommendations for an improvement and an elaboration of information given in proposals.

Section 3.6.2.5 gives recommended designs for power supplies, clocks, voters and monitors. It cannot be proved rigorously that the designs are minimal for a FO^3 fault tolerance, but if not minimal, the designs are near-minimal. Section 2.2.6 contains the conclusions and recommendations.

3.6.1   Review of Phase I Results

The Phase I study of operational reliability yielded the following conclusions and results:

- The Fail Operational-Fail Operational-Fail Safe (FO-FO-FS) criterion was identified as the failure tolerance requirement.

- Two basic methods for applying redundancy were identified: standby redundancy and masking redundancy.

- Numerous design techniques were identified for:

    . Error correction and failure masking.
    . Failure detection.
    . Reconfiguration.
    . Interfacing with redundant user subsystems.
    . Generating redundant clock signals.

In addition, a number of conclusions were reached concerning possible functions that may be required of the data bus subsystem to satisfy operational reliability requirements.

Possible Functional Requirements

- Staggering and destaggering for protection against interference.

- Automatic error correction and failure masking.

- Fault detection.

- Fault reporting.

- Reconfiguration based on failure detection.

- Interfacing with subsystems having different levels of redundancy.

3.6.2   Phase II Study Results

3.6.2.1   Critical Parameters and Characteristics of Systems with Standby Redundancy

Introduction

A standby system for the Data Bus of the Space Shuttle is a possibility which has long been recognized. However, the well-known texts and manuals concerning operational reliability do not give a realistic analysis of a standby system, due to extravagantly optimistic assumptions of perfect components (standby channels, monitors and switches). The Operational Reliability report remedies this situation by considering imperfect components, and by establishing a philosophy of desirable practical configurations for a stand-by system with any number of standby channels. Formulae were found for both the reliability and unreliability of such configurations. In addition, published literature does not have a useful comparison of a standby system against a voting scheme, and the effect of various assumptions on the comparison. This comparison is of a fundamental importance in the selection of a best Data Bus for the Space Shuttle. It is an inevitable stepping stone in the logical progress towards the best design.

Summary

NASA has defined mission reliability to be the probability of success of the mission. For the Space Shuttle, the parameter of mission unreliability of a standby system is equally valid and much easier to use. Tables 3.6-2 and 3.6-3 display formulae for reliability and unreliability for two concepts of a standby system and various numbers of standby channels. Since the formulae for unreliability are much simpler (than those for reliability), they are used for subsequent calculations and comparisons.

For ease of reference, the two concepts of standby system are called the Poisson Panacea and the Credible Configuration. The Poisson Panacea, philosophically elegant but definitely impractical, is the usual theory displayed in texts, which assumes perfect components. Table 3.6-1 contains unreliability formulae, plotted in Figure 3.6-1. On the other hand, the Credible Configuration is a practical goal. Figure 3.6-2 is a graph of its unreliability for up to three standby channels and also compares its unreliability to the counterpart voting schemes.

Based on certain assumptions, the Credible Configuration with three standby channels (FO-FO-FO survivability) gives one hundred times less unreliability, for the same amount of redundant hardware, when compared to a pure 4-out-of-7 voting system for the Space Shuttle. The Credible Configuration under these assumptions is therefore much better. This is the first major finding of section 3.6.2.1.

If, however, the assumptions of the Credible Configuration are not met, it is likely that a standby system will be much worse than a voting scheme. This was the second conclusion. For a system with three standby channels, there are the following critical factors: (1) the monitor itself must have

triple redundancy. Otherwise the monitor will establish the limit on system reliability and not the standby channels. (2) The monitor must have a negligible probability ($\ll 10^{-10}$) of sending a false open signal to all switches in sequence. Otherwise the monitor will again be the bottleneck of reliability. (3) The switches must not only be independent of each other in their operation, and in general be of very low unreliability (10^{-5} for contact failure and static failure), but dynamic failure (failure to switch when required) must have negligible probability ($\ll 10^{-10}$). (4) If the uncoverage is greater than 10^{-8}, the product term ff_c in the expression for system unreliability (f_{syst}) dominates the other terms, and therefore is decisive in establishing the unreliability of the system.

The last condition regarding uncoverage is possibly the most severe of all, particularly since the concept of uncoverage contains more than one cause of failure. Included in uncoverage are:

(a)   The unreliability of the monitor hardware.

(b)   The transmission unreliability associated with the monitors.

(c)   The end portions (of the channels being monitored) which are not in the "field of view" of the monitor.

(d)   The diagnostic time necessary for the monitors in relation to the permissible flow of erroneous data.

Coverage is defined as the conditional probability, given a fault has occurred, that it will be detected and corrective action will occur in time to prevent the loss of significant information or function.

The first major finding of section 3.6.2.1 has to be tempered by the following considerations. A pure voting scheme has two fundamental advantages which cannot be matched by a pure standby arrangement. (1) Assuming

separate channels which are physically widely spaced, it is conceivable that persistent induced noise may occur in one or two channels of sufficient magnitude to cause frequent word errors. A voter will mask such induced noise on a continuous basis; whereas an unsophisticated standby scheme will rapidly exhaust itself. (2) A voter needs no diagnostic time to be sure that switching is needed. It is possible that the necessary diagnostic time, for a standby scheme to switch, may be greater than the minimum allowable interruption in the flow of correct information between the equipments connected to the Data Bus; if so, a standby system meets a major obstacle.

As far as can be seen at the present time, there is little chance that the disadvantages of the standby schemes listed would influence the operation of the Space Shuttle. Nevertheless a pure voting system does have the desirable attributes cited above, and in the light of operating experience with the Shuttle in years to come, they do form an important part of design philosophy and policy.

The criterion of fault tolerance of the Data Bus was taken to be effectively triple fail-operational (FO-FO-FO) since the Data Bus has the same importance in reliability studies as all the other avionic-astrionic subsystems (that is, the line replaceable units - LRU's) in their totality. The FO^3 criterion applies to every component (switches, monitors, etc.) in relation to the topology of their interconnections. However, in establishing fundamental limits strictly based on the FO^3 criterion, the analyst is confronted with the two intangibles of (1) the ingenuity of the circuit designer and (2) the assumed state of the art concerning NASA-approved components. To illustrate the latter point, the FO^3 criterion applied to circuits and components available in 1960 produces vastly different results than when applied to the 1973 state of the art.

Essentially, the analysis of this section 3.6.2.1 does consider FO^3 fault tolerance, but not in the strict sense. FO^3 requirements are considered only at the channel level. For instance, a pure standby system has to have at least three standby channels. Then, since a fourth order (f^4) annihilation of channel unreliability (f) results, the analysis pinpoints other fundamental criteria necessary for the entire Data Bus to possess this desirable fourth order property. For instance, the analysis reveals that at least three redundant monitors are needed to accompany the four channels.

Since FO^3 fault tolerance was included only in the very general way indicated above, the lower bounds on system unreliability and the necessary conditions given in this section 3.6.2.1 will not be as severe as those given in Section 3.6.2.6. Strict FO^3 analysis and detailed blocked circuits can be found in volume IV, section 4.2.6. However, for reasons given earlier, the conclusions of this section are the more fundamental.

The Poisson Panacea

The analysis given in this section is given in some form or other in every text and manual on reliability. However, it was found to be over-simplified and inadequate for the very high reliability requirement of the Data Bus of the Space Shuttle.

Two of the assumptions of this section are valid for the Data Bus: (1) all channels are the same except for being powered or unpowered, and (2) failure rates are constant. The other two assumptions used here are not good assumptions: (3) standby channels have a zero failure rate and (4) the diagnostic and switching device is perfect.

The Poisson Process was described in Appendix A of Volume IV, and in Appendix B system unreliability (f_{syst}) was simplified to

$$f_{syst} = \frac{1}{(n+1)!} f^{n+1}$$
(3.6-1)

where f_{syst} = system unreliability

f = channel unreliability

and n = number of standby channels

Thus, the system unreliability of the Shuttle Data Bus was found to be $\frac{f^2}{2}$, $\frac{f^3}{6}$ and $\frac{f^4}{24}$ for 1, 2 and 3 standbys, respectively. With $f = 4 \times 10^{-3}$, these became 8×10^{-6}, 11×10^{-9} and 10^{-11}, respectively. Find this effect plotted in Figure 3.6-1; Formulae are displayed in Table 3.6-1.

The Credible Configuration

Unlike the Poisson Panacea, the Credible Configuration did not assume perfect standby channels, monitors and switches. Also, certain constraints on their designs were specified. The design goals have a reasonable chance of being attained, thus the name "Credible Configuration".

The following facts were established with regard to switches (for standby channel switching):

i)   At least one suitable switch (Teledyne electromechanical toggle relays) is available to provide independent switch-out of the working channel and independent switch-in of standby channel(s).

ii) At least one such switch design (see above) has a negligible probability ($< 10^{-5}$) of contact failure (failing open) and static failure (switching when not required). It is not known for certain whether any single switch can satisfy the far more severe condition ($\ll 10^{-10}$) on the
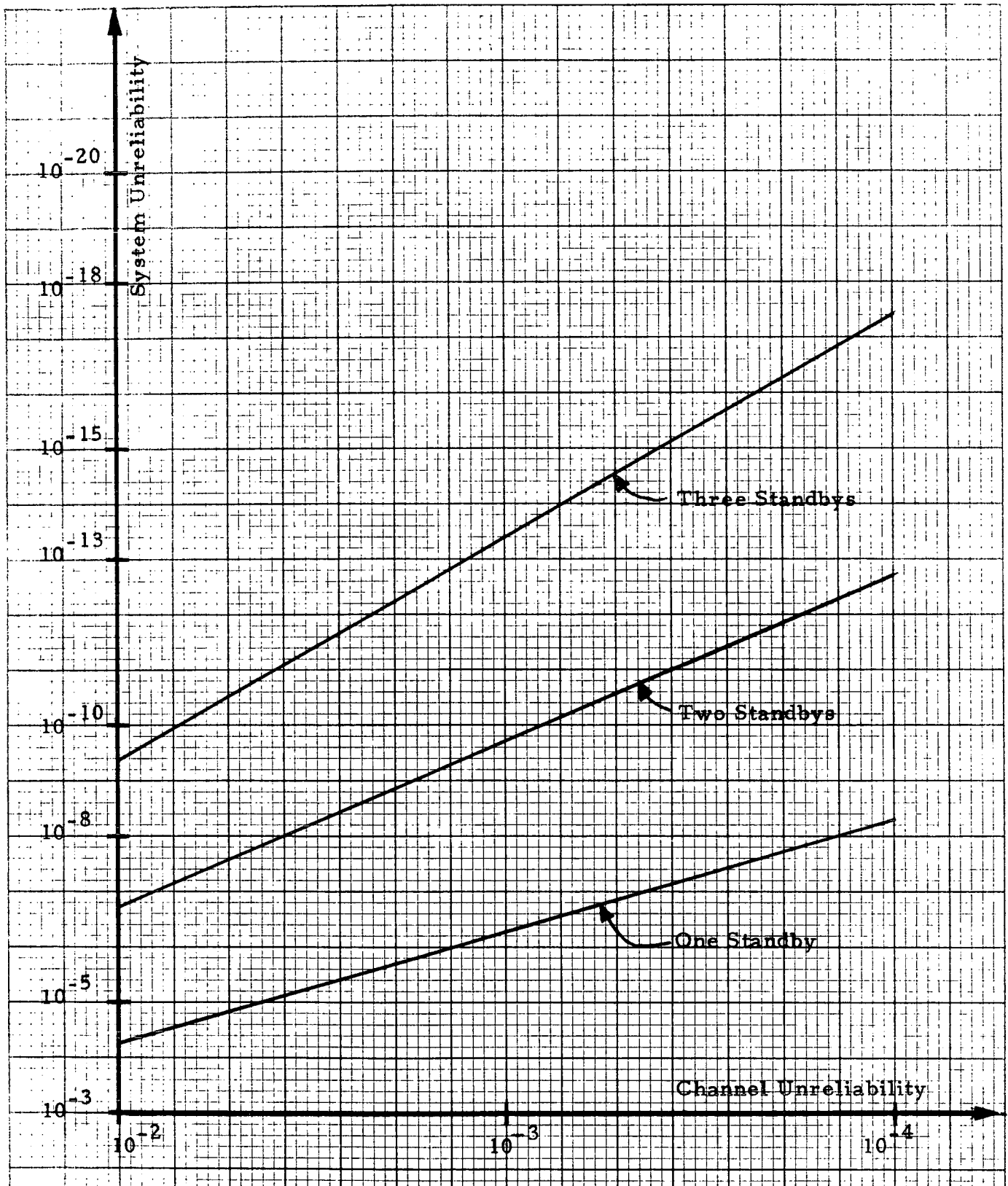
FIGURE 3.6-1. LOG-LOG PLOT OF SYSTEM UNRELIABILITY OF POISSON PANACEA

F

TABLE 3.6-1

FORMULAE FOR THE POISSON PANACEA

Number of Standby Channels		System Mission Unreliability
0	p	f
1	$p\left(1 + \ln\frac{1}{p}\right)$	$\frac{1}{2}f^2$
2	$p\left[1 + \ln\frac{1}{p} + \frac{1}{2}\left(\ln\frac{1}{p}\right)^2\right]$	$\frac{1}{6}f^3$
3	$p\left[1 + \ln\frac{1}{p} + \frac{1}{2}\left(\ln\frac{1}{p}\right)^2 + \frac{1}{6}\left(\ln\frac{1}{p}\right)^3\right]$	$\frac{1}{24}f^4$
m - 1	$p\sum_{r=0}^{m-1}\frac{\left(\ln\frac{1}{p}\right)^r}{r!}$	$\frac{1}{m!}f^m$

unreliability associated with dynamic failure (failure to switch when required).

iii)   More than one standby channel must be accompanied by redundancy in the monitoring system. No possibilities of single/point failure should exist in the monitoring system. There must be an insignificant chance ($\ll 10^{-10}$) that the monitoring system can send a false open signal to <u>all</u> switches at once.

Realistic formulae for the reliability of a Standby System were proved in Appendix C, Volume IV, and are mathematically much more complex than those for the Poisson Process. Assumptions made in deriving the new formulae were as follows:

1)   switches operate independently of each other.

2)   single switches, or interlocked pairs of switches, exist whose a) contact unreliability is $< 10^{-5}$, b) static unreliability is $< 10^{-5}$, and c) dynamic unreliability is much less than 10^{-10}.

Realistic, yet simpler formulae for the Standby System was proved (Appendix D, Volume IV) for system UNreliability. The comparative formulae are shown in Table 3.6-2. An example of the System Unreliability formula for a two standby case would be as follows:

assume $f_s = 0.2 f$, $f_c = 0.2 f$. f_c is then replaced by $3f_c^2$.
Result: $f_{system} = 0.42 f^3$

TABLE 3.6-2. FORMULAE FOR THE CREDIBLE CONFIGURATION

Number of Standby Channels	System Mission Reliability	System Mission Unreliability
0	p	f
1	$p\left[1 + \dfrac{\lambda}{\lambda s}\ p_c\ (1 - p_s)\right]$	$f\left[f_c + \dfrac{1}{2}\left(f + f_s\right)\right]$
2	$p\left[1 + \dfrac{\lambda}{\lambda s}\ p_c\left(1 - p_s\right) + \dfrac{1}{2}\left(1 + \dfrac{\lambda}{\lambda s}\right)\dfrac{\lambda}{\lambda s}\ p_c^{\,2}\left(1 - p_s\right)^2\right]$	$ff_c + \dfrac{1}{6}f^3 + \dfrac{1}{6}ff_s\left(3f + 2f_s + 3f_c\right)$
3	$p\left[1 + \dfrac{\lambda}{\lambda s}\ p_c\left(1 - p_s\right) + \dfrac{1}{2}\left(1 + \dfrac{\lambda}{\lambda s}\right)\dfrac{\lambda}{\lambda s}\ p_c^{\,2}\left(1 - p_s\right)^2\right.$ $\left. + \dfrac{1}{6}\left(2 + \dfrac{\lambda}{\lambda s}\right)\left(1 + \dfrac{\lambda}{\lambda s}\right)\dfrac{\lambda}{\lambda s}\ p_c^{\,3}\left(1 - p_s\right)^3\right]$	Not Calculated
n	$p\displaystyle\sum_{i=0}^{n}\left[\begin{array}{c} i - 1 + \dfrac{\lambda}{\lambda s} \\ i \end{array}\right]\left(p_c\right)^i\left(1 - p_s\right)^i$	Not Calculated

LEGEND:

P = reliability of one working powered channel.

P_s = reliability of one standby unpowered channel.

λ = failure rate of working channel.

λ_s = failure rate of a standby channel.

P_c = coverage, or conditional probability, of a successful system correction (switch-in of standby given that the working channel fails and the standby is unfailed.

f = unreliability of one working (powered) channel.

f_s = unreliability of one standby (quiescent) channel.

f_c = uncoverage

Standby Versus Voting

Three different comparisons were made here: 1) standby systems evaluated using Poisson Panacea, 2) Credible Configuration evaluation, and 3) should the assumptions required in "2" not be met, the third comparison is made recognizing the actual limitations.

The first resulted in the Poisson Panacea (standby system) being about 100 times better than the 3-out-of-5 classic redundant voter.

The second comparison resulted in the Credible Configuration (standby system) being adjudged about 30 times better than the counterpart voter, for FO-FO survivability. Figure 3.6-2 is a plot of various configurations of system vs channel unreliabilities.

The third comparison presented cites the outcome when Credible Configuration assumptions are not met, as follows:

a)   Unacceptable toggle relays. In view of AND gate mission unreliability of 1.5×10^{-5}, the limitation created by dependent switching is not serious with only one standby channel (f^2). However, for FO-FO-FO channel survivability it becomes unacceptable.

b)   Single point failure at interconnect point of monitors and switches. Failure such that a false open signal can be sent to all switches results in standby system unacceptability.

c)   Large, very frequency noise levels. The standby system cannot be made which under these conditions will not exhaust itself, and thus be unacceptable.
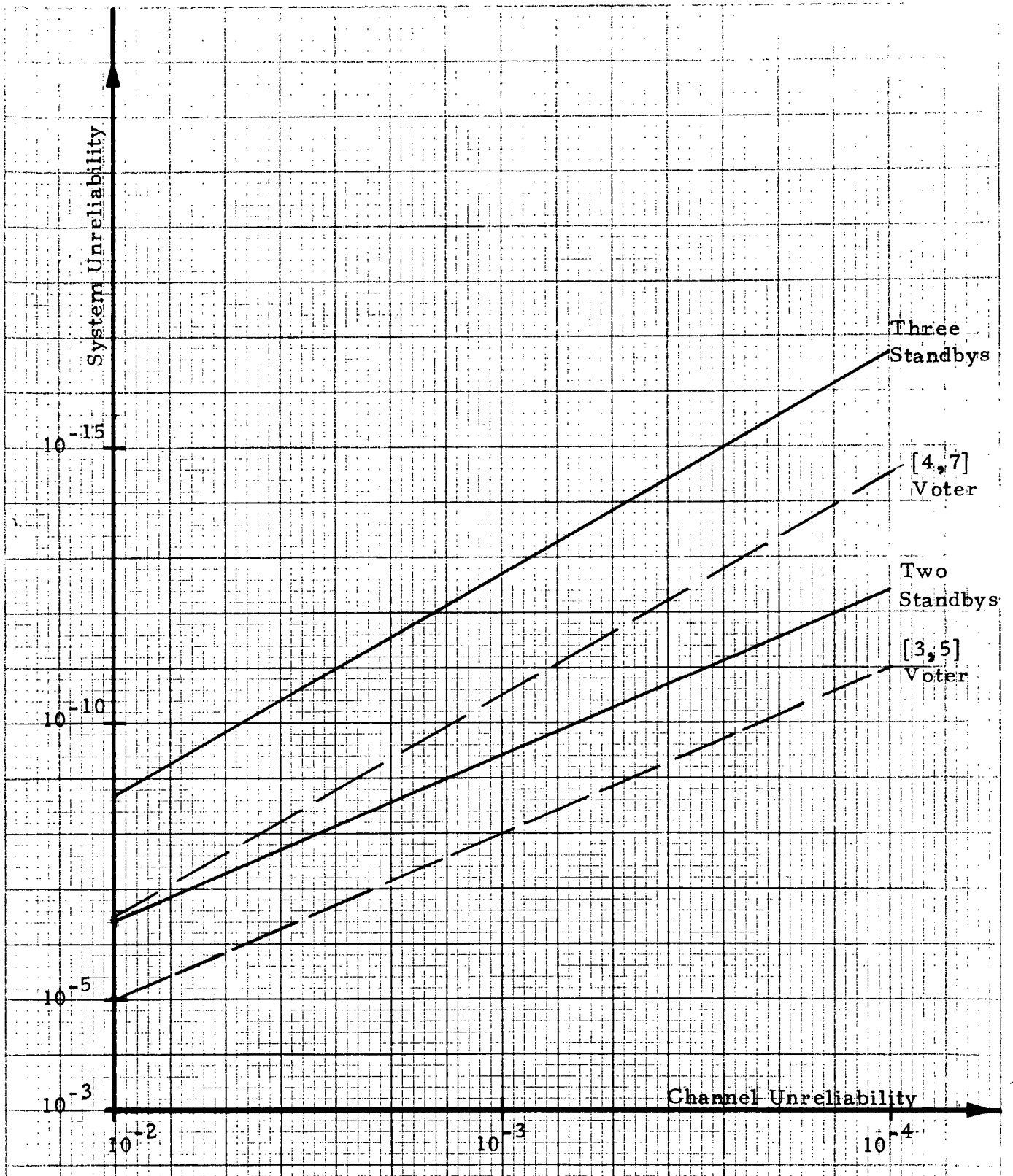
FIGURE 3.6-2   LOG-LOG PLOT OF SYSTEM RELIABILITY OF POSSIBLE
CREDIBLE CONFIGURATIONS

d)   Switchover time relatively too great. When the time to diagnose and switch is too long a time, resulting in unacceptable loss of data, the standby system is out.

In summary, the Credible Configuration can suffer from the following degradations:

1)   Unreliable monitors, especially in regard to false "open" commands.

2)   unreliable and dependent switches.

3)   imperfect coverage.

4)   excessive and persistent noise.

5)   excessive diagnostic time.

3.6.2.2   Critical Parameters and Characteristics of Systems with Masking and Hybrid Redundancy

Introduction

This section addressed a number of problems.

1)   New types of voting systems have been applied to ultra-reliable spaceborne computers. However, it was unclear which would be best for a Data Bus.

2)   The reliability equations for the different types of voter (in terms of the reliability of their components) are not complete in the literature.

3)   The reliability equations have different algebraic forms which are complicated, making comparison difficult. New and very simple equations have been formulated for the eight different kinds of voter, written for their UNreliability.

4)   There is uncertainty as to the number of channels which should be
      used.

In 1963 NASA defined (Appendix III-F9) reliability as "the probability that a
system, subsystem, component or part will perform its intended functions
under defined conditions at a designated time for a specified operating
period". This definition has never changed (Appendix IV-F, 10, 11, 12).

Eight schemes using voting were reviewed, including:

    (A)   Classic unredundant voting
    (B)   Classic redundant voting
    (C)   Adaptive voting
    (D)   Triple modular redundancy (TMR)/single channel
    (E)   TMR/single plus spare channel
    (F)   TMR/hybrid
    (G)   TMR/hybrid/single
    (H)   TMR/hybrid/single plus spare channel.

The majority of Space Shuttle missions will be of 1 1/2 to 2 1/2 days
duration with only a few extending to 6 days. Therefore a good simplifying
assumption is to consider a fixed mission time of fifty hours. This
assumption enables the time-dependency of reliability probability to be
removed.

The reliability predictions of the eight voting schemes is given, in the
manner appropriate for investigations at the conceptual stage of a design,
using various assumptions one of which is the usual assumption that
probabilities are statistically independent (reference Appendix E, Volume
IV).

Summary

Although NASA defined mission reliability in terms of its probability of
success for the Space Shuttle, mission UNreliability was used because it is
susceptible to a "first order" but accurate system approach. Simple
formulas, all originated by SCI, for even complicated voting schemes are
displayed in Table 3.6-3. They are shown to provide a short and successful
answer to most of the problems already mentioned.

It was found that when the number of parallel channels is three or more, the
more sophisticated voting schemes almost annihilate the effect of channel
unreliability on the system as a whole. This has motivated the designers of
ultra-reliable fault-tolerant computers to develop designs of elaborate
voting devices (incorporating switching and sparing) for NASA and the Armed
Forces. With four parallel channels and an elaborate voter (type H1 of this
report), a channel unreliability (f) of 4×10^{-3} will affect the stage or system
unreliability by only its fourth power (f^4) namely 2.6×10^{-10}. However,
elaborate voters of the required unreliability (less than 1×10^{-4}) are a
major challenge (as is the FO-FO-FS criterion) to ingenuity and creative
design. The possibility of manual switchover, to partly avoid the problem,
should be considered. Even so, it is certain that redundancy of the voting
devices themselves is needed. Redundancy of channels has to be accom-
panied by redundancy of any type of voting device.

Numerical calculations were given of the reliabilities of the different
schemes. With the assumption of a certain rule for evaluating the
complexity of voting devices, the classical redundant voting schemes B23
and B35 are the best, with unreliabilities of 5×10^{-5} and 6×10^{-7}, respec-
tively. But the demonstration may not be fair to the more elaborate types
of voter. A fairer comparison will be made when (1) they too are configured
with redundant voting devices and (2) when estimates of their unreliability

are determined from ingenious designs rather than by a rule good for a limited number of cases.

Eight Schemes Using Voting

For ease of reference, the eight schemes are designated as Voter Types A through H.

Voter Type A - The Non-Redundant Classic Majority Voter.
Only one voter is used for each stage of majority voting. In some systems, several channel/voter stages in series make up the whole system.

These majority voters are such that if one component fails, the entire voter is incapacitated. Indeed, the assumption is usually made in reliability analyses involving majority voters, that the voter is one integral component in series with all channels, that the voter has a certain probability of failure and that when it fails all voting of that stage is finished.

Voter Type B - The Redundant Classic Majority Voter.
This arrangement (Appendix III-F 15, 16) is like Type A except that redundant voters are present.

With 3 channels or modules, the classic majority voter (Type A or B) is often described as a Triple Modular Redundant (TMR) system, especially in computer literature.

Voter Type C - The Adaptive, or Reconfigurable, Voter.
It eliminates channels as they fail and maintains its voting function during the elimination. It becomes inoperable when there is a disagreement between the two channels which finally remain. For instance, if the voter were initially

configured as a Type A35 voter (a Type A voting 3 out of 5 channels) and two channels failed, it would reconfigure to a Type A23 voter.

Unlike the classic majority voter where both nonredundant and redundant versions (Types A and B) have been given, Voter C and subsequent voters were only considered as nonredundant voters. This penalizes them in relation to the classic voters because there is no redundancy to offset voter unreliability (as distinct from channel unreliability).

Voter Type D - Triple Modular Redundancy (TMR)/Single (Appendix III-F 5, 17, 18). In recent years the use of Voter Types D through H in ultra-reliable digital computers has either been made or is contemplated.

Voter Type D utilizes three good channels at the start. If one channel goes bad, a decision and switching device automatically disconnects it. The device also discards one of the remaining good channels. So the final operating state of the system utilizes one and only one good channel. The advantage over simple TMR is that the chance of failure of one good channel (failure rate λ) is less than that of two good channels together (failure rate 2λ) which is the terminating mode of simple TMR.

Voter Type E - TMR/Single Plus Spare (Appendix III-F-19). This is an extension of Voter Type D. The good channel which was discarded is now used as a standby. This gives the greatest reliability of any scheme which utilizes three channels.

Voter Type F - TMR/Hybrid (Appendix III-F-17, 20, 21). This is a classic voting scheme, but supplemented by one or more standby channels. These spare channels are automatically switched in to replace faulty channels. When all spare channels have been used up, TMR/hybrid redundancy becomes identical to the Type A23 voter.

Voter Type G - TMR/Hybrid/Single (Appendix III-F-17). This is a classic voter scheme with two additional features. First, there are standby units which are switching in as required to maintain the 3 level voting of TMR. Second, the final operating state of the system before failure is one channel, not two (as with simple TMR). Thus Voter G is a combination of the concepts embodied in Voters D and F.

Usually Triple Modular Redundancy (Voter Type A or B) is used, with a certain number(s) of spares (as with Voter F) automatically replacing those powered channels which fail. However, final behavior utilizes only one channel as Voter Type D.

Voter Type H - TMR/Hybrid/Single/Single. This is identical to Type G except that the final good channel is used. Thus, this scheme is a combination of Types E and F. Such a system performs until all channels except one have failed.

Each of the above schemes will provide masking redundancy for the Space Shuttle.

Table 3.6-3 is a tabulation of the eight types of voter, showing the analytical expressions for both the reliability and the UNreliability of one channel voter stage in terms of the reliability of each channel (p) and each voter (p_v) as well as the number of parallel channels.

The different voters annihilate the channel unreliability (f) as indicated by the power of f in the formula for the stage unreliability displayed in Table 3.6-3. A second order annihilation (f^2) is achieved by voters A23, B23, C3 and D. Three channels are used in each case. Voter Type D annihilates by a further factor of 2, since it contributes the term $\frac{3}{2} f^2$ instead of $3f^2$.

Third order annihilation (f^3) is performed by 5 channels (voters A35, B35), 4 channels (voters C4, F1, C1) and 3 channels (voter E). Third order annihilation with 3 channels is indicative that the stage performs to the last good channel, whereas with 5 channels it indicates the reliabilities of 2 channels are not used. Voter E annihilates by a further factor of 10 compared to the classic voters (A35, B35).

Fourth order annihilation (f^4) is carried out by both 5 channels (types C5 and G2) and 4 channels (type H1). Voter H1 annihilates by a further factor of 5 compared to the adaptive voter C5.

A comparison of these schemes is given in Figure 3.6-3.

With the use of certain assumptions, an evaluation of the minimum number of modules was made. In terms of relative complexity, the results were as follows:

TABLE 3.6-4

Voter Relative Complexity Comparison

A23 -------- 1	A35 ---------- 2
B23 ------- 3	B35 ---------- 10
D --------- 14	C5 ---------- 31
E --------- 16	F2 ---------- 24
F --------- 17	G2 ---------- 28
G --------- 21	H2 ---------- 32
H --------- 25	

Using these results and those of Table 3.6-3, Tables 3.6-4 and 3.6-5 were generated. Of these voters examined, the redundant voters (Types B23 and B35) are by far the best.

Table 3.6-3

Reliabilities and Unreliabilities of One Stage of Channel/Voter (See Note 1)

Configuration	Designation	Reliability for one Mission	Unreliability for One Mission of Stage
Voter A Classic Non-Redundant (k out of m)	Akm	$p_v \sum\limits_{i=k}^{m} \binom{m}{i} p^i (1-p)^{m-i}$	$f_v + \binom{m}{k} f^k$
Voter A (2 out of 3)	A23	$p_v[3p^2 - 2p^3]$	$f_v + 3f^2$
Voter A (3 out of 5)	A35	$p_v[6p^5 - 15p^4 + 10p^3]$	$f_v + 10f^3$
Voter B Classic Redundant (k out of m)	Bkm	$\sum\limits_{j=k}^{m} \binom{m}{j} p_v^j (1-p_v)^{m-j} \sum\limits_{i=k}^{m} \binom{m}{i} p^i (1-p)^{m-i}$	$\binom{m}{k}[f_v^k + f^k]$
Voter B (2 out of 3)	B23	$(3p_v^2 - 2p_v^3)[3p^2 - 2p^3]$	$3(f_v^2 + f^2)$
Voter B (3 out of 5)	B35	$(6p_v^5 - 15p_v^4 + 10p_v^3)(6p^5 - 15p^4 + 10p^3)$	$10(f_v^3 + f^3)$
Voter C (Adaptive Voter) with m channels	Cm	$p_v[1 - m(1-p)^{m-1} + (m-1)(1-p)^m]$	$(f_v + mf^{m-1})$
Voter C (with 4 channels)	C4	$p_v[1 - 4(1-p)^3 + 3(1-p)^4]$	$f_v + 4f^3$
Voter C with 5 channels)	C5	$p_v[1 - 5(1-p)^4 + 4(1-p)^5]$	$f_v + 5f^4$
Voter D (TMR/Single)	D	$p_v[\frac{3}{2}p - \frac{1}{2}p^3]$	$f_v + \frac{3}{2}f^2$
Voter E (TMR/Single plus spare	E	$p_v[1 - (1-p)^3]$	$f_v + f^3$
Voter F (TMR/Hybrid with s spares	Fs	$p_v[1 - (1-p)^{s+2}(1 + p(s+2))]$	$f_v + (s+3)f^{s+2}$
Voter F (TMR/Hybrid with 1 spare)	F1	$p_v[6p^2 - 8p^3 + 3p^4]$	$f_v + 4f^3$
Voter G1 (TMR/Hybrid/ Single with 1 spare)	G1	$p_v[p^4 - 2p^3 + 2p]$	$f_v + 2f^3$
Voter G (with 2 spares)	G2	$p_v[-\frac{3}{2}p^5 + 5p^4 - 5p^3 + \frac{5}{2}p]$	$f_v + \frac{5}{2}f^4$
Voter H (TMR/Hybrid/ Single + Spare with s spares)	Hs	$p_v[1 - (1-p)^{s+3}]$	$f_v + f^{s+3}$
Voter H (with 1 spare)	H1	$p_v[1 - (1-p)^4]$	$f_v + f^4$

Note 1: Voter reliability (p_v) and voter unreliability (f_v) are not the same for different types of voters. Later (Section 5), voter unreliability is taken to be proportional to voter complexity.
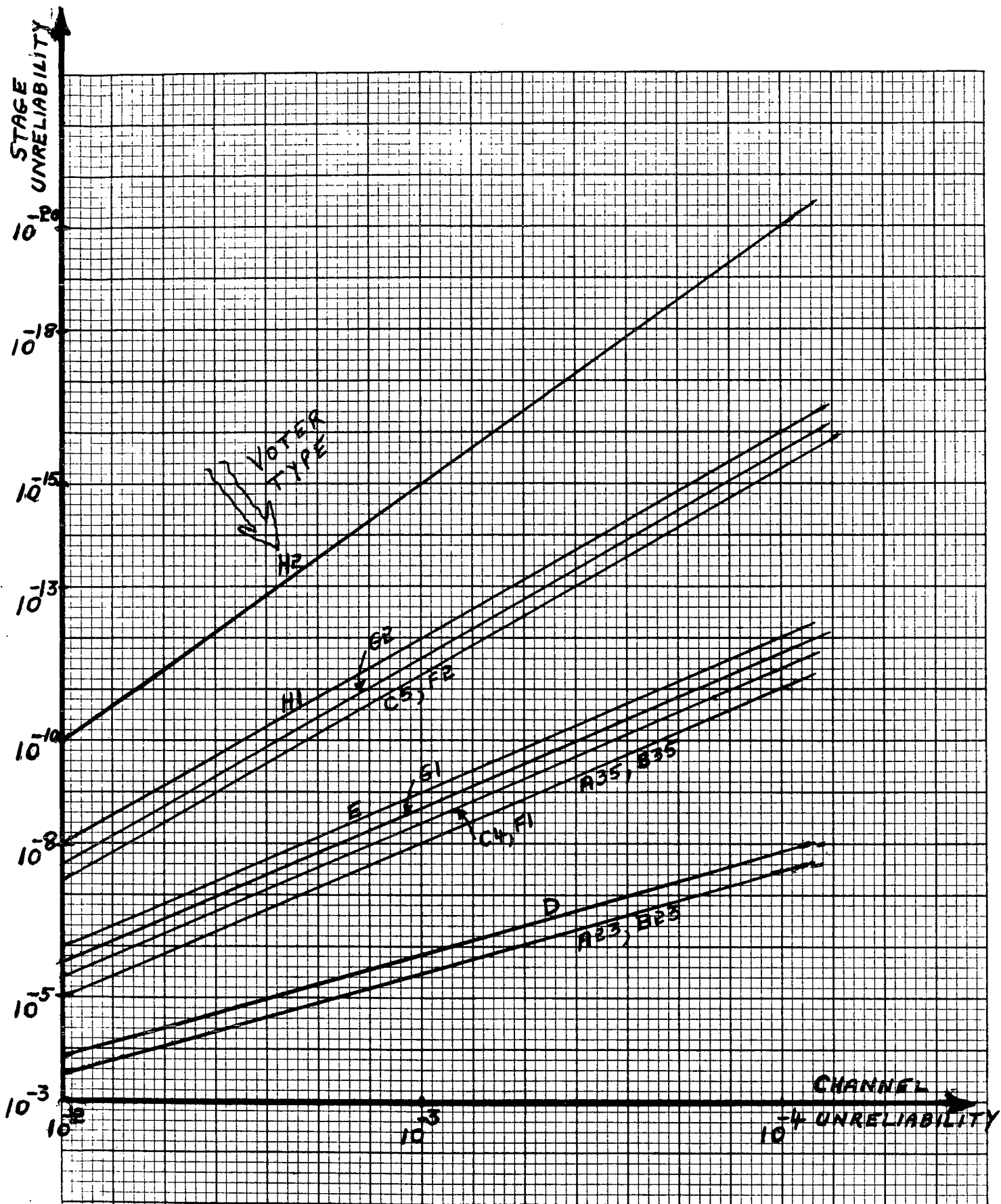
FIGURE 3.6-3

LOG-LOG PLOT OF DEPENDENCY OF STAGE

UNRELIABILITY (f_{Stage}) ON CHANNEL UNRELIABILITY

Table 3.6-5

Sample Calculation of Unreliabilities of Stages Using 3 or 4 Channels

Designation	Formula From Table 1	Stage Component Due to Voter	Stage Component Due to Channel $f = 4\times10^{-3}$	Total Unreliability of Stage ($\times10^{-6}$)	Dominating Element
A23	f_v+3f^2	1×10^{-4}	48×10^{-6}	148	Non-redundant Voter
B23	$3f_v^2+3f^2$	27×10^{-8}	48×10^{-6}	48	Channels
D	$f_v+\frac{3}{2}f^2$	14×10^{-4}	24×10^{-6}	1424	Non-redundant Voter
E	f_v+f^3	16×10^{-4}	64×10^{-9}	1600	Non-redundant Voter
F	f_v+4f^3	17×10^{-4}	256×10^{-9}	1700	Non-redundant Voter
G1	f_v+2f^3	21×10^{-4}	128×10^{-9}	2100	Non-redundant Voter
H	f_v+f^4	25×10^{-4}	256×10^{-12}	2500	Non-redundant Voter

Table 3.6-6

Sample Calculation of Unreliabilities of Stages Using 5 Channels

Designation	Formula From Table 1	Stage Component Due to Voter	Stage Component Due to Channel $f = 4\times10^{-3}$	Total Unreliability of Stage ($\times10^{-7}$)	Dominating Element
A35	f_v+10f^3	2×10^{-4}	640×10^{-9}	2,000	Non-redundant Voter
B35	$10(f_v^3+f^3)$	1×10^{-8}	640×10^{-9}	6	Channels
C5	f_v+5f^4	31×10^{-4}	1280×10^{-12}	31,000	Non-redundant Voter
F2	f_v+5f^4	24×10^{-4}	128×10^{-12}	24,000	Non-redundant Voter
G2	$f_v+\frac{5}{2}f^4$	28×10^{-4}	640×10^{-12}	28,000	Non-redundant Voter
H2	f_v+f^5	32×10^{-4}	1024×10^{-15}	32,000	Non-redundant Voter

3.6.2.3 Minimum Total Unreliability (Hardware Unreliability plus Transmission Unreliability) Due to a MONITOR

The hardware unreliability and the transmission unreliability of a Data Bus had in the past been considered as separate phenomena. It was here demonstrated that the two unreliabilities could be combined into one figure of merit for each of the monitors shown in Table 3.6-7. This technique makes it possible to choose a best monitor for the SSV Data Bus, providing certain critical information concerning the Shuttle Data Bus is available.

The relative importance to be placed on each of the two unreliabilities (hardware and transmission) is a critically important characteristic of the Line Replaceable Unit (LRU) and is seen to be the greatest length (N) of a series of erroneous words which can be sent to the LRU WITHOUT THE SAFETY OF THE SHUTTLE being affected! The importance to be placed on transmission reliability increases as the number (N) of tolerable erroneous words decreases.

The corresponding question concerning hardware unreliability was how the unreliability of the monitor affects the unreliability of the whole redundant channel system which provides the complete data link to that LRU under consideration.

The equation for a one-standby system takes the form,

$$f_M = (f_{TW})^N + f \cdot f_{MH} \qquad (3.6-2)$$

where: f_M = total unreliability

$(f_{TW})^N$ = probability of N successive words being erroneous

f = unreliability of a powered channel

f_{MH} = monitor hardware unreliability.

Monitor Principle (Error Indication and Maybe Correction)	Transmitter Complexity (Equiv. Nands)	Receiver Complexity (Equiv. Nands)	Total Complexity	Hardware Unreliability Per Hour 1 Nand = 3×10^{-7}	Hardware Unreliability Per Millisecond	Transmission Unreliability per Block of 50 Words with Independent Bit Noise General	n = 18	p = 10^{-6}
Horizontal Parity	4	10	14	4.2×10^{-6}	11×10^{-9}	$\binom{n}{2}\cdot p^2 \times 50$	$50 \times 153p^2$	7.6×10^{-9}
Two-Dim. Parity	72	180	252	7.6×10^{-5}	20×10^{-12}	$\binom{m}{2}\cdot\binom{n}{2}p^4 \times (1-p)^{mn-4}$ where m = 51	$1.87\times10^5 \times p^4$	1.9×10^{-19}
Signal Internal (Bipolar NRZ)	0	20	20	6×10^{-6}	16×10^{-13}	$2(n-2)p^2 \times 50$	$50 \times 32p^2$	1.6×10^{-9}
Echo Check With Hor. Parity Included.	4	44	48	1.4×10^{-5}	3.8×10^{-12}	$\binom{n}{2}\cdot p^4 \times 50$	$153p^4 \times 50$	7.6×10^{-21}
Repitition Coding Simultaneous (2 out of 3) bit voting	0	4	4	1.2×10^{-6}	3.2×10^{-13}	$3p^2 \times 18 \times 50$		2.7×10^{-9}
BCH m=31, k=21, t=2 (10 redundant bits)	83	83	83	2.5×10^{-5}	6.7×10^{-12}	$\binom{n}{2t+1}p^{2t+1} \times 2^{k-n} \times 50$	$50 \times 1.7 \times (10^{-28})$	8×10^{-27}

Assumption (1)   Each word length (without redundancy) is n = 18 bits.

Assumption (2)   Significant unreliabilities for comparison are over 1 msec; i.e. a block of 50 words.

TABLE 3.6-7   HARDWARE UNRELIABILITIES AND TRANSMISSION UNRELIABILITIES OF SOME MONITORS

i. e., for a monitor using horizontal parity, 18 bits, N = 10, Total Monitor

Unreliability per 10 Word Times = Transmission part + Hardware part,

$$= (153 \times 10^{-12})^{10} + 4 \times 10^{-25} \simeq 4 \times 10^{-25}$$

From this it can be concluded that transmission unreliability has negligible effect on total unreliability when N $>$ 2 or 3.

Section 3.6.2.3 has described a new methodology for assigning a total figure of merit, that is a total reliability, to the various kinds of possible monitors. A simple example with one standby channel was calculated. No attempt was made to numerically calculate a best monitor for the case of three standby channels, or any other possible configuration of the SSV Data Bus because of the lack of the appropriate critical parameters.

3.6.2.4 Unknown Critical Parameters of the Four Proposals

The critical parameters necessary to evaluate the reliability of any proposed Data Bus for the Space Shuttle were listed, and it became apparent that, in the area of operational reliability, the four proposals A, B, C and D contain none of the critical parameters.

Form of Redundancy

Proposals A and C stated an intention to use standby redundancy, whereas proposal D uses masking redundancy. These three proposals assume that all Line Replaceable Units (LRU's) adapt their redundancy to that of the Data Bus.

However, proposal B takes the view that 90% of these LRU's would be Triple Modular Redundant and therefore have 2-out-of-3 voting or masking redundancy. These 90% would require the same redundancy from the Data Bus. On the other hand, the remaining 10% would require standby redundancy from the Data Bus to match their own standby redundancy.

For the 90% of the LRU's allegedly requiring masking redundancy, proposal B wishes to use the most complicated type of hybrid voter (Type H of section 3.6.2.2) without offering any evidence that reasonable mechanization is possible. Section 3.6.2.2 demonstrated that the unreliability of a single voting and switching device soon dominates the channel unreliability by many orders of magnitude as the device complexity increases. Since no information whatsoever is given concerning the circuitry of the Type H voting devices, there is absolutely no basis to judge the operational reliability of proposal B.

Monitors

Each proposed concept gave its views on the best number and types of monitors and these are listed in Table 3.6-8, but none of the proposals had any methodology for achieving an optimum number and best kinds of monitors. The required methodology, formulated by SCI, is indicated in Section 3.6.2.3. It uses the concept of "total unreliability" which is compounded of both the transmission unreliability and the hardware unreliability.

The four unknown critical parameters related to monitors are the following.

(a)   No proposal gave any data concerning the hardware unreliability of the ten or more different kinds of monitors which are a part of standby redundancy or hybrid redundancy.

(b)   Transmission unreliability is heavily dependent on the statistical property of the channel noise. However, the unknown statistical properties of the noise must be classified as a major unknown critical parameter, having a radical influence upon the total reliability of performance of each proposal.

(c)   As shown in Section 3.6.2.3, the transmission unreliability becomes an important consideration when $N > 2$. It was not provided, and without this missing critical parameter, the four proposals cannot be evaluated, nor can a best Data Bus be formulated.

(d)   The channel coverage conferred by a certain monitor is not stated. For instance, does an echo check in Proposal A check out 60, 80 or 100% of the channel?

Switches

The severe requirements on the reliability of switches for standby systems was discussed in Section 3.6.2.1, but no information regarding the configuration and types of switches was given in any of the proposals. This lack of information is equivalent to a number of missing critical parameters.

Reliability Logic Diagram

Not one of the four proposals contained a reliability logic diagram, an item of fundamental importance. Efforts to construct a reliability block diagram for each proposal failed because of insufficient information. This left a strong implication that there was a basic lack of definition of the hardware on which each proposal was supposedly founded.

The lack of reliability logic diagrams has to be interpreted as a missing critical parameter, since without it the component reliabilities cannot be properly combined into a system reliability.

TABLE 3.6-8

MONITORING REQUIREMENTS OF

PROPOSED CANDIDATE SYSTEMS

		A	B	C	D
1	Parity - Horizontal	X	X	X	X
	- Vertical	No	X	No	No
2	Signal Internal Bipolar NRZ	No	No	No	
3	Echo Check	X	X	X	No
4	Time Out Check	No			
5	Word Count	No	X		
6	Serial Repetition Coding (Repeat Commands for Critical Msgs.)	Address Only Send Complement.	X	No	
7	Voting with Monitor (Error Reporting)	No. TR_0 90% of LRU's require voting, No DI.		No	
8	Voted Parity	No	No	No	X
9	BCH	No	No	X	No
10	Parallel Repetition Coding (Masking Voting)	No (pure standby redundancy)	90% as LRU's require	No	X
11	Periodic Test Messages		No		X
12	Parallel Repetition Coding with Staggering	No	No	No	X

3.6.2.5   Practical Problems and Techniques

Practical problems and techniques related to the design of specific operationally reliable circuits are summarized in this section (detailed account published in $\emptyset$2, Volume IV report, Section 4.2.6, of the same name as above). These include:

(a)   various monitoring schemes associated with both standby and masking redundancy, and required number of monitors;

(b)   two techniques for generating synchronous redundant clock signals for masking redundancy schemes;

(c)   and power distribution and power supply redundancy problems and techniques.

For practical standby configurations, it was shown that a Fail Operational (FO) fault tolerant circuit would require the following components: 2 channels, 2 switches, and one monitor circuit. Further, FO-FO requires 3 channels, 6 switches, and 3 monitors; and for FO-FO-FO, the quantities go to 4, 12, and 6, respectively.

A list of nonredundant voters which satisfy the FO-FO-FO failure criterion of the SSV are as follows:

* Type A47 - Classical 4-out-of-7 voter.
* Type C5 - Reconfigurable 3-out-of-5 voter.
* Type F2 - TMR (Triple Modular Redundant) hybrid with 2 spare channels.
* Type G2 - TMR hybrid/single with 2 spare channels.
* Type H2 - TMR hybrid/single with 1 spare channel.

The reliability and unreliability of each voter above is given in Table 3.6-3. The C5 voter is somewhat more complex than the type A47 voter, but it requires only 5 channels whereas the A47 voter must have 7.

The two types of practical monitors, Types I and II, reviewed can be constructed entirely from conventional digital integrated circuits, portending reduced size and simplicity. Each consists essentially of an error detector and an error counter with a time period reset multivibrator. Differences in error detection method distinguish the Type I from the Type II monitor.

Bit-by-bit voting of parallel redundant channels creates significant synchronization problems, introducing seemingly conflicting requirements:

- The parallel channels must be statistically independent as regards to their reliabilities,

- and the redundant serial data streams conveyed by the parallel channels should all be in synchronism.

Both of these requirements can be met by means of a highly reliable central clock source which satisfies the FO-FO-FO failure criterion by supplying four sets of redundant timing signals which are all in synchronism. It was shown that two different types of <u>redundant clock sources</u> satisfying the FO-FO-FO failure criterion could be constructed:

1) using four Phase Locked Loops (PLL), and
2) using 7 type A47 voters.

A summary comparison follows:

	PLL	7 - A47
Count of Total IC's	164	214
Volume	3 in^3	3 in^3
Power	6 watts	10 watts
Oscillators * required	8 - 1 MHz	8 - 8 MHz

* These should be temperature compensated crystal controlled devices for each clock scheme.

The reliability of prime power generation and distribution, and local power supplies is a major concern to the design approach taken in a data bus system. The former is truly an area of design concern related to all electronic/electrical subsystems, not just the data bus subsystem. Design alternatives would include the manner of communicating power system information - along with the power buses or separately, the number of power buses - probably four, method of power backup - battery configuration of some sort which is charged by prime power.

Of more direct influence on the data bus design are the local power sources. Two facets are noted:

• power sources are notoriously unreliable,

• and reliability is easily achieved through redundancy.

Of the methods explored for remote terminal power supplies, the technique preferred was that comprised of redundant supplies (i.e. 4) which draw power from 2 or more (i.e. 4) redundant power buses, ORed to make a single output.

3.7   EVALUATION OF CANDIDATE DATA BUS DESIGNS

This section endeavors to present comparisons of the four candidate data
bus systems (A, B, C, D) bringing to bear resultants of the Multiplex Data
Bus Techniques Study. Evaluation criteria are outlined first, followed
by relative comparisons. Most of the data available on the A, B, C, and
D Systems are found summarized in the User Subsystem Interface Study
section of Volume IV, Phase II. Unfortunately, insufficient data is avail-
able to make conclusive reliability analysis, as pointed out in Section 3.6.

3.7.1   Evaluation Criteria

Evaluation criteria provide a rational means of comparing the different
candidate system designs. These designs currently consist of the systems
A, B, C, and D referred to in the Phase II Report.

There are several significant problems associated with the development
of an appropriate set of evaluation criteria for the SSV data bus. Evalua-
tion consists of comparing system requirements with system capabilities.
In order to do this both requirements and capabilities must be expressed
in common terms. Once this is done, it becomes apparent that all the
required characteristics of the SSV data bus are not specifically defined,
and the degree to which a system must satisfy certain requirements is
free to vary, often over a considerable range. In addition, it is in many
cases difficult to determine certain specific capabilities of a system in
terms of its descriptive parameters.

In view of the foregoing considerations, it appears that the evaluation
criteria for the candidate SSV data bus systems should be based on:

- The identification of all known specific requirements.

- The identification of key characteristics common to each candidate system.

- The identification of significant relationships between desired features and specific system characteristics, and interrelationships between different system capabilities.

3.7.1.1   Specified Requirements

The following requirements have been specified for the SSV data bus:

- Error protection - Operation within specification with a Bit Error Ratio of 10^{-6} (uncorrected) induced by noise or other effects during the transmission process.

- Reliability:
  - Failure Criteria: Modified FO-FO-FO.
  - Failure Probability: 10^{-10} for 168 hour mission (note: this is derived from the failure criterion and the estimated reliability of a single thread—reference Volume IV of Phase II Report).

- Data Flow, type, and quantity of signals, distributions: As per Vol. III of Phase II Report.

- Physical/Environmental Conditions:
  - Physical locations (reference Volume III of Phase II Report).
  - EMI (reference Volume II of Phase II Report).
  - Temperature (reference Volume III of Phase II Report).
  - Vibration/Shock (reference Volume III of Phase II Report).

- On-board checkout for fault isolation and replacement

- Built-In Test Equipment (BITE).

- Terminal-to-terminal transfer.

- Multiple destinations for periodic data; for commands.

- Flexibility and adaptability to variations from one mission to the next.

- That each of the four systems can meet and exceed (for expansion purposes) the maximum required data rate when operating at 1 Mbps clock rate.

3.7.1.2   Key Characteristics and Relationships

The following discussion lists key characteristics and relationships to be considered in the evaluation of candidate SSV data bus designs. The objective in evaluating each design using these criteria is to show, where possible, the position of each candidate design on a set of relative scales which relate desirable system performance and/or attributes to certain basic system design parameters.

1.   Reliability

Transmission Reliability

It is desirable to show the probability of undetected errors as a function of bit error ratio. In addition, it would be helpful to show the susceptibility of each candidate system to noise. The probability of undetected errors is dependent upon the monitoring techniques employed, as well as the reliability of the hardware which performs the monitor function.

Hardware Reliability

The hardware reliability of each system should be assessed, at least on a subjective basis. Of particular interest is the relationship between hardware reliability and system complexity.

C5

2. System Throughput Efficiency

System throughput relates the bit rate on the transmission media to the required rate of flow of information. Inefficiencies arising from redundant coding, message formatting schemes, message routing techniques, etc. should be identified and evaluated in quantitative terms where possible. While high throughput efficiency makes it possible to transmit data at a higher rate over a channel with a given capacity, it may entail greater hardware complexity in order to assure a given transmission reliability. Hence it is desirable to show the relationships between throughput efficiency, transmission reliability, and hardware complexity.

The efficiency of a system having a specified set of formatting, channeling and routing techniques can be expressed in terms of the peak data rate required on the primary transmission medium for a specified data flow model. The relationship between a large number of selected message formatting, channeling and message routing techniques has been determined for the SSV data flow model described in Volume III of the Phase II Report, and is reported in Section 2.2.7.3 of Volume IV of the Phase II Report. These results should be used in the evaluation of candidate Systems A through D and also should assist in determining the overall system throughput.

3. Programming

Two significant trade-offs are involved in the area of programming. They are:

- Centralized vs. Distributed Programming

- Hardware vs. Software Programming

Software and hardware complexity, and system flexibility are the primary factors which would be considered in each of these trades.

4. Terminal Hardware Architecture

Three main aspects of terminal hardware architecture should be considered. They are:

- Subsystems Interface Compatibility - The hardware architecture should be capable of satisfying a wide variety of user requirements.

- Modularity - This combines subsystems interface compatibility with the concepts of standardization and maintainability.

- Local Busing Philosophy - Parallel and serial direct coupled buses should be compared for connecting terminals which are in the near vicinity of one another. This should be compared with techniques which involve communication between all subsystems via the primary transmission medium.

5. Computer/Bus Controller Organization

It appears that a direct interface between a computer and the Bus Controller will be required in the SSV. The degree to which the computer exercises control over the detailed operations of the bus, via the bus controller, should be ascertained. A bus controller which has a high level of autonomy should free the computer to perform more abstract system functions. On the other hand, the complexity of the bus controller can be reduced considerably by letting the computer perform most if not all of the detailed functions associated with bus control. Hence the computer/bus controller organization constitutes a trade study that should be performed.

6.   Cost, Weight, Size and Power Consumption

The cost, weight, size and power consumption of a data bus system are all directly related. These relationships should be ascertained, where possible.

7.   Growth Potential and Flexibility

It is desirable to identify and compare features which limit the future growth of the system. This is especially important because the data flow model is apt to change as the SSV design progresses. Various combinations of types, quantities, routing, sampling rates, etc. must be satisfied from mission to mission also.

3.7.1.3   Features, Characteristics and Capabilities of the Systems

This section complements the previous section, identifying significant relationships between desired features and specific system characteristics, and interrelationships between different system capabilities not previously addressed. The scope of subjects included is tempered by the practicality of information available.

1.   Features

● Suitable to service all the types of signals and total quantities for the SSV Booster and Orbiter.

● Modularity (see #6, para. 3.7.2)—such to accommodate the previous feature, with a minimum of unused hardware and with minimum weight, size and complexity penalty.

● Programming flexibility—submits to change without causing permanent or costly "scar".

- Commonality and interchangeability—

  . between booster and orbiter hardware and functioning,

  . ease of maintenance; plug-in/modular approaches enhanced,

  . facilitate ease of setup and calibration checks,

  . compatible with cold plates/rails,

  . equipment rack designed, for small and large bay uses.

- Time division multiplex, baseband modulation employed.

- Solid state, hi-rel components.

- Suitable LRU interfaces—conditioning inputs and output, including:

  . Multiplexing

  . A/D and D/A

  . Data Buffering

  . Ground Isolation

  . Sensors, Single-Ended, Double-Ended, with bridge completion; also special conditions (i.e. thermocouple wire, or zone box).

  . Conditioning Power

2. Characteristics

- Accommodate all data rates, as required.

- Easily handled and nondisruptive connect/disconnect implementation.

- Comparison with Biphase-Level and Bipolar NRZ, with AWG and impulsive noise.

- Hardware complexity.

- Required transmission bandwidth.

- Use of transformer coupling.

- Presence of sufficient synch. data.

3. Capabilities, Interrelationships

- Less than 100 Remote Terminal couplings to Data Bus.

- Transmission medium-to-modulation and detection process.

- Error detection capabilities.

3.7.2 Evaluation

3.7.2.1 Reliability

Section 3.6 summarizes (detailed in Phase 2 Report, Volume IV, 4.2.1.4) a method of simplifying reliability numerics, which results from replacing "Reliability" by "Unreliability" figures. Also shown was an integrated approach to Minimum Total Unreliability due to a monitor which results from a combination of Hardware Unreliability and Transmission Unreliability.

Four trade areas are as follows:

1) Form of Redundancy
2) a) Switches for Standby Redundancy
   b) Type Voters
3) Monitors
4) Reliability Logic Diagram—Circuit Configuration

Systems A and C employ standby redundancy and system D uses masking redundancy. System B uses masking redundancy for 90% of the LRUs, 2-out-of-3 voting. Standby redundancy is used for other 10%. Type H, the most complicated type of hybrid voter would be used. There is no basis

upon which to judge the operational reliability because of the lack of System B information. Details are also lacking in the A, C and D Systems, to the point that a judgement with regard to each system's choice of reliability cannot be made.

A warning flag should be raised concerning the constraints associated with using standby redundancy: fallibility to repetitive bursts of noise, its finite switchover time, minimum acceptable switch unreliability, imperfect coverage, and unreliable monitors. If the SSV cannot tolerate any of these constraints, then standby redundancy alone may not legitimately be referred to as FO-FO-FS, and consequently could not be used.

Switches for standby redundancy must be independent in all respects. They must have contact unreliability $< 10^{-5}$, static unreliability $< 10^{-5}$, and dynamic unreliability (failure to switch when required) $\ll 10^{-10}$. None of the proposed systems provides information necessary for comparison.

Monitoring requirements of the proposed systems are tabulated in Table 3.6-7. Four reasons were presented in Section 3.6 as to why the A, B, C, D Systems could not be properly evaluated, including 1) lack of data concerning hardware unreliability, 2) lack of data on channel noise, needed for transmission unreliability weighting, 3) sensitivity of LRUs to a series of erroneous words, and 4) channel coverage.

Certain comparisons can be derived from Table 4.2.3-1, "Hardware Un-reliabilities and Transmission Unreliabilities of Some Monitors", Volume IV. Monitor complexity is given in terms of equivalent NAND gates. For total complexity (transmitter plus receiver) the following was given:

Monitor Principle	Total Complexity (Equivalent NAND Gates)
• Horizontal Parity	14
• Two-Dim. Parity	252
• Signal Internal (Bipolar NRZ)	20
• Echo Check	48
• Repetitive Coding (twice)	4
• BCH (M = 31, K = 21, t = 2)	83

Using these data, the following table was derived.

Type Monitor / System	A	B	C	D
1. Parity - Horizontal - Vertical	14	252	14	14
2. Echo Check	48	48	48	—
3. Repetition Coding				
- Serial	4	4	—	—
- Parallel (Voting)	—	4	—	4
- Parallel (w/stagger)	—	—	—	4
4. BCH	—	—	83	—
5. Voted Parity	—	—	—	14
6. Periodic Test Message	—	—	—	0
	66	308	145	36

TABLE 3.7-1. COMPARISON OF SYSTEM MONITOR COMPLEXITY

The combined reliability for each of the four systems was analyzed. BER = 10^{-6}. As in Table 3.6-7, Transmission Unreliability is taken over 50 words. The results were as follows for undetected errors:

System	Transmission Unreliability
A	1.8×10^{-9}
B	4.59×10^{-20}
C	8×10^{-27}
D	4.8×10^{-26}

It can readily be seen that System A is far inferior to the other three. System B may be acceptable, but it too is inferior to Systems C and D. These two are within a factor of 6 of each other.

3.7.2.2   System Throughput Efficiency

System Throughput Efficiency (E_{ST}) is the ratio of the flow of useful output data to the total input bit rate required to maintain that data flow.

$$E_{ST} = \frac{y}{x}$$

where y = useful output data flow rate

x = total input bit rate
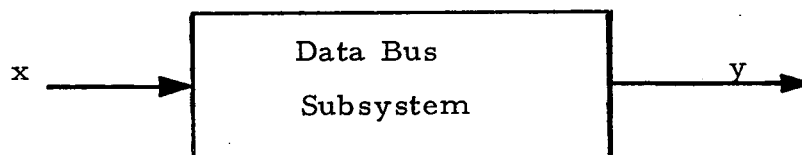
This takes on meaning when it is recalled that during SSV Booster mission Phase PL the raw data rate was found to be about 422 kbps (ref. Table 3.1-1, page 3.1-16). Taking 0.422 Mbps to be y, and the 1 Mbps design

limit of the Data Bus to be x, then the minimum acceptable E_{ST} (with no spare capacity) is as follows:

$$E_{ST} \text{ min.} = \frac{.422 \text{ Mbps}}{1.0 \text{ Mbps}} = 0.422$$

Note also that measurements constitute about 2/3 of the total bit rate during mission phases PL and LA and about 90% for the subsequent five phases, and controls (commands) make up the remainder, respectively.

A consolidated summary of information relative to date flow for the four systems can be found in Volume IV, Figure 3-5 and Table 3-1, with points of interest as follows:

System A

- Duplex connection (however, operates 1/2 duplex).
- Command-response method of Bus Control.
- Data routing through BCU (Bus Control Unit) under BCU control.
- Echo-check and horizontal parity used.
- 9 bits per word (8 + parity).
- Byte or block transfer (to 225 8-bit data words).
- BCU transmits messages (commands or requests) when active, and when not active sends "idle" signal as subsystem clock to all ACTs.

System B

- Half-duplex operation.
- Command-response method of bus control, initiated and controlled by CPUs.
- Data routing through BCU.

- Echo check, horizontal and vertical parity.

- 9 bits per word (8 data and parity).

- Block transfer—locally stored (19 bytes receive/35 bytes transmit).

System C

- Duplex (although "duplex" operation cited, method of data exchange not certain. Terms such as "transceiver" cause doubt).

- Command-response method of Bus Control.

- Data routing—through BCU.

- Echo check and BCH error detect coding.

- 8 bpw.

- Byte addressable; 4 byte blocks.

- Designed for 5 Mbps bus rate. (Normalized here with reference to 1 Mbps bus rate for sake of comparison).

System D

- Full duplex operation (includes simplex supervisory line and 1/2 duplex data line).

- Command-response method of BCU control.

- Data routing—through BCU; also data terminal-to-terminal.

- Masking redundancy (voting), parity check, plus staggered transmission of data.

- 8 bpw.

- 20 bits contains 2 data bytes.

- Byte addressable.

Consider data flow for message commands and data requests, for single word transfer rates and for block transfer rates.

SEQUENCES:

System A, Command, Single Data Word Out:

BCU to ACT	BOM	2 bits
	ACT Address (True)	9 bits
	ACT Address (Complement)	9 bits
	Function Code	18 bits (2 words)
	EOM	2
		40 bits

ACT to BCU	ACT Address	9 bits
	ACT Status	9 bits
		18 bits

BCU to ACT	(As Above)	40 bits
	Data Word	9 bits
		49 bits

TOTAL

107 bits
for single word out

System A, Data Request for Single Word:

BCU to ACT	BOM	2 bits
	ACT Address (True and Complement Words)	18 bits
	Function Code (2 Words)	18 bits
	EOM	2
		40 bits

3.7-14

ACT	ACT Address	9
to	ACT Status	9
BCU	Data Word	9
		27

TOTAL

┌─────────────────────┐
│   67 bits   │
│   │
│   for single word │
└─────────────────────┘

System <u>B</u>, Command, Single Data Word Out:

BCU	Gap Sync	2 bits
to	Address	9 bits
DIU	Function Code	9 bits
	Verticle Parity	9 bits
		29

DIU	Gap Sync	2 bits
to	Address (Echo)	9 bits
BCU		11 bits

BCU	Gap Sync	2 bits
to	Address	9 bits
DIU	Function Code	9 bits
	Data Word	9 bits
	Vertical Parity	9 bits
		38 bits

Total

┌─────────────────────┐
│ 78 bits   │
│   │
│ for single word out│
└─────────────────────┘

System B, Data Request for Single Word:

BCU
to   ⎡
DIU   ⎣   29 bits

DIU   ⎡   Gap Sync   2 bits
to
BCU   Address (Echo)   9 bits

            Data Word   9 bits

        ⎣   Vertical Parity Word   9 bits
                                                    ‾‾‾‾‾‾‾
                                                    29 bits

            Total   ┌─────────────────┐
                                           │ 58 bits for   │
                                           │ Single Word   │
                                           │   │
                                           └─────────────────┘
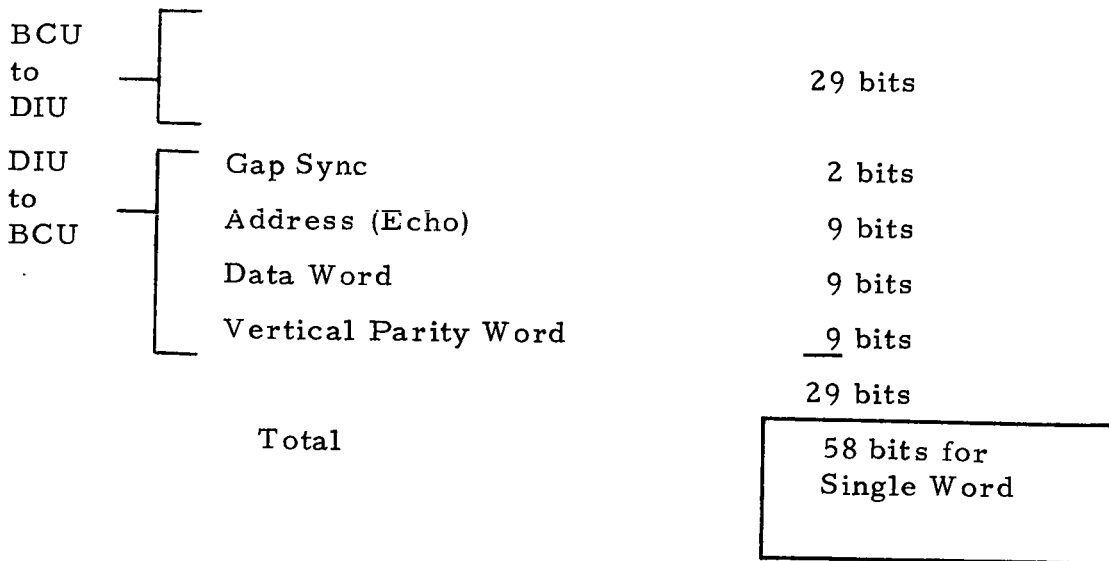
System C uses a standard 33 bit word, which can contain one or two 8-bit bytes.

System C, Command, Single Data Word Out:

BCU   ⎡
to
SIU   ⎣   33 bits

SIU   ⎡
to   ⎦ (Echo Back)   33 bits
BCU   ⎣

BCU   ⎡
to
SIU   ⎣   Command with One Data Out Byte   33 bits
                                           ┌──────────────────────┐
            Total   │ 99 bits   │
                                           │ for single (or double)│
                                           │ word out   │
                                           └──────────────────────┘

3.7-16
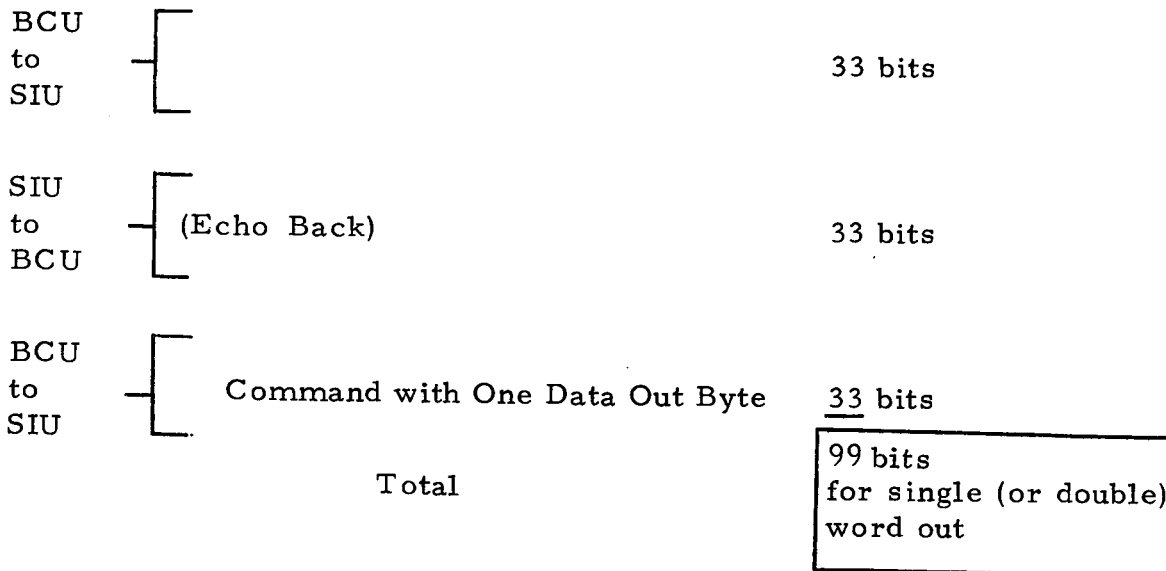
System C, Data Request for Single Word:

BCU to SIU   33 bits

SIU-to-BCU   33 bits

Total

33 bits
for single word

One or two 8-bit bytes of data are acquired in just a 33 bit time because 1) System C's full duplex operation permits successive requests to be transmitted on one line at the same time data replies are being returned on the other line; and 2) the request message and the data reply take equal time on the bus, thereby allowing unbroken concurrent operation. This is true for System D, as well.

System D uses a standard 20 bit word, which can contain two 8-bit bytes. Stagger and destaggering of quad redundant bus required, but does not affect data rate. No echoing employed. Data outputted via Data Terminal (DT) and Mux/Demux Unit (M/DU).

System D, Command, Single Data Word Out:

BCU
to   20 bits for single word (8 bits) or double word (16 bits) out.
DT

System D, Command, Multiple Data Words Out:

(Transfers are not blocked. However, transfers can be maintained to various users at rate of two data words per 20 bits.)

System D, Request for Data, Single Word:

(Interchange is with DT only, data being taken from DT memory.)

BCU-to-DT	20 bits
DT-to-BCU	20 bits
	20 bits

The reasons given above for System C apply here: full-duplex operation, and requests and replies use same size words.

Having defined Systems A, B, C, and D sequences for central-to/from-remote terminal exchanges, throughput efficiency was examined. Table 3.7-2 tabulates the results for data acquisition. To acquire one 8-bit data byte using System A requires a total of 67 bits; 58 bits required for System B, 33 bits for System C, and 20 bits required for System D. Systems A and B work with 8 bit increments, but systems C and D operate with words that can include two 8-bit increments, respectively. The table points up the following with regards to two-byte data:

System	Total Bits Required	Est (%)	Data Rate per 1 Mbps
A	76	21	210 Kbps
B	67	24	240 Kbps
C	33	48.4	484 Kbps
D	20	80	800 Kbps

Stated another way, this means that operating at 1 Mbps, actual data would flow at the rate tabulated in the right hand column above.

TABLE 3.7-2

RECEIVED DATA THROUGHPUT EFFICIENCY

8-Bit Data Words	System A		System A[1]		System B		System C		System D	
	Total (bits)	%	Total (bits)	%	Total (bits)	%	Total (bits)	%	Total (bits)	%
1	67	11.9	40	20	58	13.8	33	24.3	20	40
2	76	21	40	40	67	24	33	48.4	20	80
3	85	28.3	45	53	76	31.6				
4	94	34	54	59	85	37.8				
5	103	38.9	63	63.5	94	42.5				
6	112	42.8	72	66.7	103	46.5				
7	121	----	81	69	112	50				
8	130	----	90	71.2	121	53				
9	139	----	99	72.7	130	55.2				
10	148	54	108	74	139	57.5				
15	193	62	153	78.4	184	65.2				
20	238	67	198	81	229	70				
25	283	71	---		274	73				
30	328	73	288	83.3	319	75.5				
35	---	----	---	----	364	77				
256	2362	86.6	2322	88	---	----				

Systems C * and D exceed the 422 Kbps maximum requirement while employing their single word exchange. Systems A and B do not, and consequently must employ blocking.

The System A sequence for a single word data request requires 67 bits. For each additional data word returned to the BCU, a parity bit is included - takes 9 bits to get 8 data bits. This is tabulated in Table 3.7-2 for from 1 to 256 data words, and graphed in Figure 3.7-1. It can be seen that an average of 6 data words per message must be received at the BCU in order to accommodate the Pre-Launch data rate of 422 Kbps. This operation complies with System A description, "The DB operates in a half-duplex manner, tied up until the addressed ACT completes its response called for by the BCU".

However, if the 40-bit request portion of the message, BCU-to-ACT, was allowed to be sent while the previous message is being returned to BCU (full-duplex operation), the throughput could be improved as shown by curve A^1, Figure 3.7-1. While a 40-bit request is being sent, a 27-bit reply containing one 8-bit data word is being returned; and 36 bits are returned when two 8-bit data words are returned. At three data words, 45 bits are returned, which then governs the throughput. This operation is made possible by the duplex lines, clearly illustrating the improvement in operation over half-duplex. The capability to transmit and receive at the same time and to control these operations must also be present. Curve A^1 indicates that an average of three data words per message would have to be blocked.

* System C operating at 5 Mbps would have the same Est, but would pass 5 times the data.
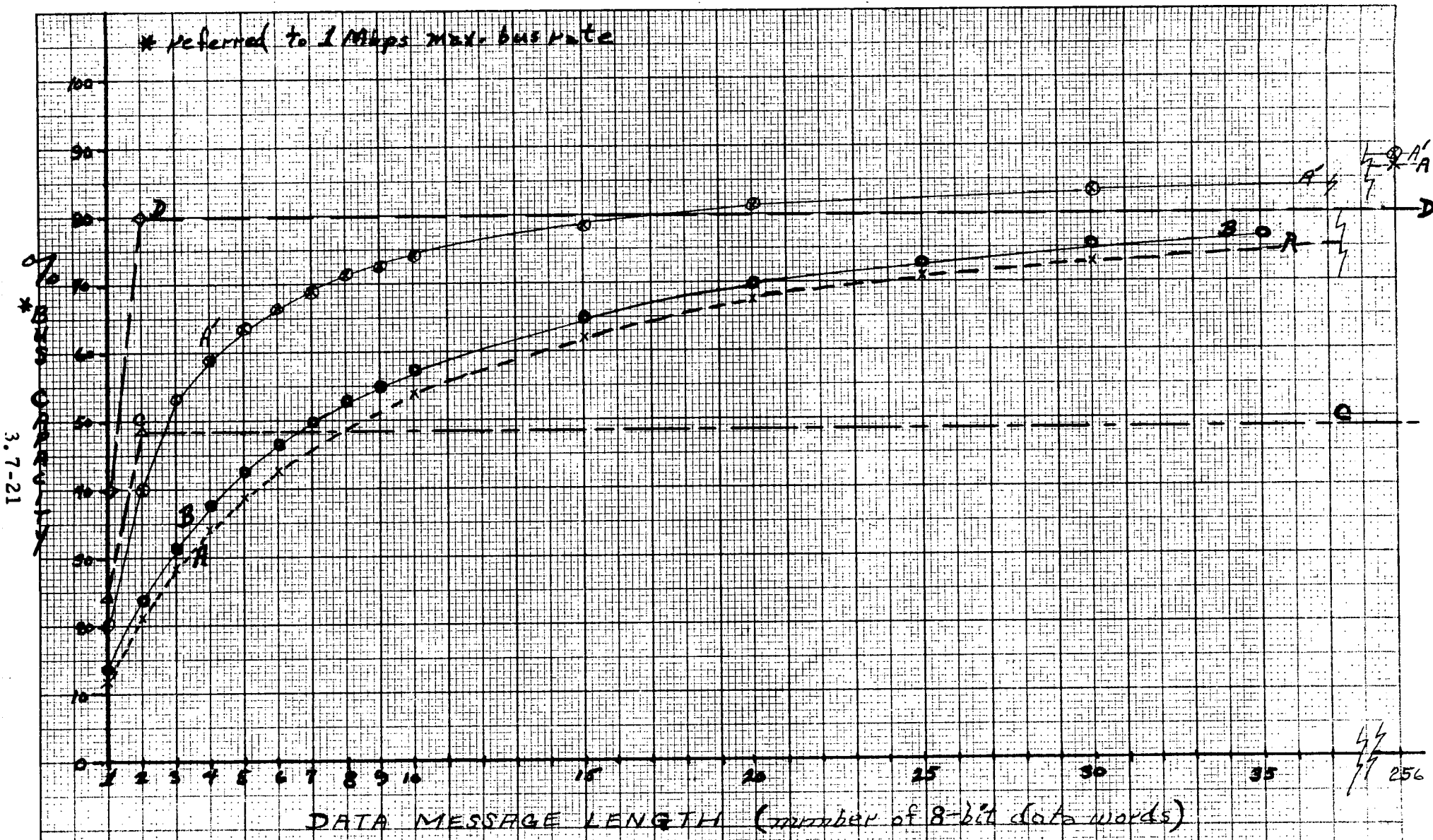
Figure 3.7-1   BUS CAPACITY
vs
DATA MESSAGE LENGTH

* referred to 1 Mbps max. bus rate

3.7-21

System B requires 58 bits to get back 8 bits of data. Its 1/2-duplex block-ing resultant is plotted in Figure 3.7-1 and shows that an average of at least five data word blocks would be required to meet mission phases PL and LA data throughput requirements. At its maximum of 35 data word replies, its maximum efficiency is shown to be 77%.

Systems C and D are similar in that they operate full-duplex with fixed word lengths. System C when returning one data word is 24% efficient, and when returning two data words is 48% efficient. System D likewise is 40% and 80% efficient. Since two word transfers are their normal mode of operation, Systems C and D operate continuously at throughput efficiencies of 48% and 80%, respectively, without blocking.

Commands throughput efficiency for the four systems is tabulated in Table 3.7-3 and plotted in Figure 3.7-2. The poorer efficiencies shown for Systems A, B, and C reflect the penalty to throughput resulting from echo-back type operation. System A also suffers from the constraint to operate 1/2-duplex (transmit-receive interleaving operation is not reasonable with this system when echo-back is employed). To meet the minimum mission phase PL requirement, System A must block on an average of ten command words; and System B must block on an average eight command words.

System C operating full-duplex with echo-back allows interleave operation to two addresses. While one address is being called up on one line, another address point is replying on the other line, such that both lines are employed 100% of the time. When only transferring one command word to each of two addresses, throughput efficiency is about 18%; and at two command words per transfer, efficiency is about 24%. System C can send two - 33 bit command messages per transfer. Therefore, a maximum of eight 8-bit commands could be sent in six 33-bit periods with a resulting

TABLE 3.7-3

COMMAND DATA THROUGHPUT EFFICIENCY

8-Bit Words	A Total (Bits)	A %	B Total (Bits)	B %	C Total (Bits)	C %	D Total (Bits)	D %
1	107	7.5	78	10.2	132	12.1	20	40
2	116	13.8	87	18.4	↑	24.2	20	80
3	125	19.2	96	25	↓			
4	134	24	105	30.5	132	24.2		
5	143	28	114	35				
6	---	---	---	---	165	29		
8	---	---	---	---	198	32.3		
10	188	42.5	159	50				
15	233	51.5	204	59				
19	269	56.5	231	65.8				
20	278	58						
25	323	62						
30	368	65	↓	↓	↓	↓		
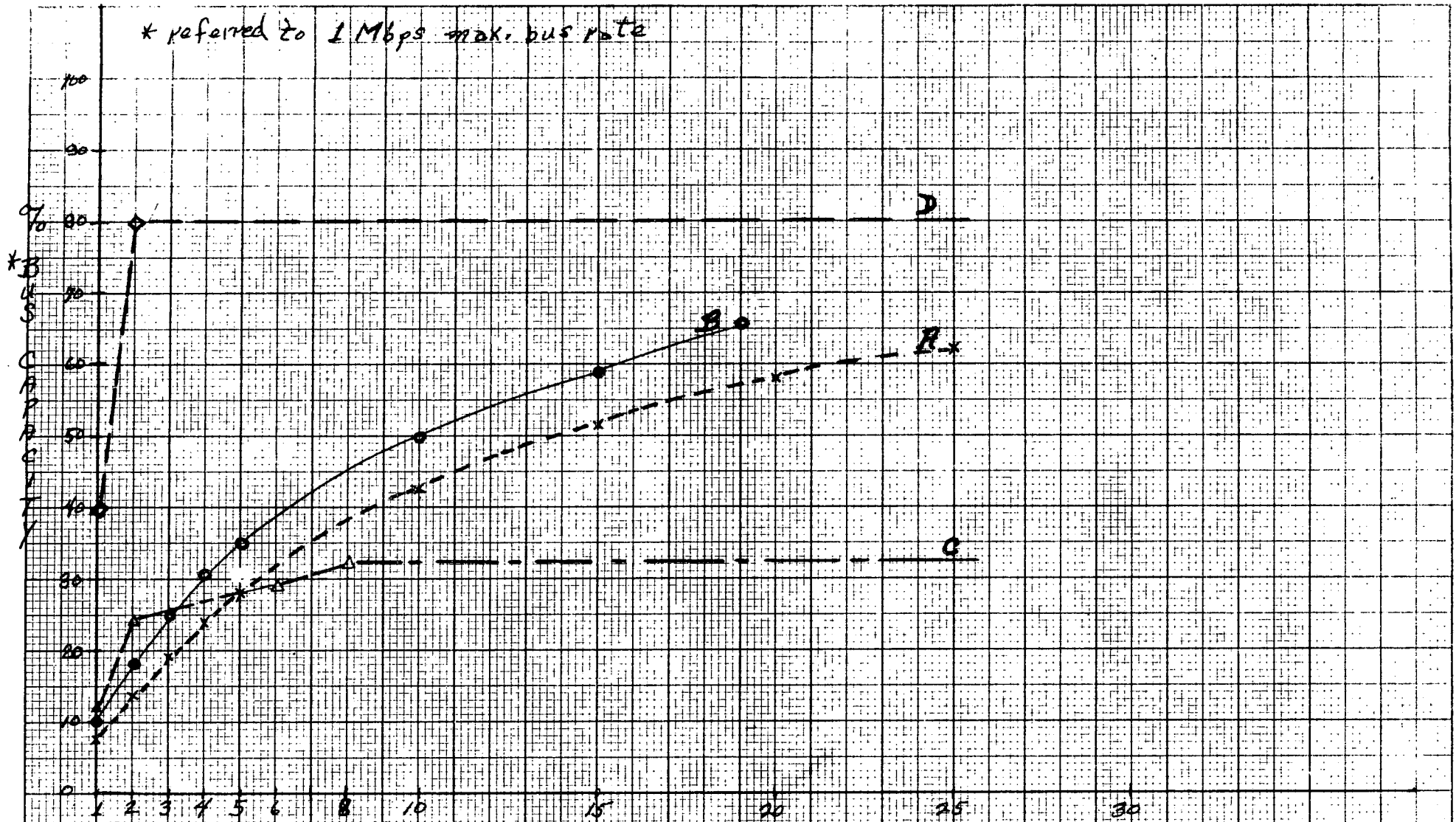
Figure 3·7-2   BUS CAPACITY vs COMMAND MESSAGE LENGTH

throughput efficiency of about 32% (at 1 Mbps this is not sufficient, but is acceptable at 5 Mbps).

System D does not use echo-back, and consequently its throughput efficiency for commands is the same as that for data: 80% continuously at two commands per 20-bit word.

Conclusions drawn from the System Throughput Efficiency examination of the four systems follows:

- Systems A and B must block transfer data to meet booster data requirements.

- Systems A and B must block transfer commands to meet booster commands requirements.

- System A' illustrates system throughput improvement made possible by full-duplex operation in place of half-duplex operation.

- At 1 Mbps, System C satisfies the booster data rate requirement when transferring two data bytes per standard 33-bit word.

- At 1 Mbps, System C does not satisfy booster command rate requirements (-- but would satisfy command requirements at its design rate of 5 Mbps, although throughput efficiency does not improve).

- At two 8-bit bytes per standard 20 bit word, System D throughput efficiency is a constant 80% for both data and commands.

The undesirability of blocking has been scored in paragraphs 2.2.4 and 3.4.2, which cover these points:

- Causes additional hardware complexity.

- Blocking limits bus access. Aperiodic commands must await the completion of a block transfer before they can be transmitted.

- Blocking and unblocking hardware must be programmed at each data terminal. This constitutes a lack of flexibility.

- Central programming is constrained to organize data requests and commands in groups - blocks. This increases programming complexity.

- Eavesdrop type data stripping operations become difficult, if not unreasonable, because of data blocking. The eavesdrop terminal must take all the data in the block, or large segments.

- For some of the same reasons, Terminal-to-Terminal transfers would not be practical.

Hardware Complexity

Elements of each system are as follows:

System A: Transmission Line (TL) — 5 lines total

Bus Control Unit (BCU)

User Subsystem Interface —

Line Coupling Unit (LCU)

Acquisition Control and Test (ACT)

User I/O Interface Modules

System B: Transmission Line — 4 lines total (plus one each optional)

Input/Output Control Unit (BCU)

User Subsystem Interface — Digital Interface Unit (DIU)

System C: TL — 8 lines total

(BCU)

User Subsystem Interface —

System Interface Unit (SIU)

Electronic Interface Unit (EIU)

System D: TL — 8 lines total

(BCU)

User Subsystem Interface —

Data Terminal (DT)

MUX/DEMUX (M/DM)

These cannot be properly evaluated based upon the spotty information available. The wide variation in approaches would require taking the complement of components needed for a booster or orbiter, or some representative bay area, and structuring by use of the four systems. In fairness to system B which is comprised of certain signal conditioning capability, and also to gain a complete view of the systems, the interface with the user would have to include signal conditioning. The Table 3.7-1

comparison of monitoring complexity for each system, as relates to redundancy, is an illustration of partial complexity. It does not include the additional complexity caused by having memories in systems B and D, or the redundancy cross-strapping added in System D, or that caused by an amplifier per channel in System B. It is also not fair to credit a system as being less complex while placing more of the hardware requirement on the user subsystem equipment. This is somewhat true of System A.

Transmission Reliability

This was scored earlier in terms of Transmission Unreliability. Systems C and D scored highest. The more intense error checking method is related to the lower data throughput realized in System C. Blocking was required in Systems A and B.

3.7.2.3   Data Transfer Methods

Data flow considerations include very important items such as 1) terminal-to-terminal (TTT) transfers, 2) provisions for stripping data for subsystems working in an edit (eavesdropping) mode, and 3) the need for transfers to multiple destinations.

Direct TTT transfer capability is built into System D, the only one of the four systems. The other three systems would have to transfer the data to central which would then re-transmit it to the destination terminal. For TTT transfers, this is a cumbersome, slower, inefficient method. A large amount of data flow was identified as being TTT type transfers, which emphasizes the importance of this capability being built into the Data Bus system.

Editing was recognized as a requirement by each of the four systems, although details were not complete. Editing, or an equivalent function, is needed within the SSV Data Bus Subsystem to make selected data available to secondary destinations, such as tape recorders, telemetry, GSE Data Bus, and Orbiter-Booster interface. System D includes a programmable function in the Bus Controller for selection of data for tape recorder and telemetry. The other systems would require special terminals for the editing operations.

Transfers to multiple destinations could be important to the reduction of data rate on the bus. An example of this might be the transmission of discretes which are to be both displayed in the crew area and also taken into the computer for limit checking. Systems A, B and C would require data flow to the CPU and then retransmission to the crew area. System D could be programmed to receive the single transmission at both locations simultaneously.

3.7.2.4   Programming

Programming flexibility such that changes from mission to next mission, or within a single mission, could be accomplished without hardware changes would be an asset to the Data Bus System. All four systems possess the capability for having changes made at central. But changes required in terminal functions must be made at the terminals.

System A ACTs have 32 channel input mux capability—28 analog including a "wrap-around" check channel, and four other serial channels which accept 8-bit digital inputs each or up to 8 events each. Number assignments can be altered. 31 event outputs or four digital outputs present a similar alterability. Terminal-to-terminal alteration is not within the design of the system. I/O modules are used for user interface.

System B remote terminal changes are made by choosing one of three types of terminals, called Area, Crew and IMU DIUs. Each has a different combination of analog, digital and event channels. Signal conditioning and transducer excitation are included (not so in A, C or D systems), and a resident memory allows programming of gain and calibration of the analog channels. Sampling sequence is also stored. So although I/O combinations are limited to the three type terminals, user interface flexibility exceeds that of the other three systems. However, TTT transfers are through the BCU, which provides programming flexibility but a high handling overhead.

System C has SIUs with up to 32 EIUs each. Each EIU has 32 analog and 256 discrete inputs, and 8 analog and 64 discretes outputs. No memories are included. Changes in assignments are possible, but the TTT transfer situation is the same as in Systems A and B.

System D has DTs with up to 16 M/DMs per each. Each M/DM has 32 analog and 32 discrete inputs, and 32 analog and 32 discrete outputs. Obviously, some variation in combination is possible. The memory provides data storage for immediate response of data to BCU. Secondary addresses are programmable within a terminal such to allow two or more terminals to respond to an address, one becoming the transmit terminal and the other(s) receive terminals, thereby providing TTT transfer capability. These also are changeable at the terminals.

3.7.2.5   Terminal Hardware Architecture

Three items were cited in Section 3.7.1 under the above name. They were 1) subsystem interface compatibility, 2) modularity, and 3) local busing philosphy.

- The first was addressed in the previous section. From information available, it appears that System B has the greatest amount of user interface circuitry capability built in. This also includes some low level capability, only apparent in one other system, System D. Also of interest is that both Systems A and B use power strobing to conserve power. System A shows a power drain change from 1.5W on standby to 25W ON.

- Modularity is seen in Systems A, C and D. System B offers either of three different terminals. System A proposes modular submultiplexers to provide flexible interface with users. However, this manner of channels expansion comes at a correspondingly lower data rate. System C varies its interface module size by the number of EIUs used per SIU, up to 32. System D varies in the same manner, with up to 16 M/DMs possible per DT.

- Local busing is used in System D only, although System C permits separating of SIUs and EIUs. This capability permits ease of attaching/detaching user interface units. It does this with fewer cables, but with added receive/transmit circuitry. The potential benefit of positioning the interface units close to the user subsystem is somewhat curtailed due to the need to mount the units in bays having cold plate temperature conditioning.

3.7.2.6   Computer/Bus Controller Organization

Computer/bus controller organization studies were not made sufficiently to perform trades. It was postulated that there would be computers in control at central, but as previous discussions have shown, there are many system methods and components to be decided upon first—data/control formats, message and word sizes, exchange methods including routing and

channeling, degree of data packing, blocking, addressing, redundancy method and implementation, terminals with memories, signal conditioning, I/O configuration, etc. The sophistication of the Bus Controller (BCU) then would support the resultant decisions associated with these, not guide them.

3.7.2.7   Cost, Weight, Size and Power Consumption

Sufficient data on the above subjects for each of the four systems examined are not available. In lieu of the trade comparisons then, System B (Phase B contractor system) is presented in summary form in Table 3.7-4. Some scope and frame of reference can be derived from this mid-1971 Data Management summary, which includes redundancy. A few numbers were estimated based on similar units in the other SSV.

Summary costs for this Baseline Data Bus/DIU were given as follows:

Total Equipment Cost	$112
Risk Cost	3
Operations/Checkout Costs	22
Equipment/Weights Cost	36
Total Cabling Weight Cost	17
Power, Cooling, Energy	10
GSE Costs	5
	$205 million

3.7.2.8   Growth Potential

The potential for growth can be interpreted in terms of 1) the ability to add more of the same type terminals, with attendant transmission rate increases, - This does require a safety factor in throughput, 2) adaptability to various new requirements (variations in I/O complements) or for new

TABLE 3.7-4   DATA MANAGEMENT SYSTEM EQUIPMENT (SYSTEM B)

Subject	Orbiter (Max. Data Rate Per Bus = 155 Kbps)						Booster (Max. Data Rate Per Bus = 340 Kbps)					
	Units Per Vehicle	Per Unit Weight (lbs.)	Total Per Vehicle Weight (lbs.)	Total Per Vehicle Volume (cu. ft.)	Per Unit Power Max. (Watts)	Total Per Vehicle Max. Power (Watts)	Units Per Vehicle	Per Unit Weight	Total Per Vehicle Weight	Per Vehicle Volume (cu. ft.)	Per Unit Max. Power (Watts)	Total Per Vehicle Max. Power (Watts)
● Central Computer	4	85	340	5.2	450	1800	4	85	340	5.2	450	1800
● System Control Unit and Panel	1	7	7	.1	52	52	1	7	7	.1	52	52
● I/O Control Unit	4	6.2	24.8	.4	20	80	4	6.2	24.8	.4	20	80
● Mass Memory	2	16	32	.5	30	60	2	16	32	.5	30	60
● Maintenance Recorder	2	50	100	4.0	250	500	2	50	100	4	250	500
● Area DIU	24	5.8	139.2	1.3	10	240	28	5.8	162.4	1.5	10	280
● Flight Control DIU	12	2.5	30	1.2	4	48	28	2.5	70	2.8	.4	112
● Crew Station DIU	24	5.7	136.8	1.3	15	360	20	5.7	114	1.3	15	300
● IMU DIU	4	5	20	.1	20	80	4	5	20	.1	20	80
● Data Bus Wire	—	27	27		—	—		40	40			
TOTALS	—	—	826.8	14.1	—	3220	—		910.2	15.7	—	3264

purposes, 3) suitability to reconfigure terminal locations, 4) suitability to couple to various numbers of other buses, such as orbiter/booster, or OFI/DFI, or Data Buses/GSE.

Limitations similar to that of most Data Acquisition Systems are possible — lack of memory expansion capability at central, address and format constraints, finite processing times, limit to number of terminals that can be coupled to Data Bus line ($\sim$100) and their locations, throughput limitation with respect to new high rate data, data resolution constraint, etc. Any finite system has some combination of these. Those that are spotlighted in the four systems examined are as follows:

- System A is limited in I/O data rate vs. number of data interface connections, due to the addition of channels by submultiplexing per ACT. Of course, more ACTs can be used up to some maximum number.

- Some locations will require A/D converter capability greater than 8 bits. This must be implemented, such as in Systems A and B.

- 8-bit byte sizing of data words can be awkward to handle when larger size words are required (i.e. 11 bpw data). Data formats for Systems C and D readily accommodate up to 16 bits. Systems A and B must split the longer data word into two bytes, or make some other arrangement.

- System B is designed using three types of terminals, with no further I/O modularity. This restricts its lattitude of expansion and degree of flexibility.

- Memories used in Systems B and D have finite limits of size.

- Redundancy (adding four redundant units to add one functionally) may make costs, weight and size increase too much to be practical.

- A system which is based upon normally transferring data in blocks limits the addition of any data with high resolution time (faster than the existing system access time). Such a system is inflexible and suffers from the items listed at the end of paragraph 3.7.2.2.

- Signal types are limited to high level analogs in Systems A and C. System B has a limited amount of signal conditioning interface circuitry.

APPENDIX

APPENDIX I

GLOSSARY OF TERMS AND ABBREVIATIONS

ABE - Air Breathing Engines (subsystem).

AC - Alternating Current.

ACPS - Attitude Control Propulsion System.

ACT - Acquisition Control and Test (unit).

ADC - Analog-to-Digital Converter. A device that converts analog signals to digital form.

AGC - Automatic Gain Control.

AIB - Asynchronous Integrating Biphase.

AL - Approach and Landing.

APU - Auxiliary Propulsion Unit.

Attenuation Constant - (α) The real part of γ, describing the change in signal amplitude with distance (radians/meter).

Automatic Checkout (OBCO) - The autonamous, automatic function or subsystem used to test, detect and isolate faults.

AWG - Additive White Gaussian (noise) (also stands for American Wire Gage when associated with wire).

BAC - British Aircraft Corp.

Balanced Operation - The use of circuits which are electrically symmetrical with respect to ground.

Baud - The unit of signaling speed equal to one code element per second.

I-1

Baseband Modulation - Those modulation techniques which produce power density spectra which extends to or near zero hertz.

BCH - Bose-Chaudhuri-Hocquenghen.

Bit Error Rate (BER) - The average number of erroneous bits received per bit transmitted over a channel.

Bi-$\emptyset$ - Biphase.

bps - bits-per-second.

Built-In-Test Equipment (BITE) - A provision in the multiplexer/data bus system and word format for allowing testing of different subsystems within the data bus, and possibly user subsystems.

Bus Control Unit (BCU) - The Bus Control Unit is an element of the data bus subsystem which provides timing and control for data transfer on the data bus.

Byte - A byte is a designated set of binary digits which are handled as a group.

Carrier Modulation - Those modulation techniques whose positive spectra are symmetrical about a carrier frequency greater than zero.

CD - Control and Display (subsystem).

Central Computer (CCR) - A singly-located subsystem used to provide computational services for user subsystems.

Characteristic Impedance (Z_0) - The impedance of a transmission line which is independent of the use or termination of the line, and is determined by the line's construction (its distributed parameters).

CMD - Command.

CMR - Common Modes Rejection.

Code, Block - A group of bits, or n-ary digits transmitted as a unit over which a coding procedure is generally applied for error-control purposes.

Code, Redundant - The adding of redundant bits to message bits in a manner which may be used for error control.

COMM - Communications.

Computer Input/Output Unit (CIU) - A special class of signal adapter (SA) for a computer subsystem interface.

COSMOS - Complementary-Symmetry Metal-Oxide Semiconductor.

CPU - Central Processing Unit.

CRC - Cold rail cooling.

D/A - Digital-to-Analog.

Data Flow Model (DFM) - A detailed description of each message path between the physically separated electronic elements of the Space Shuttle vehicle. The model includes information needed for study and design of a data bus subsystem such as: point of origin, destination(s), signal function, type of signal (analog, discrete, digital word, etc.), resolution, accuracy, occurrence statistics and any special characteristics or requirements pertinent to the data bus design and operation. A given model also specifies variations in the data flow requirements which occur as a function of vehicle mission profile.

Data Path - The signal flow path from source to destination(s).

Data Terminal (DT) - The Data Terminal is an element of the data bus subsystem which provides for the interchange of data and control signals with the user equipment.

Data-Transmission Channel (DTC) - That channel (TDM, FDM or separate cable) which transfers message information between user subsystems.

Data Word - A data word is a binary word containing a specified number of bits designated as data or commands to be transferred between user subsystems. The word may also contain bits designated for synchronization and error detection.

DB - Data bus.

db - Decibel.

DC - Direct current.

D & C - Displays and Controls.

DCRL - Data and Control Requirements Listing.

Delay Distortion - A term used to denote the nonlinearity of the group delay versus frequency curves.

Demultiplexer (DEMUX) - A device that separates signals that had originally been multiplexed into a single signal, and outputs them on two or more output lines.

DFI - Developmental Flight Instrumentation.

Differential Encoding - The process of denoting a "1" in binary data as a change in polarity from the previous state, and a "0" as no change in polarity.

Digital-to-Analog Converter (DAC) - A device which converts digital information to analog form. For the purposes of the study, digital information will be coded in straight binary form unless otherwise specified.

Dispersion - The dependence of distributed cable parameters L and C on frequency.

Distributed Computer/Microprocessor (DCR) - One or more subsystems at or near user subsystems to provide local computational services.

Distributed Interface - A user subsystem interface whereby signals are widely physically separated from each other.

DIU - Digital Interface Unit.

DMS - Data Management Subsystem.

DSBSC - Double side-band suppressed carrier.

Duplex/Full Duplex - A type of operation in which simultaneous two-way messages or information may be conveyed between any two or more given points.

ECLSS - Environmental Control and Life Support subsystem.

EMI - Electromagnetic Interference.

ENP - Energy to Noise Parameter.

Envelope Delay - See group delay.

Error Correction - A means of arranging digital data, with redundant digital symbols so that by suitable processing at the receiver it is possible to correct transmission errors.

Error Detection - A means of arranging digital data with redundant binary information so that by suitable processing at the receiver, it is possible to detect transmission errors.

F - Ferry.

Failure - An uncontrolled event which results in a malfunction of any part of a system. A failure occurs when the system ceases to perform its intended function in a specified manner.

False (Logic) - Logic state. Lo voltage level for positive logic.

FB - Fly-back.

FDM - Frequency Division Multiplex.

FEP - Fluorinated ethylene propylene (*Teflon).

FO - Fail Operational.

GD - General Dynamics.

GIN - Generalized Impulsive Noise.

GN&C - Guidance, Navigation and Control.

Group Delay - The change or derivative of the phase with respect to frequency.

GSE - Ground Support Equipment.

Hardware Redundancy - The use of additional hardware, above the minimum required, in order to increase the immunity of a subsystem to failure.

Half Duplex - A type of duplex operation in which operation can only be done alternately for two-way message or information flow.

Hertz - Cycles-per-second.

IAS - Integrated Avionics System.

IC - Integrated Circuit.

I/O - Input/output.

IOCU - Input-output control unit.

*Dupont Trademark

JFET - Junction Field Effect Transistor.

*Kapton - Polymide-fluorocarbon

KHz - Kilo-Hertz.

LA - Launch and Ascent.

LCU - Line Coupling Unit.

LED - Light-emitting diode.

LH_2 - Liquid hydrogen.

LO_2 or LOX - Liquid oxygen.

Localized Interface - A user subsystem interface(s) whereby signals are in close physical proximity (i.e. connector, LRU, etc.).

LRU - Line replaceable unit.

LVDT - Linear variable differential transformer.

Mass Data Storage (MDS) - A subsystem used to store large amounts of digital information.

Matched - The termination of cables with a component (usually resistive) whose value is equal to the characteristic impedance of the cable.

Mbps - Megabits-per-second.

MDC or MDAC - McDonnell Douglas.

M/DU or MDU - Multiplexer-demuultiplexer (MUX/DEMUX).

* Dupont Trademark

MI - Module Increments.

MINCOMS - Multiple Interior Communications Systems.

MOS - Metal Oxide Semiconductor.

MPS - Main Propulsion System.

MS - Millisecond (10^{-3} seconds).

MSC - Manned Spacecraft Center (NASA).

MSFC - Marshall Space Flight Center (NASA).

MSU - Mass Storage Unit.

MTBF - Mean-time-between-failure.

MOSFET - Metal oxide semiconductor field effect transistor.

Multiplexer (MUX) - A device that combines two or more signals from different sources, and outputs them on a single output terminal.

MUX/DEMUX (M/D) - A combined multiplexer and demultiplexer. It is a function element between a Data Terminal and one or more user subsystems.

Mv - Millivolt (10^{-3} volts).

NA - North American

na - Not applicable.

NAR - North American Rockwell.

NASA- National Aeronautics and Space Administration.

NRZ - Nonreturn-to-zero.

OFI - Operational Flight Instrumentation.

OM - Order of smallness.

OMS - Orbit Maneuvering System.

OO - Orbit Operations

PAM - Pulse amplitude modulation.

Parity Bit - A bit added to a binary code group which is used to indicate whether the total number of ONES in the group is odd or even. This coding technique is used for transmission error detection.

PDC - Power Distribution and Control (subsystem).

PDS - Propellant Depletion System.

Phase Constant (β) - The imaginary part of γ, describing the variation of phase with distance (radians/meter).

P/L - Payload.

PL - Prelaunch.

PLL - Phase locked loop.

Probability of Success (P_j) - The probability that a system element successfully performs its function, as required, throughout the duration of the mission.

PROM - Programmable read-only-memory.

Propagation Constant (γ) - A value associated with transmission lines consisting of the attenuation constant and the phase constant.

Propagation Factor - A nominal value, usually associated with wire cables, is defined as the phase velocity divided by the speed of light.

PRSG - Pseudo-Random Sequence Generator.

PSF - Presampling filter.

PSK - Phase shift keying.

PU - Propellant utilization.

RAM - Random access memory.

RE - Re-entry.

RIA - Requirements identification and analysis.

ROM - Read-only-memory.

RSSB - Reusable space shuttle booster.

RT - Remote Terminal.

RTE - Resistance temperature element.

RZ - Return-to-zero.

SCI - SCI Systems, Inc. (formerly SCI Electronics, Inc.).

Scratch Pad Memory (SPM) - A memory used for temporary storage of data.

SCU - System control unit.

SIA - Subsystem interface assembly.

Signal Adapter (SA)— A functional element of the data bus subsystem which may physically be packaged with the data terminal, the multiplexer/ demultiplexer or the user subsystem. Its main function is to normalize signals conveyed into or out of the user subsystem to a level and format suitable for multiplexer/demultiplexer (M/D) or data terminal (DT) standardized interface. The SA may also provide special conditioning or parameter extraction functions such as derivation of a discrete when an analog signal exceeds a selected threshold.

Signal Redundancy - The use of additional signal bandwidth, above the minimum required, in order to increase the immunity of a communications channel to internal or externally induced interference.

SIU - Standard interface unit.

S/N - Signal-to-noise (ratio).

SSV - Space Shuttle Vehicle.

Stagger/Delay - In transmission of data over separate media, the delaying of one channel with respect to the other.

Sub Bus - A multiplexed signal thoroughfare which transfers information between the data terminal and user subsystems.

Supervisory Channel - That channel (TDM, FDM or separate cable) which carries commands and instructions for control of access to the data bus, message routing and message identification.

System Failure - An event which occurs when a system ceases to perform its intended function in a specified manner. A system failure may result from occurrence of more than one failure.

System Reliability (R_i) - One minus the probability of system failure.

TBD - To be determined.

TDM - Time division multiplex.

Termination - The lumped component(s) associated with signal coupling at designated points of a transmission line. These may be either resistive or reactive components.

TFE - Tetrafluoroethylene.

TLM - Telemetry.

TMR - Triple modular redundant.

TN - Technical note.

Transmission Media - The material through which signals containing information are transmitted from one point to another.

True (Logic) - Logic state. Hi voltage level for positive logic.

TSP - Twisted shielded pair.

TTL - Transistor-transistor logic.

TTT - Terminal-to-terminal.

U/D - Up-down (counter).

UF - Utilization factor.

usec - microsecond (10^{-6} seconds).

User Subsystem Interface (USI) - The electrical/mechanical interface which is defined for compatible connection of the user equipment to the data bus.

VCO - Voltage Controlled Oscillator.

Z_o - Characteristic impedance of transmission line.

APPENDIX II

TECHNICAL REPORTS
MULTIPLEX DATA BUS TECHNIQUES STUDY BY SCI

1. Technical Phase Report No. 1 for A Study of Multiplex Data Bus Techniques for the Space Shuttle.

2. Volume I, Transmission Media, Technical Phase Report No. II for A Study of Multiplex Data Bus Techniques for the Space Shuttle.

3. Volume II, Signal Design and Detection, Technical Phase Report No. II for A Study of Multiplex Data Bus Techniques for the Space Shuttle.

4. Volume III, Requirements Identification and Analysis, Technical Phase Report No. 2 for A Study of Multiplex Data Bus Techniques for the Space Shuttle.

5. Volume IV, Synchronization, Timing and Control, User Subsystems Interfaces, and Operational Reliability, Technical Phase Report No. II for A Study of Multiplex Data Bus Techniques for the Space Shuttle.

APPENDIX III

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