IBM

PROPOSAL

Research to Develop Multiprocessing Techniques for Processing Diverse Requirements of Unmanned Orbiting Multifunctional Satellites

Prepared For

National Aeronautics and Space Administration
Electronics Research Center
575 Technology Square
Cambridge, Massachusetts 02139

8 August 1966

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FOREWORD

IBM is pleased to respond to Request for Proposal No. 66-1375 titled "Research to Develop Multiprocessing Techniques for Processing Diverse Requirements of Unmanned Orbiting Multifunctional Satellites" for the NASA Electronics Research Center. This proposal shows how IBM intends to achieve the objective of the proposed contract, that is, "to develop new concepts of multiprocessing oriented toward the computational needs of future long-lived multifunctional space satellites."

IBM proposes to provide a team of senior engineering personnel with an extensive background in practical applications of computers to the various subsystems identified in the RFP. The key personnel which IBM will assign to this contract have advanced degrees in electrical engineering with major emphasis in communications, signal analysis and computer architecture and related areas of major importance to the project. They also have extensive experience in reducing advanced subsystem functional concepts to hardware for use in a variety of communications and signal-processing applications. IBM feels that to ensure a fruitful program the key contributors must have extensive experience and understanding of the subsystem functions and adaptive concepts as well as in multiprocessing. The individuals assigned have the above background.

The personnel proposed for this study report to Dr. Herman Blasbalg, Satellite Communication Technology Manager in the Center for Exploratory Studies. His contributions to automatic observing systems, compaction techniques, pseudo-noise modulation and satellite communications are well-known. He will take an active part in directing the proposed project, particularly during initial planning phases and periodic reviews of progress.

Many well-qualified consultants in areas relevant to the proposed study are available as required within the Center for Exploratory Studies and in other parts of the Federal Systems Division. Particularly relevant education and experience in space science is provided by personnel of Cambridge Advanced Space Systems under Dr. J. P. Rossoni, who are located in Cambridge, Massachusetts. The study will also draw on the capabilities of the Computer Mathematics Department under Dr. H. D. Mills. If required, the study may obtain expert consulting assistance from Space Systems Center personnel at Bethesda, Maryland. and Huntsville, Alabama. The latter facility includes over 1500 people, of which over half are engineers, physicists and mathematicians working on the Saturn Instrumentation Unit.

Discussion of the Statement of Work

The objective of the proposed contract is to develop new concepts of multiprocessing oriented toward the computational needs of future long-lived multifunctional space satellites. The result obtained should provide a sound technological base for further development of a general-purpose satellite multiprocessing computer system.

The new concepts developed in multiprocessing are aimed at hardware and software, and will exclude electric circuit design and production engineering. This RFP emphasizes the development of new concepts and techniques in multiprocessing and in machine organization, conventional patterns need not be followed. Modularity and reconfiguration by means of hardware or software are important considerations here.

The multifunctional satellite system can be part of a system designed to meet both operational and scientific requirements.

An integral part of the study is to define the computation requirements for the major subsystems; i.e., checkout, communication and telemetry, control and stabilization, energy management, sensors, and data handling. It is desirable to define the computational requirements of the various subsystems linked by the computer system in a general, preferably parametric, form. This will be accomplished with the guidance and final concurrence of the ERC Technical Director assigned to this project. The total computation requirements will be specified in terms of meaningful computational criteria such as word length, data storage, speed, etc.

After studying the subsystem functions and defining the computational requirements, several of the most appropriate multiprocessing configurations, satisfying the computational requirements, will be formulated and developed. These configurations should satisfy the following broad operational factors:

a. Reliability
b. Flexibility and adaptability
c. Hardware realization
d. Hierarchy of mission control

Among the more specific operational factors are such things as diagnostic capability, self-repair, self-reconfiguration, information protection of memories, load sharing with remote computers, programming before and after launch, modularity and minimization of the number of distinct modules, reconfiguration program vs. hardware, etc.

The preferred multiprocessing configurations will then be evaluated against a set of meaningful criteria which will be established with the guidance and approval of the ERC Technical Director.

In Section 5, the proposal suggests several criteria which are likely to prove useful during the evaluation phase. The evaluation will clearly identify the features and technical limitation of the preferred configurations. Computer simulation will be used during the evaluation phase to the extent fruitful and feasible in a study of this size.

IBM Approach

A prerequisite for developing new concepts of multiprocessing oriented towards the computational needs of future long lived multfunctional satellites is a thorough understanding of subsystems and overall system operations. IBM has taken a first cut in this proposal at the mathematical and conceptual formulation of the operation of the major subsystems and the overall system (Item 1 of the RFP). The subsystem and system concepts which are introduced are aimed at the future and not at the present and are, therefore, consistent with the aims and goals of the RFP. Detailed block diagrams have been prepared to show advanced concepts related to channel and sensor monitoring, adaptive sampling, multiplexing and channel selection under the control of a computer. IBM has developed a mathematical theory for processing pictures by a digital computer which has worked successfully. For example, the on-board processor can be used for extracting picture contours (line drawings) and for image enhancement. The adaptive guidance and control computer algorithm which is presented in this proposal also uses concepts of the future, and here, too, the algorithm has been simulated on a computer.

IBM intends to use these advanced subsystem concepts, some of which have already been developed and tested by means of computer simulation, for the purpose of establishing the computer requirements in parametric form. Because a good mathematical model exists for each subsystem, the parameters and, hence, the computer requirements can be bounded. A representative mission will then be selected (with the approval of the Technical Director), the subsystem parameters calculated, and the computer requirements established.

Since there is a trade-off between the on-board processing requirements and the overall communication link capacity, the IBM approach will specify a representative communications link which is compatible with a multifunctional satellite system. The multifunctional satellite system will be interconnected to one or more Ground Control Facilities via a synchronous communications repeater satellite. This system concept, discussed in Section 1, is considered an important part of this study since the trade-off between the on-board and earth-based share of the processing load is only meaningful when a constraint is placed on the communications capacity. For example, if the link capacity is as large as desired, it would appear desirable to transmit the raw data down to ground-based computers thereby minimizing the on-board processing capability. The fact that the link capacity is bounded makes this problem an interesting one.

The IBM approach to the multiprocessing problem may be summarized as follows. Applying standard multiprocessing techniques that have been developed for large ground-based computer systems, to the multi-functional satellite problem is not necessarily the best approach. Rather, once the basic satellite functions common to all future satellite systems are understood, then efficient, small, and modular special-purpose processors can be designed to perform and execute these functions on board the satellite. For example, a communications processor would execute such functions as coding and decoding digital data to and from the earth control station. It would also perform and control digital antenna beam forming for both increasing antenna gain and also for despinning the antenna.

All of these processors would be controlled by a small general-purpose control computer also located on board the satellite. This computer would monitor the parallel processing for all of the satellite functions and would control any reconfiguration that is necessary to overcome the effect of equipment failures. The IBM approach to equipment reconfiguration is described in Section 1 and utilizes both software and hardware. The IBM team will attempt to develop new multi-programming concepts utilizing such advanced ideas as evolutionary and adaptive programming. The challenge here is to develop the hardware and programming systems simultaneously so that the two are melded into a unified multifunctional system.

During the study, advanced concepts of switching and partitioning theory will be applied to provide the basis for a multiprocessing system required for a long-lived multifunctional space satellite. Some of these concepts, described in Section 3, link themselves to a design characterized with being modular, reliable, flexible, easy to maintain and economical.

In the IBM approach, the overall multifunctional satellite system is considered as a complex communication system. All of the peripheral special purpose processors must communicate with one another and the central control computer onboard the vehicle. The central control computer acts as a complex switching center not only for the purpose of routing information from one special processor to another, but also for purposes of reconfiguration. The IBM team members assigned to this study have a considerable amount of experience in the fields of digital communication and computer design. They will bring advanced concepts of both of these areas to bear on the multifunctional satellite problem.

Outline of the Proposal

The subjects to be treated in the study, are described in Sections 1-5. Section 1 introduces the proposal and considers certain problems of reconfiguration, programming and multi-satellite systems. Section 2 discusses the prime areas of study in the context of multiprocessing systems for multifunctional satellites. Section 3 is a discussion of multiprocessing techniques and some new concepts that IBM plans to introduce. Section 4 is concerned with methods for applying information theory techniques to systems analysis and synthesis. Section 5 presents criteria of effectiveness and analysis techniques to be employed in evaluating performance of alternative subsystem and sytems designs.

Section 6 presents the project plan, the direct manpower to be assigned, and the schedule. Resumes of project personnel and consultants are given in Section 7. Section 8 gives a brief discussion of the IBM organization and facilities pertinent to the proposed study. Section 9 concludes the proposal with a synopsis of the extensive experience of IBM in areas related to the proposed study.

Section 1

INTRODUCTION

1.1 Multi-Functional Satellite Systems

It is a recognized fact that present satellite systems generate large volumes of data which is transmitted to earth, although only a small fraction is actually processed. With an increase in the sophistication of future satellite systems, there will be an increase in the amount of data collected which will overload not only the communication and telemetry equipment, but also the data processing capabilities of the ground-based computers. The answer to this problem is a flexible, reliable multifunctional (MF) satellite system monitored and controlled by a ground control facility (GCF), all of which are linked together by a synchronous communication satellite. Figure 1-1 shows schematically one way this is accomplished using a single synchronous communications satellite and two GCF's. The GCF terminals are in contact with one another via the synchronous satellite repeater and each MF satellite is in contact with one or the other GCF terminals. Thus, a communication path can be established between any two MF satellites either via a single GCF station or via two GCF stations and the synchronous satellite repeater. In principle, this technique can be extended to cover the entire earth by providing three or more synchronous satellites in communication with many earth stations. In such a system , the entire MF satellite system complex can be used to optimize the collection of useful data, thereby reducing the load in the ground-based processing equipment, as well as on the communications and telemetry links.

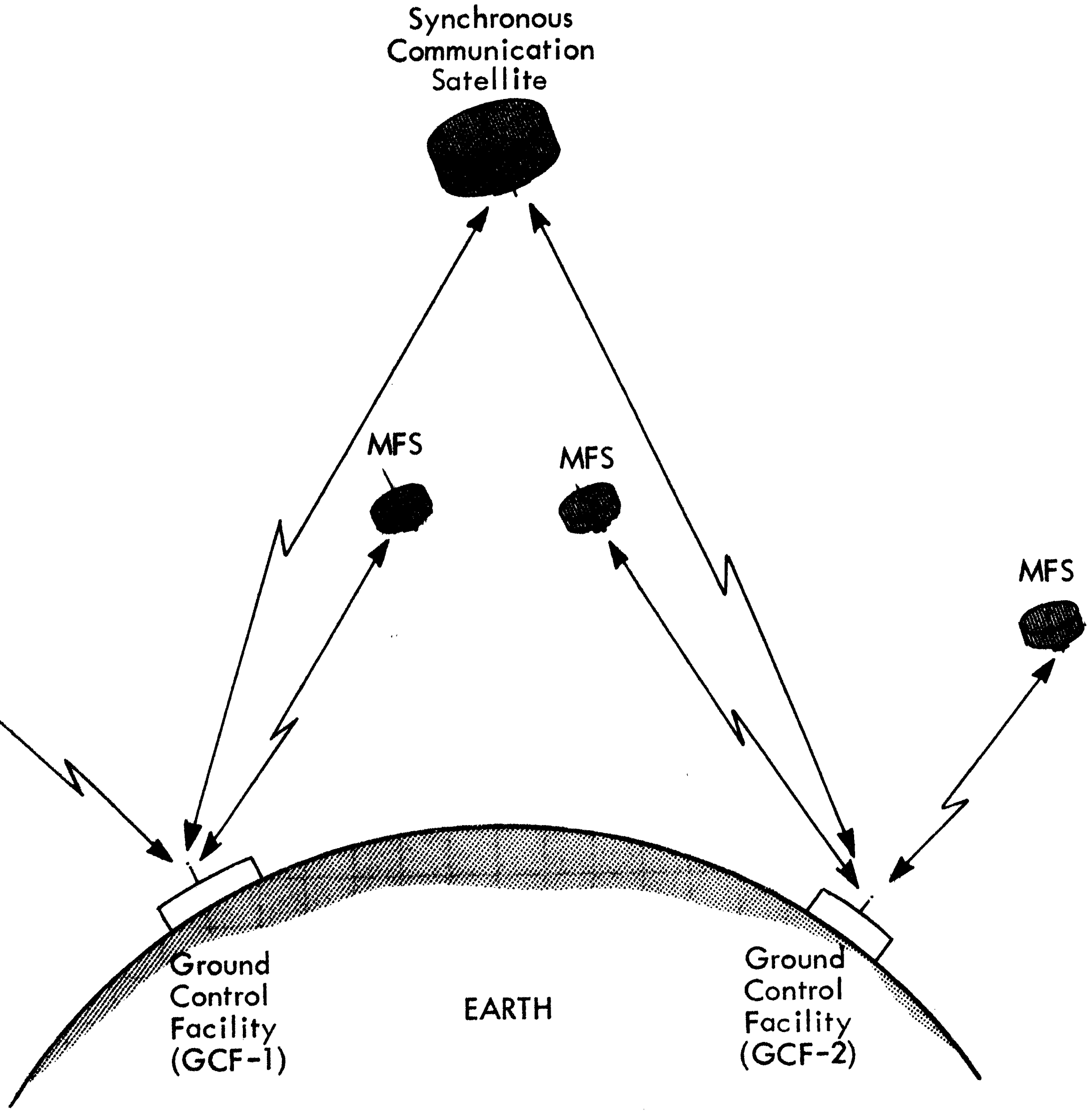

Figure 1-1. Satellite Communication System

A satellite continues to perform its prescribed and limited functions repeatedly for long periods of time, only because it cannot be used for anything else. On the other hand, a multifunctional satellite can be reconfigured to perform other useful data collection and processing functions once a mission is completed. The proposed system transmits down only information that is useful; hence, all of the satellite facilites can be used optimally.

The goals of a satellite system, operational or scientific, are to transmit to earth useful data. Useful data is generally extracted from the raw sensor data by some form of processing. The raw sensor data can be transmitted down and processed in the ground-based processors, or it can be preprocessed in the vehicle and only the important characteristics and parameters transmitted down. The latter system contains processing equipment located in the vehicle; while in the former, processing is performed on the ground, provided a high-capacity communications link is available. Thus a trade-off exists between the capacity of the communications system and the computing power of the satellite-processing equipment.

A multifunctional satellite, if it is to be used efficiently, should have access to a large Ground Control Facility from almost all points in the orbit, and vice versa. In present unmanned satellites, the data is stored in the vehicle and transmitted down during the relatively short period that the satellite is within view of the ground station. For each set of measurements, one would expect an optimum time at which to retrieve the data. A multifunctional satellite system can achieve efficient operation at all times if its communication and telemetry subsystem is connected to the GCF via a synchronous communication repeater satellite network. In fact, if there are multiple satellites in orbit, all can be connected via GCF stations and synchronous satellite repeaters. In this manner, the GCF can monitor the overall space system and optimize the combined missions.

It is also possible to distribute many small ground stations over the earth which simply repeat the data back to a synchronous satellite, which is actually a multiplexing point for multifunctional satellite communications network, and is then repeated down to the GCF. The details of the communications configuration are not required, although a thorough understanding of the limitations of such a communication satellite network is essential since there is a trade-off between its capacity and the on-board computer requirements. The IBM team proposed here, in addition to having intensive experience in designing multiprocessing systems, has a strong background in satellite communications.

1.2 Basic Satellite Multi-processing System

One on-board multiprocessing architecture that IBM proposes to study for all multifunctional satellite systems is shown schematically in Figure 1-2a. A general purpose computer called the Central Control Computer (CCC), is shown surrounded by a ring of special-purpose digital processors. Each of the special purpose processors is designed to perform and execute specific functions common to all satellite systems. All of the processors are connected via the CCC which monitors and controls the entire on-board system.

Figure 1-2b shown an earth-based General Control Facility (GCF) in communications with the CCC aboard the satellite. This facility is composed of a large general purpose computer and is used for ground control and backup. This computer will be programmed to request and accept data from the MF satellite. It will also be used to back up the CCC on-board the vehicle in case of failure.

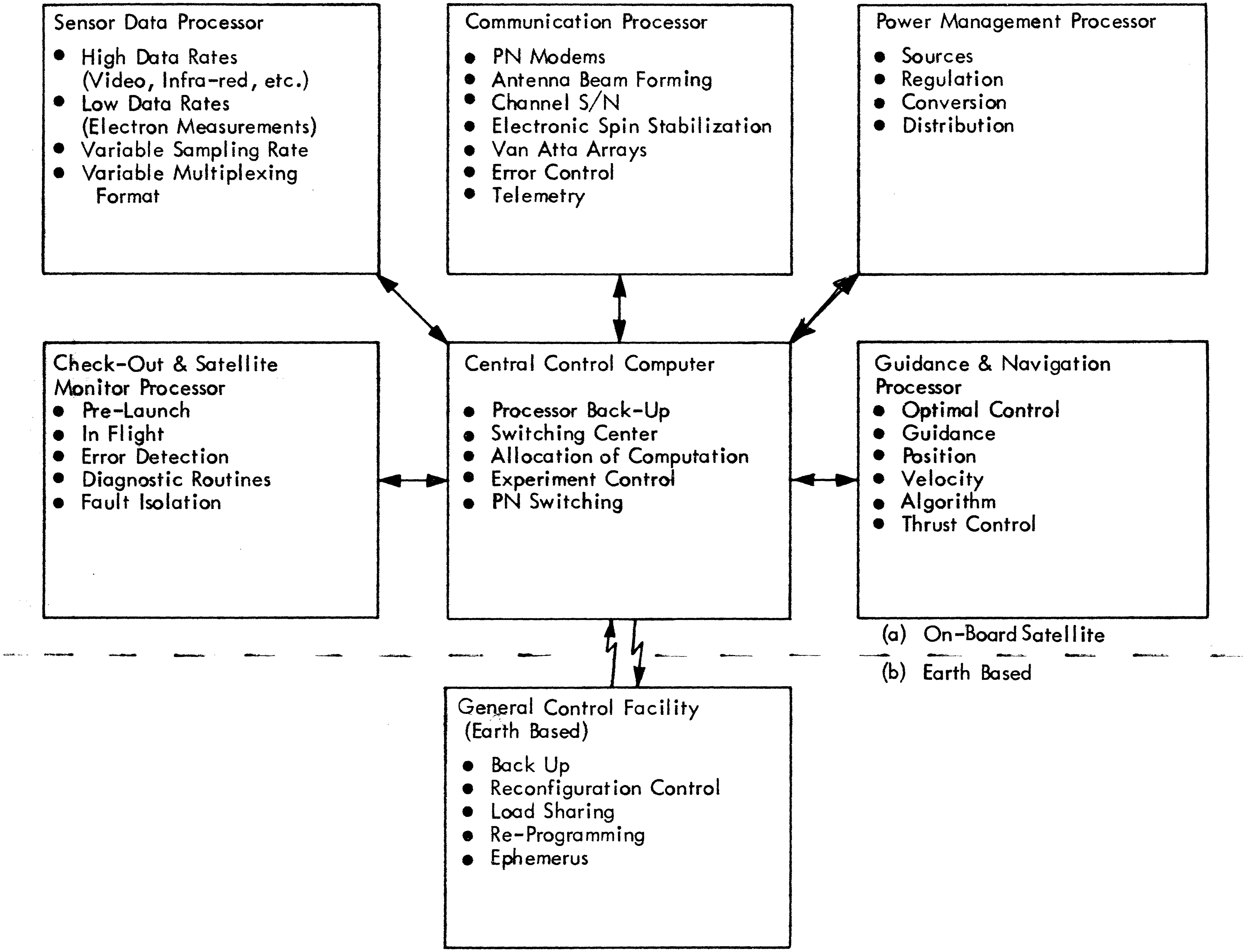

Figure 1-2. A Satellite Multiprocessing System

The philosophy behind the approach given in Figure 1-2 is this: the whole purpose of an on-board processing system is to reduce the amount of data transferred between the satellite and the earth. This is necessary because the amount of raw data gathered by a multipurpose satellite far exceeds the capacity of the satellite-earth communication link. Thus, a considerable amount of on-board preprocessing is required to reduce this raw data to fit the satellite-earth channel capacity. In the IBM approach, the key functions that any multipurpose satellite must perform have been portioned into five general areas: (1) communications, (2) power management, (3) guidance and navigation, (4) sensors, and (5) checkout and monitoring. An earth-based general purpose computer is also shown and is in constant communication with the central control computer on board the satellite.

The multiprocessing system shown in Figure 1-2 is viewed as a communication network. The central control computer communicates to the input-output (I/O) units (i.e., sensors, telemetry, antennas) and vice versa via I/O channels, each of which contains a special-purpose processor. Each of these processors is essentially a small special-purpose digital computer tailored to fit one of the five functions required of any multifunctional satellite. For example, the speed, memory size, and instruction repertoire of each processor will be a function of the task that the processor is designed to perform. In Figure 1-2, the actual I/O elements, such as antennas and sensors, are not shown.

The general form of each of the elements of Figure 1-2 will now be described.

Guidance and Navigation Processor

This processor will be designed to optimally execute the guidance and navigation algorithm described in Section 2. This machine will accept inputs from the various guidance and navigation sensors and will also control the thrust mechanisms.

Communications and Telemetry Processor

This processor will perform all of the subfunctions related to communications. Some of these are: digital antenna multiple-beam forming, pseudo-noise modem processing, estimation of channel signal-to-noise ratio, electronic spin stabilization, and error control

The antenna beam-forming processor will process the antenna element outputs directly and form the antenna beam in the direction that will optimize the on-board power allotted for this purpose. This processor will accept inputs from the guidance and navigation processor via the central control computer to effect electronic spin stabilization.

The electronic spin stabilization processor cancels out the effects of satellite spin stabilization. This is accomplished by electronically rotating the antenna beam that is always pointed toward the ground station. This technique results in very large values of effective radiated power.

Error control is another communication subfunction that can be neatly handled by a special-purpose processor. Here the processor, operating as a decoder, will detect errors in the data and perform error correction. Acting as an encoder, the processor would encode all data transmitted to the ground terminal using a powerful error correction code.

Sensor Data Processor

Of all the functions performed by a multifunctional satellite, this is probably the only one that will change from mission to mission. Typically, however, this function would include such diverse sensors as video television (which has an extremely high data rate), low data rate sensors such as electron density measurements, variable sampling-rate equipment and variable multiplexing format processors. Consider the processing requirements of these various sensors:

Video Sensors—Here the processor must operate on the video signal and, according to some rule which is programmed into the processor, process the raw video data prior to transmission to the earth station. Picture processing is discussed in Section 2.

Low Data Sensors, Variable Sampling and Multiplexing—This processor, under control of the central control computer, samples each of the sensors at a variable rate depending upon certain parameters measured by the central control computer. As the sampling rate changes on the individual sensors, the multiplexing format must also change. This special-purpose processor adapts to these changing conditions by modifying the internal stored program. The central control computer accomplishes this modification by means of an algorithm. An example of a variable-sampling, variable-multiplexing processor is given in Section 2.

Power Management Processor

This special processor is used to control the distribution of power throughout the satellite, thus making maximum utilization of the available on-board power. This processor will control the regulation, conversion, and distribution of this power.

1.3 Adaptive Multiprocessing Techniques and Reconfiguration

The configuration shown in Figure 1-2 is not only modular, but can be reconfigured and thus can adapt to any changes from the norm. One way this can be accomplished is by replacing faulty hardware with software. For example, suppose that a binary self-checking counter located in the guidance and navigation processor fails and this fact is detected by the satellite monitoring processor. Ordinarily, a failure of this type would disable the device. However, in this system, the central control computer performs the counting function by means of a micro-program. Note that this approach assures a graceful rather than a catastrophic degradation of the satellite system.

What is proposed here is a combination of software and hardware. Thus, whenever a section of hardware becomes disabled due to a failure of some kind, it will be replaced by a software program that performs the function that the original section of hardware performed.

The central control computer located in the vehicle would be programmed to back up any of the peripheral special processors in case of failure. Further, the GCF on earth will be programmed to back up, at least partially, the CCC on-board the vehicle in case of failure. This system will ensure reliability, long life, and a graceful degradation of the satellite.

1.4 Programming Considerations

The mission of the multifunctional space satellite embodies, in a single system, all elements of current day multiprocessing systems and can be viewed as a generalization of current systems. Programming techniques to handle parallel and diverse operations in a multiprocessor environment are requisite but not totally sufficient. Additional techniques must be developed to accommodate multiprocessing within the stringent reliability and integrity requirements and, at the same time, within the demands for the flexibility necessary to the experimental environment.

IBM proposes to design such techniques based on extending previously developed ideas that show promise of satisfying these requirements. Generally, programming techniques in the proposed study would be considered under the three major areas of:

1. System Organization—because of space and weight requirements and the operational similarities of the multiple processors, the total system must be organized about elemental operational components to effect required economies and efficiencies.
2. Functional Processing—optimization and generalization of known functional techniques must be developed to achieve, on one hand, the sophistication required of the mission and, on the other hand, the flexibility required by space experimenters.
3. Program Implementation—the open-ended functional requirements demand new techniques for program implementation and checkout that are characterized by machine independence, incremental development and checkout and system modification without loss of integrity.

The following sections treat these three areas in detail. The major technical problems are discussed, as are, the study approaches that would be followed in their solution.

System Organization

The proposed system is composed of multiple processors, each of which will perform parallel processing in a discrete but broad functional area, e.g., satellite power management. However, reaction to contingencies, such as sudden changes in the experimental environment, must be possible by time sharing processor elements with other processors in the system. Thus, modularity and interface compatibility are key elements in the system, not only for contingencies but also for normal operation.

These capabilities cannot be accomplished at the cost of redundancy; however, because of the space constraints of the overall system. Thus, current operating system techniques cannot be employed wherein duplication is repeated at various levels.

Rather, basic operating components of an elemental nature must be identified, isolated, and organized into an Integrated Operating System. The integrated approach would permit machine realization by the operating system and not by intermediaries such as compilers, loaders, etc. Interface compatibility would be ensured without duplicate programming and modularity to finer degrees than currently obtainable.

In addition to elemental components common in current systems, e.g., I/O operations, IBM proposes the inclusion of the following:

1. Memory management functions which would not be limited to a single processing strategy, but generalized to include all strategies possible in the multiple processors. Typically, the organization of a functional processor would be different from that of the CCC. However, each

performs certain similar operations and may be required to handle each other's functional operations. By generalizing memory management, redundancy in programs could be avoided, since they are not tied to a particular strategy.

2. Data management, not only in the I/O sense, but also in declaration sense. Current compiler ideas on the scope of data variable declarations should be extended such that the operating system is solely responsible, not only for I/O manipulation, but also for all aspects of data variable handling.
3. Device independence and interchangeability ideas must be extended to include, not only peripheral storage but also central processors. In this way, time sharing of processor components can be implemented efficiently.

These components have been isolated in previous work and show promise as minimum inclusions in the proposal. During the course of the study, additional components should be determined as these basic ideas are extended.

Functional Processing

The proposed IBM approach is organized into five functional processors under the immediate control of the central control computer. The latter processor is in turn directed by the general control facility. Each processor is normally dedicated to either system management or discrete aspects of the mission function.

While the basic programming for any of these discrete functions exists, the system requires greater degrees of sophistication plus the accommodation of total mission requirements.

Functional programs must be geared to optimal performance, thus adaptive in nature, to cope with the changing experimental environment. Techniques similar to those developed by IBM for the Saturn navigation and guidance problem should be developed for all functional processing. This applies to the control processors in such functional areas as message handling and routing.

In addition to optimal processing of discrete functions, the programs must be adaptable to changes in mission. Revised or new experimentation must be generally possible through resequencing of program execution without the necessity for program loading. This required generality should be possible by isolating discrete functional modules which can operate as elements in multiple environments.

The reliability requirement of the total system demands that all modules be capable of operating during malfunction with a minimum of system degradation. Thus, program design must also be geared to varying environments, with minimal changes resulting in functional outputs.

Program Implementation

One of the most challenging aspects of the proposed system is the actual development and checkout of required programs.

The multiplicity of processors and functions, plus the necessity for an open-ended system, demand new techniques in the area of compilers. This suggests the need for an Abstract Programming System which will permit programs to be written in source programming languages to perform desired programming functions. Such programs would be machine independent and rely on the Integrated Operating System to effect a particular machine realization. In this way, the actual satellite programs could be thoroughly checked out in a ground-based machine realization and then directly transferred to the appropriate satellite processor.

The initial characteristics of the Abstract Programming System are being investigated by IBM as an extension to their Evolutionary System for Data Processing (ESDP). The coordinate structures generated within the ESDP system for documentation of programming systems can potentially be used as the basis for converting the source language of the Abstract Programming System into multiple machine realizations through the Integrated Operating System.

In the area of program checkout, new techniques will also be required to cope with the evolutionary nature of the program development both before and after launch. Thus, techniques for checkout of program increments in simulated operational environments must be available, as must extensive system simulation techniques. The system can then be responsive to changing requirements without any loss of integrity.

The ESDP system should play a major role in this area. First, its documentation capabilities are prerequisite to the modification of a system of this size and complexity. Resources available from existing programs will be identifiable as will the ramifications and extents of proposed changes. Without automatic and comprehensive program documentation capabilities, system evolution and response would be constrained.

The ESDP structures will play another role during incremental program checkout since they identify the interaction of program elements. This can be used in simulating the system environment for new program elements without demanding full system operation.

Conclusion

IBM recognizes the challenging technical problems in the programming of the multifunctional space satellite and the needs for new techniques in at least three major areas. Current work in the ESDP system, satellite navigation and guidance systems, diagnostic and adaptive control systems offer promising approaches to the overall programming considerations.

This past work will give a basic foundation for the study and should provide immediate solutions in certain areas. The extension of the developed ideas should provide a cohesive design for a revolutionary programming system that meets the demands of the multifunctional space satellite's mission.

1.5 Summary

To summarize, the configuration shown in Figure 1-2 is reliable, modular, and adaptive. The system by its very nature performs all of its processing in parallel, and each processor is self-sufficient and can operate independently of all the others. If necessary, each processor can perform certain tasks for a processor that has failed. Load sharing is inherent in the system since each special-purpose processor is assigned a particular class of tasks. The reliability of the system is very high due to the on-board diagnostic and fault-finding capability, and also the fault isolation and corrective procedures that are possible using software. Additional reliability is obtained by designing the system such that the central control computer can, in case of failure, execute certain functions normally performed by one of the special-purpose processors. The modular characteristics of the system provide the ability to accommodate a wide variety of diverse missions. In fact, it is entirely possible to re-program the satellite while in orbit to carry out a different mission.

Section 2

ADAPTIVE SATELLITE SUBSYSTEM CONCEPTS

This section discusses adaptive satellite subsystem concepts and clearly shows the part played by the special purpose processor (SPP) in each subsystem. Each subsystem is then discussed in depth and is backed-up by detailed block diagrams which identify the key functions within each subsystem. It will become clear that some of the subsystem functions can be combined with a low capacity SPP and the entire subsystem can then be under control of a central control computer (CCC).

The level of detail presented in this section is essential for developing new multiprocessing concepts.

A multi-functional satellite system consists of subsystems that are common to all missions. These are, Data Handling (adaptive sampling, multiplexing, channel selection, etc.); Communications and Telemetry; Navigation, Guidance, Control and Stabilization, Check-out, Energy Management and the Central Ground-Control Facility. The Sensor Subsystem is mission oriented although even here, a classification into pictures (very high source rate), and scientific sensors (relatively low source rate) is quite reasonable.

Pictures represent an extremely high information rate which generally swamps the information handling capacity of a processor.

It will be demonstrated that the functions of the non-mission oriented subsystems can be mathematically formulated with sufficient accuracy to permit the development of useful multi-processing concepts and configurations without constraining the techniques to a particular mission. Once the concepts have been developed, a representative mission will be selected to determine the efficiency of the multi-processing configuration. This will test the fundamental hypothesis that the problem stated in the RFP is well defined and amenable to multiprocessing concepts, and give further insight into the problem—possibly leading to an optimum approach.

2.1 Data Handling

This section develops information preserving (IP) compression and entropy reducing (ER) techniques. The latter involve on-board pre-processing and represents the largest potential pay-off. ER operations will reduce the communication and telemetry channel requirements and, equally important, substantially reduce the vast amount of raw data received on the ground. The key study here will be to develop techniques for deriving optimum multiplexing rules which depend on priorities, the communication channel throughput, and estimates of the sensor parameters.

2.1.1 Predictive Compression Techniques (1)

2.1.1.1 Non-Adaptive Compression

A predictive compressor removes the redundancy in a message by exploiting the probability constraints within a message ensemble. The output sequence, encoded into fewer bits than the input, is completely random, i.e., all the redundancy has been removed. At the receiver, the rule for reconstructing the message is known, and hence, the message can be decoded. In practice, it is essential to insert a controlled amount of redundancy in the form of error control in order to protect the message against channel errors which otherwise would cause catastrophic degradation.

Figure 2-1 shows a predictive compression which is useful when strong correlations between adjacent L-bit sequences exists. Here the present and previous L-bit sequences are compared in a modulo-2 adder and the resultant sequence is fed into a run-length encoder. If there are many bits in agreement, long strings of zeros will be generated which can be compressed by means of run-length coding. At the receiver, an exact inverse exists for reconstructing the message sequence.

Figure 2-2 uses Shannon-Fano coding to achieve compression. Here the sequences are subdivided into two groups each having equal probability. If the observed sequence falls into group one, the binary number one is generated; if in group two, binary zero is generated. If the decision is, say, $d_1 = 0$, then the second group of sequences is subdivided into two groups of equal probability and the procedure is repeated. If the decision is $d_2 = 1$, the binary number one is generated. This procedure is repeated until the sequence is finally classified. The coding for this case is, therefore, 01------.

The code length in Shannon-Fano coding is variable but unique in that "flags" for word identification are unnecessary. Here the high probability sequences are assigned short codes and the low probability

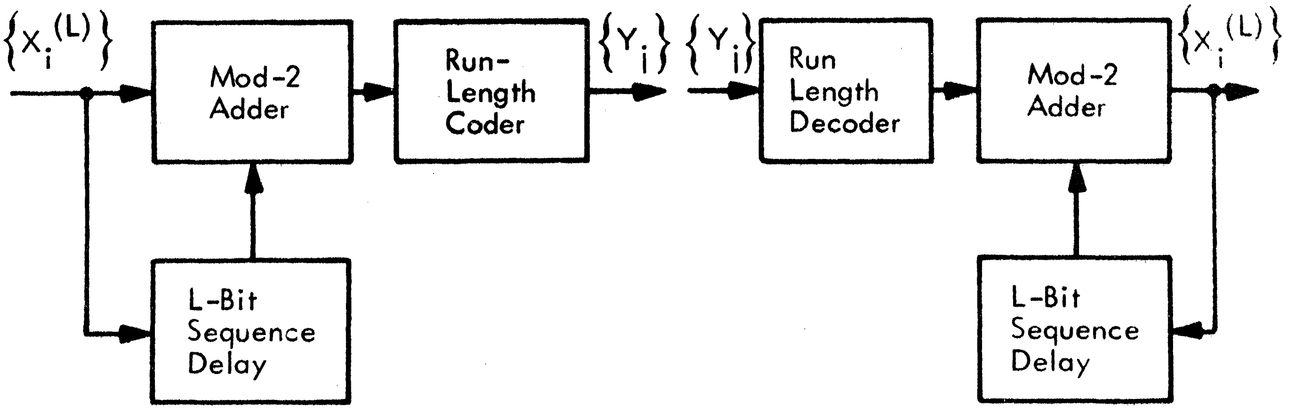

Figure 2-1 *Previous Sequence Compressor*

Previous Sequence Expander

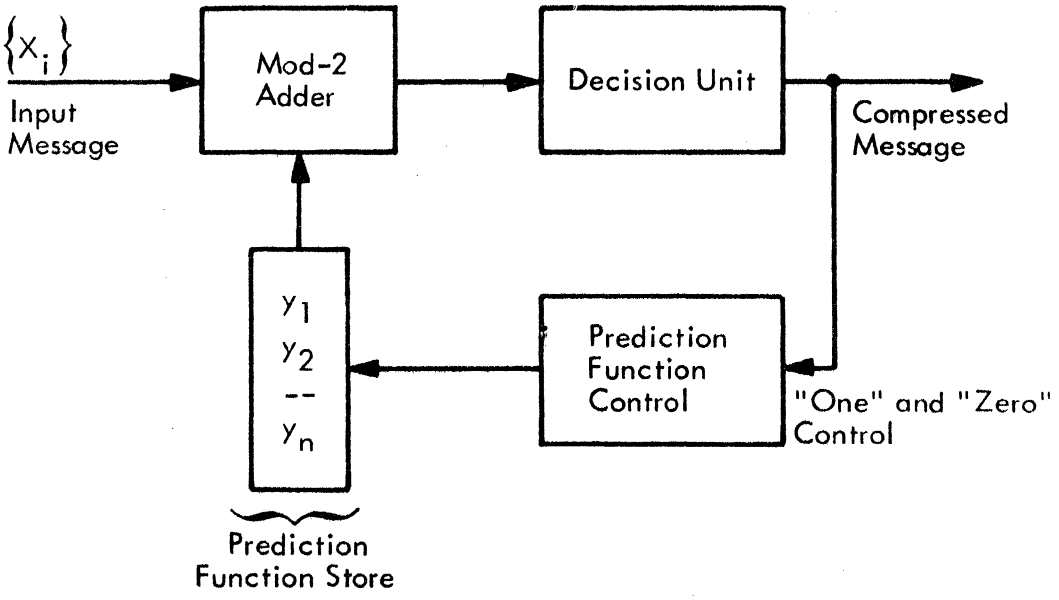

Figure 2-2 *Shannon-Fano Compressor*

sequence use long codes such that the average code length is

$$H = -\sum_{i} p_i \log p_i$$

where p_i are the message sequence probabilities.

A major difficulty with techniques of this type is that the higher-order message statistics must be known in order to achieve efficient compression. This information is generally not known and is very expensive to collect requiring a large amount of data and a large number of measurements.

2.1.1.2 Adaptive Compression

Adaptive compression is a compromise between exact coding where the message statistics are known and straight transmission. Here the message statistics are measured and used to encode the subsequent message interval. While this procedure is in progress, the efficiency of the coding presently in use is monitored and in addition new statistics are measured. If the compression efficiency falls below a given level, the newly measured statistics are used, i.e., the coding is up-dated. The adaptive procedure is effective provided the message statistics change slowly with time. As long as the rule for adapting is known at the receiver the message can be reconstructed.

Figure 2-3 is a block diagram of an adaptive compressor. The probability distribution analyzer measures the statistics (λ_i) during some prescribed time interval. After measurement we call these (p_i). A

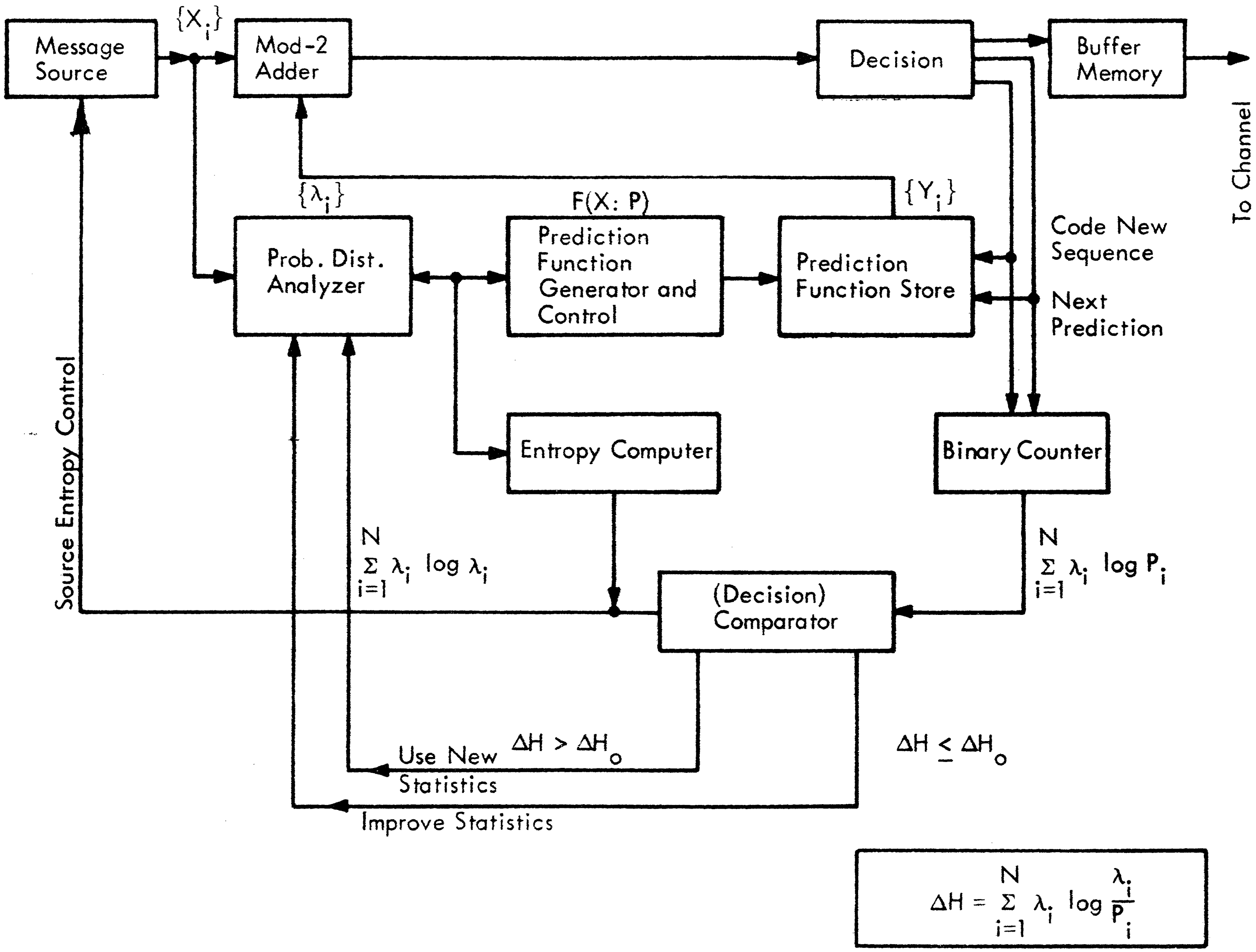

Figure 2-3 *Functional Block Diagram of Adaptive Coder for Quasistationary Message*

Shannon-Fano prediction function (described previously) is generated and stored. The next message interval is encoded in accordance with the stored prediction function and the coding efficiency is monitored.

If the (p_i) are used and (λ_i) are the newly measured statistics, then the average code length is,

$$H_p = -\sum_{i=1}^{N} \lambda_i \log p_i$$

On the other hand if the (λ_i) were used to encode the message, then the average code length would be

$$H_\lambda = -\sum_{i=1}^{N} \lambda_i \log \lambda_i$$

The figure of merit which is used to determine the coding effectiveness is

$$\Delta H = \sum_{i=1}^{N} \lambda_i \log \frac{\lambda_i}{p_i} \leq \Delta H_o$$

where $\Delta H \geq 0$. The function ΔH gives the excess number of bits which are transmitted when (p) is used and (λ_i) are the true statistics. If $\Delta H \leq \Delta H_o$, the coding continues with p and the statistics are improved; if $\Delta H > \Delta H_o$, the (λ_i) statistics are used to generate a new prediction function.

In all compression techniques, buffering is required since the input bit rate is variable while the output is uniform. To prevent buffer overflow and hence catastrophic degradation, it is preferable to degrade the message fidelity gracefully and in a controlled manner. This can generally be accomplished by reducing the number of message bits per sample.

The practical usefulness of the adaptive technique in Figure 2-3 (developed by IBM) will be tested on real or simulated data in order to make a constructive evaluation.

2.1.1.3 Adaptive Coding Penalty

Erroneous statistics used for coding can lead to message expansion, i.e., the encoded message contains more bits than the original message. This is shown for a binary message in Figure 2-4. When $\lambda = .5$, the most efficient coding transmits the message directly. However, if the message is encoded in accordance with $p = 0.1$, there is a 50% excess in the number of bits which can be translated into a 50% increase in channel bandwidth. This simple example shows the transmission rate penalty for coding in accordance with statistics which do not represent those of the source.

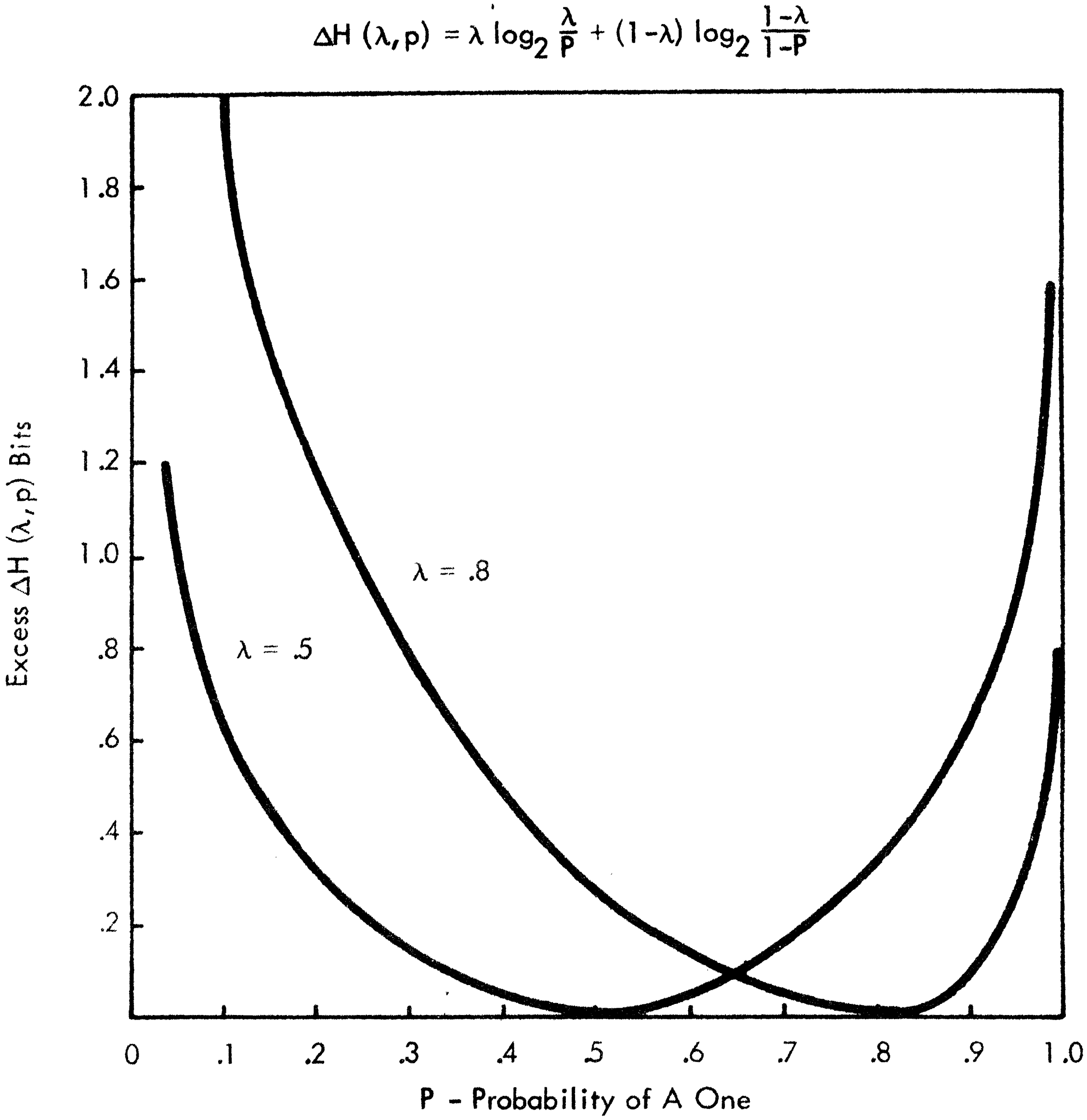

Figure 2-4 *Excess Bits When Code is Derived from Probabilities P and the True Probabilities Are* λ

It should be clear from this section that an SPP can, and probably should, be used if predictive compression techniques are to be considered. Generally, these techniques require large memories since efficient predictive compression requires knowledge of past message statistics. IBM's study of data compression has led to the conclusion that most effective compression techniques reduce source entropy. In short, entropy-reducing transformations extract the useful information from the message prior to the satellite transmission to earth. Here the sensor signal output cannot be reconstructed exactly from the measured results.

2.1.2 Adaptive Multiplexing and On-Board Signal Processing

Adaptive multiplexing is an entropy-reducing transformation which monitors the sensor outputs and the telemetry channel throughput, and then, based on priorities, defines a multiplexing and sampling rule for transmission.

In addition, on-board signal processing extracts the useful sensor parameters and transmits them down to earth. This will not only reduce the data rate but also the load on Earth-based signal-processing systems which cannot handle the present volume of data collected in space. This latter problem is serious now, and is sure to become much more serious unless entropy-reducing transformations are used in the vehicle.

2.1.2.1 Operational Diagrams of Over-All Adaptive Telemetry Subsystem

Figure 2-5 is a block diagram of the over-all adaptive telemetry system. At the transmitter there are three subsystems; multiplexer, processor and pseudo-noise (PN) modem. (The latter will be discussed in Section 2.2.1.)

The processor monitors the sensor parameter set θ, the channel throughput H and, based on the priority matrix P, computes the sampling and multiplexing rule (or program) D (θ , H, P). The function D generates the sensor-scan pattern which controls the time-division multiplexer. The output of the multiplexer is fed into an encoder which supplies redundancy to combat channel errors. The multiplexing program D is also transmitted to the Earth station which performs the inverse operation.

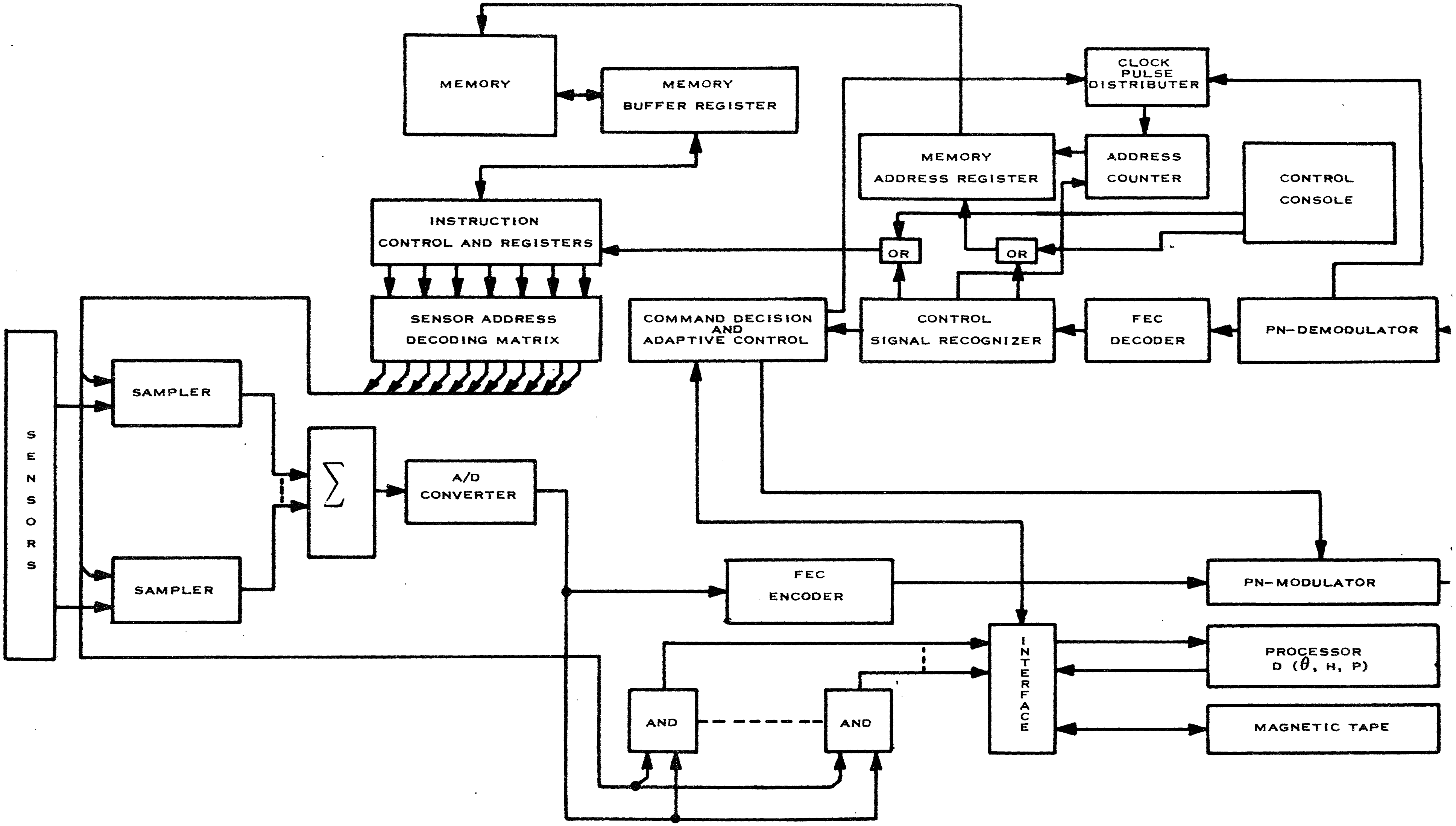

Figure 2-5 Functional Telemetry Block Diagram for the Adaptive Multiplexer

2.1.2.2 Adaptive Multiplexer(4)

Figure 2-6 is a detailed block diagram of the adaptive multiplexer. The sensor array feeds a conventional time-division multiplexer which is under program control. The processor monitors the sensor outputs θ, the channel throughput H and, for specified priority matrix P, computes the sensor scanning program D (θ, H, P). This program is fed into a memory which is driven by a clock derived from the PN modem. The PN modem clock rate is consistent with the channel throughput H.

The multiplexed message is fed into an A-D converter and into the forward-error-control unit F.E.C. This message is then fed into the PN modem and transmitted down.

Command information is received in the vehicle by means of the PN demodulator. This information may contain the multiplexing rule D (θ, H, P) which is stored. Thus, the ground station can generate the multiplexing program or it can be generated by the on-board processor.

2.1.2.3 Adaptive Demultiplexing(4)

Figure 2-7 is a block diagram of the adaptive demultiplexer. The PN demodulator at the ground stations recovers the message bits which are corrected for errors in the F.E.C. decoder. The processor generates the demultiplexing rule D (θ, H, P) and controls the demultiplexer operation. The information transmitted up to the vehicle is control information which may include the multiplexing program D.

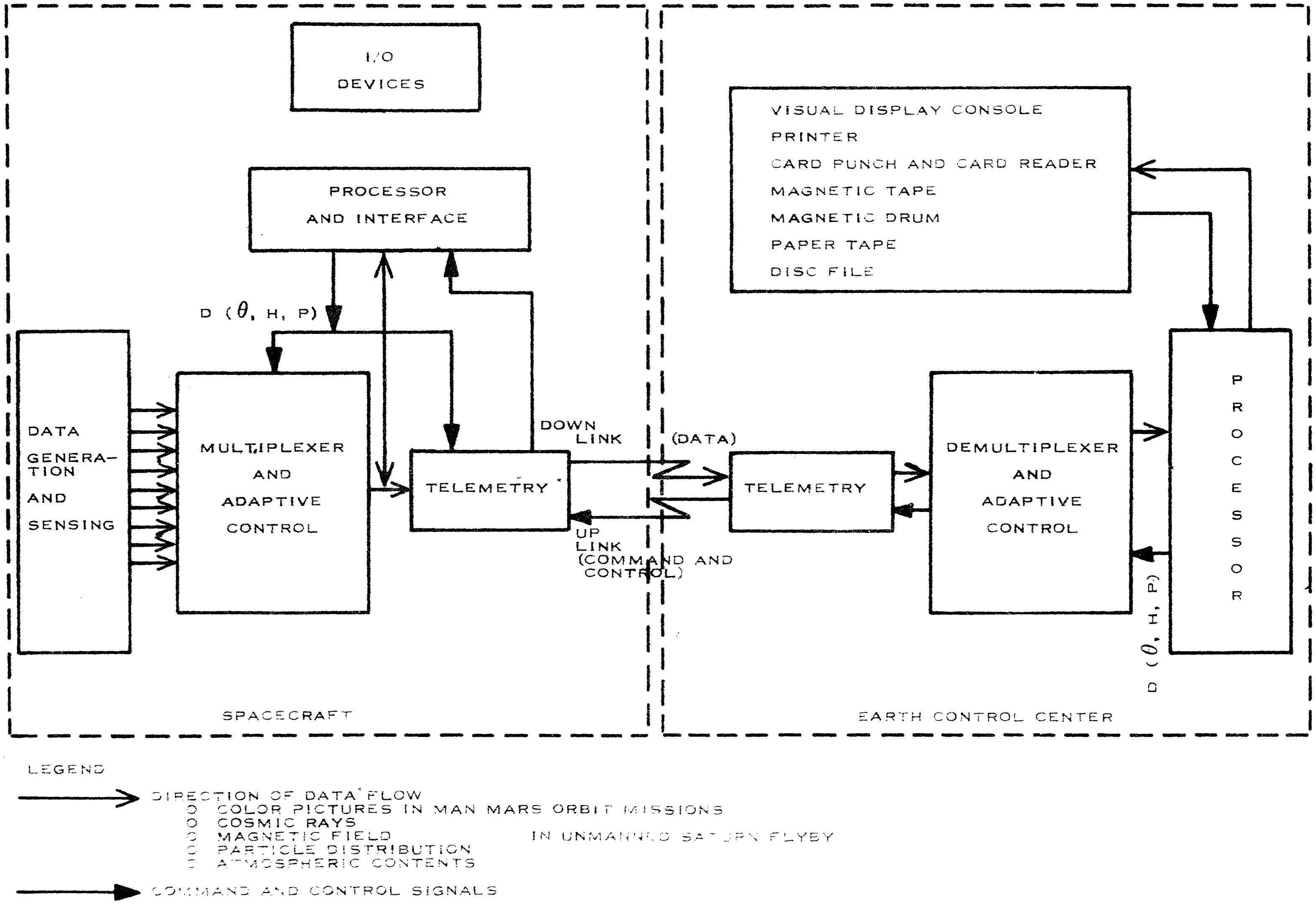

Figure 2-6 Functional Block Diagram for the Spacecraft and Earth Control Center

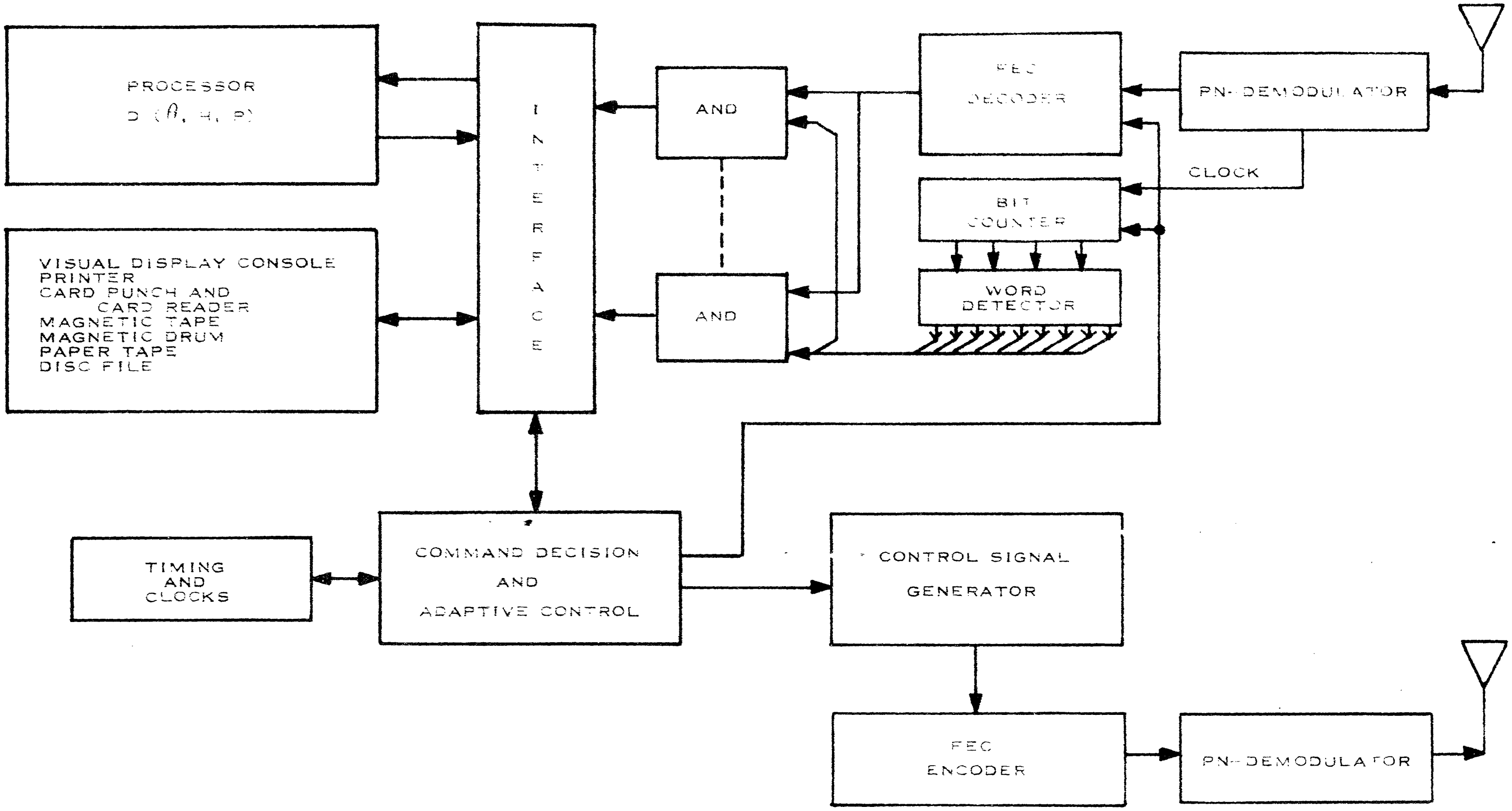

Figure 2-7 Functional Telemetry Block Diagram for the Adaptive Demultiplexer

Note that the program D $[\theta, H, P]$ depends on the measured sensor parameter point θ and on the estimated channel throughput H; the priority matrix P can, of course, also be changed. Based on measurement a decision d is made which selects the program, say, D_i. The set of programs $D = \{D_i\}$ can be pre-stored, transmitted to the vehicle from the ground control center, and most interesting of all, derived by means of a mathematical algorithm. That is, the project team will study concepts of "adaptive programming" where programs are derived by the processor from measured data which optimizes the overall subsystem system operation. Once again, meaningful results should be obtained since it is clearly evident from this section that the concept of adaptive sampling and multiplexing is well understood and that the operations can be clearly identified.

The role played by a processor in this subsystem is again clearly identified to pinpoint the useful multi-processing concepts for the overall system.

2.2 Communications and Telemetry

The communications and telemetry subsystems of the multi-functional satellite of the future will surely be under the control of a processor. It has been shown how the processor can control multiplexing and that the channel throughput H must be monitored at all times. In addition, the satellite of the future will surely have a phased-array antenna on-board the vehicle with beam-forming under control of a processor. This processor function is a real life fact in Earth based systems such as RADAR and SONAR. A multi-beam steerable array antenna abroad the vehicle can direct the RF power to any point on earth with a high degree of directivity and a large amount of effective radiated power (ERP), thereby reducing interference with ground communication systems. This antenna can also be used to illuminate several Earth stations simultaneously permitting the ground stations to share the processing load. Furthermore, highly directive phased array antennas necessarily contain many radiating elements and hence an inherent redundancy. Failure of radiating elements will certainly degrade the performance and hence the information throughput. The processor monitoring the array can detect the elements which have failed and can reconfigure the phasing of the remaining elements so as to optimize the performance. This is one of the most important functions performed by a processor and again a function which can be formulated and defined mathematically.

Dr. D'Antonio, the proposed Project Engineer, has a significant amount of experience in the area of "digital beam forming" applied to SONAR. His background is certain to be of value on this task.

JPL has used pseudo-noise (PN) modulation successfully for interplanetary telemetry. This form of modulation, because of efficient power utilization and its inherent ability to reject all forms of interference effectively is very likely to be used in multi-functional satellite systems. The next section shows how the mod-demod subsystem can be controlled by a processor in an adaptive communication system.

Since many satellites are likely to be in orbit and since it is desirable to control them so as to optimize the missions, the communications problem from satellite to earth can be extremely severe. It is essential to understand the overall communications problem particularly since the ground control facility is certain to play a significant role in optimizing the space system configuration. One or more complex control stations can have the satellites in view for long periods of time if one or more synchronous communication satellites are used to repeat the transmitted messages down to earth and of course the control signals from the ground will also be sent via communication satellite. In satellite communications, this type of problem is called "the multiple-access problem" (i.e., many stations have access to a common repeater satellite). Pseudo-noise modulation techniques have been found very useful for this type of link because of the inherent ability of these signals to withstand severe amplitude distortion and all kinds of interference. The IBM group assigned to this program has made significant contributions to the field in PN modulation applied to multiple access satellite communications.

As stated, the ground control center monitoring the performance of a multitude of satellites in orbit can be used to optimize the overall data collection system. It can also be used to optimize the utility of the existing communication system by controlling the communications load transferred through the limited capacity communication satellite link. As an example, the ground processor being aware of the computing load of the satellites in orbit can select the appropriate satellites at the appropriate time for unloading the processed data. Note that the available capacity limits the amount of data which can be transmitted down and that this constraint has a necessary bearing on the multi-processor configurations in orbit.

A reduction in link capacity necessarily requires a corresponding increase in the on-board computing power and hence a corresponding increase in payload and decrease in reliability. IBM proposes to find the trade-off between payload and the consequence of large payload and the communications capacity of the overall system. The engineers assigned to this program are knowledgeable in the two important areas, communications satellite systems and multiprocessing. They are uniquely qualified to perform this trade-off study.

A large processing capability in orbit implies that only the essential data will be transmitted to Earth, as a result, this data must be received reliably. Efficient coding against channel disturbances is the insertion of a controlled amount of redundancy into a message to combat errors introduced by the medium. Adaptive coding matches the code to the type of channel disturbances thereby optimizing performance. The coding and decoding operations can certainly be performed by a processor and once again this is a well defined problem mathematically.

Finally, it should be evident that multi-processing concepts can be applied to the communications and telemetry subsystem and meaningful results can be expected since this entire problem can be formulated mathematically.

2.2.1 PN Modulation

Satellite telemetry requires efficient utilization of the on-board power. Every db saved by using an efficient modulation scheme is a db saved in the on-board power.

An efficient modulation scheme for digital telemetry requires accurate synchronization. In a Gaussian-noise channel, the most efficient means of establishing synchronization is to use the information.

contained in the modulated signal. That is, it is essential to put all the power in the message and synchronization signal side-bands; power splitting between message and sync is inefficient.

The required RF synchronization information can be extracted from a double-side-band suppressed-carrier signal. However, in such a modulation scheme, bit, word, frame, etc. synchronization must be derived from the data transitions, and special code words within the message format. When the data transitions are used, the timing jitter necessarily depends on the time distribution of the transitions, which may be a problem, particularly at slow data rates. A more efficient way of acquiring and maintaining synchronization is to combine, modulo-2, the digital message with a maximal length sequence from which all timing can be derived accurately. Here the power is put into the message and sync signal side-bands as required. This optimization is achieved at the expense of RF bandwidth. At first this may appear as a severe penalty; however, careful study will show that by using spectrum spreading the power density (watts/cps) received on the ground can be maintained at a sufficiently low level so as not to interfere with existing earth based requirements. If B is the RF bandwidth of the PN signal and B_o the bandwidth of a conventional telemetry signal then the interference caused by the PN signal in the band B_o is simply $\frac{B}{B_o}$. If $B = 50 \times 10^6$ cps and $B_o = 50 \times 10^3$ cps, then for the same received power, the spread-spectrum signal is 30 db below the narrow-band signal in the band B_o. Equally important, the narrow-band signal is suppressed 30 db in the PN-receiver. The wide-band telemetry system which we will now describe makes optimum use of on-board power and at the same time minimizes the interference with conventional equipments. It is suggested that future space telemetry systems be designed with this in mind. A bound should be set on the power density received on the ground since this is the only important measure of interference. This will limit the number of users of a common frequency band. Frequency allocation makes inefficient use of the over-all spectrum since, once allocated, the band is no longer available even when the channel is inactive. Clearly, this is a wasteful way of using the available spectrum particularly for space telemetry.

Finally, since PN signal rejects other interfering signals it is possible for several such signals to share a common broad band. This type of multiplexing is called "Code-Division Multiplexing" (CDM). If the RF bandwidth is approximately four times the ratio of received signal power to noise power density, the CDM performance is for all practical purposes thermal-noise limited and not mutual-interference limited, and hence the over-all behavior is essentially equivalent to, say, time-division multiplexing (TDM).

2.2.1.2 PN Modulator

Figure 2-8 is a block diagram of the PN modulator. Note that the

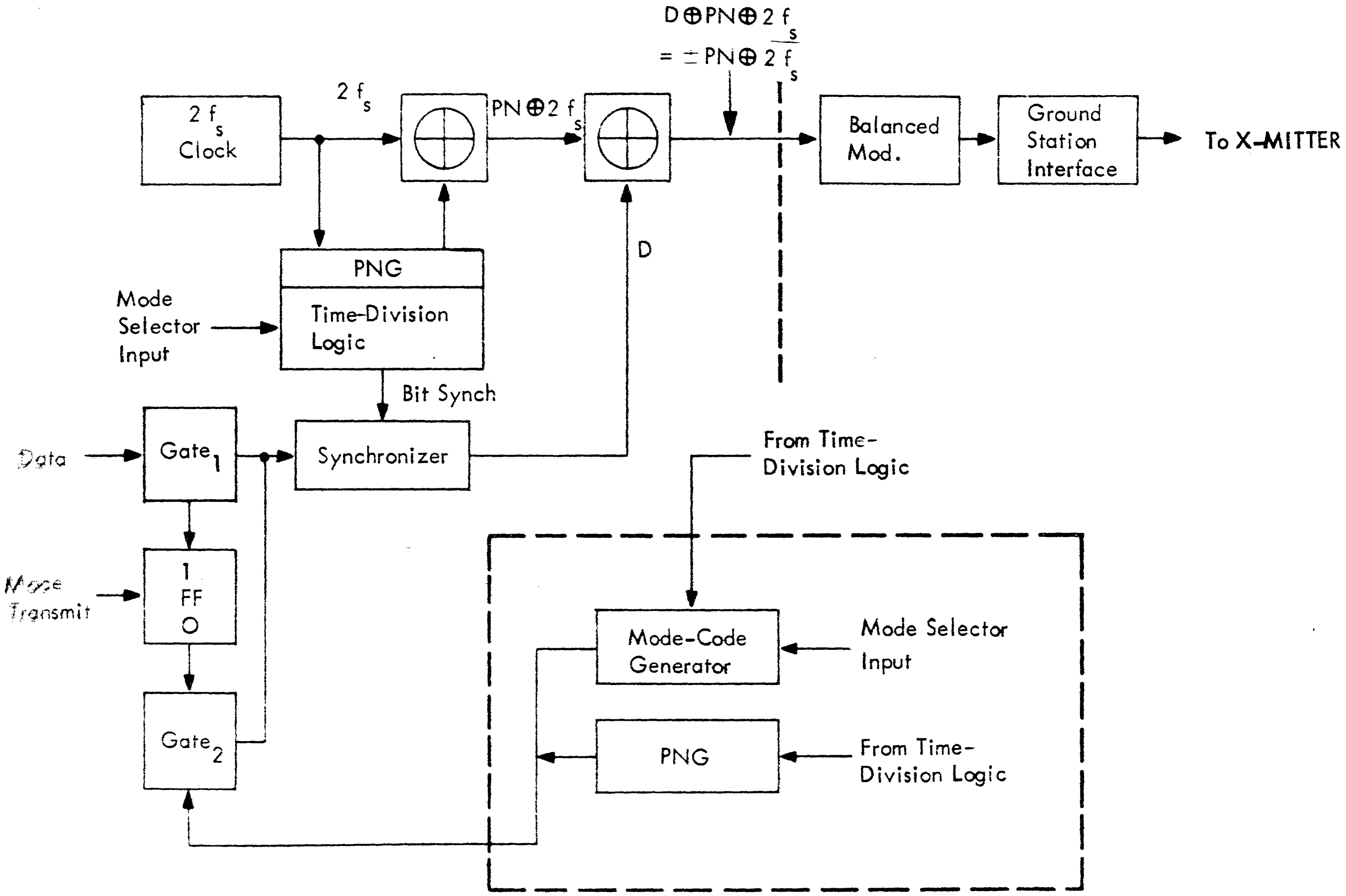

Figure 2-8. *Transmitter Modulation and Sending End Logic*

clock $2\ f_s$ is combined with PN and data as shown which, in turn, bi-phase modulates the RF carrier. In this manner, data and timing are combined such that full power is placed in message and sync side-bands.

2.2.1.3 Adaptive PN-Demodulator

Figure 2-9 . shows the PN (baseband) demodulator. Here it is assumed that the RF carrier was extracted and used to demodulate PN coherently. The acquisition and tracking characteristics are shown in Figure 2-10 . Note that these characteristics are precise, i.e., the timing accuracy is maintained well within a PN bit. The VCO is swept until PN and PN^* are in-phase. When this instant is detected, the search sweep is stopped and the loop locks up since it is within the pull-in range. All timing is now available. The message data can now be recovered.

The purpose of having two arms in the baseband loop is to remove the data modulation from the clock. Without this operation lock-up cannot be achieved. The channel throughput monitor selects the filter which matches the bandwidth of the existing data rate.

Figure 2-11 shows the RF carrier extraction and tracking circuit. When the PN reference is in phase with the incoming PN-signal, the resulting bandwidth is equal to the message band. The IF filters are therefore matched to the data rate prior to the squaring operation which extracts twice the carrier frequency. This frequency has a $(0,\pi)$ uncertainty which is removed by sending a test signal of known phase. The recovered

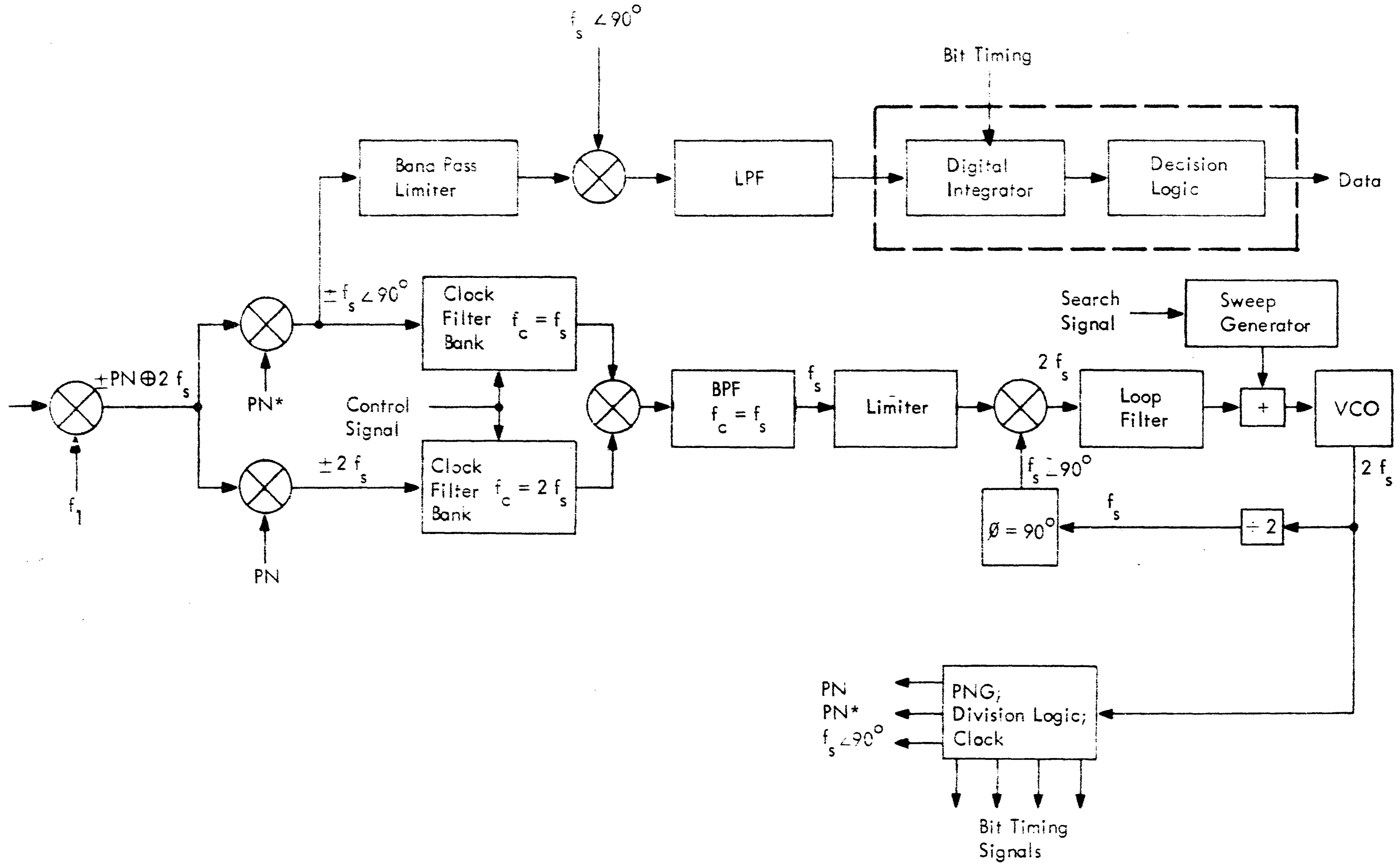

Figure 2-9. *Synchronization and Data-Extraction Subsystem*

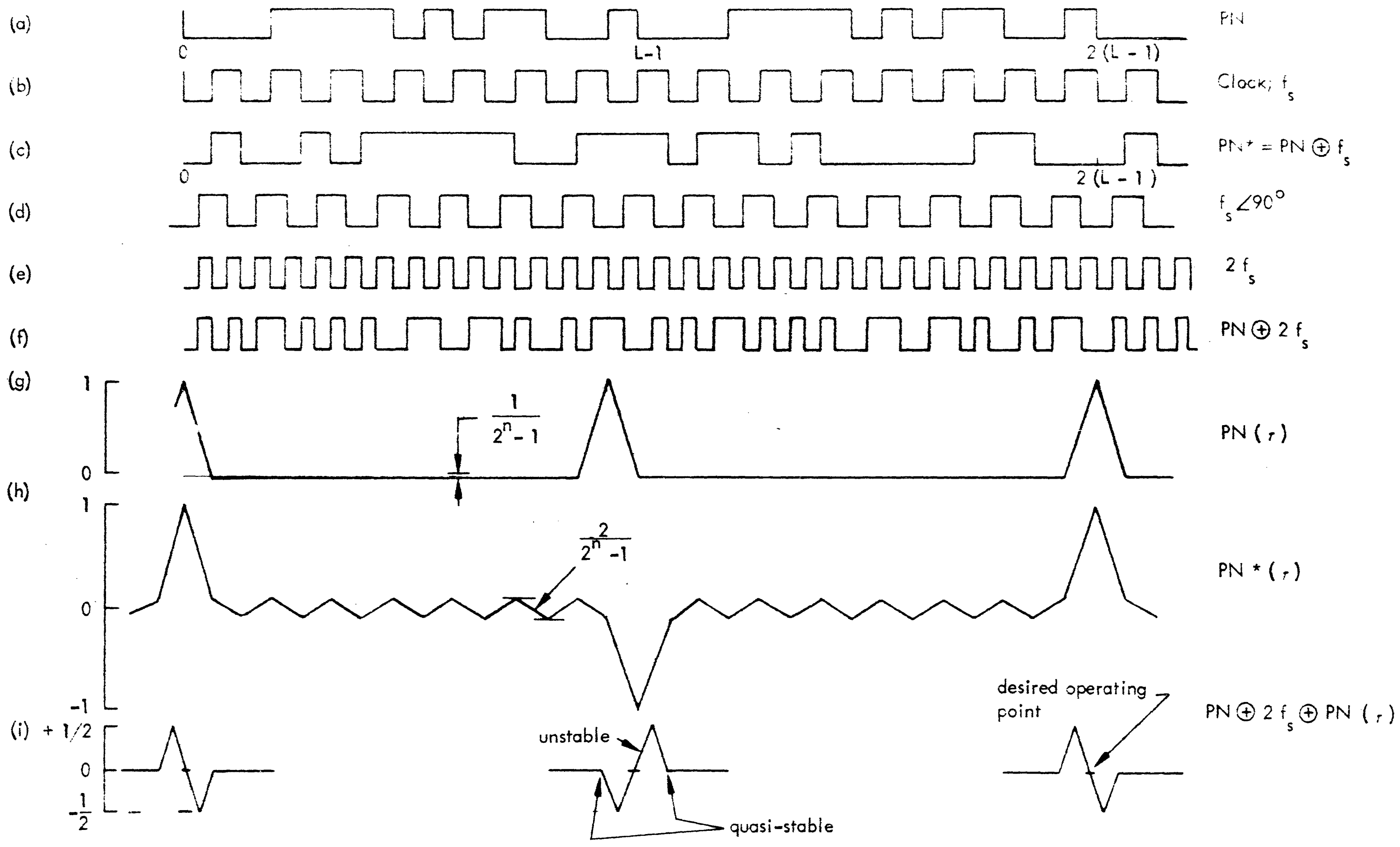

Figure 2-10. *PN Synchronizing Signals*

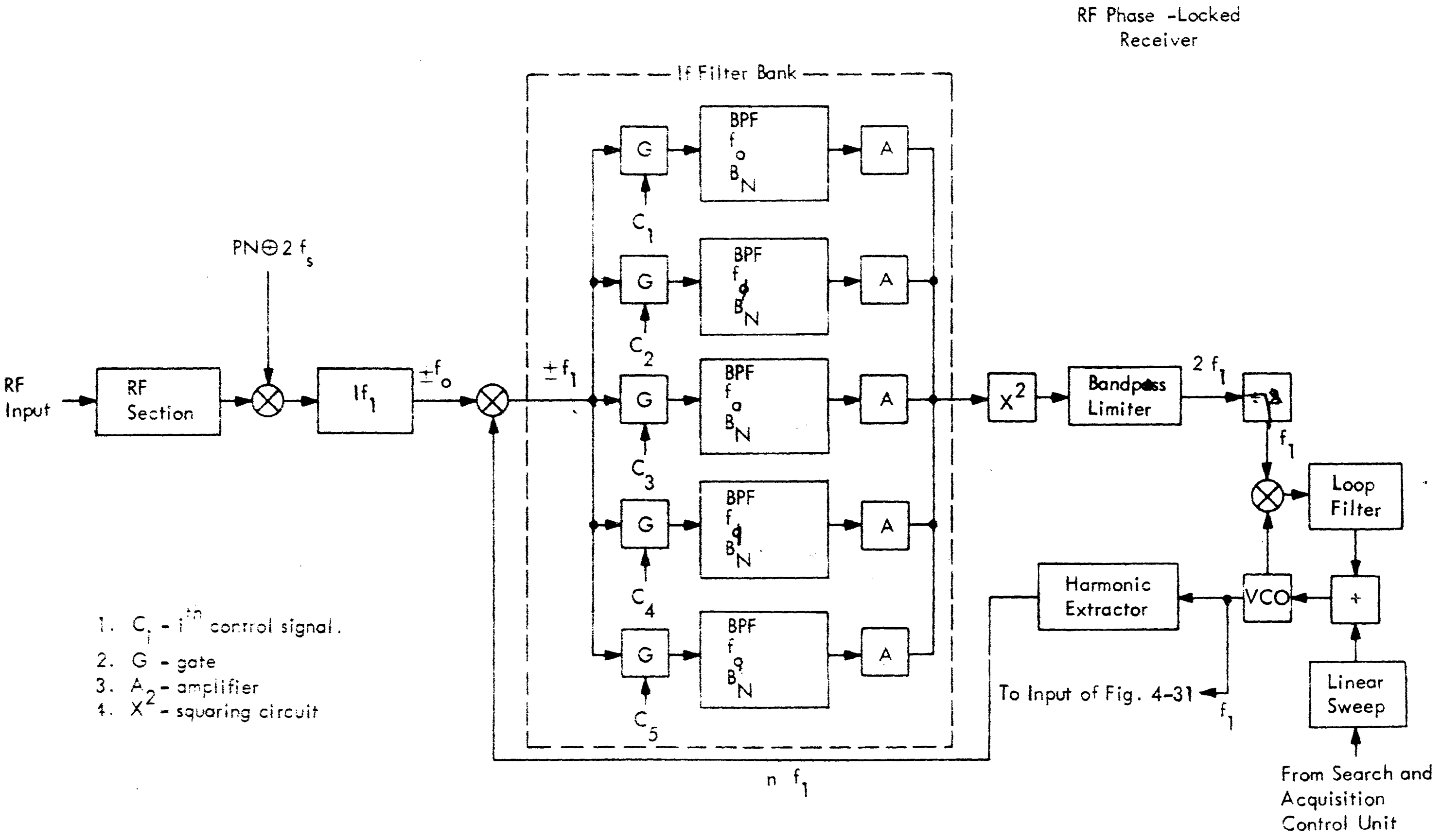

Figure 2-11. RF Phase-Locked Receiver

carrier is injected coherently into the received signal which in turn yields the base-band PN signal as shown in the figure.

Figure 2-12 shows the performance of several digital modulation schemes, two of which are experimental and the others theoretical. The optimum modem discussed here has a performance shown by curve number one which falls with 1/2 db of theoretical curve number three.

2.2.1.4 M-ary Alphabets

An M-ary alphabet assigns a signal waveform to each message sequence. The signals used are generally orthogonal or bi-orthogonal, since these yield optimum or near optimum performance for large values of M. With an alphabet of size M, we can send $\log_2 M$ message bits with orthogonal codes and $\log_2 2M$ bits with bi-orthogonal codes. The bandwidth required for orthogonal codes is

$$B = \frac{M}{T \log_2 M}$$

where T is the duration of a message bit. In the case of bi-orthogonal codes the message band is halved for the same data rate; however, a small increase in signal-to-noise energy per bit is required.

If M = 1024, we can achieve a 4-db improvement over bi-phase modulation curve 8. For a megabit/second message rate, an RF band of approximately 100 megacycles is required for orthogonal codes and 50 megacycles for bi-orthogonal codes. This is within the realm of

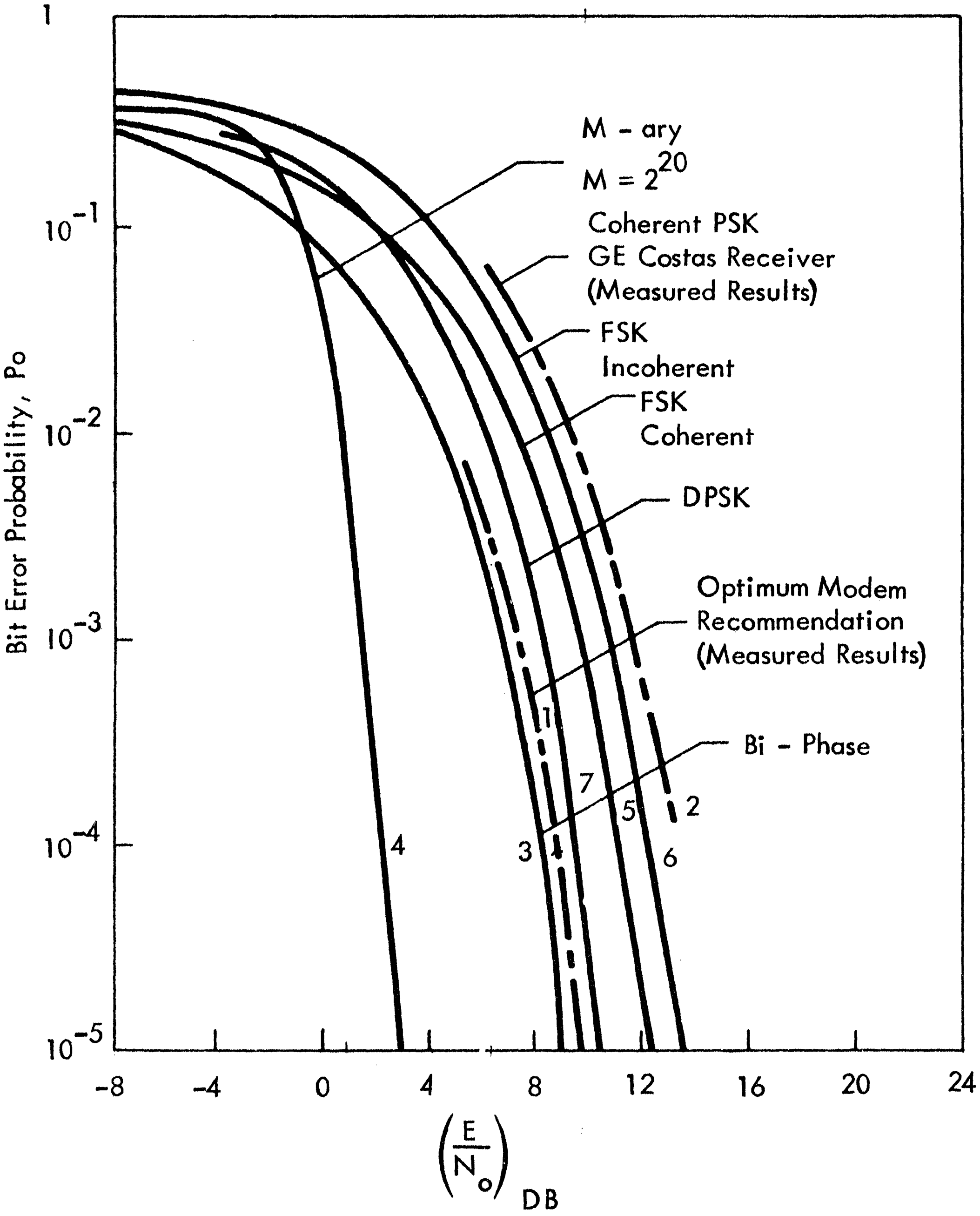

Figure 2-12. *Comparison of Various Techniques (Theoretical and Experimental Results)*

practicality; however, the synchronization problem is severe and the ground receiver is complex requiring 1024 active correlations. If $M = 2^{20}$, a 6-db improvement can be achieved over bi-phase modulation as shown in curve number four. However, the RF bandwidth is at least 50 giga-cycles which is entirely impractical.

Finally, although we have discussed binary orthogonal codes, one can also use orthogonal sinusoids. The codes, however, have superior synchronization properties since the auto-correlation function is generally quite sharp if M is large.

2.2.2 Efficient Coding Against Channel Disturbances

The inherent redundancy in a message prevents catastrophic degradation caused by channel errors. The message becomes more vulnerable to severe degradation caused by errors if more redundancy is removed, say by compression. The channel errors can be controlled, and hence, the fidelity, by inserting a controlled amount of redundancy in the form coding. It is desirable either to adapt the codes so as to match the channel characteristics or to use codes that are efficient against a number of disturbances.

Coding requires a digital data transmission system. In addition, in order to code and decode economically, the data should be multiplexed into a single bit-stream prior to modulation. In the latter case, only a single encoder-decoder combination is required. Thus, the coding requirement eliminates the use of analog modulation techniques and asynchronous multiplexing on economical grounds.

2.2.2.1 Principles of Error Control Subsystem

A digital data transmission link in a data processing system typically is more prone to error than other data handling media. Accordingly, all such links in IBM systems are protected by error-control subsystems.

Dr. D'Antonio of the proposed IBM team has been active in the design of these subsystems for several years.

Usually three basic classes of error-control techniques are employed:

a. Error detection and retransmission or throw-away of erroneous messages.

b. Forward error correction, where erroneous messages are corrected without retransmission.

c. A hybrid system, where retransmission is used to ensure a low-error rate and forward error correction is used to maintain a high net data rate.

In this subsection the relative merits of these techniques and their application to the satellite communications problem will be discussed.

Error detection and retransmission is the most common type of error control system for digital data transmission. It is used when all the following circumstances occur:

a. A high degree of reliability is required in the data after correction (e.g., a very low error rate like 10^{-9} or 10^{-10} is sometimes specified).

b. The raw error rate before correction is reasonably low (say 10^{-4} or 10^{-5}).

c. A return link is available for sending OK or request for retransmission (RQ) messages.

Forward error correction requires the use of more complex equipment than error detection and retransmission. Furthermore, it cannot assure post-correction data which is essentially error-free. Indeed, and improvement in error rate of two decimal orders of magnitude (say from 10^{-2} to 10^{-4}) is about the limit achieved on real links.

However, forward error correction can be used in two cases where error detection and retransmission fails:

a. When the raw uncorrected error rate is relatively high (say 10^{-1} or 10^{-2}), the net data throughput with error detection and retransmission is substantially lower than with forward error correction.

b. When, for security and other reasons, a return link is not available, only forward error correction and/or error detection and discard can be used.

Finally, a hybrid of error detection and retransmission coupled with forward error correction is used when the raw error rate is high and, at the same time, a very low corrected error rate is required. In the past, this hybrid has been employed very rarely.

Within each of the three basic types of error control systems, there are three types of coding that may be employed:

a. Recurrent or sequential codes where checking bits are often interlaced among data bits and no blocking format is used.

b. Cyclic group codes where check digits are inserted at the end of each data block.

c. Simple character and block codes such as character parity-checking, fixed-weight codes, and longitudinal redundancy codes.

In the third class, the codes are basically the classic methods employed many years before the advent of today's more sophisticated coding concepts. The new generation of equipment (including data terminals in IBM System/360) employs cyclic codes. The technical superiority of these codes for an error-detection and retransmission system has been established beyond doubt by tests of IBM and others. For those few installed systems employing forward error correction, the relative merits of recurrent, sequential, and cyclic block codes are still being weighed, and a clear-cut general evaluation does not exist. The evaluation must be sought on a system-by-system basis. It has been IBM's experience that the cyclic code is most suitable for the majority of systems. Indeed, for the single or double error correction, the Bose-Chaudhuri cyclic-block-codes seem ideal. These codes, as a by-product, also provide a degree of burst-error security.

2.2.3 Error Control Techniques

Advanced space systems will probably require advanced concepts such as adaptive error control. This subsection considers the problems encountered in implementing three basic adaptive error control techniques:

1. Variable block length, fixed redundancy,
2. Fixed block length, variable redundancy, and
3. Variable use of fixed redundancy with a fixed block length.

These systems will be discussed with respect to feasibility of encoding, decoding, and maintaining synchronization. For the first two systems, it will be assumed that the control logic needed to maintain both encoder and decoder in the same mode is provided in the spacecraft control subsystem.

Variable Block Length, Fixed Redundancy

Designing a variable-block-length encoder and decoder by modifying a system designed to handle the largest desired block length is relatively simple. In a standard encoder, the redundancy is calculated over a number of information bits determined by sensing a value in a counter. To decrease this number it is sufficient to incorporate controls so that the encoder will sense a specified smaller number in the counter when a mode change is made and return to sensing the original value when the mode is changed back again. Any combination of bit rate, block size, and coding structure constitutes a "mode" of operation. The problem in the decoder is only slightly more complex. Again, it is necessary to change the value sensed in a counter to indicate the length of the block and thereby also indicate when the check word or syndrome has been constructed. In all systems, except for a few error-detection-only systems, it is also necessary to store the information bits in the decoder until the checkword has been constructed and then retrieve the bits in the proper order. This requires modifying the controls on the storage element used. If the storage is a core memory, this is trivial. It is necessary to change only the sensing of a maximum address before resetting the address register to zero.

Synchronization for this technique presents some difficulties unless the timing of the mode changes at both the encoder and decoder can be precisely coordinated. One method for obtaining initial synchronization is to use the encoded structure of the message. The advantages of this technique are that it does not take additional channel space away from information bits and then whenever it is not received correctly the first time, it can be detected on the second, third, or subsequent transmissions. However, a resynchronization requirement when going to a shorter block length is undesirable: the reason for going to a shorter block length is that more errors are occurring in the channel. Therefore, resynchronization is more difficult. The most desirable technique still appears to be use of the coded structure of the message, eliminating as much of the problem as possible by coordinating the time of mode change in the encoder and decoder.

Fixed Block Length, Variable Redundancy

A fixed-block-length system will be simpler to implement than a variable-block-length system. None of its problems will be of the same order of difficulty as the synchronization problem described in the previous section. In fact, in a fixed block length system there is no synchronization problem except for a "start-up" procedure which is required even for a non-adaptive system.

The encoder and decoder for a fixed block length, variable redundancy system must handle a different number of information bits in each mode. Thus, they include the same problems with the same solutions described in the subsection on variable block length, fixed redundancy. In addition, the registers for constructing the redundancy in the encoder and the checkword in the decoder must be modified for each mode change. Since the capability to implement the mode with the most redundancy must be included, this becomes a simple change when using polynomial coding. It is merely a matter of changing feedback paths in a shift register with "exclusive-or" circuits between the stages. If the mode change is not perfectly coordinated at the encoder and decoder, the decoder will get a checkword indicating that errors have occurred. The only additional circuits needed are the added "exclusive-or" circuits and the gating to control which feedback path should be used.

Variable Use of Redundancy

A system incorporating variable use of fixed redundancy in a fixed block length is not faced with the synchronization problems described in the subsection on variable block length, fixed redundancy or with the variable storage and feedback problems of encoding and decoding. It must, however, include the correction circuitry for two types of correction, a complexity comparable to the other two systems. This system, however, is not faced with the problems of coordinating mode changes between the encoder and decoder since the encoder operation remains constant.

A forward-error-control system has been designed and fabricated and is now in operation at the IBM Engineering Laboratory. The first model of this technique utilizes a block length of 3200 bits, equally divided between data and redundancy and encoded as shown schematically in Figure 2-13 with m = 200, k = 4 = 8. The 1600 data bits labeled $D_1, \ldots D_{1600}$ are assigned to the positions shown in the data portion of the block. In this machine, there are eight 200-bit columns of data. The redundancy bits $R_1, \ldots R_{1600}$ are arranged in eight columns of 200 bits as shown. The data and redundancy bits in each row form a 16-bit sub-block which is encoded using an eighth-degree polynomial capable of correcting any two errors within the sub-block.

The system detects whether errors have occurred at random or in correctable bursts and corrects them accordingly. Random errors are corrected on a 16-bit sub-block basis. When a correctable burst error has been detected, the decoder considers the 3200-bit block as one word that was encoded using a burst-code polynominal of degree 1600. Thus, the data is always encoded in rows as shown in Figure 2-13 but is decoded in either of two ways depending upon the nature of the errors. In this system, the data and redundancy bits are interleaved so that the data bits of block i

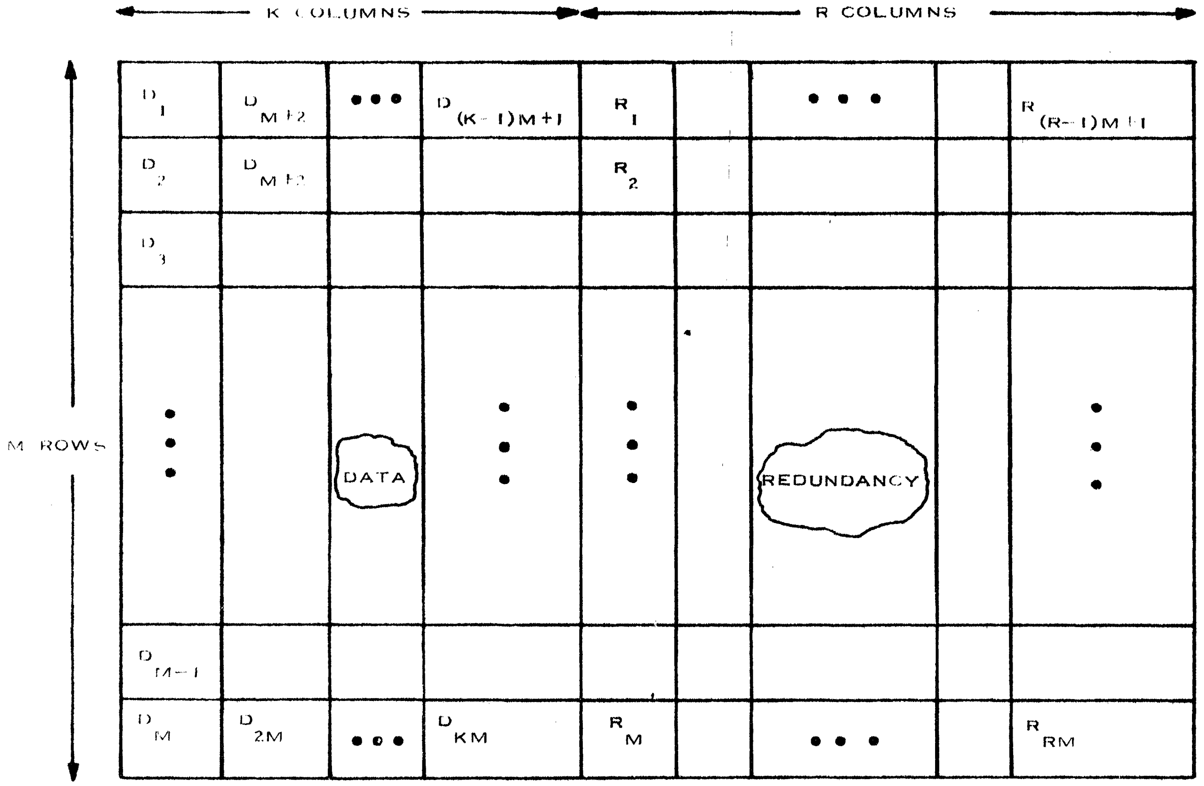

Figure 2-13 Block Format for Interleaved Variable Error Control Techniques; Block Length $N = m(k + r)$

and the redundancy bits of block i - 1 are alternated on the channel. This staggered interleaving eliminates the need for storing data in the encoder while the redundancy is being calculated, and doubles the burst length that can be corrected. Thus, the encoder must provide storage only for the redundancy associated with blocks i and i - 1. In operation, one storage area is used to interleave redundancy from block i - 1 with data from block i while the other storage area is used to store the redundancy calculated from the data in block i.

This equipment has the capability of correcting bursts of 2800 bits. In the random-correction mode, the system has the capability of correcting two errors in each interleaved 16-bit subword.

Initial block synchronization is established by searching for 200 consecutive error-free sub-blocks and framing on them. Further block synchronization is then maintained by bit sync and counters. Since this equipment was built, an improved framing technique has been developed whereby only four consecutive interleaved subwords need be correctly received in order to obtain initial block synchronization.

The parameters used in this example are merely illustrative. The number of data bits or redundancy bits in each row as well as the number of rows are all arbitrary parameters for the system designer. The length, spacing, and density of expected bursts determine these parameters.

Dr. D'Antonio of the proposed IBM team contributed to the design and test of this system and ultimately assumed full responsibility for the project.

Error-Control Subsystem Design Objectives

The proposed approach to the error-control subsystem design objectives includes the following steps:

a. A precise quantitative comparison of adaptive forward error correction and adaptive bit-rate control for overcoming periods of poor signal-to-noise ratio.

b. Channel-equality measuring technique including a comparison of error-detecting codes and direct signal-to-noise measurement.

c. Selection of code type (cyclic block, sequential or recurrent) and parameters (block length, code polynomial, buffer size, etc.) for adaptive forward error correction and error detection on critical messages.

d. Complete block diagram subsystem design for adaptive forward error control and error detection on critical messages.

e. Tradeoff, operational, throughput, and residual error rate analyses for the final subsystem.

f. Processor as an error control subsystem.

2.3 Navigation, Guidance, Control and Stabilization

In this section the synthesis of a navigation, guidance and optimum control subsystem is described in detail. This problem, as treated here, is much more than a standard approach to the solution. The adaptive concepts and mathematical optimization techniques are presently being implemented by IBM on digital computers and tested on real missions. It is quite possible that 5 to 10 years hence the technology will be available for implementing this algorithm in the spacecraft. This is another example of a well defined mathematical problem which is already being implemented on large scale Earth based processors. This subsystem with its processor is now a well defined component of the overall multi-processor system.

Optimum navigation, guidance, control and stabilization is a very essential part of a long-life multi-functional satellite system. If long-life is indeed the goal, then clearly this is certainly influenced by the efficiency with which the on-board fuel is used to maneuver the satellite. If the ground control communication link capacity is to be maintained at a reasonable size, then once again a trade-off exists between the computation capabilities of the processor and the communication link capacity.

A well-designed information transmission and processing system should supply each element of the over-all aerospace system with data of adequate precision and at an adequate rate so that, for no single element, is the quality of the information it receives or the quality of the information it generates the "limiting factor" degrading the performance of the system as a whole. In general, it will not be possible to design a system in which all elements will be balanced in this sense at all times, and we are unable at this point even to give a quantitative statement of this goal. In the course of the study we prepose to formulate a principle by which, given the instantaneous information needs of the various subsystems, we may allocate our channels optimally among them.

The information needs of each system should be low, and should be supplied from sources which can communicate easily with that system. Thus once in orbit, the vehicle-state estimation should be self-contained, requiring no more than a low data rate control signal from earth.

The need to function with little information from Earth imposes a requirement of on-board flexibility to cope with mission changes. Thus both the procedure for state estimation (navigation) and the computation of optimal control (guidance) must be completely free of any commitment to consider only small deviations from a pre-planned nominal orbit.

The on-board computer must:

(a) use come subset of prior measurements to estimate present vehicle state (position, velocity) and propulsion parameters (mass, mass flow rate, thrust as a function of fuel and oxidizer rates)

(b) compute the optimal thrust direction, as a function of present state and time, to transfer the vehicle to the desired terminal conditions so as to minimize some weighted combination of transfer time and fuel expenditure. The values of state and vehicle propulsion parameters used are those estimated in (a).

The following sections outline numerical techniques for real-time on-board solution of the problems of estimation and control. The computer program may be divided into: (1) a state-history subroutine which is common to both the estimation and control subroutines, (2) the estimation subroutine, (3) the control subroutine.

2.3.1 State History

Given position and velocity at some epoch time t_0, the ephemeris of the relevant attracting planets, current estimates of the affects of prior thrust maneuvers, and current plans for future thrusts, position and velocity are integrated from t_0 to an estimated final time t_f, which is the current estimate of the time at which desired terminal conditions will be reached. Computation time for this integration will be kept to a minimum by judicious adjustment of step size as a function of distance to gravitating bodies (5) and simple polynomial approximations for the motion of planets.

The performance of the state integration will be checked by comparison with the 8th-order Cowell method of Hillsley (6).

2.3.2 Estimation

To each set of assumed values of state components at epoch and propulsion parameters there corresponds a state history x(q,t) depending on the assumed values q, and to this assumed state history there corresponds a measurement history

$$z_i = z\,[x\,(q,t_i)]$$

at measurement times t_i. We wish to estimate q given the actual z_i which, due to measurement noise, does not correspond exactly to any q.

Our definition of the maximum likelihood estimate of q is the conventional one (see for example, Lee (9), p. 61, eq. 3.61), but our procedure for maximizing the conditional probability density function differs from current practice in the following: we treat the problem by a direct search algorithm MAX. We do not linearize the relation between parameters to be estimated and state at observation time, and we do not linearize the relation between measurements and state.

Let J (v) be a scalar function to be maximized with respect to the n-vector v. The MAX algorithm precedes in two stages. The first stage consists of alternating cycles of:

(a) stepwise ascent, in which v_i, $i = 1, n$ is incremented and possibly decremented at a sequence of points in v space, with a one-dimensional step being taken as the result of each evaluation of the response of J.

(b) motion along a direction which is the vector sum of successful steps taken in (a).

The second stage includes the cycle (a) as above, but $\frac{\partial J}{\partial v_i}$ is evaluated for one v_i, by finite differences. The vector $\frac{\partial J}{\partial v_i}$, $i = 1,,n$, although not a true gradient (since not all partials are evaluated at the same point) is treated as a true gradient in a version of Davidon's method. (10), (11) The program is intended to shift from stage 1 to stage 2 as convergence is approached, and J approaches a quadratic function of v. Stage 1 resembles the SD6-SD1 procedure of Winfield (7). Stage 2 is being developed for use in a booster-staging optimization problem under contract NAS 8-1400.

2.3.3 Control

To transfer a rocket vehicle from the state estimated in (2.3.2) to terminal conditions of a particular orbit, we require a guidance law which specifies at each instant the direction of thrust. If the engine is throttleable, thrust magnitude, rather than simply an on-off decision, may be required as well (8).

We propose an algorithm for efficient numerical calculation of optimal thrust programs to reach prescribed functions of terminal state. The algorithm chooses control to minimize a Hamiltonian function (see for example, Athans and Falb, (12) Section 6-9). This reduces the optimal guidance problem to a boundary-value problem in ordinary differential equations. The boundary-value problem is solved by a modified Newton-Raphson iteration scheme, which iterates on initial values of costate and final time until state at the final time satisfies the desired terminal conditions. Thus our method searches within the class of optimal trajectories to find optimal trajectories which also meet terminal constraints.

The partial derivatives needed in the Newton-Raphson scheme are obtained by numerical integration of variational differential equations. Transversality conditions have been constructed explicitly for a variety of orbital injection missions involving fewer than six constraints on final orbital elements. This permits efficient solution of many such problems with no increase in the dimension of the Newton-Raphson search. The choice of a fundamental coordinate system that preserves theoretical and computational simplicity and the use of an efficient numerical integration scheme makes possible an iteration rate for typical boost-guidance missions that is compatible with "state-of-the-art" digital flight computers. Thus on-board repetitive numerical solution of the optimal guidance problem can yield a discrete-time solution of the optimal guidance "synthesis problem."

Simulation results indicate that a single pre-calculated nominal trajectory provides an adequate initialization to ensure convergence of the Newton-Raphson search in the presence of "worst case" in flight perturbations.

The algorithm has been implemented on an IBM 7094 under contract NAS-8-1400 and used to solve

(1) the orbital rendezvous mission

(2) flight to a desired orbit, with time at any position free

(3) flight to orbit of given size and shape, with orientation within orbit plane free

for about ten minutes of powered flight time, starting from conditions at the first stage cutoff. In the absence of atmosphere, 0.2 seconds of IBM 7094 time are required per iteration of the initial-value problem (one integration of state and costate differential equations from initial to final time). If an on-board computer of the 1970-1975 era can duplicate this capability, then the algorithm will be suitable for on-board guidance.

The following figure shows how the algorithm can be used to perform real-time trajectory control for space boosters. The important output for control is the present value of the optimal initial costate vector, p_0, since its last three components determine the direction, and its first three components determine the rate of change of direction, of the optimal thrust. Since the time variations of present navigation state $x(t)$ are slow relative to the iterative loop, this method of generating optimal steering commands is adequate for real-time guidance.

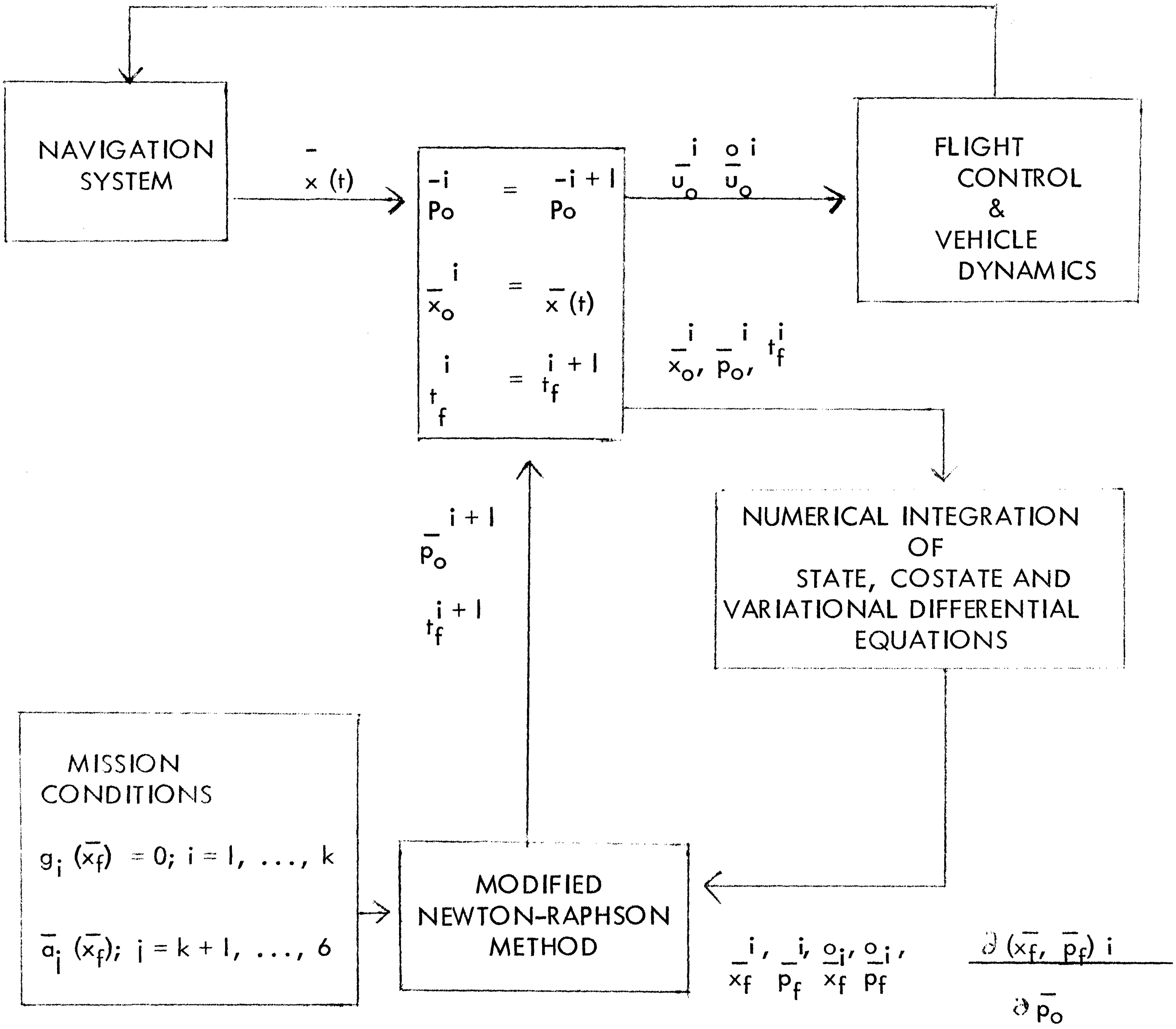

Figure 2-14 - Discrete-Time Solution of the Synthesis Problem

As indicated in figure 2-14, for the ith iteration of the initial value problem, $\bar{x}_o^i$ is set equal to the most recent navigation state $\bar{x}(t)$, and p_o^i and t_f^i are available from the Newton-Raphson linearization of the boundary value problem. The initial estimates of $\bar{p}_o$ and t_f can be chosen to correspond to those of a pre-flight optimal trajectory calculation based on nominal operating conditions. The convergence of the Newton-Raphson search is nearly quadratic for this type of initialization, even in the presence of worst-case in-flight perturbations, for typical orbital transfer missions. The present estimate of initial co-state $\bar{p}_o^i$ provides thrust direction and direction-rate commands to the attitude-control system as a trapezoidal extrapolation of the continuous solution of the synthesis problem over the next iteration period of the optimal guidance algorithm.

2.3.4 Guidance and Stabilization Subsystems

In certain satellite systems it is desirable to keep a satellite in a specified orbit at a particular relative position with respect to other satellites. For a satellite with a communications subsystem it is also desirable to maintain the satellite at a certain attitude with respect to a fixed reference. This enables the use of directional antennas on-board the vehicle, for example, the antenna array systems described in Section 2.5 of this proposal.

To control the orbit, one must first determine deviations of the position of the satellites from a nominal orbit by measurement. This is achieved by tracking the position to a certain accuracy and comparing the measured position with the calculated position that the satellite is supposed to have. Figure 2-15 illustrates how the proposed system will perform this function. The schematic is similar to the one used for the malfunction detection subsystem but illustrates on-board operations.

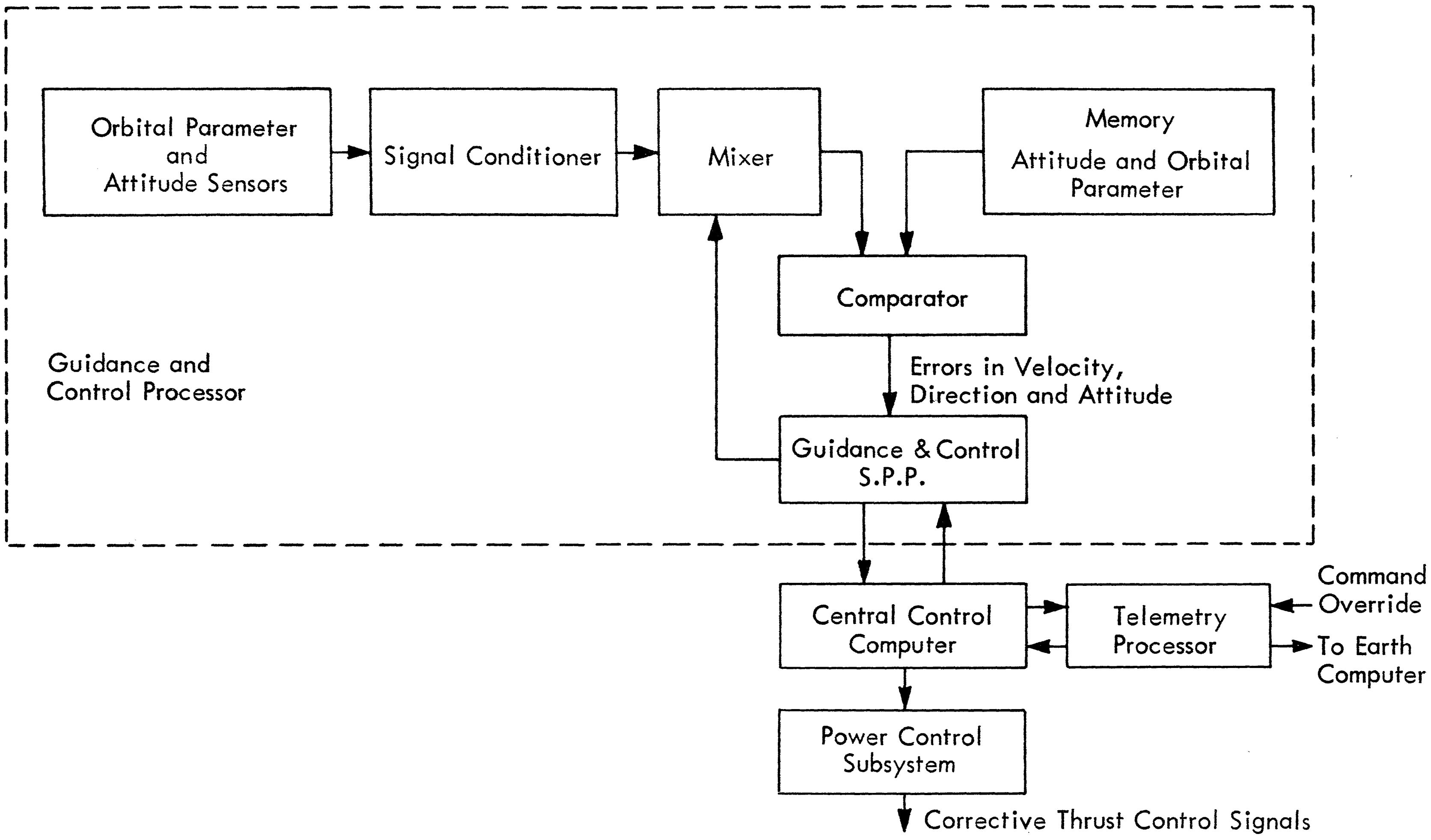

Figure 2-15. Orbital Control and Attitude Control Subsystem

Orbital and attitude information is obtained from a set of sensors and translated into a digital multiplex channel. The data is compared with the desired orbital parameters which are stored in the memory of the guidance and control unit. Pertinent error information is then sent from the guidance and control processor to the central control unit. After the data is processed it is transmitted to earth via the telemetry processor. The central control computer will then command the power control subsystem to correct the orbit and attitude of the vehicle with the application of corrective thrusts.

As for the MDS system, the required memory capacity will depend upon the number of parameters monitored and the accuracy with which they must be controlled. The orbital parameters may be continuously or discretely monitored—depending on the way the control processing unit is programmed. The number of parameters to be monitored will depend on the stabilization requirements of the vehicle.

There are two basic methods of stabilization: active and passive. Active methods employ torquing devices which consume power such as jets or reaction wheels. Passive systems derive the torque from the environment such as gravity gradient or the earth magnetic field.

Another way to distinguish attitude control is by the number of body axes aligned with the axes of the reference frame. Of primary interest are one-axis stabilization and three-axis stabilization. In the case of a rotationally symmetric vehicle, a stabilization of one axis may be sufficient.

For many purposes, two conflicting requirements must be met, such as pointing an antenna toward earth and orienting a solar cell array toward the sun. In this case a three-axis stabilization becomes necessary. Of the methods which can be used, magnetic orientation, gravity gradient orientation, and spin-stabilization orient one axis, whereas the others can orient all three axes.

The following types of stabilization systems could be employed in a multi-functional vehicle:

Magnetic Field Stabilization

This method may be used for earth satellites since it will orient and axis of the satellite parallel to earth's magnetic field. The satellite with magnetic stabilization is so oriented that the north pole of the satellite points in the direction of the magnetic north pole of earth. A satellite in equatorial orbit will orient its axis parallel to the magnetic earth axis. A satellite in a magnetic polar orbit will rotate twice per orbit about an axis normal to its magnetic axis to keep the magnetic axis properly aligned. This rotation is not uniform; it has a zero acceleration at the equator and a maximum acceleration at a latitude of 26 degrees.

Reaction Jets

This active method of attitude control can be most universally applied. It can be used for earth satellites and for space vehicles or probes. Its ability to change the vehicle momentum is unlimited; its overall capacity is limited only by the amount of propellant carried on-board the vehicle.

Reaction Wheels

Reaction wheels are momentum interchange devices that are based on the principle of action and reaction. When a wheel in the space vehicle is accelerated, its momentum will grow and the momentum of the vehicle will so decrease that the total momentum of the vehicle-wheel system remains unchanged. Three reaction wheels can control the vehicle's attitude about three axes.

Spin Stabilization

This is a means of keeping the orientation of one prefereed body axis fixed in inertial space while the body revolves around it. The spin axis itself may be in the plane of the orbit or normal to it.

It is assumed that the spin axis is left uncontrolled, after having been initially established, except perhaps to correct the effects of small perturbation torques. Magnetic interaction with earth's fields tends to realign the spin axis and gradually damps the spin angular velocity. Typical damping time constraints tend to be on the order of 10 days. Estimates of the initial alignment accuracy which can be reasonably expected are of the order of one degree. Controlling the axis alignment and the spin velocity is the essence of the control problem for spin stabilized communications satellites.

Despin

Before the attitude control can go into effect it is necessary to stop the spin which is usually imparted to the satellite during launch operations. To damp the spinning, it is necessary to remove angular kinetic energy. This can be done by exchanging energy with earth's magnetic and gravitational fields, photons (sun rays), gas molecules, or by removing some of the initial mass of the satellite. A despin method could be programmed into the central control computer.

For an on-board control system, the following sensors may be used:

Sun Sensors - Sun sensors establish the direction of the sun in the vehicle reference frame. A simple mechanization for a sun sensor consists of a differential array of photosensitive elements. Consider a pair of elements with a small protruding shadow vane between them. If the vane points directly toward the sun, both photosensitive elements will produce the same output. A pair of such sensors, arranged so that the vanes are crossed relative to each other, will align one axis quite accurately toward the sun (0.05 degrees). Electrically, the photosensitive elements are arranged in the form of a bridge. The limitation in accuracy is due to thermal shifts in the bridge null position.

Horizon Sensors - Horizon sensors are used to determine the center of a near celestial body such as earth in the case of a satellite. For lunar or planetary missions a lunar or a planetary horizon scanner will be used.

Most horizon scanners use the planetary infrared emission. One method is to use an infrared camera with a wide angle optic. From the infrared picture of the planet, the center can be determined quite accurately.

Earth Tracking - Earth tracking as such is important to orient the vehicle antenna properly.

Star Tracking - Star tracking provides an inertial frame. Tracking three stars is sufficient to define the frame and star trackers can be mechanized with highly photosensitive devices. Stars are virtually point sources; they can be identified by their light intensity and spectral filters can be employed as an additional recognition device. Another way of identifying a star is using a camera with a wide field of view and matching the sensed picture to a star map or catalog. The latter method required a computational capability which can be furnished by the processing unit.

Gyros - A gyroscope tends to keep its axis aligned in inertial space. By using this property, gyroscopes offer three ways for attitude sensing: stabilizing a reference platform, using it as a gyro compass, and acting as rate gyro.

Stabilization affects the efficiency with which the on-board RF power is used to transmit messages. For high gain (narrow beam) antennas, the stabilization requirements are severe since the instability must be substantially smaller than the beam-width. The stability affects the effective power which is received at the ground and hence the communications efficiency. Of course, it is also a factor in determining the accuracy with which certain classes of experiments can be performed.

In general, the computational capacity of the processor will increase with stability and control requirements.

2.4 Sensors

The sensors (other than telemetry) in a satellite are mission oriented, i.e., they are selected to accomplish a certain goal. However, it is still possible to classify these as "pictures" and not pictures."

In a multifunctional satellite system, the processing and transmission of pictorial messages must be considered since the extremely high data rate can swamp both the on-board processor capacity as well as the space communications capacity. Pictures, however, have a significant amount of redundancy (i.e., pictures have structure) which it is desirable to remove prior to transmission. Information preserving compression (i.e., previous value prediction) techniques will yield no more than a compression factor of two or three for relatively complex pictures which is not adequate for future missions. The bigpay-off is on-board processing with the aim of extracting the useful information for transmission.

Several years ago, IBM took a big step in this direction by developing an algorithm which permits a digital computer to enhance a picture and to generate the picture contours (i.e., line drawings). The mathematical theory of this operation is presented here since it shows a good example of how an on-board processor can be used for extracting the important information from a picture.

In general, messages derived from other sensors will have a much lower data rate. The tendency here is to develop digital sensors; that is, hte output is a binary number. In some cases, it may be quite reasonable to view the combination of sensing device and small processor as a multi-mode digital sensor. All of these sensors, as previously discussed, will be monitored and controlled by a control computer. The sampling, multiplexing, and the accuracy of the output will be under computer control.

It seems that a further classification of sensors according to function and values of the information theoretic parameters is very desirable. In this manner, the maximum source entropy can be calculated. Such a classification was performed several years ago by IBM for some scientific sensors and is included as an example.

2.4.1 Picture Compression and Computer Generation

In the last decade a considerable amount of effort has been devoted to finding new methods of transmitting television pictures, with the aim of reducing the bandwidth required for transmission of animated television pictures substantially below the 4.5 megacycles used in present commercial broadcasting. Analog systems comprised the bulk of the early work; but recently a number of ideas for digital television have been tested. Simple digital techniques that have been considered actually require substantially more than 4.5 megacycles, but the many advantages of digital transmission make digital television most desirable.

IBM performed a study entitled "Improved Coding for Military Digital Television" (see Section 9, Part F) in which the purpose was to obtain more efficient digital television systems applied to intercommunications (video telephone), briefing, and observing hazardous operations. Promising ideas and techniques developed during this study were evaluated by simulation on an IBM 709 computer.

Most of the effort during the first phase of the contract was devoted to reducing the amount of transmitted information necessary for acceptable reproduction of a single picture at the receiver. After suitable processes had been determined for a single frame, animation and flicker were studied from the point of view of reducing bandwidth. The animation and flicker considerations were strongly dependent on the application considered.

2.4.1.1 The Generation of Line Drawings

It has long been recognized that the precise location of edges of objects constitutes important information to the human observer. A program has been written to simulate a method of producing line drawings which was first suggested by Kovasznay and Joseph.[13] This method is based on calculating.

$$F(x,y) = [\,\nabla f(x,y) \cdot \nabla f(x,y) = \left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2$$

Here $F(x, y)$ describes the gray level as a function of position for the picture. The function $F(x, y)$ is clipped to yield a function F, where

$$F^*(x,y) = \begin{cases} 0 \text{ if } F(x,y) \leq c \\ 1 \text{ if } F(x,y) > c \end{cases}, c = \text{clip level}$$

Lines exist at points for which $F(x, y)$ is equal to 1. Experiments were performed using this program. The purpose of these experiments was to show that line drawings could indeed be generated in the computer and to investigate the effect of the clipping level on the quality of the line drawings.

It was concluded from the experiments that:

(a) The simple finite difference approximation to the gradient function does yield a satisfactory line drawing.

(b) A high degree of fidelity in the digitizing equipment is not necessary to ensure an acceptable line drawing. However, a non-linear digitizing process does create problems.

2.4.1.2 Finite Difference Form of Laplaces Equation and Gradient Vector Squared

Statement of the Problem

The problem [14,15,16] is to express Laplace's Equation

$$\nabla^2 F = \frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial y^2}$$

and the square of the absolute magnitude of the gradient vector

$$/\nabla F/^2 = \left(\frac{\partial F}{\partial x}\right)^2 + \left(\frac{\partial F}{\partial y}\right)^2$$

in their simplest finite difference form with minimum error. That is, we desire to transform the above partial differential equations into partial difference equations with minimum error.

Analysis

The simplest 3-point central difference formulas [14, 15, 16] for

$$\left(\frac{\partial F}{\partial x}\right), \left(\frac{\partial F}{\partial y}\right), \left(\frac{\partial^2 F}{\partial x^2}\right), \text{ and } \left(\frac{\partial^2 F}{\partial y^2}\right)$$

using the rectangular lattice in Figure 2-16 are:

$$\left.\frac{\partial F}{\partial x}\right|_0 = \frac{1}{2a}(F_1 - F_3) - \frac{a^3}{6}\left(\frac{\partial^3 F}{\partial x^3}\right) \qquad (2-1)$$

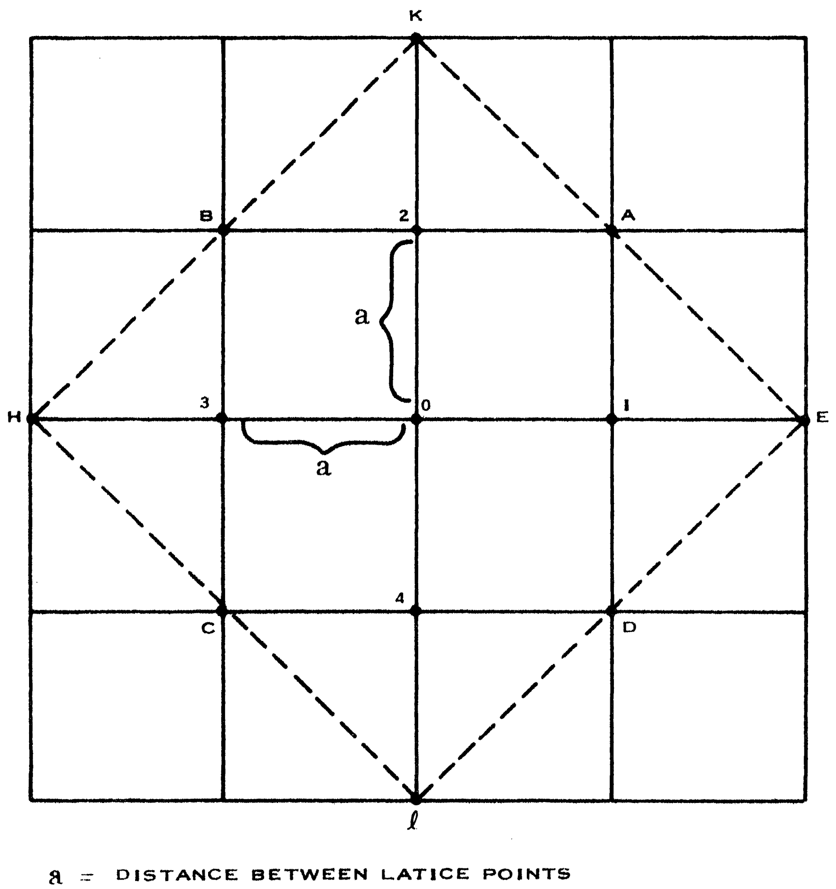

Figure 2-16. Geometry Used to Evaluate Laplacian and Gradient Operators

$$\left.\frac{\partial F}{\partial y}\right/_0 = \frac{1}{2a}(F_2 - F_4) - \frac{a^3}{6}\left(\frac{\partial^3 F}{\partial y^3}\right) \tag{2-2}$$

$$\left.\frac{\partial^2 F}{\partial y^2}\right/_0 = \frac{1}{a^2}(F_2 + F_4 - 2F_0) - \frac{a^4}{24}\left(\frac{\partial^4 F}{\partial y^4}\right) \tag{2-3}$$

$$\left.\frac{\partial^2 F}{\partial x^2}\right/_0 = \frac{1}{a^2}(F_1 + F_3 - 2F_0) - \frac{a^4}{24}\left(\frac{\partial^4 F}{\partial x^4}\right). \tag{2-4}$$

Using equations(2-3)and(2-4)Laplace's equation becomes

$$\nabla^2 F = \frac{1}{a^2}\left[(F_1 + F_3 - 2F_0) + (F_2 + F_4 - 2F_0)\right]$$

$$- \frac{a^4}{24}\left[\frac{\partial^4 F}{\partial x^4} + \frac{\partial^4 F}{\partial y^4}\right]. \tag{2-5}$$

Neglecting the fourth derivative terms, the finite difference approximation using the 3-point central difference formula for the rectangular lattice becomes

$$\nabla^2 F \approx \frac{1}{a^2}\left[F_1 + F_2 + F_3 + F_4 - 4F_0\right]. \tag{2-6}$$

From equations (2-1)and(2-2)the expression for the square of the absolute magnitude of the gradient vector becomes

$$/\nabla F/^2 = \left[\frac{1}{2a}(F_1 - F_3) - \frac{a^3}{6}\frac{\partial^3 F}{\partial x^3}\right]^2 + \left[\frac{1}{2a}(F_2 - F_4) - \frac{a^3}{6}\left(\frac{\partial^3 F}{\partial y^3}\right)\right]^2, \tag{2-7}$$

which becomes:

$$|\nabla F|^2 = \frac{1}{4a^2}\left[(F_1 - F_3)^2 + (F_2 - F_4)^2\right] - \frac{a^2}{6}(F_1 - F_3)\frac{\partial^3 F}{\partial x^3} + (F_2 - F_4)\Bigl(\frac{\partial^3 F}{\partial y^3} + \frac{a6}{36}\left[\left(\frac{\partial^3 F}{\partial x3}\right)^2 + \left(\frac{\partial^3 F}{\partial y^3}\right)^2\right]. \tag{2-8}$$

Neglecting those expressions which involve third derivatives, equation (2-8) becomes

$$|\nabla F|^2 \approx \frac{1}{4a^2}\left[(F_1 - F_3)^2 + (F_2 - F_4)^2\right]. \tag{2-9}$$

Therefore equations (2-6) and (2-9) express the partial difference equations, which yield minimum error, of the Laplacian and the square of the absolute magnitude of the gradient vector using the 3-point formula for the rectangular lattice.

2.4.2 Sensor Instrumentation—Example

The following charts summarize some of the characteristics of a number of instruments which have been used or are under development for making scientific measurements from a satellite or space probe. The data given in these charts are typical values. For any specific experiment, the results are dependent on the particular application of the instruments. For example, the counting rate of a Geiger-Mueller tube is not primarily a

Summary—Measurement Instruments for Space Probes

Class of Experiments	Instruments	Intrinsic Signal Form	Range	Mode of Operation	Signal After Processing (Pulse Height Analysis, Scaling, Amplification, etc.)	Satellite and Space-Probe Environments	Comments
Spectroscopy	IR Spectrograph	A	2–5 μ	S	About 20 peaks superimposed on 300-cps carrier.	Will scan surface of Mars.	Primarily interested in detecting [illegible] charact istic of life.
	UV Spectrograph	A	1700-3100 A°	S	About 20 peaks can be resolved.	Will scan surface of Venus.	For spectroscopic analysis of atmosphere.
	Lyman-alpha Telescope	A	1010-1340 A°	S	Integrated [illegible] by vehicle spin.	Produces pulse each time sun is scanned.	Lyman-alpha is strongest UV line from hydrog
	X-Ray Telescope	D	2-3 A°	C	Pulses counted.	Produces pulse each time sun is scanned.	Measures X-rays released during solar flares.
Ionosphere	Ion Probe	A	$>10^3$ ions/cm^3	2 sec	2 analog currents [illegible] time, 0.2-sec sweep.	Currents vary over two decades as probes pass through ionosphere.	Measures ion concentration and electron temp ature.
	Langmuir Probe	A	$>10^3$ electrons/cm^3	1 sec	Analog current versus time.		Measures electron temperature and satellite p tential.
	Electric Field Meter	A	0-10 V	C	Analog voltage on 1000-cps carrier.	Field strengths are about −5 vdc.	Measures field at surface of space vehicle.
Radiation Budget	Albedo Meter (Scanning)	A	2 decades	C	Change in resistance due to scan.	Uses a reflector for scanning a limited field.	For studying energy balance in earth's atmo phere.
	Omnidirectional Radiometer	A	2 decades	C	Change in resistance.	Uses a spherical surface to absorb radiation from all directions.	
	Neutron Proportional Counter	D	1000 cps	C	Pulses counted for two detectors.	Expected rates are about 1000 cps.	Must be flown below Van Allen belts.
Atmospheric Pressure	Thermionic Ionization Gage	A	10^{-5}-10^{-9} mm Hg	C	Ionization current collected varies over 3 decades; each detector must be laboratory-calibrated.	Range of pressures encountered are from 1 atm (at earth's surface) to as low as 10^{-14} mm Hg; the measured pressure depends on vehicle orientation and velocity.	Ionization caused by electrons from hot filu
	Radioactive Ionization Gage	A	1 atm-10^{-9} mm Hg	C			Ionization caused by particles from radioac emitter.
	Cold-cathode Ionization Gage	A	10^{-5}–10^{-7} mm Hg	C			Ionization caused by electrons from cold cath
	Redhead Gage	A	$>10^{-13}$ mm Hg	C			A specialized cold-cathode ionization gage
	Pirani Gage	A	10^{-1}–10^{-3} mm Hg	C	Change in resistance (two decades).		Resistance of filament is decreased when co by gas.
Atmospheric Structure	RF Mass Spectrometer	A	2 decades	1 sec	Analog current versus sweep voltage.	14 peaks have been resolved.	Satellite velocity vector must be taken into count when analyzing results.
	Magnetic Mass Spectrometer	A	10^{-5} amp	5 sec	Current from many collectors [illegible] tabulated.	Measures preselected constituents.	
	Thermistors	A	3 decades	C	Logarithm of current.	Temperatures measured are space-craft temperature—not atmospheric temperature.	Atmospheric temperature must be inferred fr kinetic theory since radiation is chief mode [illegible] fer.
	Thermocouples	A	2 decades	C	Voltage change.		

Abbreviations: D = Digital A = Analog D-A = Discrete event with analog magnitude F = Frequency γ = Gamma G = Counts C = Continuous

Summary—Measurement Instruments for Space Probes

Class of Experiments	Instruments	Intrinsic Signal Form	Range	Mode of Operation	Signal After Processing (Pulse Height Analysis, Scaling, Amplification, etc.)	Satellite and Space-Probe Environments	Comments
Cosmic Rays	Geiger-Mueller Tube	D	10^5 cps	C	Current measured or pulses counted.	Normal counting rates in space are low (about 10 cps) but may increase by a factor of 1000 during a solar flare.	Intensities in space are within G-M tube range.
	Cerenkov Telescope	D-A	10^5 cps	C	Analyzed by pulse height and counted.		Measures particles with relativistic velocities.
	Cosmic Ray Telescope	D	5×10^3 cps	C	Pulses scaled 2^5 and counted.		Uses a triple-coincidence circuit.
	Integrating Ionization Chamber	D	100 cps	C	Pulses counted.	Normal rate expected is 1 pulse per hr.	Each pulse represents 1.3×10^{-4} roentgen.
	Nuclear Emulsion			C	Package recovered and tracks analyzed.	Exposure time will be several days.	Must be recovered.
Radiation Belts	Ionization Current Gage	A	10^{-11}–10^{-4} amp	C	Current measured.	Within the radiation belts, shielding must be used to prevent saturation of the counting circuits.	Measures total energy released in the detector.
	Thin-walled G-M Tube	D	10^5 cps	C	Current measured or pulses counted.		10^5 cps is optimistic for a G-M tube.
	Scintillation Counter	D-A	6×10^4 cps	C	Analyzed by pulse height and counted.		Limit of counting rate is set by the circuitry, not the crystal.
Solar Particles	Electrostatic Analyzer	A	10^{-13}-10^{-6} amp	2 min	Current measured for each of 12 bias levels.	In space, counting rates are not expected to exceed 1000 cps; approximately 90% of the solar particles are protons.	Uses electrostatic focusing.
	Proton Ionization Gage	D	10^5 cps	C	Pulses counted.		Uses "magnetic broom" to remove electrons.
	β-Ray Spectrometer	D-A	5×10^5 cps	C	Analyzed by pulse height and counted.		Uses magnetic focusing.
	Ion Scintillation Spectrometer	D-A	5×10^5 cps	C	Sorted by particle type and analyzed by pulse height.		Thin crystal determines particle type, thick crystal measures energy.
Magnetic Fields	Flux-gate Magnetometer	A	0.6-1200 γ	C	Analog current proportional to component of field.	Field strength near earth is 0.7 gauss and slowly decreases to 2.5 gamma at approximately 13 earth radii; in space, surges of 40 gammas have been recorded.	Can be designed for almost any range.
	Rotating-coil Magnetometer	A	0.6-1200 γ	C	A-M sinusoidal current proportional to component of field.		Measures component perpendicular to spin axis.
	Proton-precession Magnetometer	F	0.07–1.0 G	10 sec	Frequency proportional to magnitude of field.		Measures absolute field but can be used to measure components of field by using biasing coils.
	Rubidium-vapor Magnetometer	F	0.05-105 γ	10 sec	Frequency proportional to magnitude of field.		
Micrometeorites	Resistance Grids	A	12 levels	C	Discrete changes in resistance.	Two hits were recorded in 1 sec.	Measures penetrating ability of larger particles.
	Erosion Gage	A	2 decades	C	Continuously increase in resistance.	Several months exposure are necessary.	Measures surface erosion due to sand blast effect.
	Microphone	D-A	$> 10^{-5}$ $\frac{\text{gm-cm}}{\text{sec}}$	C	Analyzed by pulse height and counted.	Rates of 5 cps have been recorded.	Records momentum.
	Light-flash Detector	D-A	$> 10^{-8}$ erg	C	Analyzed by pulse height and counted.		Measures light energy released upon impact.

Abbreviations: D = Digital A = Analog D-A = Discrete event with analog magnitude F = Frequency γ = Gamma G = Gauss C = Continuous function of the type of tube (although this may establish an upper limit) but depends on the orbit of the satellite, the amount of shielding, and the circuitry used to record the pulses.

In this summary the "Intrinsic Signal Form" is the type of output of the sensing element before processing and does not depend on the circuitry. The "Range" and "Signal After Processing" and "Mode of Operation" are determined by the design of the experiment. These can be changed for different experiments by varying the circuitry, geometry, type of filters, etc. The column headed "Satellite Environment and Space Environment" gives an indication of the range of values expected for the scientific measurements depending on whether the vehicle is in the vicinity of the earth or in deep space.

2.5 Checkout and Malfunction Detection System

The checkout or malfunction detection system (MDS) will determine the status of system components to assess the probability of mission success and determine if corrective measures may be taken in the event of malfunction. The MDS system will forward status information to the telemetry processor via the central control computer for transmission to the control station. A major consideration in the design of the MDS is the selection of the mission parameters to be monitored, and the requency each will be interrogated.

Figure 2-17 is a diagram of a general MDS system. Those vehicle parameters which are most important in the mission success are continually monitored. A priority system must be established to determine the frequency with which various mission parameters are monitored.

The sensors which monitor the parameters are controlled by the sensor control unit and it is assumed the sensor configuration may be varied during the flight.

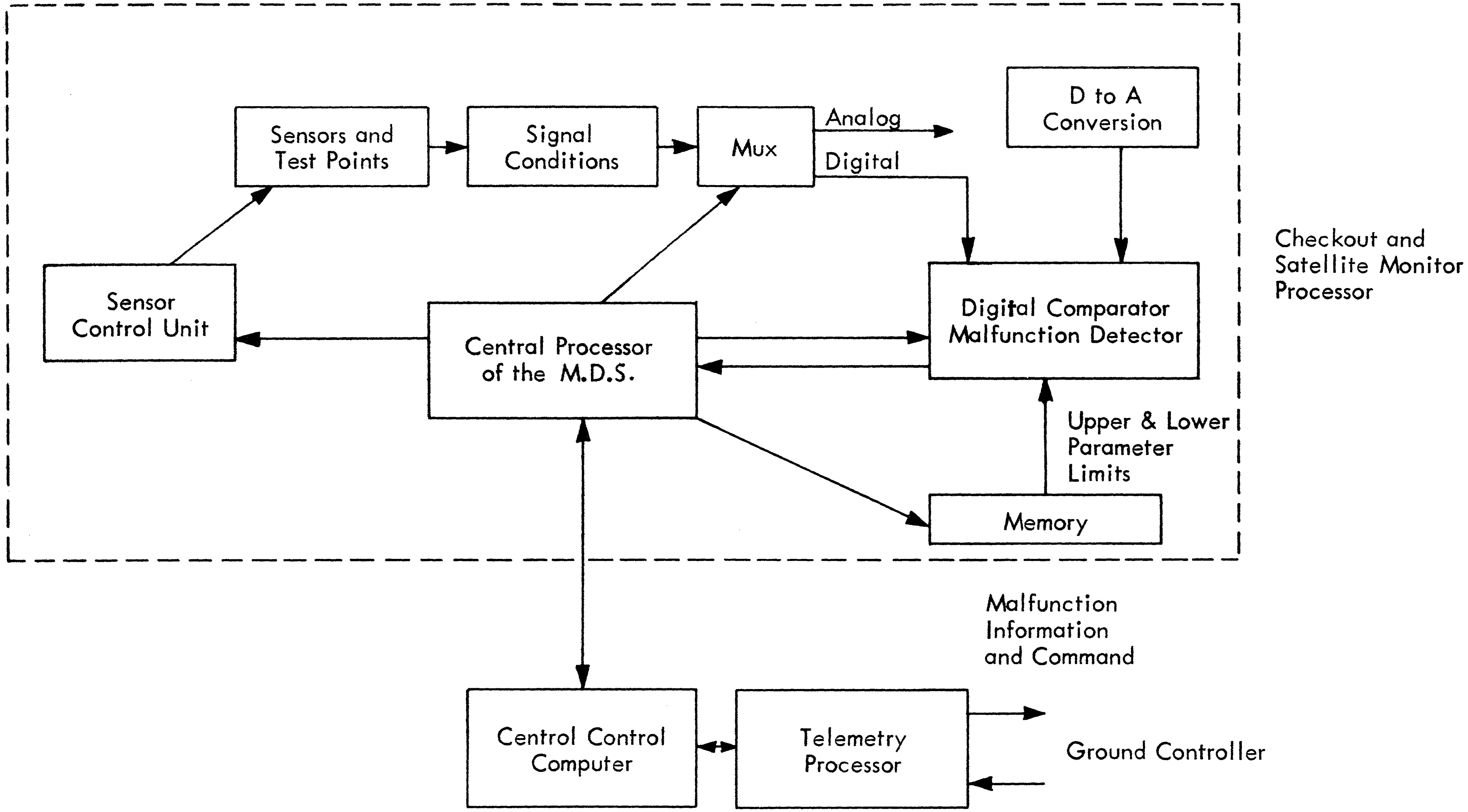

Figure 2-17. Malfunction Detection System Schematic

The electrical signals from the sensors are conditioned to be in the same voltage range. The signals are then multiplexed with the multiplexing controlled by the SPP. The SPP is programmed to recognize the variation in interrogation frequency between parameters in the muxing operation. The analog signals are then digitized and the signals are compared with the acceptable range of operation from the SPP memory. Malfunctions are then determined in the digital comparator and the information is sent to the central control computer.

The SPP memory size for the MDS system is determined by the range of operation designated by the upper and lower bounds of operation, the accuracy with which the bounds must be specified, and the number of parameters to be monitored. The accuracy of the bounds is limited by the sensor accuracy and sensor error. The interrogation or multiplexing channel will have a limited capacity. This will place a limit on the accuracy of the information.

The SPP program for the MDS must control the multiplexing and switching operations. As the mission progresses, and the status of various on-board functions change, it may be necessary to modify the program through the command channel. The program must therefore have an adaptive capability.

2.6 Computer Control of the Antenna Systems

The functions which must be performed by the special purpose communications processor for the desired antenna operations will be determined by the antenna requirements which in turn are dependent upon the mission objectives, types of stabilization and orbital parameters. The desired antenna systems may have the following characteristics.

- Multiple beams for transmission or reception to separate areas of the same frequency.

- Sterrable beams which will enable the antennas to be pointed at different areas upon command.

- The antenna may have to track a source of power while there is relative motion between the vehicle and source.

- Variable beam width. At different times in the mission it may be desirable to have a narrow beam to increase gain to illuminate small regions and receive as much signal power as possible, or it may be desirable to increase the illumination area or be able to receive from receiving locations distributed over a wide angular range.

- Antenna beams must be switched on and off or from transmit to receive

The above requirements can be met with multiple antennas or an antenna array, with a well designed processing unit which integrates the antenna requirements with the mission objectives and vehicle characteristics.

Antenna Configuration

Detailed computer requirements can only be established if the antenna configuration which will be necessary to meet the prescribed requirements is known. In a gravity gradient stabilized system, complex antenna requirements can more easily be met than in a spin stabilized system.

The antenna system can be characterized in terms of:

1. The number of beams,
2. The total angular range over which each beam may be required to steer,

3. The range of their beam width,

4. Whether the antenna must transmit or receive or transmit and receive.

Figure 2-18a shows the geometry of a rectangular planner array where E_{ij} is the element in the ith row and jth column. If each element is omnidirectional, the radiation pattern of a single row will be omnidirectional, the radiation pattern of a single row will be omnidirectional in a plane perpendicular to that row if the elements are equally spaced as shown in Figure 2-18b.

The normalized radiation pattern is given by

$$\frac{G(\Theta_R) = \sin^2(NTT\ (d/\lambda)\ \sin\theta)}{N^2 \sin^2 (II(d/\lambda)\ \sin\theta)} \qquad (2\text{-}10)$$

where θ_R is the angle from the X axis in the X-Z or x-y plane. For maximum gain, $d = \lambda I_2$, and the half-power beamwidth is $\theta_0 = 101.8/N$ (2-11)

and the gain is $G_0 = N$ (2-12)

Equation (2-10) also applies to the case where a column of elements is considered a linear array, in which case, a pattern is formed which is orthogonal to the pattern that was formed from the row. It then follows that if all elements are considered, a narrow beam is generated along the perpendicular to the plane of the array.

If each element in the array is directional, the resulting pattern is for the rectangular planar array is

$$G(\theta_R, \theta_C) = \frac{\sin^2 (NTT(d/\lambda)\ \sin\theta_F)\ \sin^2 (MTT(d/\lambda)\ \sin\theta_C)}{N^2 \sin^2 (TT(d/\lambda)\ \sin\theta_R)\ M\sin^2 (TT(d/\lambda)\ \sin\theta_C)}\ G_E \qquad (2\text{-}13)$$

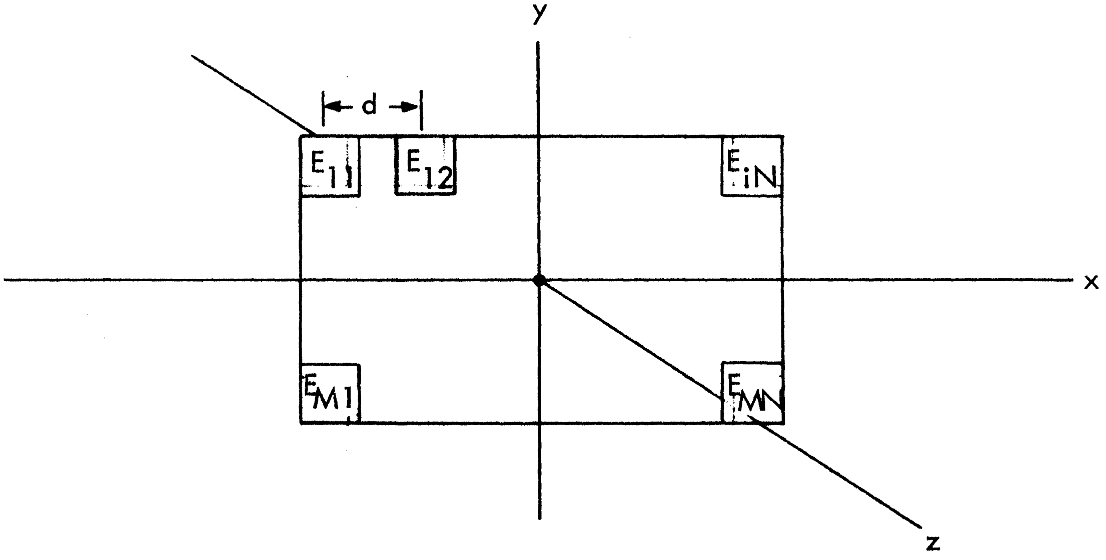

Figure 2-18a. Planar Array Geometry

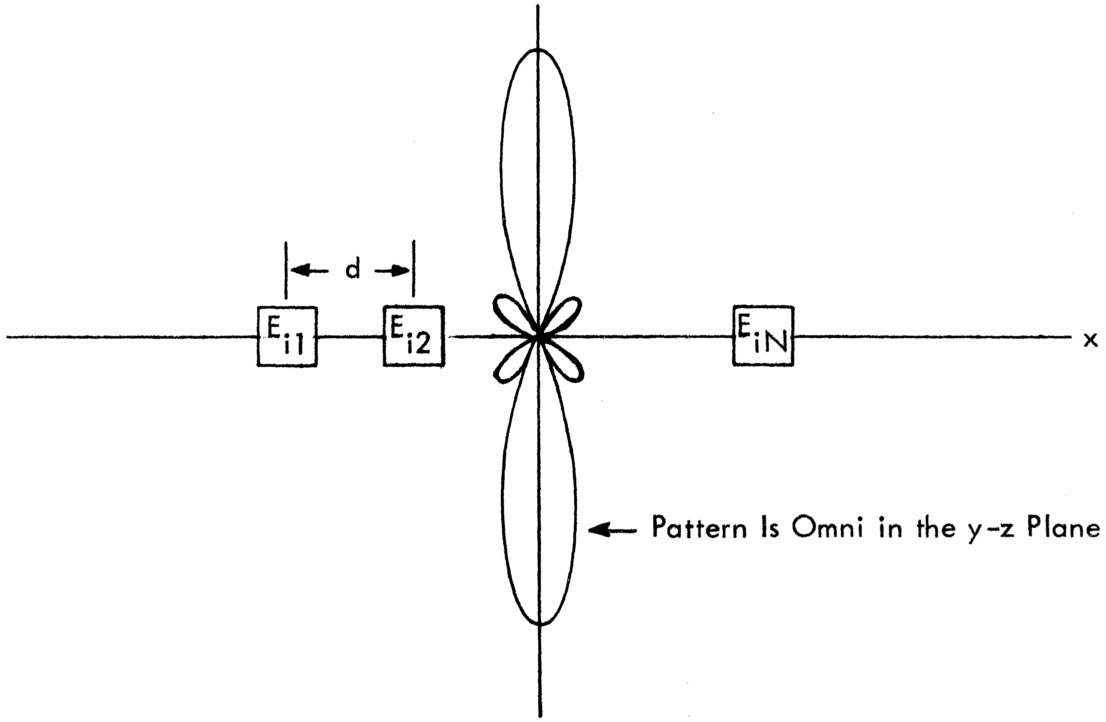

Figure 2-18b. Radiation Pattern from A Single Row

Figure 2-18. Antenna Array Geometry

Where G_E is the gain of the individual element, the individual elements may be anything from a dipole to a parabila.

By controlling the electrical spacing between elements, the beam of the planar array can be offset from the perpendicular. If θ_0 is the offset desired, then the required phase spacing of adjacent elements is

$$\phi = 2\,TT(d/\lambda)\sin\theta_0 \tag{2-14}$$

Figure 2-19a illustrates the relative phasing of the individual element feeds to produce a pattern offset in a single angular dimension. By electronically adjusting the phase shifters, the pattern can be rapidly steered in a single angular coordinate, or for a planar array it may be steered in two coordinates. If a second source is used, and feeds the individual elements through a second set of phase shifters, a second beam can be generated from the antenna. As many beams can be formed as desired as long as a separate set of phase shifters is used for each beam. The central control computer will designate the beams to be formed and furnish this information to the communications and telemetry processor which will steer the antenna.

Equation (2-13) can be used to establish the architecture of the antenna system. The gain of the individual elements must be compatible with the overall coverage range. The array parameters are then selected to provide a steering capability within that coverage range. This will then determine the requirements of the individual phase shifters through Equation (2-14).

The number of elements required will be determined by the ratio of the total coverage range to the desired beamwidth—both of which are illustrated in Figure 2-19a.

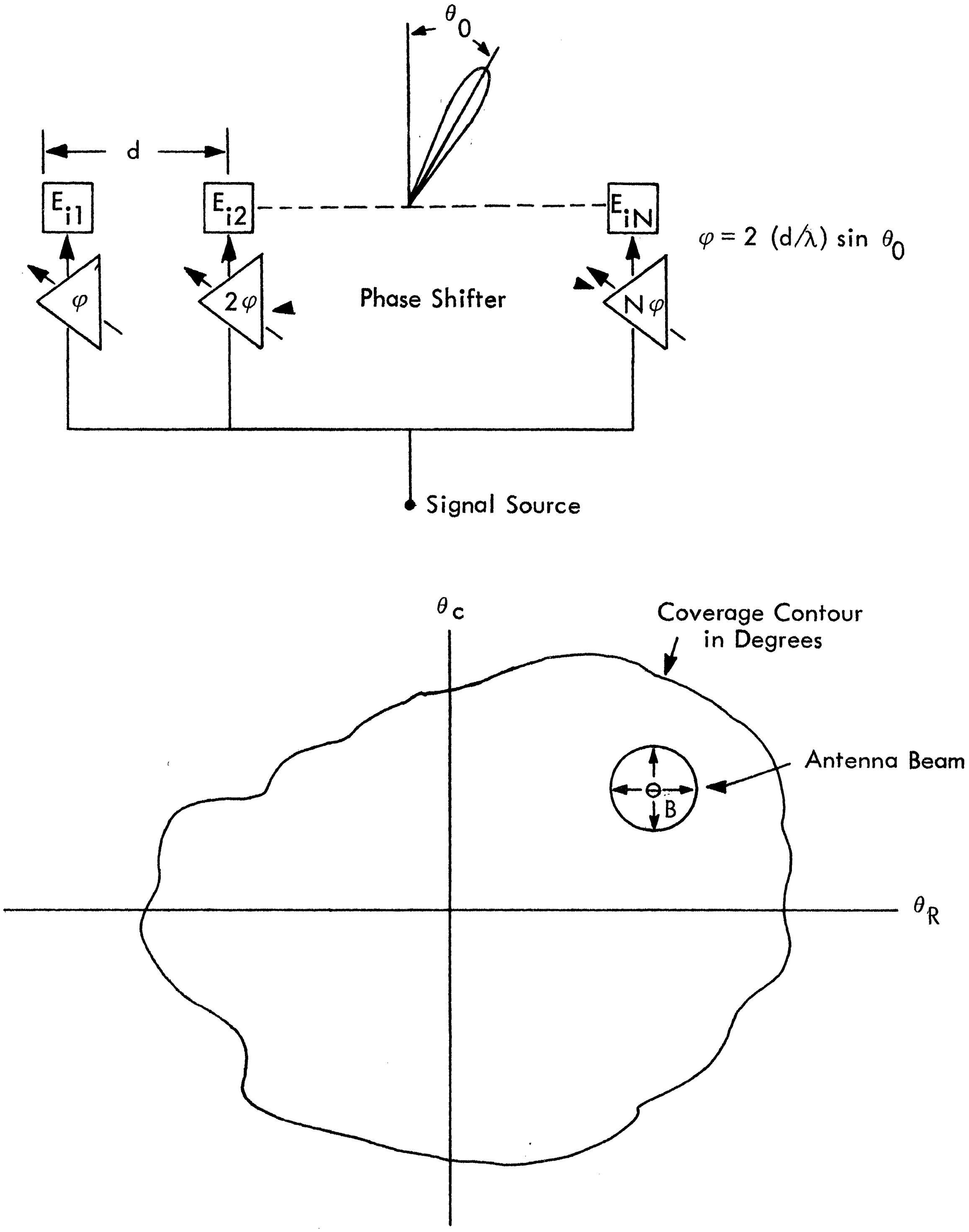

Figure 2-19. Steerable Arrays and Coverage Range

Phase Shifters and Control Signals

The type of control signal furnished by the communications processor will depend upon the characteristics of the electronically controllable phase shifters which are used. These include the use of ferrite materials, gaseous discharge rubes, traveling-wave tubes, transmission lines, varactors, etc. The major difference, as far as the computer is concerned, is whether the beam must be continuously steerable or discretely steerable.

If the beam is discretely steerable, the configuration which are preset to give a particular beam direction. For a continuously steerable system, the computer must adapt the control signal to the phase characteristic of the device in order to achieve the desired beam direction.

Figure 2-20 illustrates how control signals are used in a two dimensional scan system. The required accuracy of the control signals is determined by the sensitivity of the phase shifter to the control signal, the beam width of the array, and the stabilization accuracy of the vehicle.

Tracking Capability

A tracking system which employs a phased planar array, the communications and telemetry processor and the central control computer is illustrated in Figure 2-21. Although the tracking capability is illustrated for a single angle only, the capability for volumetric tracking follows directly from Figure 2-20. The number of elements is divided into two sections, with each section forming a beam which is offset from the intended boresight. The sum of the two beams will be a symmetric beam about the boresight. The received signals from both sets of elements are added in one channel and subtracted in another. The phase difference between the sum and difference channels will determine the direction from boresight where the source is

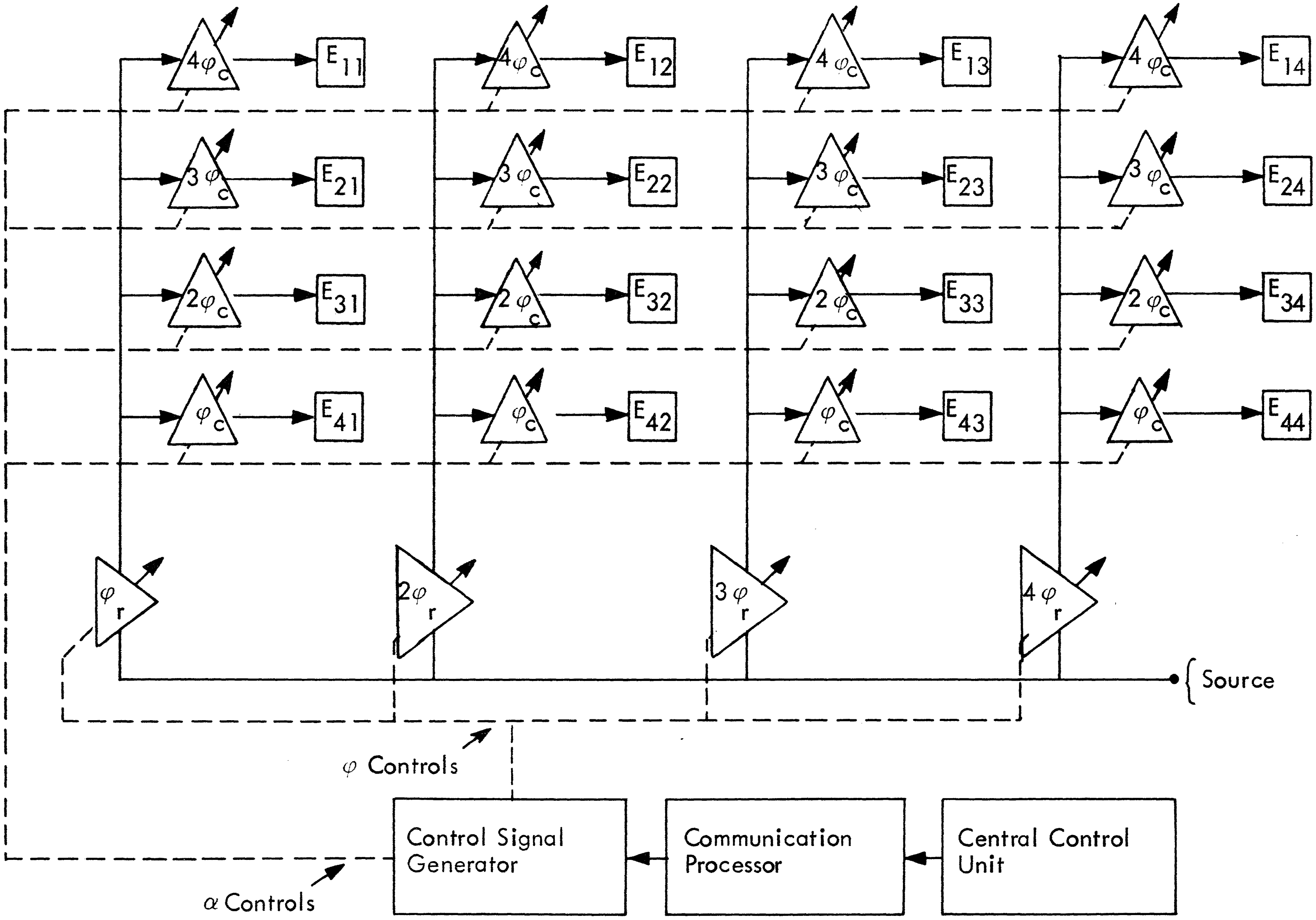

Figure 2-20. Control System for Scanning In Two Angular Coordinates

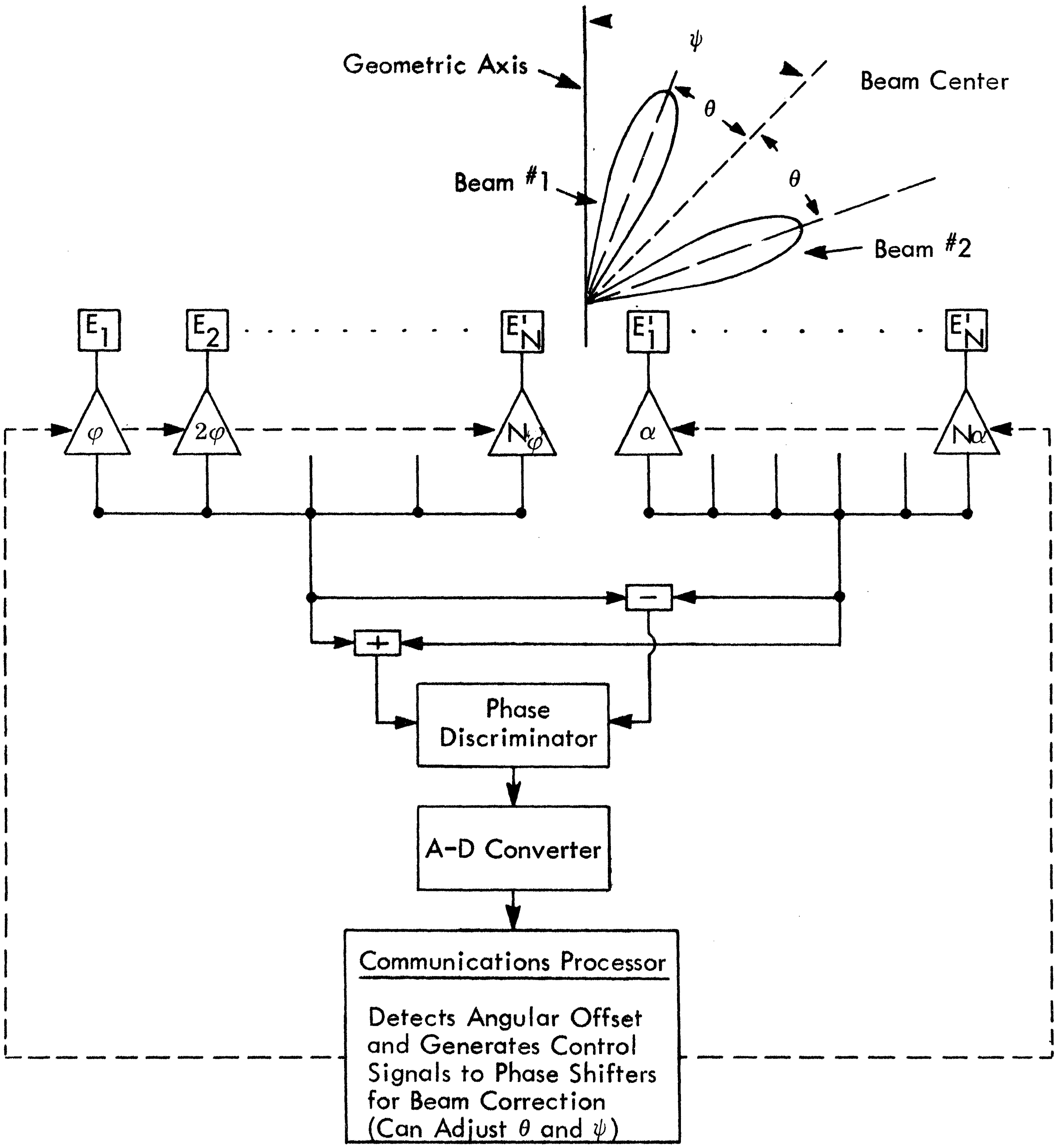

Figure 2-21. A Single Dimension Tracking System

located. The discrimination output will contain the error information. This will be processed by the communications processor, which will generate error correcting signals to the phase shifters which will correct the angular offset of the boresight.

Spin Stabilized Antennas

The beam forming techniques which have been discussed, apply to a vehicle which is stabilized in three coordinates. It is assumed that the geometric center of the array is pointed at the same angle relative to the earth. If the vehicle is spin stabilized, complex antenna requirements are difficult to meet. If the array could be scanned at the rotational velocity of the vehicle, a narrow beam could be directed at a fixed point on earth. Power compensation would be employed to compensate for the variations in antenna gain. A system of this nature would be extremely complex.

A simpler system for spin stabilized vehicles is illustrated in Figure 2-22. Antennas are mounted around the periphery of the vehicle in the plane of rotation. The antenna beam, under computer control, would rotate at an angular velocity equal to but opposite to the rotation of the space craft. The antenna pattern which is positioned most nearly at the desired direction of propagation would be selected and as the vehicle rotates, the adjacent channel would be used.

To accomplish this task, information from the guidance and navigation processor would be processed by the central control computer and fed to the communication processor. This processor would control the antenna beam velocity in accordance with the position of the satellite as determined in the navigation and guidance processor.

DIMUS

A very convenient system which has been used for beam forming in sonar work is DIMUS (digital multibeam steering). This system, as may be applied to the

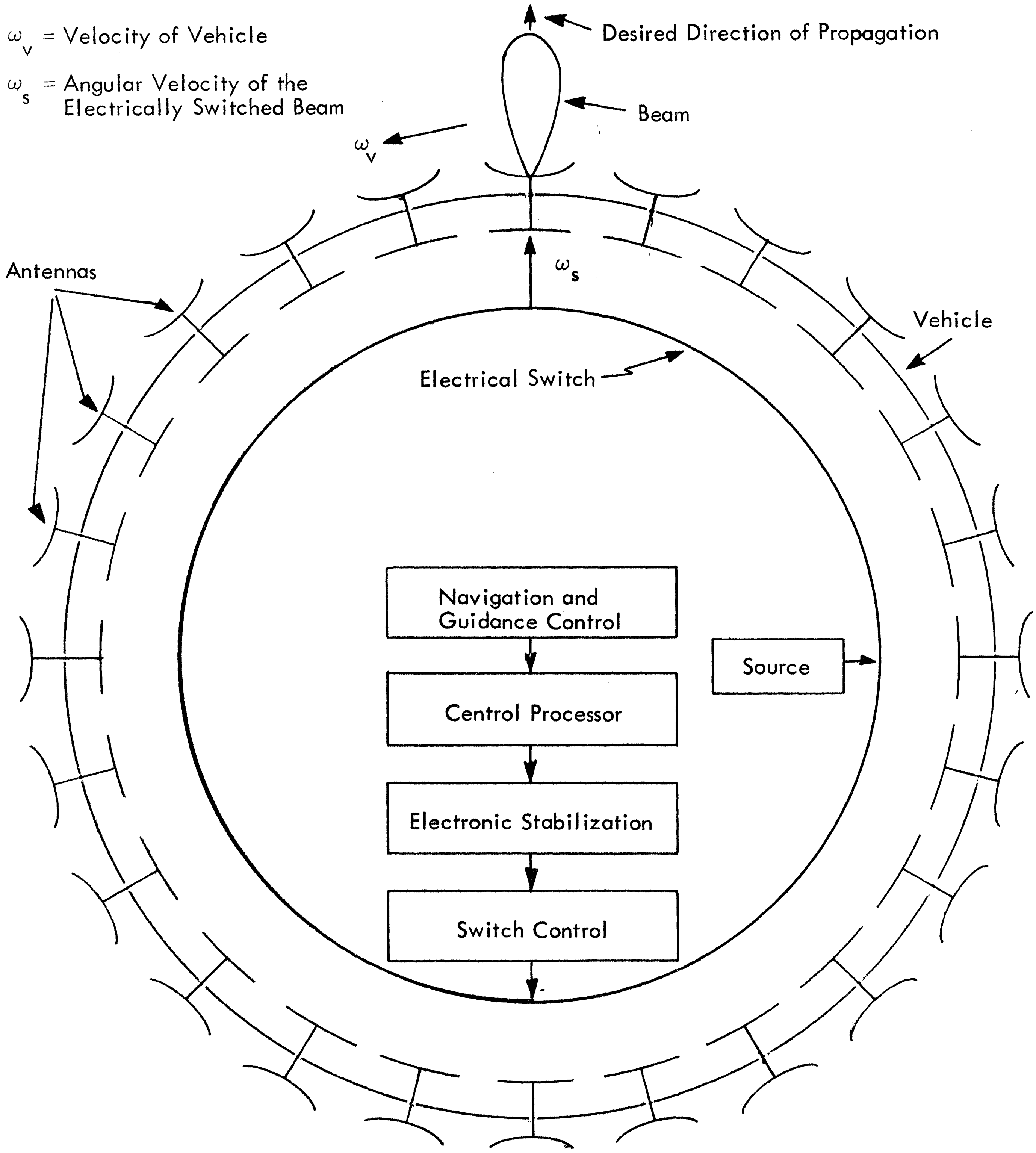

Figure 2-22. Antenna Switching Arrangement For Spin Stabilized Vehicles

satellite system, is illustrated in Figure 2-23. The desired signals from the various elements of a planar array are selected by the array control. Each signal is then clipped and fed into a shift register or delay line. The desired beam is then formed by selecting the appropriate taps on the shift register or delay line. By shifting taps, the beam may be steered. Multiple beams are easy to form by increasing the number of tap connections.

The communication and telemetry processor would control the tap connections to conform to the desired beams which are described by information from the central control unit, and also control the shifting of the clipped signals.

2.7 Total Computing Requirements

A first step towards establishing the total computer requirements is to describe the future subsystem functions mathematically. As shown in the previous sections (and in Section 4 later), IBM has already begun work on this problem. This portion of the problem requires a mathematical representation of subsystem operation. The second step is selecting a multiple-function mission and defining the critical milestones as a function of time so that subsystem computing requirements and the overall system computing requirements can be obtained. However, as long as the subsystem and overall system computer requirements are contained in parametric form, it is a simple matter to relate these to a particular mission.

With the subsystem and overall system computer requirements parameterized, the multiprocessing configuration problem begins. It appears desirable to bound the parameters of the subsystems to obtain an upper bound on the computing requirements. To obtain a "good" bound, deep insight into the future subsystem functions and overall system operation related to a large class of missions is required.

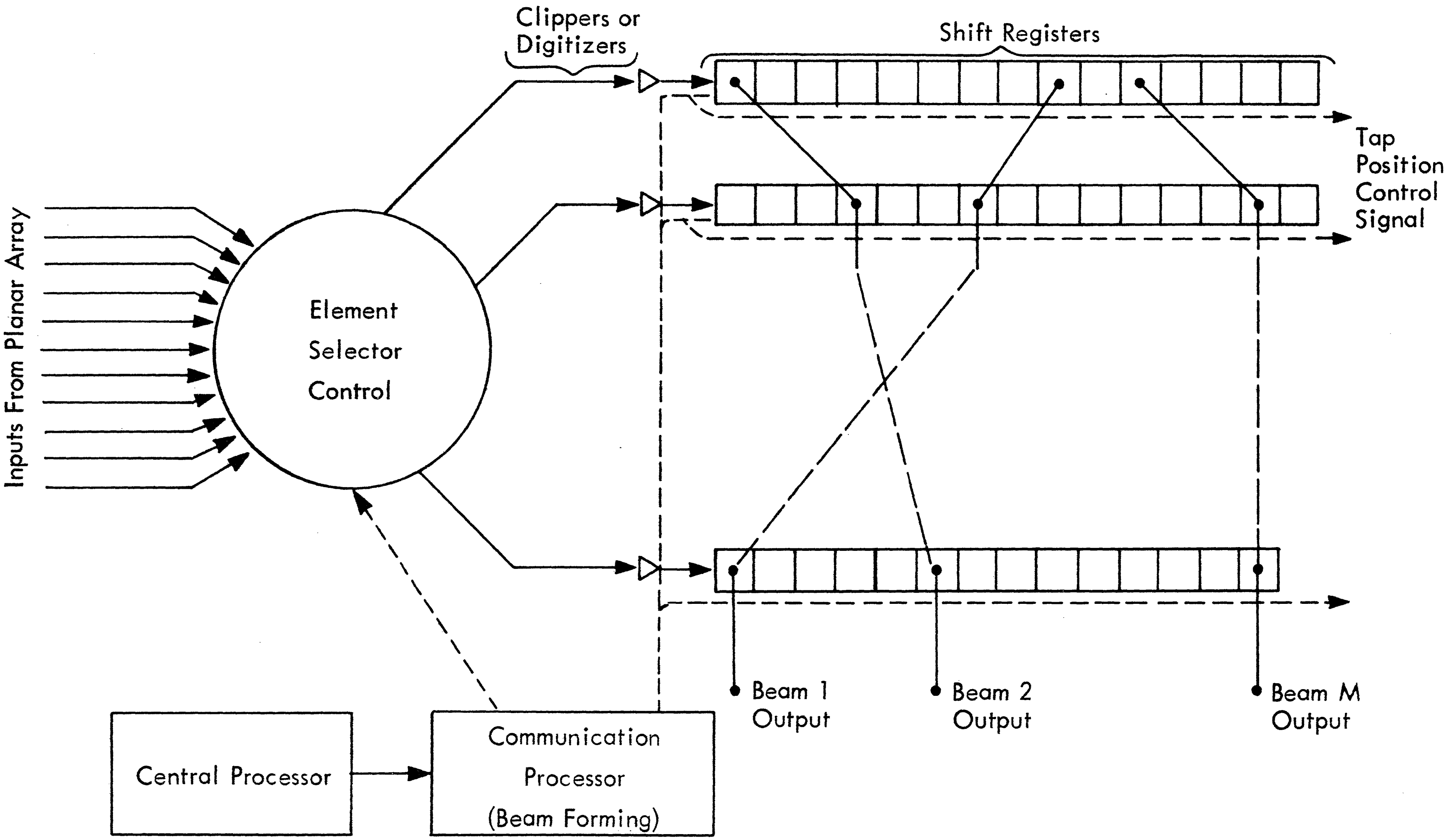

Figure 2-23. Illustration of DIMUS Approach to Beam Forming Using A Planar Array

IBM's experience in this area demonstrated in this section should be of significant value. A good test for the usefulness of the bounded reference system is to check its performance for one or more representative missions.

2.8 PN-Switching Considerations

It is felt that PN-switching, a new approach for providing an efficient and reliable switching, seems to offer all that is needed in both central switching and I/O switching. During the study, PN techniques will be considered as a new tool in switching theory that may be applied to multiprocessing systems. Here is a brief description on the theory of PN-switching from the digital communication standpoint.

There are two basic PN switching techniques which we will define:

a. Synchronous Orthogonal Switching (SOS)

b. Synchronous Quasi-Orthogonal Switching (SQS)

Synchronous Orthogonal Switching (SOS)

SOS uses orthogonal binary codes. It permits distortionless transfer of digital and analog data between any two terminals and between cascades of terminals. A connection is established by electronically setting a sending-end and receiving-end M sequence to the same initial state. This requires shifting in a number, closing feedback loop and supplying clock signals. Here it is possible to switch any sending-end terminal directly to any one or more receiving terminals. The switching can be performed at sending line or at receiving line or at both places. In addition groups of lines can be switched to groups of lines, low-pass signals to low-pass, low-pass to band-pass, band-pass to band-pass.

The multiplexing in SOS is linear and can be accomplished in a Kirchhoff adder. If the message is analog, sampling at the PN rate is required; if digital, Mod-2 addition is required. It is preferable that the sampling rate or bit rate in the case of digital data be synchronous with the PN orthogonal code. However, for low data rates orthogonality can be maintained for all practical purposes without synchronizing binary data.

A major advantage of SOS in the case of voice channel switching is that cross talk is reduced to random noise and hence the severe requirements on crosstalk may in fact be non-existent here.

Since the switching technique is synchronous bi-orthogonal codes can be used reducing the bandwidth of the switching circuits for a given number of lines. The channel activity factor should be taken advantage of here by keeping PN carriers off when message is not present. This can easily be done. This will reduce the dynamic range in the multiplexer just as in FDM.

Synchronous Quasi-Orthogonal Switching (SQS)

In SQS information is switched with a certain degree of distortion which is a function of the number of signals multiplexed and the number of PN bits per sample or message bit. Here for a given fidelity at the receiving lines and for a given number of PN bits per sample, only a prescribed number of lines can be switched simultaneously.

If digital data is switched then each pulse can be detected, reshaped and transmitted to the next switch. In fact, with detection and pulse regeneration, SQS can be distortion free (except for quantization noise) and can be as effective as SQS with the added advantage that the PN signals can be multiplexed by majority logic. Thus, all logic operations become Mod-2 additions and majority logic. The SQS is efficient when extremely large numbers of channels are to be switched, and when only a relatively small percent are active at any one time.

Most efficient use of SQS would require taking advantage of the channel activity factor, i.e., PN carrier transmission only when information is present. This can easily be done by gating the PN signal into the majority logic only when the message is present.

Just as in SOS, the phase of the incoming signals can be used to reduce the number of signals.

Once again, SQS, just as SOS, permits switching from few lines to many, or vice versa, bandpass, low-pass to low-pass, low-pass to bandpass, and directly without bandpass signals.

The major advantage of SQS over SOS is that all operations are digital (except for integrator).

An interesting problem here is to find sequences whose majority logic combination yield a minimum of mutual interference at the output of the receiving line. Since synchronous operation is used, it may be that one can find such sequences which minimize interference.

SQS appears to be extremely attractive for data switching applications. It should also be recognized that the same sequence generators can be used for SOS and SQS systems. In addition, the multiple feedback paths of the PN generators can be used to obtain other switching functions.

In SOS and SQS, the PN codes can be chosen such that if channel failure occurs, at worst, there will be some residual noise in the useful channels. Increased loading under heavy traffic conditions can cause gradual degradation of a random noiselike nature. The annoying crosstalk will, however, not increase.

In SOS and SQS, there is an inherent privacy. Security can be obtained automatically in SOS and SQS by using very long codes.

Finally, in SQS, if random link signals are used it is necessary to synchronize only those terminals that transfer data between each other. It is expected that synchronization will not help much in reducing interference if the code lengths are very long.

Preliminary Mathematical Theory of PN Switching (PNS)

If we have a maximal length sequence generator of length P, then $P = 2^N - 1)$ pseudo-noise bits can be generated before the sequences repeat. There are N cyclic permutations of the sequence whose crosscorrelation coefficient is (-1).

Let T be the duration of a message symbol (i.e., analog sample or bit). Then the orthogonal sequence of N bits spans the symbol duration T. We now assign two PN-orthogonal subcarriers to each channel. There are N such subcarriers and hence N such channels. We now will assume that the PN subcarriers are periodic with period T or N and that these are synchronous (i.e., driven by a common clock).

Let $f_i(t)$ represent the messages on each channel. A clock reading the messages at the instant t generates the sample values $\{f_i\}$ $i = 1, 2, \ldots, N$, where f_i is the value at that instant in the ith channel. This value is held on a pulse stretching circuit for a duration T when another sample is obtained.

Let $f_i(t)$ $i = 1, 2, \ldots, N$ be the set of orthogonal codes of duration T and N bits long derived from the sequence generator. During the interval T the ith subcarrier output when modulated by the sample f_i has the value $f_i(t)$. If we now add the amplitude modulated PN subcarriers during the interval T we have, as the output

$$\psi(t) = \sum_{m=1}^{N} f_n \, \phi_n(t) \qquad 0 \leq t \leq T \tag{2-15}$$

Another set of sample values taken at the next sampling instant yields another set of values for $\{f\}$, the $\psi(t)$ having the same form.

A switching operation from the transmitting line r to the receiving lines p, i.e., r → p is defined as

$$T \vec{\phi}_{nr}(t) \, \overleftarrow{\phi}_{kp}(t) \, dt = \delta_{nk}^{(rp)} \quad \begin{array}{l} = 1 \text{ when } n = k, \ r \quad p \\ = 0 \text{ when } n \neq k \end{array} \tag{2-16}$$

where $\vec{\phi}_{nr}$ represents the transmitted carrier at line r and $\overleftarrow{\phi}_{kp}$ represents the reference orthogonal carrier at receiving line P. $\delta_{nk}^{(rp)} = 1$ represents the connection of line r → p via PN signal r. We assume the orthogonal components to be normalized. Equation 2-16 will be written symbolically as

$$\vec{\phi}_{nr} \quad \overleftarrow{\phi}_{kp} = \delta_{nk}^{(rp)} \tag{2-17}$$

For the sake of simplifying the notation, assume that $\{\phi_n\}$ $n = 1, 2, \ldots, N$ corresponds to the sending line 4 - 1, 2, ... , N and that switching is accomplished at the receiving line. In practice this can be accomplished either way or both ways.

The connection r → p will transfer the data component of ψ from the rth sending terminal to the pth receiving terminal. This operation can be expressed as

$$\vec{\psi} \cdot \overleftarrow{\phi}_{rp} = \sum_{n=1}^{N} f_n \int_0^T \phi_n(t) \, \phi_{rp} \quad dt \quad \begin{array}{l} = f \text{ when } n = r \\ = 0 \text{ elsewhere} \end{array} \tag{2-18}$$

In order to specify a connection $\log_2 N$ bits must be used to initialize the maximum length sequence generator. Thus, by simply presetting the sending and receiving PN generator to the same state, analog or digital message transfer from one line to another can be accomplished simply.

The same basic theory is applicable to quasi-orthogonal signals as well except that information transfer is not distortionless. In voice, the distortion will be of a random nature rather than intelligible cross-talk. For the same power, the latter is much more objectionable. Referring back to Equation , in the quasi-orthogonal case, the desired output f_r will have a random component added and the channels which have no signal will also have a random component. However, the random component is reduced by the processing gain of the code.

It is a simple matter here to switch a group of lines simultaneously to another group. Here each bit in the orthogonal sequence constructed from the same set except at N times the speed. If T is the duration of a message symbol, then (t/N) is the duration of a PN bit. If each PN bit of duration (T/N) is multiplied by an orthogonal sequence (preferably in the same set) of bit duration (T/N^2) then the resultant PN sequence will also be orthogonal. Thus the second PN generator has N times the speed of the first. As an example, the pair of sequences (1, -1), (1, 1) are orthogonal. The sequences (1, -1, -1, 1), (1, 1, -1, -1), (1, -1, 1, -1) (1, 1, 1, 1) are also orthogonal. These are constructed by substituting for each bit in the short sequence the two bit sequences. In terms of implementation, these codes can be obtained by combining synchronously Mod-2, and the output of slow speed and high speed maximum length sequence generators. Although orthogonal, the resulting sequences are no longer maximal length.

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Section 3

MULTIPROCESSING SYSTEMS

There are two competing trends in modern data processing, the trend toward large, complex, centralized systems and the opposite trend toward small, simpler decentralized systems. Advocates of the centralized systems point to the growing need for communication between computers and the resulting ability to gather large quantities of data at one place. Then, they argue, the most efficient, most reliable, most flexible way to handle this large mass of data is by multiprogramming and multiprocessing. Decentralization advocates point to the convenience of small computers and argue that a simple computer can do a simple task more economically.

At the present, the trend is to develop systems with multiple remote terminals, each "time-sharing" the centralized system. These systems assume the existence of multiprogramming so that each terminal may operate as though the others do not exist and it alone controls the computer.

3.1 General Considerations

Multiprocessing systems emphasize the characteristics of reliability, efficiency, performance capability to differing extent depending on the application.

3.1.1 Multiprocessing Features

3.1.1.1 Efficiency

Fuller use of equipment can be brought about by "time-sharing" and "space-sharing." Processors, switching equipment, input-output controls and memory address registers may be time-shared. Core memories, disk files, and to some extent, magnetic tapes and printers may be space-shared.

3.1.1.2 Reliability

Multiprocessing systems provide increased reliability by: sharing duplicate equipment, automatic switchover and recovery facilities, built-in error detection and correction, prevention of error by automatic supervisory control and performance monitoring, the use of diagnostic programs to catch marginal conditions, and improved maintenance facilities on the computer site. Many of these capabilities are available in uniprocessing systems but receive added emphasis in multiprocessing systems. In general, the large volume of operation on multiprocessing systems makes increased reliability necessary but also provides economic feasibility by sharing costs over many tasks.

Sharing of Duplicate Equipment

An efficient centralized system can use duplicates of each item of equipment to share the total operational load. Good design consists of balancing the system so essential peak activities can be handled even if some part of the system fails. In normal operation the additional capacity can be fully absorbed doing routine work. If necessary, additional work load can be brought in via communication links to keep the system fully loaded.

Automatic Supervisory Control

Many programming errors can be prevented or made harmless by a good supervisory program. A major source of programming errors is I/O handling. The programmer's task is simplified on I/O since the details are handled by the supervisory program. In addition, program loops, memory address errors, and other program errors are prevented from tying up the system.

Automatic Switchover and Recovery Facilities

A price paid for multiprocessing and multiprogramming is the complexity of the system. The Executive, Scheduler and other control programs are difficult to write. When an error occurs, it may affect several programs.

It is essential to provide backup and recovery capability in the system. In case of subsystem failure, it is relatively easy to provide for switching in another subsystem.

It is recognized that reliability is an important consideration in the design of any space system, and the reliability benefits obtained through the use of multiprocessing must be defined in depth in order to fully define the technical limitation of this technology for space application. In this respect IBM will apply the resources of research in order to define and evaluate an advanced multiprocessing configuration with the following reliability operational factors:

- Diagnostic capability
- Fault isolation and correction
- Reconfiguration capability upon failure
- Information protection during parallel operations
- Computational backup requirements.

3.1.1.3 Performance

There are several performance measures that can be used as an evaluation criteria. A measure of performance commonly used is the time required for a system to completely process the job load. For simple types of measurements this is a satisfactory measure, but it is inadequate for comparisons of performance on different job loads. Some jobs are inherently short and others are long. A more satisfactory measure is the efficiency with which the hardware components are used.

The performance of a system may or may not be improved by multiprocessing or multiprogramming operation depending upon a number of factors. Significant among these factors are the amount of storage available to the system, the number of autonomous devices in the system, and the mix of the functional requirements being handled in the system. Efficiency increases with increasing load up to the point where competition for storage creates excessive amounts of storage management activity. This property has several important implications for system design. The operating system should continuously monitor its operation, and automatically reduce its level of multiprogramming, by setting work aside, if it detects an overload condition. Second the system must have adequate execution store if the full benefits of multiprogramming or multiprocessing are to be realized.

Research conducted at IBM also considered a provision to allow the time-sharing of multiprocessing system when turnaround time was of great importance. Experiments using this capability demonstrated that time-sharing has significant advantages even when turnaround and response times are not important.

3.1.1.4 Capability

Some tasks require high speed processors, large memory capacity, many tape units, large disk files or multiple path communications. These tasks cannot be done effectively on small systems. Sorting of large files, design automation programs, and telemetry problems are three examples where large memory and many I/O units are required.

In some applications, faster computation is more important than better organization or parallel computation. Several problems requiring speed increases 100 times as great as present computers such as: ballistic missile and satellite launch and the meteorological research problems. It is felt that large, fast memories would be required for these applications.

Faster computation or increased thruput capacity is possible on some problems by using multiple processors to run the same program.

3.1.2 System Requirements

3.1.2.1 Priority and Interrupt Control

Multiprogramming and multiprocessing cannot be done effectively without the ability to establish priority between programs and to interrupt operations when events of higher priority demand attention.

Present systems provide multi-level interrupt ability so that an interrupt causes direct transfer of control to the location of the program which is to handle the interrupt.

Several types of interrupt may be provided. Some types are:

1. I/O interrupts; at the completion of an assigned task by a peripheral, arrival of an I/O request or perhaps from an operator at a console.
2. Program interrupts may occur due to arithmetic overflow, the periodic signal from an elapsed time clock or an interrupt instruction in the program itself.
3. Malfunction interrupts are those from an I/O malfunction such as a broken tape, card jam, or parity error, or major equipment malfunctions such as memory parity, error or failure of a subsystem to respond when interrogated.

Each interrupt must be accepted and eventually handled. If too many control interrupts come in and some are lost there is loss of input or output information. To prevent this, interrupts must be handled rapidly with the highest priority items handled first. Queues of interrupts are built up on each requested facility under the control of a supervisory program in the operating system.

The requirements of service are taken into account in assigning priority levels. Highest priority must go to serious malfunctions such as power failure, next to error causing malfunctions such as memory parity error, then to peripherals which must be serviced within a limited time, and finally to requests from the processor itself.

3.1.2.2 Central Switching

Requests for memory access can come from many processors. It could come from Data Sampling Processor, Communication and Telemetry Processor, Power Management Processor, Guidance and Navigation Processor, Check-Out and Satellite Monitor Processor. Many of these requests may be urgent and must be handled on a priority basis.

Crossbar Switch

The crossbar switch or cross point matrix provides multiple-wire paths from M requesting modules to N accepting modules. Each path may be on the order of 50 to 100 lines wide in order to carry full memory words, memory addresses and control signals. Sometimes cables are unidirectional so that another set of 50 to 100 lines is required in the opposite direction. (Figure 3-1)

Crossbar switches were first developed for telephone switching and were electromechanical. The crosspoint matrix switches used in computers have been

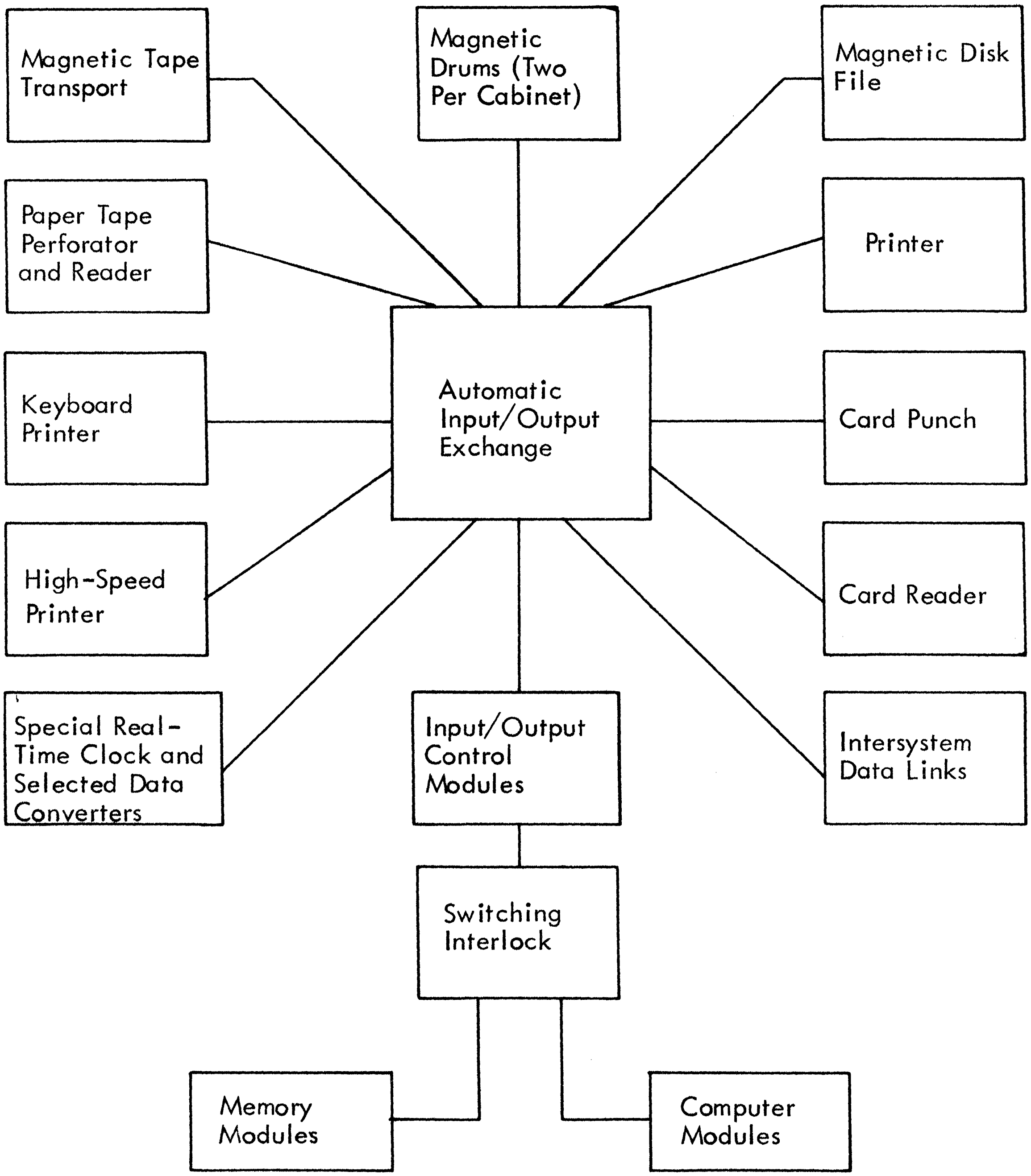


Figure 3-1. A Multiple-Computer System for Command and Control

transfluxor magnetic cores or diode AND gates. Tremendous flexibility is obtained in a crosspoint switch since any processor can connect to any memory in a fraction of a microsecond. Also, there are numerous ways to provide a function in case of failure in any part of the system. Duplication of the crosspoint matrix is required in a system requiring maximum reliability.

Multiple-Bus Connected

A lower cost system than the crosspoint matrix is provided by use of separate busses connecting a processor (or input-output channel) to one or more specific memories (Figure 3-2). The saving is due to the reduction in the number of switch points. Each computational module may have a direct connection to private storage in addition to sharing common storage. This technique is less flexible than the crosspoint matrix but may be completely adequate in a system designed for a specific range of applications. If connections are easily changed physically, it is much less expensive to set up new paths by plugging rather than by switching.

Time-Shared Bus

The lowest cost switching system, Figure 3-3, takes advantage of the availability of memory registers in each processor and each memory module to allow the bus system to be time-shared. Instead of connecting a processor and memory continuously, they are connected for only the time required to transfer information. This technique is especially useful if memory accesses can be preplanned such as in sequential instruction fetches and data fetches. More than one channel can be used if the number of accesses required becomes large enough to slow down the total access time. Multiple bus channel control, priority switching requirements and the need for two-way transmission add to control complexity.

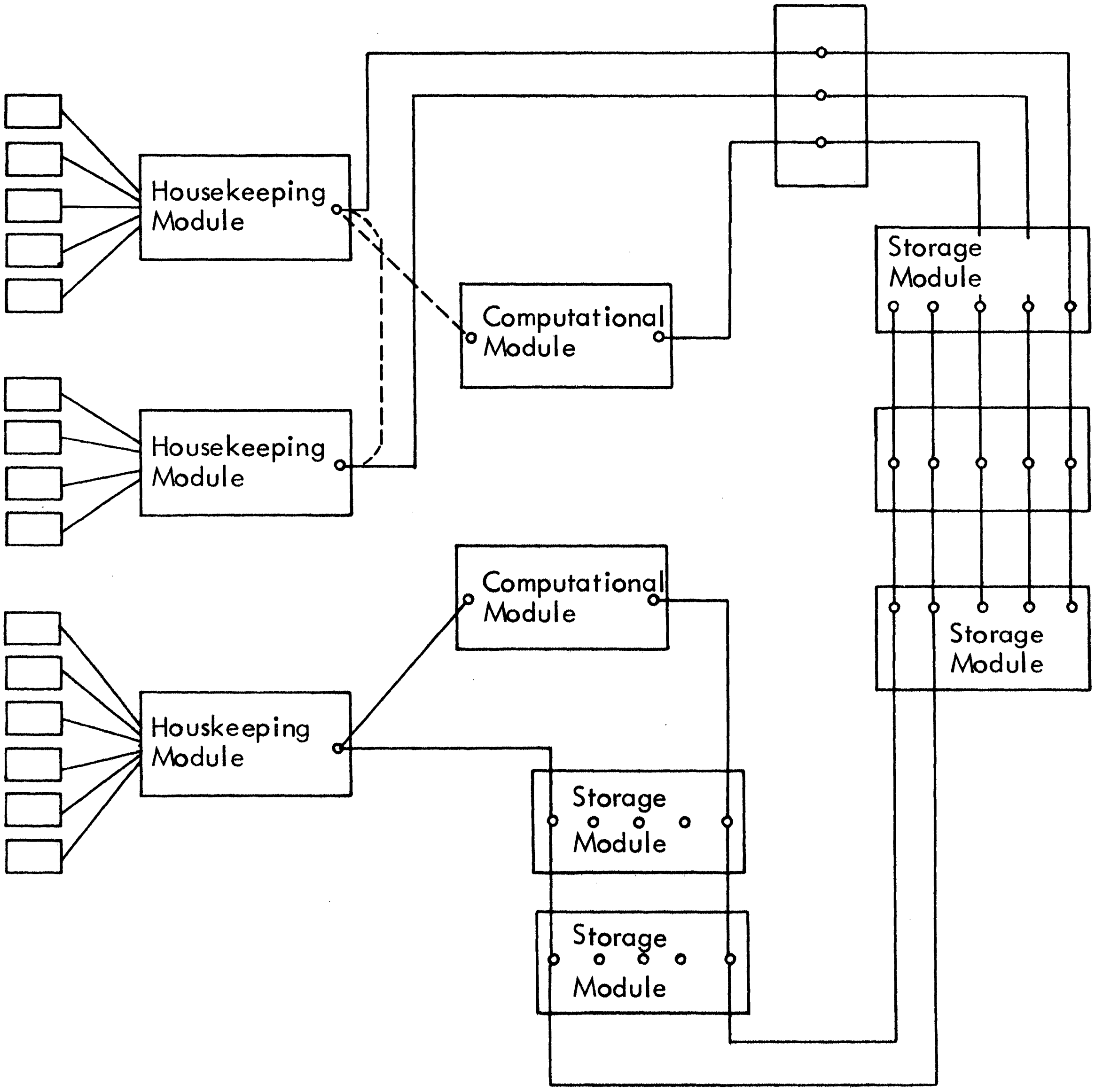


Figure 3-2. Two-Computer System With Private and Common Storage

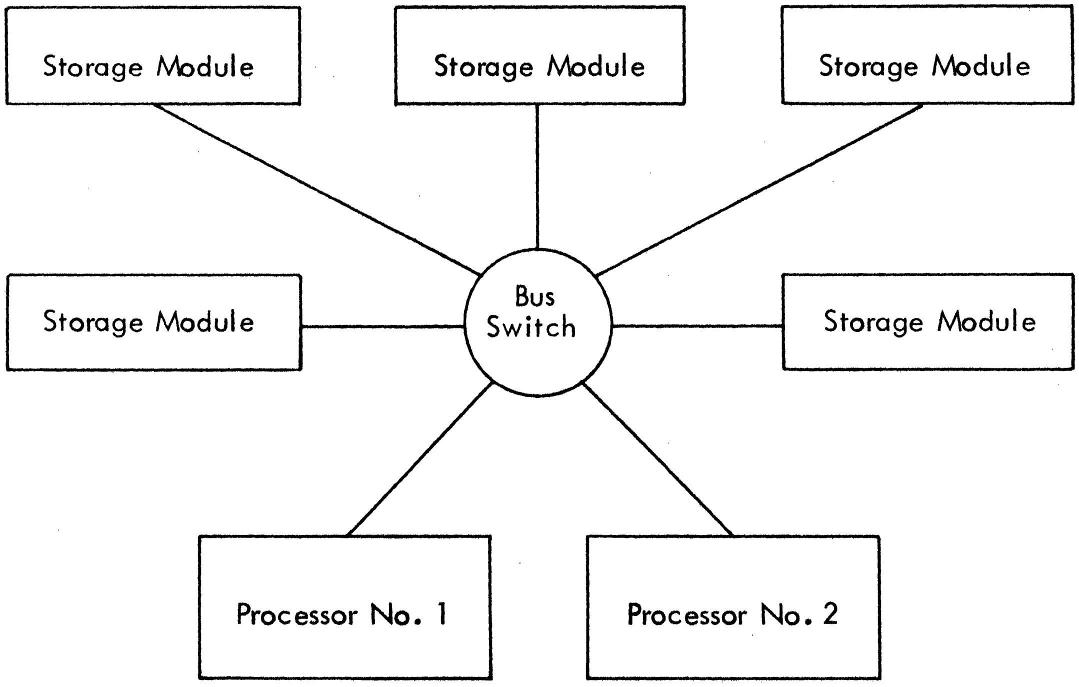


Figure 3-3. Time-Shared Bus Assignment

3.1.2.3 I/O Switching and Control

Asynchronous Input-Output Requirements

Multiprocessor systems must operate in an uncontrollable environment, accepting information from many sources simultaneously, processing it and dispatching the processed information to many points.

Earlier systems attempted to provide synchronous switching systems to cope with these problems but had no way to handle the frequent, probabilistic stacking up of control or information requests. It was found necessary to provide for queuing of requests and buffering of information flow.

Control Word Philosophy

Instead of providing hardware registers to store addresses and counts for the control of peripheral channels, the control words are stored in a fast core memory and one set of hardware registers are time-shared in a rapid, asynchronous sequence. When a memory access request is made, the required control words are pulled from memory to the control registers and used to set up the necessary switching paths. These control words are then updated by adding one to the address, deducting one from the word count, modifying status conditions, and replaced in memory.

Queuing of I/O Requests

Systems loading is controllable to some extent by refusing to start new tasks until previous tasks are completed.

Three types of queues are maintained in a multiprocessing system:

1. New tasks not yet started.
2. Tasks partially completed, awaiting completion of a specific peripheral operation.
3. Tasks being run on one of the system processors.

In addition, there may be "standby" tasks such as diagnostics, program check runs, or billing runs which can be pulled in whenever processor loading permits.

Queuing is controlled by an operating system program called the Peripheral Control Program, Input-Output Supervisor or a similar title. These programs maintain peripheral control tables containing essential information about each program and each piece of equipment.

I/O Processors

It is possible to use the central control computer as an I/O processor. In a multiprogrammed system with powerful interrupt and sufficiently rapid storage and retrieval of status information, time-sharing of the central control processor becomes feasible. When all registers are in thin-film memory, for example, program interruption can be accomplished by merely changing the program counter to a new address so that no time penalty is paid for an interrupt.

3.2 Design Considerations

A configuration of a multiprocessing system is shown in Figure 3-4. In this figure, a central control computer on board the space vehicle controls five special purpose processor units. These processor units are sampling data, communication and telemetry, checkout and channel monitor, guidance and navigation, and power management processors. All of these processors can have access to the central control computer by interrupting it, and a priority interrupt will be assigned to them to regulate and control the multiple access problem.

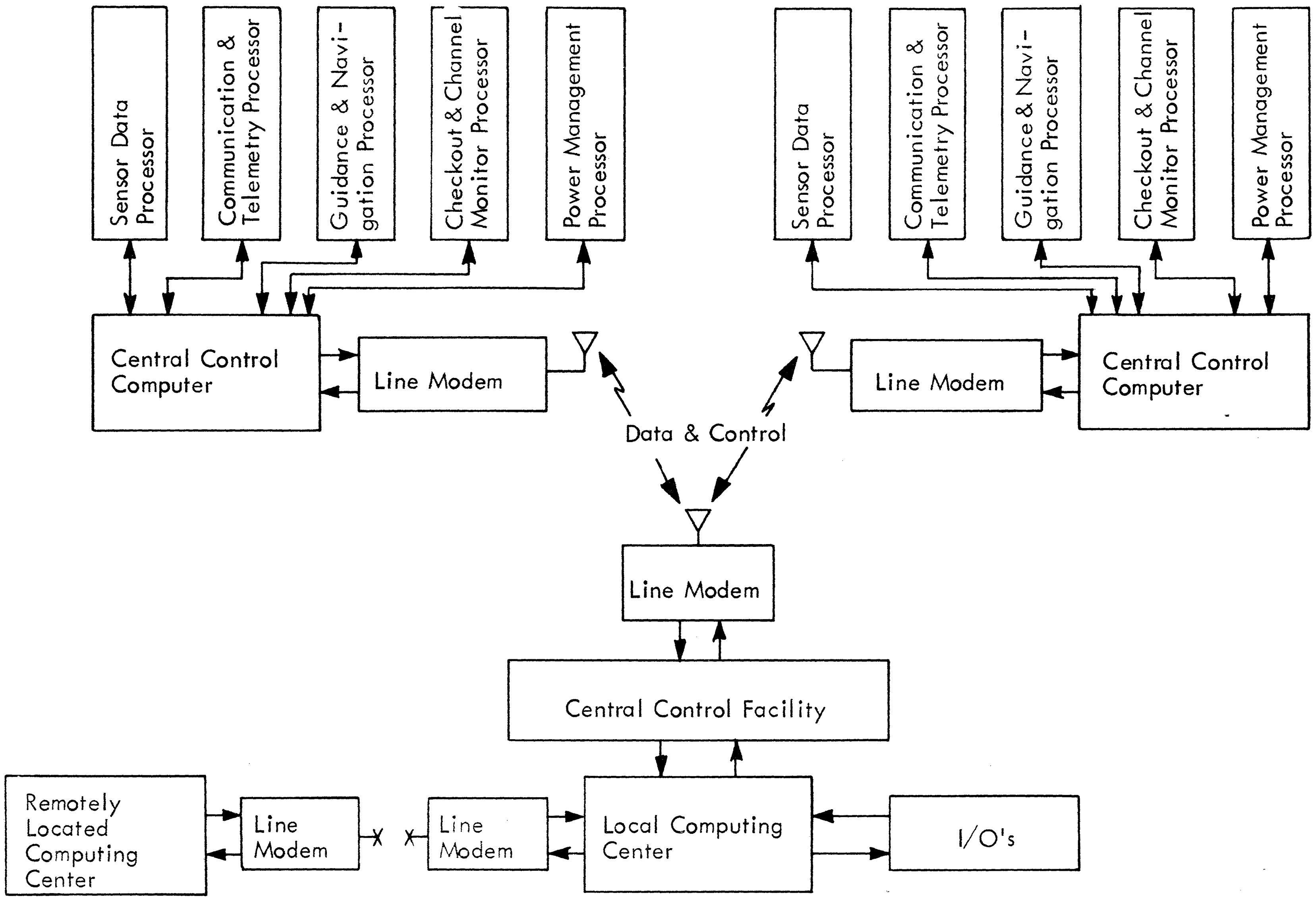


Figure 3-4. Multiprocessing System For a Multifunctional Space Satellite

The central control computer is linked with on-ground computer and also with other central control computers in the orbit via the satellite link. A hardwire connection will be established by any two computing centers through central control facility using link modems. This configuration provides a truly centralized multiprocessing network. Such system is capable of replacing any of the five processor units by the central control computer in the case of a catastrophic failure in any one of them. Also, when the central control computer ails, it will be replaced by any other central control computer whether it is in the orbit or onthe ground. In addition, the multiprocessing network provides the flexibility to share the load among various central control computers. This can easily be done through the satellite links, and also through the communication facilities on the ground. The latter is possible since the local computing center in the central control facility is connected to other remotely located computing centers via private and switched networks (see Figure 3-4).

During the study, tradeoffs between the amount of processing on board the multifunctional space satellite and channel capacity will be established. Clearly, a large quantity of raw data will be generated on board the satellite and the critical problem is to filter out the redundant data and transmit the essential information. This is highly important since channel capacity is limited and thus only certain bit rate (thruput) can be transmitted down. For this reason and many others, we prefer to look upon the multiprocessing system not strictly from the computer standpoint but also from the communication end. Most of the concepts in communication theory and information theory are applicable to a system of this nature, and therefore we intend to bridge the gap that exists between computer and communication techniques.

In the design of multiprocessing system, we shall consider various techniques that are conventional in nature and are used extensively in the logic area of digital computers. In addition, several advanced techniques of switching theory which are presently not in use will be considered. As an example, partitioning theory seems to offer unique features if applied to the design of a multiprocessing system. This has not been done yet, and we intend to utilize it as one possible approach of synthesis. For example, any of the processor units in Figure 3-4 can be looked upon as a sequential machine of finite internal states. The behavior of such a machine can be described quantitatively in the following excitation matrix.

$$\begin{array}{c|cccc|}
 & I_1 & I_2 & \text{- - - - - - - -} & I_m \\
\hline
S_1 & S_{11} & S_{12} & \text{- - - - - - - -} & S_{1m} \\
S_2 & S_{21} & S_{22} & \text{- - - - - - - -} & S_{2m} \\
\cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & & \cdot \\
\cdot & \cdot & \cdot & & \cdot \\
S_n & S_{n1} & S_{n2} & \text{- - - - - - - -} & S_{nm}
\end{array}$$

The left-hand column indicates the present state, the top row,the present input and the entries give the corresponding next state. For example, if the input I_1 is applied to state S_1, the resulting next state will be S_{11}. In general

$$(S_i)\, I_j \rightarrow S_{ij}$$

The concept of partitioning theory may be applied to the synthesis of this machine to decompose it into several parallel submachines each independent of the other. Certain requirements will have to be met in order to accomplish this goal. But we feel, once we embark on the study program and are able to define the functions of each processor unit, then the internal states could be defined in terms of binary variables and hence the partitions could be constructed to possess a substitution property. Such a property is essential for parallel decomposition, and it lends itself to a design that is modular, reliable and easy to maintain. For example, the machine described in the above matrix will result in the configuration shown in Figure 3-5. Note in this figure how each subsystem is completely independent from the other ones, in the sense that there are no feedback paths from one subsystem to the other. This means a malfunction in any subsystem does not cause total system failure. The impact of this approach becomes evident if one thinks in terms of system maintenance and the time it takes to locate and detect the malfunction. Thus, the problem of optimizing the reliability and maintainability of a multiprocessing system can be accomplished in the most efficient and economical way. Furthermore, the approach makes it very easy to provide self-repairing capabilities which are of vital importance, especially to systems of this nature that are used on board unmanned multifunctional space satellites. To get the feel for the reliability improvement using these new techniques, consider Figure 3-5 again, and let the failure rates of the parallel decomposed subsystems be designated by

$$\lambda_1, \lambda_2, \text{----------}, \lambda_n$$

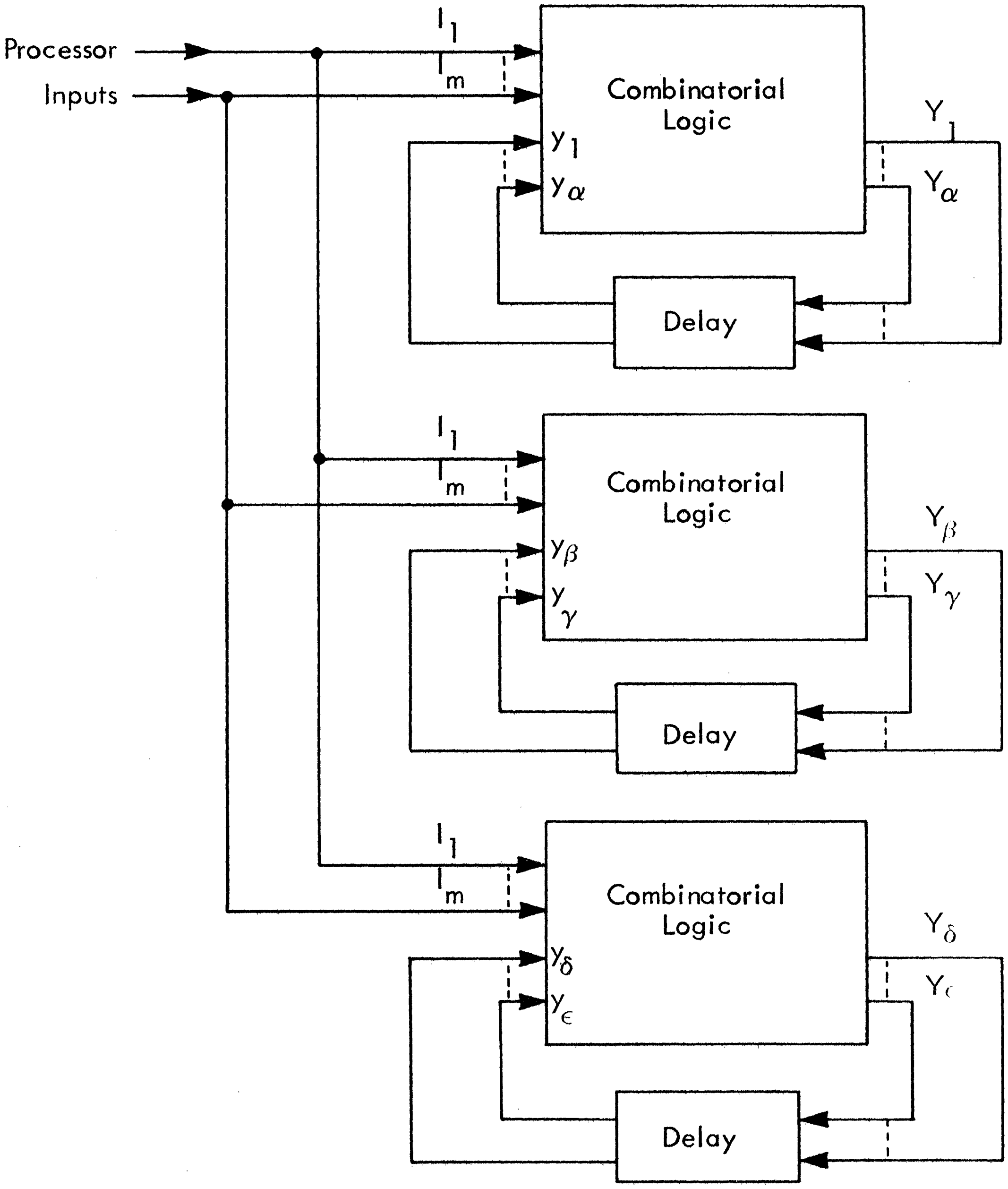


Figure 3-5. Decomposition of Processor Units Into Parallel Subsystems

The total failure rate of a processor unit will be simply

$$\Lambda = \frac{\lambda_1 \lambda_2 \lambda_3 \text{ - - - - - - - } \lambda_n}{\lambda_1 + \lambda_2 + \text{ - - - - - - } + \lambda_n}$$

$$= \frac{\prod_{i=1}^{n} \lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{3.1}$$

The MTBF will thus be

$$\frac{\sum_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} \lambda} \tag{3.2}$$

If these subsystems were not in parallel, the failure rate of the processor unit would be the sum of all the failure rates, i.e.,

$$\Lambda = \lambda_1 + \lambda_2 + \text{ - - - - - - } + \lambda_n = \sum_{i=1}^{n} \lambda_i \tag{3.3}$$

From equations 3.1 and 3.3, the failure rate can be improved by a factor of

$$\frac{\left(\sum_{i=1}^{n} \lambda_i\right)^2}{\prod_{i=1}^{n} \lambda_i}$$

Consequently, the overall reliability will exponentially increase by this factor, i.e., the increase in the overall reliability of a processor unit over a period t is

$$\exp - t\left(\frac{\prod_{i=1}^{n} \lambda_i}{\sum_{i=1}^{n} \lambda_i} - \sum_{i=1}^{n} \lambda_i\right)$$

$$= \exp - t\left[\frac{\prod_{i=1}^{n} \lambda_i - \left(\sum_{i=1}^{n} \lambda_i\right)^2}{\sum_{i=1}^{n} \lambda_i}\right]$$

It follows from the above that we at IBM envision several advanced techniques that can be developed and applied to the problem of synthesizing a multiprocessing system that is most efficient, reliable, easy to maintain and economical. The above approach has been one example of many that we will consider during the study program.

In addition to developing new techniques that will lend themselves to a reliable design, tradeoffs between hardware and processing time (software) will be established. For example, if it is found that to compute a given operation the "time" is not critical, then a program will be allowed to perform the computation. On the other hand, hardware units such as a counter will be provided to perform the computation at the fastest speed (shortest time) possible. All this and many other tradeoffs will be considered during the study in order to successfully optimize the design for maximum reliability.

Thus far, we have touched briefly on the system reliability and showed one way to improve it using partitioning theory concepts to design the system. The other trend in reliability is the protection of information during parallel operations within the system and also when it is transmitted from the satellite to ground via the satellite link. Clearly, to protect the information in the channel is of the utmost importance. There are several methods that can be applied to resolve this problem. Most of these techniques utilize cyclic codes to encode the raw data on board the satellite and decode it when it is received by the central control facility for error detection and correction. Here we shall consider other codes during the study program and try to develop new techniques of applying them. Codes such as Hadamard, orthogonal, biorthogonal and simplex which have special properties will be among many that we will study.

In Section 2, a discussion on error controls has been presented in some detail. There, we show how the information can be protected against both random and burst noise, since the noise is the principal agent of causing errors.

Next is to show a method of establishing memory capacity for efficient multiprogramming. One way to establish such criteria is as follows:

Let $k_1, k_2, \ldots\ldots, k_n$ be total number of instructions required to execute N programs simultaneously. Further, let $M_1, M_2, \ldots\ldots, M_n$ be the storage capacity in bits required to store the above instructions respectively. Therefore, maximum memory capacity "M" required is given by

$$M = k_1M_1 + k_2M_2 + \ldots + k_nM_n$$

or

$$M = \sum_{i=1}^{n} k_iM_i$$

If the word length is w, the memory capacity in words becomes

$$\frac{1}{w} \sum_{i=1}^{n} k_i M_i \leq 2^{\ell} \tag{3.4}$$

where ℓ is the number of bits in the address register.

Since it is a good practice to make

$$\frac{1}{w} \sum_{i=1}^{n} k_i M_i = 2^{\ell}$$

Therefore,

$$\ell = \log_2\left((\frac{1}{w} \sum_{i=1}^{n} k_i M_i \right) \tag{3.5}$$

Thus, the hardware complexity "C" for the memory and the related address register is given by

$$C = \sum_{i=1}^{n} k_i M_i + \log_2 \left(\frac{1}{w} \sum_{i=1}^{n} k_i M_i \right) \tag{3.6}$$

If the memory cycle (speed is T microseconds, then the time required to execute N programs sequentially; is

$$\frac{T}{w} \sum_{i=1}^{n} k_i M_i \tag{3.7}$$

To execute N programs in parallel, the time required is simply

$$(k_m M_m) \frac{T}{w} \tag{3.8}$$

Where the product $k_m M_m$ represents the longest instruction within N programs, i.e., the instruction that requires maximum storage capacity in bits.

Clearly, one can conclude from equations 3.7 and 3.8 that

$$\frac{T}{w} (k_m M_m) << \frac{T}{w} \sum_{i=1}^{n} k_i M_i$$

or

$$k_m M_m << \sum_{i=1}^{n} k_i M_i$$

This last result proves that parallel multiprogramming systems are by far more efficient than sequential multiprogramming systems. Consequently, our approach during the study will emphasize on parallel multiprogramming operations, but still consider the merits of sequential operations. This by no means is to be interpreted that we will be restricted to these two trends. Our intention is to evaluate the present techniques and develop new tools that are by far more powerful than the existing ones.

In addition to what has been already mentioned, several other system configurations will be considered during the study program. For example, real and virtual systems will be among those system configurations that we will evaluate, since they seem to offer the features that are significant to future long-lived multifunctional space satellites. Therefore, the following discussion will consider these two types.

A real system is a configuration of real duplicate hardware units operating in a multiprocessing mode, and a virtual system is a conversion of the real system operating in a multiprocessing or sequential mode. A virtual system shown in Figure 3-6 consists of n virtual computers, each of which has an enlarged set of resources. In particular, each has a directly addressable storage, address fields in its instructions, instruction and index registers in its processing unit, and the required number of channels. The storage size is extremely large and the registers are correspondingly wide.

In all other respects we may take each virtual machine to be conventional in nature. Its processing unit has a conventional set of instructions, it has an interrupt system, problem/supervisor mode provisions, memory protect features, etc. In short, the virtual system is best thought of as a set of n machines, each like the real machine but with more storage and channels than any installation could really afford to have.

From this point on, the system organization is quite conventional. The conversion mechanism provides none of the required user functions, and these are supplied in an operating system for the virtual machine. Finally, there grows up a body of applications program. Here the operating system and applications are written directly for the real system. Thus from an architectural point of view, the difference between the virtual system approach and the ordinary one lies in the insertion of the conversion mechanism between the real system and the main body of programming.

The resources managed by the conversion mechanism are the processing unit or units, channels, and core storage. We turn now to the question of how this management is done.

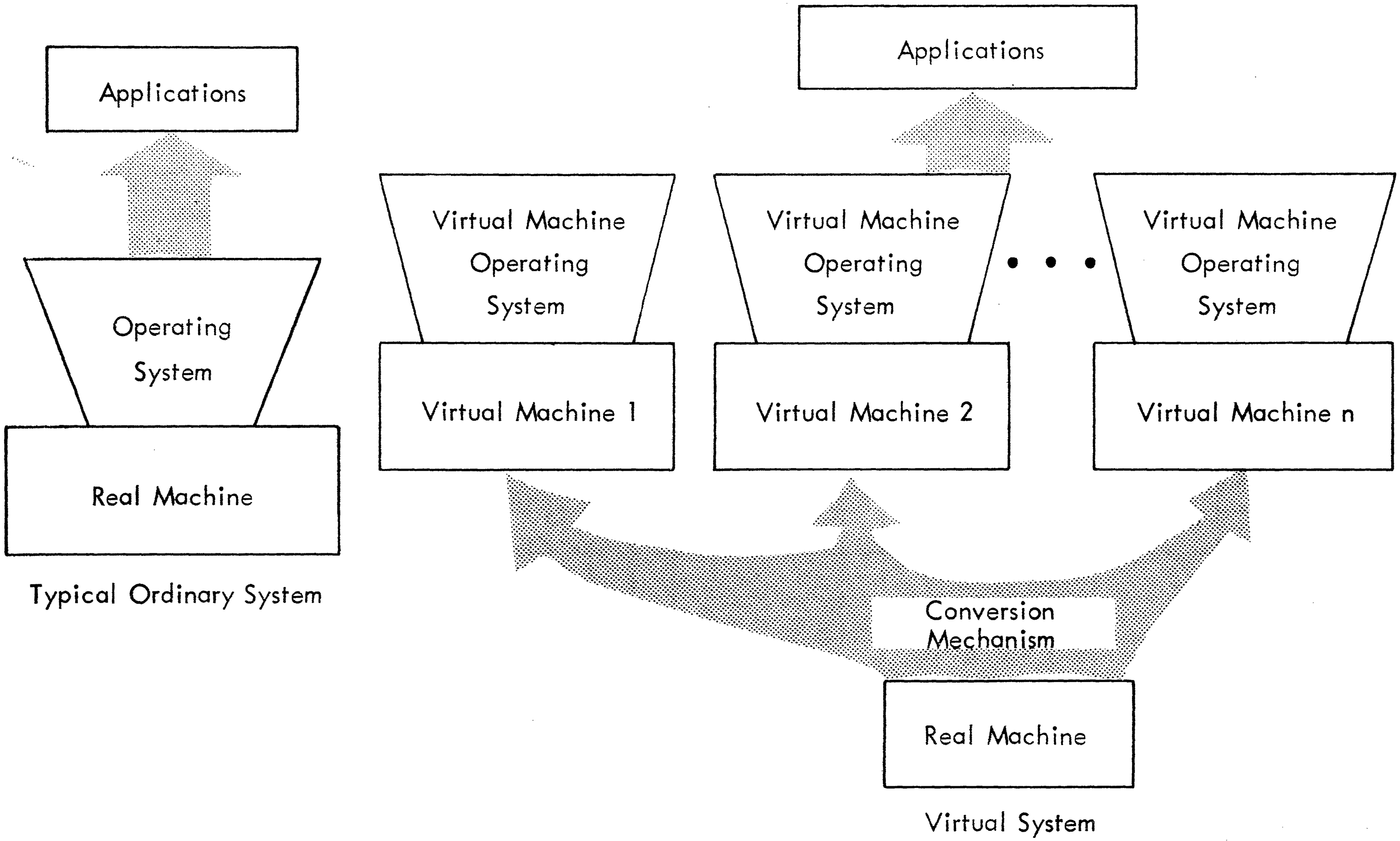


Figure 3-6. Overall Arrangement of Virtual System

Consider a list of resources that include a number of virtual processors, a larger number of virtual channels, and a very large number of virtual core blocks, and if one imagines computational activity to be proceeding in the virtual system, then at any moment of time some of the items in the list will be in use by the computation and the remainder will be idle. In the real system there are a certain number of real processors, real channels, and real core blocks. The conversion mechanism assigns these real resources to play the roles of the virtual resources required by the computation. It monitors the computational activity as it proceeds, so as to know when virtual resources become required by the computation, and updates the set of assignments accordingly. Thus, the resource management consists of dynamically mapping the set of real resources into the set of virtual resources, hopefully in such a way that it is at all times mapped into that subset of virtual resources which can best allow the computation to proceed.

It is envisioned that multifunctional space system applications will require a multiprocessing configuration that is some combination of real and virtual systems. Therefore, it is proposed that in the formulation of one or more advanced multiprocessing configurations that the feature of each system type be incorporated to the fullest extent in order to satisfy all operational factors.

Section 4

METHODS OF APPLYING INFORMATION THEORY TO ANALYSIS AND SYNTHESIS

The theoretical work presented here is extracted from a paper entitled "A Statistical Theory of Automatic Observing Systems" by H. Blasbalg (IBM) which appeared in the publication, (September 1963), of the Second Symposium on Adaptive Processes as part of National Electronics Conference, Chicago, Illinois, October 28-29, 1963. This symposium was sponsored by the IEEE Discrete Systems Theory Committee. The author, Dr. H. Blasbalg, will be the over-all program manager of this contract if IBM is selected as the successful bidder. This work shows methods of applying the concepts and techniques of information theory to systems analysis and synthesis and therefore addresses the problem areas of this RFP.

In this theory, we recognize that a partially specified information system must necessarily consist of certain operators that are arbitrary; that is, the choice of the operators cannot result from a mathematical formalism. We call these transformation operators. The output of a set of transformation operators on an input signal is a set of new signals derived from the input, each of which contains a property of interest. Once the transformation operators (or the measurable properties) have been defined, we can develop a mathematical theory which describes the information system.

The theory is realized by defining a set of operators (at the output of the transformation operators) which have the same functional form except for a parameter. We call these characteristic function or statistical operators. The output of a statistical operator is "one" if a measured property takes on a particular value and "zero" otherwise. In some situations, an input signal combined with the transformation and statistical operators appears to an observer as a Markov System having certain transition probabilities. An input signal is discussed only in terms of its effect on the information system. In the Markov case, the results of measurement are the transition probabilities of the system.

We also recognize that the choice of a criterion for deciding if the results of measurement come from a known system or not, is arbitrary. We therefore attempt to choose an observable which has a consistent physical interpretation in the light of statistical decision theory and information theory. The importance we attach to the mathematical formalism is judged by the properties of the observable which the theory allows us to measure. Furthermore, we require that the basic statistical structure of the information system description remains invariant with respect to complete or incomplete a priori information concerning the class of signals. This requirement permits incompletely specified information to evolve into complete knowledge when the a priori distribution of the signal class is statistically stable. The results of measurement can then be reflected back into the information system for subsequent optimization.

There are three types of information systems and operations that are generally of interest.

First, we will consider an information system where the statistics of the signal class are known completely including the a priori probability of occurrence of each member of the class. The result is an indication as to which member of the class occurred. This is the pure detection problem often encountered in digital communication. An optimum decision procedure will be defined as one which minimizes the average error probability. (This concept can be generalized to minimize the average "loss." However, our criterion is adequate.) It is also applicable to those problems where the validity of one of a set of possible physical laws is being tested.

The second information system considered is where all signals and their statistics are known except for the a priori probability of occurrence. This is incomplete information and is often encountered in radar detection problems. Under certain conditions, estimates of the a priori distribution can be made and complete information can be obtained.

The third information system is also incompletely specified. In this case, we do not know either the signal statistics or the a priori probabilities. We also do not know the number of members in the class. Here, we must find if the measured data is caused by a signal previously observed, or if it is a new data. If new, this data must represent optimum estimates of the new signal statistics. Here, the frequency of occurrence of each decision must also be measured. Once again, under suitable conditions of the signal environment, complete information can also be obtained. This is the most common problem encountered in space missions.

We will show that the system description is invariant with respect to complete and incomplete information. Furthermore, it will be shown that the mathematical model will lead to estimation and decision procedures whose performance can be predicted prior to measurement; a necessary requirement if the theory is to be useful. The information system description is adaptive in the sense that it reflects the results of previous measurement in subsequent observations to improve system performance--possibly attaining optimum performance. Finally, it will become evident that the results of the theory will be consistent with information theory and statistical decision theory.

This work should serve as a useful guide for the application of theory and concepts to problems in space telemetry, spectral analysis, pattern recognition and other fields of present and future interest.

INFORMATION SYSTEMS THEORY CONCEPTS

This section develops a generalized mathematical model of representing information systems. The discussion covers those operations which must be specified by the observer (used in the most general sense) prior to measurement. The discussion also treats those operations which are independent of the measurable properties. A statistical decision procedure for recognizing "new" and "old" information which has very desirable characteristics is defined.

4.1 Mathematical Transformation Operators

The output of a transformation operator F corresponding to an input signal (or effect) $f(t)$ is a new function $F\left[f(t)\right] = F(t)$, which contains the property of interest. For example, the signal $f(t)$ can be considered as the output of a particular sensor in a telemetry or in a biological system. If F is a narrow band spectral filter, then the filter output $F(t)$ is the spectral component of the sensor output $f(t)$. The transformation operator F can be linear or non-linear, information preserving or information destroying. If we define a set of transformation operators $F = \{F_j\}$; $j = 1, 2, \ldots, K$; all of which operate on the r^{th} sensor output $f_r(t)$, then we have the set of outputs

$$F_j f_r(t) = F_{jr}(t); \text{ Where } j = 1, 2, \ldots, K, \tag{4.1}$$

containing the K properties of interest.

4.1.1 Orthogonal Transformations

Of particular interest is where F represents a set of linear orthogonal filters. It is emphasized, however, that the general results are just as applicable to nonorthogonal, nonlinear transformations. If the impulse responses of the filters are of duration T, the present output represents the orthogonal coefficients of the past T seconds of the input function. In the time domain, the output of a filter at time t is given by the convolution integral

$$C(t) = \int_0^t f(\tau)\, g(t-\tau)\, d\tau, \tag{4.2}$$

where f(t) is the input and g(t) is the response of the filter to a unit impulse. It should be clear from Eq. (4.2) that the mirror image of the impulse response weights the past of f(t) according to g(t).

Let

$$g(t) = \phi_n(T-t); \quad 0 \le t \le T \tag{4.3}$$

then,

$$c_n(t) = \int_0^t f(\tau)\, \phi_n(\tau + T - t)\, d\tau \tag{4.4}$$

When t = T,

$$c_n(T) = \int_0^T f(\tau)\, \phi_n(\tau)\, d\tau \tag{4.5}$$

Thus, the present output is the n^{th} orthogonal coefficient of the input which occurred T seconds previously.

4.1.2 Characteristic (or Indicator) Function Operators ("Statistical Operators")

To obtain the information in a form which is independent of the transformation operator, the filter outputs are expressed in terms of characteristic functions. If $C_{nr}(t)$ is the n^{th} orthogonal coefficient at time t when the input is $f_r(t)$, then the result of measuring ΔG is

$$\Delta G_{inr} = \Delta G_i F_n f_r(t) = \Delta G_i C_{nr}(t) = \begin{cases} 1 & \text{if } x_{i-1} < C_{nr}(t) \leq x_i \\ 0 & \text{otherwise} \end{cases} \qquad i = 1, 2, \ldots N \tag{4.6}$$

Hence, at any given instant of time, the value of an orthogonal coefficient can lie in one and only one quantum interval. The transformation operators $\{\Delta G_i\}$ map every input function into a volume element in the space discussed. In particular, a finite set of orthogonal filters combined with the $\{\Delta G_i\}$ operators maps a finite set of input functions into a set of volume elements. The mapping is universal and applicable to any physically realizable set of input functions. Furthermore, since the volume elements are disjoint the mapping goes over into an orthogonal representation, which is desirable.

To summarize, an information system is defined by a set of transformation operators or measured properties

$$F = \{F_j\};\ j = 1, 2, \ldots K; \tag{4.7a}$$

on an ensemble of signal sources,

$$f = \{f_r\};\ r = 1, 2, \ldots M. \tag{4.7b}$$

The result of measuring F is a set of numbers,

$$Ff_r = \{F_j \cdot f_r\} = \{F_{jr}\} ; \; j = 1, 2, \ldots K. \tag{4.7c}$$

The result of measuring the set of characteristic function operators

$$\Delta G = \{\Delta G_i\} ; \; i = 1, 2, \ldots N, \tag{4.7d}$$

on the j^{th} property is,

$$\Delta G F_j \cdot f_r = \{\Delta G_i \cdot F_j \cdot f_r\} = \{\Delta G_i \cdot F_{jr}\} ; \; i = 1, 2, \ldots N, \tag{4.7e}$$

where,

$$\begin{aligned} \Delta G_i \cdot F_{jr} = \Delta G_{ijr} &= 1 \text{ when } x_{i-1} \leq F_{jr} < x_i ; \\ &= 0 \text{ when } F_{jr} \text{ lies outside.} \end{aligned} \tag{4.7f}$$

Hence,

$$\begin{aligned} \Delta G_m \, \Delta G_n &= 1 \quad ; \; m = n \\ &= 0 \quad ; \; m \neq n \end{aligned} \tag{4.7g}$$

Eq. (4.7g) expresses the fact that properties m and n are not simultaneously compatible.

4.1.3 Measurement of Statistics of an Ergodic Ensemble of Signals

Let us now assume that the information signals f(t) are members of an ergodic ensemble. We can therefore obtain the ensemble statistics by using sufficiently long, non-overlapping pieces of waveform of duration T. From a practical point of view we can postulate that the statistics are stationary for time intervals that are much greater than the measurement time required to obtain stable statistics.

In order to measure the distribution of each coefficient independently, we require at most $N \log_2 S$ bits per orthogonal coefficient, where S is the number of members of the ensemble used to measure the distribution and N is the number of values of C. The system complexity grows as $KN\log_2 S(K)$, which represents the required system capacity to measure the independent signal coefficients. The sample size is a function of the number of quantum levels since we will require more samples to obtain a stable estimate when the coefficient occupies many quantum levels. To measure the joint statistics we require a large capacity binary counter of capacity $S(N^K) > N^K$ and one counter per cell. This leads to a system complexity approaching $N^K \log_2 S(N^K)$, which is an extremely large number and far beyond practical considerations. The amount of data required is also prohibitively large.

One attempts to choose the orthogonal coefficients (in general, the coordinates of the process) so that they are statistically independent. For stationary Gaussian processes, which are of particular interest practically, this can be achieved (at least in principle). The success of the orthogonalization procedure (i.e., the choice of coordinates) not only leads to a practical system, but also to a useful mathematical model from which a system can be synthesized and its performance predicted. In those cases where the statistical independence of the coordinates of the process is not evident, one is often forced to treat the problem as if independence existed. The defined operations still make sense although one may not be able to predict system performance precisely. In certain applications, the transformations will not be orthogonal and maybe highly non-linear. Hence, it will not be possible to go from measurement back to the effect in a one-to-one manner. However, in many useful applications information may not be contained in the detailed signal structure, but only in a set of defined properties or transformations.

4.1.4 The Measurement of the Discrete Probability Density of Independent Orthogonal Coefficients

Let S be the number of realizations of duration T which are used to measure the discrete probability density of the r^{th} sensor output $f_r(t)$. Let n_{ij} be the number of the S-measured realizations corresponding to the j^{th} orthogonal filter which falls in the i^{th} quantum level. Then,

$$\lambda_{ij}(S) = \frac{n_{ij}(S)}{S} = \frac{1}{S} \sum_{\nu=1}^{N} \Delta G_{ij}(\nu) \tag{4.8}$$

where $\lambda_{ij}(S)$ equals the empirical probability that the j^{th} orthogonal coefficient will have a value which falls in the interval (x_{i-1}, x_i). The probability is one that $\lambda_{ij}(S)$ approaches the mathematical probability λ_{ijr}, $S \to \infty$ and,

$$\sum_{i=1}^{N} \lambda_{ijr} = 1 \tag{4.9}$$

Corresponding to each orthogonal filter there exists a discrete probability density

$$\{\lambda_{ijr}\}, \quad i = 1, 2, \ldots, N \tag{4.10}$$

measurement of the corresponding property. Thus, there will be one element in each row which will be unity; the others will be zero. The λ -array is the average of Δ G over S realizations. The sum of the elements in each row is unity.

4.1.5 Mathematical Formulation of Pure Detection - Completely Specified Information Process

Let $\{\Lambda_r\}$ for r = 1, 2, . . . ,M, represent a set of M signal statistics shown by the array of numbers in Eq. (4.10). Also, Λ (S) is the result of measurement of an unknown signal in the class based on S realizations. The results of the observation is a set of a posteriori probabilities

$$\xi(\Lambda_r;\Lambda(S)) = \frac{\xi(\Lambda_r)\, p\{\Lambda(S);\Lambda_r\}}{\sum_{j=1}^{M} \xi(\Lambda_j)\, p\{\Lambda(S);\Lambda_j\}}$$

$$r = 1, 2, \ldots, M \qquad (4.11)$$

where

$\xi(\Lambda_r)$ = the a priori probability of signal data or system (or state) Λ_r;

$p\{\Lambda(S);\Lambda_r\}$ = the probability density of the measured results Λ (S) on condition that these originate from signal or system (or state) Λ_r.

For the case where the coordinates of the process and the realizations are statistically independent, as assumed here,

$$p\{\Lambda(S);\ \Lambda_r\} = \prod_{j=1}^{K} p\{\Lambda(S);\ \Lambda_{jr}\} \qquad (4.12)$$

and specifically,

$$P\{\Lambda(S); \Lambda_{jr}\} = \frac{S!}{\prod_{i=1}^{N} (\lambda_{ij} S)!} \prod_{i=1}^{N} \lambda_{ijr}^{[\lambda_{ij} S]} \tag{4.13}$$

$\lambda_{ij} = \frac{n_{ij}(S)}{}$ = relative number of measured realizations whose j^{th} coordinate falls in the i^{th} quantum interval.

λ_{ijr} = the theoretical or previously estimated probability that the j^{th} coordinate of the r^{th} signal will fall in the i^{th} quantum interval.

The optimum decision procedure for choosing the origin of the data $\Lambda(S)$ is, decide Λ_r, if

$$\max\{\xi(\Lambda_1, \Lambda(S), \ldots, \xi(\Lambda_r, \Lambda(S); \ldots, \xi(\Lambda_M, \Lambda(S))\} = \xi(\Lambda_r, \Lambda(S)) \tag{4.14}$$

The decision procedure equivalent to (4.14), is the following: The origin of the data is Λ_r if,

$$S\sum_{j=1}^{K} \sum_{i=1}^{N} \lambda_{ij} \log \frac{\lambda_{ijr}}{\lambda_{ij\ell}} > \log \frac{\xi(\Lambda_\ell)}{\xi(\Lambda_r}; \quad \begin{matrix} \ell = 1, 2, \ldots, M \\ \ell \neq r \end{matrix} \tag{4.15}$$

From Eq. (4.15), note that when the data originates from Λ_r, $\lambda_{ij}(S) \rightarrow \lambda_{ijr}$ almost certainly as $S \longrightarrow \infty$. Thus,

$$H_{r\ell}(S) = \sum_{j=1}^{K} \sum_{i=1}^{N} \lambda_{ij}(S) \log \frac{\lambda_{ijr}}{\lambda_{ij\ell}} \rightarrow \sum_{j=1}^{K} \sum_{i=1}^{N} \lambda_{ijr} \log \frac{\lambda_{ijr}}{\lambda_{ij\ell}} \geq 0 \tag{4.16}$$

as $S \rightarrow \infty$, almost always. The effect of the a priori probabilities goes to zero as 1/S log $1/S \log[\xi(\Lambda_\ell)/\xi(\Lambda_r)]$ when $S \rightarrow \infty$.

It is informative to express Eq. (4.11) in the form

$$\xi(\Lambda_r; \Lambda(S)) = \frac{1}{1+\sum\limits_{\substack{k=1\\k\neq r}}^{M} \frac{\xi(\Lambda_k)}{\xi(\Lambda_r)} \exp\left\{-S\sum\limits_{j=1}^{K}\sum\limits_{i=1}^{N} \lambda_{ij}(S)\log\frac{\lambda_{ijr}}{\lambda_{ijk}}\right\}} \tag{4.17}$$

If the true state is in fact Λ_r, as $S \rightarrow \infty$ it is certain that

$$\xi(\Lambda_r; \Lambda(S)) \rightarrow 1 \text{ exponentially (as } S \rightarrow \infty)$$

and

$$\xi(\Lambda_j; \Lambda(S))_{j\neq r} \rightarrow 0 \text{ exponentially}$$

This follows from Eq. (4.16). Thus, we can conclude that the initial information as represented by the a priori probabilities influence the result of a final decision less and less as more and more experimental data is accumulated, and in the limit the influence of the initial information vanishes entirely. Hence, in the absence of a priori probability, it is reasonable to observe many realizations and to assume equal a priori probabilities. The latter assumption leads to a decision procedure whose threshold is independent of a priori probabilities and only a function of the known and measured data.

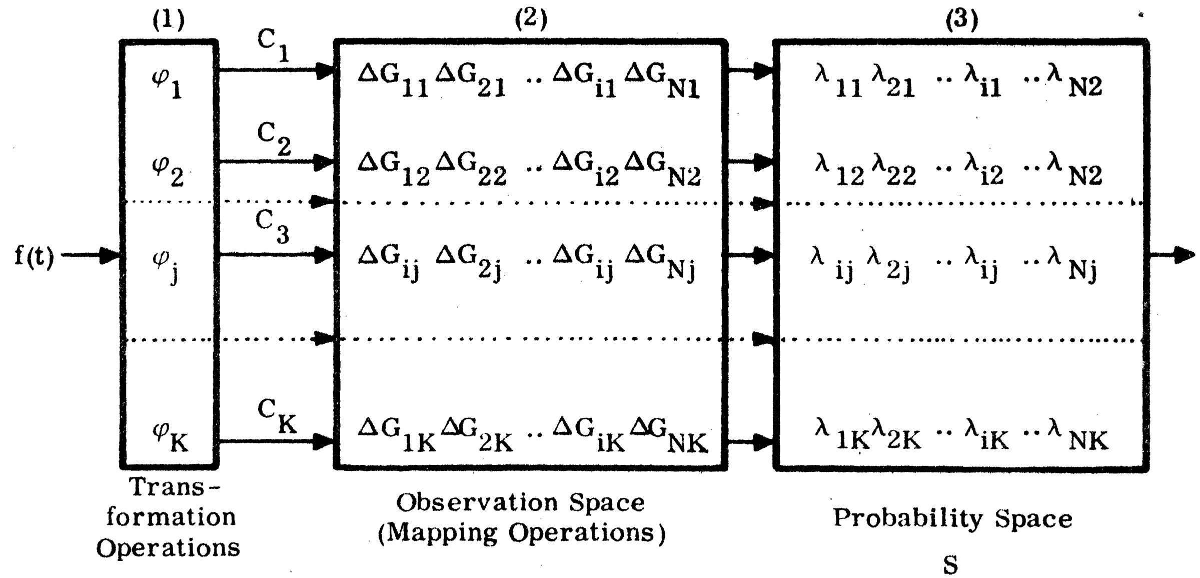
4.1.6 Case Where Some Signal Statistics are Known and Some Unknown

An incompletely specified information system where some signals are known while others are unknown will now be considered. This situation corresponding to a particular input $f_r(t)$. The result of a measurement on a particular information system is therefore the array of numbers:

$$\Lambda_r = \begin{vmatrix} \lambda_{11r}, \lambda_{21r}, \ldots, \lambda_{N1r} \\ \cdots\cdots\cdots\cdots\cdots \\ \lambda_{1jr}, \lambda_{2jr}, \ldots, \lambda_{Njr} \\ \cdots\cdots\cdots\cdots\cdots \\ \lambda_{1Kr}, \lambda_{2Kr}, \ldots, \lambda_{NKr} \end{vmatrix} \tag{4.18}$$

The sum of the elements in each row is unity; each row belongs to a single orthogonal coefficient. For each sub-system output there will be an array of numbers as shown in (4.10). If $N = K$, Λ_r has the properties of a Markov matrix, with indicated transition probabilities. Thus, to each signal f_r, there corresponds a Markov system. The results of measurement on such a system are the transition probabilities. The interesting part of this interpretation is that the formalism has lead to it; the formalism did not begin here, but with a formulation of the measurement or system description process. A system description based on the first order distribution of the input would be quite trivial; however, a description based on the first order distribution, with respect to a set of transformations on the input, is not trivial.

Fig. 4-1 is a mathematical block diagram of an information system. The $\{\phi_i\}$ represent the transformation operators; the output of the i^{th} operator is the coordinate C_i. Each row in the Δ G array corresponds to a single



$$\lambda_{ij} = \frac{1}{S} \sum_{\nu=1}^{S} \Delta G_{ij}(\nu)$$

(Average over S realization)

$$\sum_{i=1}^{N} \lambda_{ij} = 1$$

Functional Diagram of
Mathematical Theory.

Figure 4-1

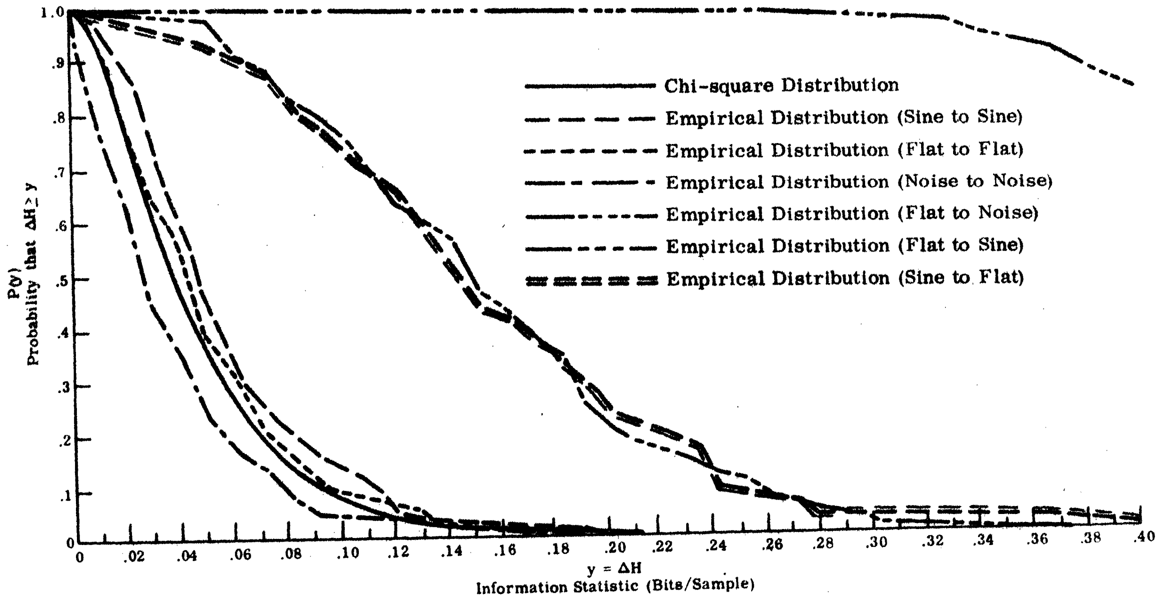


Figure 4-2

Probability Distribution of
Information Statistic
Null Hypothesis: N=5, S=64.

also implies that the a priori probabilities are not known. Let

$$\Delta h_r = S \sum_{j=1}^{K} \sum_{i=1}^{N} \lambda_{ij} \log \frac{\lambda_{ij}}{\lambda_{ijr}} - \log \xi(\Lambda_r). \qquad r = 1, 2, \ldots, M \tag{4.19}$$

The decision procedure of Eq. (4.15) is equivalent to deciding that Λ_r is true if

$$\min\{\Delta h_1, \Delta h_2, \ldots \Delta h_r, \ldots \Delta h_M\} = \Delta h_r . \tag{4.20}$$

Thus, the decision based on the likelihood ratio or a posteriori probability is equivalent to a decision procedure based on the "minimum information statistic" of Eq. (4.20).

For the case where some signal statistics are unknown we can regard this problem as similar to the case of unknown a priori probabilities. In addition, we must specify a confidence interval Δh_x with a confidence level a_x.

That is, if

$$\min\{\Delta h_1, \ldots, \Delta h_r, \ldots, \Delta h_M ; \Delta h_x\} = \Delta h_x , \tag{4.21}$$

the presence of a new signal is indicated, but when equal to Δh_r, Λ_r is present. When a new signal is recognized $\{\lambda_{ij}\}$ are optimum estimates of the statistics and can be stored. When a previous signal is detected this occurrence is counted. A careful examination of this modified decision procedure shows that it is structurally equivalent to Eq. (4.20).

Of particular importance is that the distribution of

$$2S \sum_{j=1} \sum_{i=1} \lambda_{ij} \log \frac{\lambda_{ij}}{\lambda_{ijr}} \tag{4.22}$$

for large S, is chi-square with K(N-1) degrees of freedom under the null hypothesis and approximately (2), (8) noncentral chi-square under the alternative hypothesis also with K(N-1) degrees of freedom. Confidence intervals and confidence levels can be constructed and system performance can be predicted.

4.1.7 Consequences of Finite Measurement Time

Let us consider the consequences of making measurements on information systems from a finite number of ensemble members. In particular, it is of interest to examine those probabilistic statements which can be made logically with regard to the validity of the outcome of the measurement for the cases of completely and incompletely specified information systems.

We will also consider the measurements of a priori probabilities. It should be clear that in the case where some of the signals are unknown each time a decision is made that a signal is new it is possible that this data is caused by a low probability sequence which can originate from one of the already known systems. It is also possible that such a measurement does in fact represent data from a previously unobserved system. After many measurements, there will be a certain percentage of decisions which will falsely indicate that the data come from previously unspecified information signals and a certain percentage which will in fact be caused by new events. The confidence associated with the validity of the decisions can be supported by counting the number of times each decision is made. In this manner when the relative number of decisions made favoring a particular class is significantly greater than the expected probability of error such data can be considered valid. On the other hand, all the systems specified which have a frequency of occurrence comparable to the expected errors are rejected as possibly caused by statistical fluctuations; that is, significance cannot be attached to these results. Depending on the application, such further screening can always be performed by a human observer who may have additional information at his disposal. For example, the observer might define another property, which tends to characterize a potential system which he expects to be the cause of the data, in order to see if this property is in fact associated with some of the low probability classes. Some of the concepts discussed here will now be examined with respect to the mathematical model presented.

4.1.7.1 Complete System Specification

A completely specified system was defined previously as a description of an ensemble of systems whose state probabilities are known along with the probabilities of occurrence of each system. This is the pure detection or recognition problem. It can be shown that the decision procedure which we have defined for recognizing such a system minimizes the probability of a wrong decision$^{(1)}$ for a given sample number S. The probability of making a wrong decision can be calculated for this theory.

Let

$P_S(d_r;\Lambda_i)$ = probability of the decision d_r on condition that the data $\Lambda(S)$ come from the state Λ_i,

and

$$\begin{aligned} W_{ir} &= 0 \qquad & i&=r \\ &= 1 \qquad & i&\neq r. \end{aligned} \tag{4.23}$$

The probability of making a decision on condition that the data come from Λ_i is given by

$$\beta_S(d;\Delta_i) = \sum_{r=1}^{M} W_{ir}\, P_S(d_r;\Lambda_i). \qquad i=1,2,\ldots,M \tag{4.24}$$

Then, $1-\beta_S(d;\Lambda_i)$ is the probability of a correct decision when the data comes from Λ_i. In order to obtain the probability of a wrong decision we average $\beta_S(d;\Lambda_i)$ over all states and obtain

$$\beta_S(d) = \sum_{i=1}^{M} \xi(\Lambda_i)\,\beta_S(d;\Lambda_i) = \sum_{i=1}^{M}\sum_{r=1}^{M} W_{ir}\,\xi(\Delta_i)\,P_S(d_r;\Lambda_i). \tag{4.25}$$

Thus, for a completely specified class of information systems, the error probabilities of various types can be obtained.

4.1.7.2 Incompletely Specified Information Systems

The error probabilities, Eq. (4.24) (type I error), does not require a-priori probabilities since it is conditioned relative to a particular state. If $\xi_i = 1$ in Eq. (4.25) we obtain Eq. (4.24). For a particular value d_r, Eq. (4.25) is

$$\beta_S(d_r) = \sum_{i=1}^{W} W_{ir}\,\xi(\Lambda_i)\,P_S(d_r;\Lambda_i). \tag{4.26}$$

or the probability that decision d_r is made when one of the other states occurs (i.e., type II error) is dependent on prior probabilities. Thus, $\beta_S(d_r)$ cannot be obtained without this prior knowledge. The total error probability of Eq. (4.25) can be bounded by bounding $\beta_S(d;\Lambda_i) \leq \beta_0$. Then, Eq. (4.25) is $\beta_S(d) \leq \beta_0$. In the absence of a priori probabilities we can only obtain conditional error probabilities and a bound on the average error.

When some of the statistics are unknown, Eq. (4.24) is

$$\beta_S(d;\Lambda_i) = \sum_{r=1}^{M} W_{ir}\,P_S(d_r;\Lambda_i) + P_S(d_x;\Lambda_i) \tag{4.27}$$

The conditional error probabilities relative to each known state are therefore known. Hence, we have some idea how the decision process behaves.

4.1.7.3 On the Estimation of A Priori Probabilities

We have stated previously that it is important to count each decision. Hence, if D decisions are made and d_r is the number that are in the r^{th} class, then

$$\delta_r = \frac{d_r}{D} , \qquad (4.28)$$

such that,

$$\sum_{r=1}^{M} \frac{d_r}{D} = 1$$

(4.29)

When the signals and their statistics are known, but the a priori probabilities are not, then we know the conditional probabilities $\{p_{ji}\}$, $j = 1, 2, \ldots M$; $i = 1, 2, \ldots M$, for example, the probability of d_j when Λ_i is true. The probability of the j^{th} decision follows from Eq. (4.26);

$$\delta_j = \sum_{i=1}^{M} \xi_i p_{ji}; \quad j = 1, 2, \ldots, M \qquad (4.30)$$

also,

$$\sum_{j=1}^{M} \delta_j = 1 \qquad (4.31)$$

We assume that each of the M signals is randomly chosen. If D is the total number of decisions (i.e., the number of experiments) each of which occurs with probability δ_j then the probability of making the set of decision $\left\{ d_i \right\}$, $i = 1, 2, \ldots M$, favorable to the i^{th} signal.

The maximum likelihood estimates of δ_j are given by

$$\delta_j^* = \frac{d_j}{D} \; ; j = 1, 2, \ldots, M \tag{4.32}$$

Eq. (4.30) represents M linear algebraic equations in the variables ξ_j. Thus,

$$\xi_j = \frac{1}{\Delta} \sum_{i=1}^{M} \delta_i b_{ji} , \tag{4.33}$$

where Δ is the determinant of the coefficients which is, incidentally, a stationary Markov matrix. The coefficients $\left\{ b_{ji} \right\}$ are sums and products of terms containing the $\left\{ P_{ji} \right\}$. The maximum likelihood estimate of ξ_j is simply

$$\xi_j^* = \frac{1}{\Delta} \sum_{i=1}^{M} \delta_i^* b_{ji} , \tag{4.34}$$

since any single valued function of a maximum likelihood estimate is also a maximum likelihood estimate(3). If the total number of decisions D is sufficiently large, the $\{\xi_j^*\}$ can be reflected back into the detection problem as thresholds, and the incomplete information has now evolved into one of pure detection. This is consistent with our philosophy that only "good" estimates are reflected back into a system description in order to specify it more completely.

Assume that there are two sources available for measurement, each occurring with the unknown probabilities (ξ, $1-\xi$) where ξ may be equal to unity. The observer makes D experiments and estimates that the proportion of decisions favorable to each state is (δ_1^*, $1-\delta_1^*$). It is desired to test the hypothesis $\delta_1^* = p_{11}$ and $\delta_2^* = p_{21}$ or equivalently ($\xi_1 = 1$, $1-\xi_1 = 0$). Applying the information statistic, Eq. (4.16) to this problem yields

$$\delta_1^* \log \frac{\delta_1^*}{p_{11}} + (1-\delta_1^*) \log \frac{(1-\delta_1^*)}{p_{21}} \le \epsilon_0, \qquad (4.35)$$

when the null hypothesis is satisfied. If Eq. (4.35) is not satisfied, a different source is present, for example $\xi \neq 1$. An equivalent test exists for the multidecision problem. When

$$\xi_1 = 1,$$

$$\delta_j = p_{j1}; \qquad j = 1, 2, \ldots, M \qquad (4.36)$$

and

$$\sum_{j=1}^{M} \delta_j^* \log \frac{\delta_j^*}{p_{j1}} \le \epsilon_0 (M) \qquad (4.37)$$

To test if the measured results come from sources of probabilities $\xi = \{\xi_i\}$; i = 1,2,...,M we compute $\delta = \{\delta_j\}$; i = 1,2,...M from Eq. (4.30) and construct a test of the form $\delta^* = \{\delta_j^*\}$. If

$$\sum_{j=1}^{M} \delta_j^* \log \frac{\delta_j^*}{\delta_j} \le \varepsilon_0(M) \tag{4.38}$$

then the hypothesis that the distribution of states is $\{\xi\}$, is verified; otherwise the hypothesis is rejected.

Thus, the theory developed can be reapplied to further improve recognition. If the a priori probability is of the same order as the conditional error probabilities, then clearly a sufficiently long sample is required in order to decide that the low probability events are in fact distinct events rather than just fluctuations. In this sense, the problem is equivalent to trying to measure a parameter whose value is of the same order of magnitude as the fluctuation in the measurement.

The previous discussion is also applicable to the multivalued decision problem. Eq. (4.30) can be expressed as

$$\delta_j = \xi_j P_{jj} + \sum_{i=1}^{M} \xi_i W_{ij} P_{ji} \tag{4.39}$$

Let $p_{ji} \le P_0$, for all $i \ne j$. Then,

$$\delta_j \le \xi_j p_{jj} + (1 - \xi_j) P_0 , \tag{4.40}$$

or

$$\xi_j \geq \frac{\delta_j - P_0}{P_{jj} - P_0} , \tag{4.41}$$

and

$$\xi_j^* \geq \frac{\delta_j^* - P_0}{P_{jj} - P_0} \tag{4.42}$$

For a stable environment, after a sufficient number of observations, if $\delta_j^* = Po$, then $\xi_j = 0$. Such events can only be associated with decision errors. In general, any value of δ_j^* in the neighborhood of p_o must be rejected as possibly resulting from statistical fluctuations unless a sufficient number of decisions have been made.

4.2 Empirical Probability Distribution Function of Information Statistics

Theoretical considerations indicate that the large sample distribution of the information statistic 2S H(S) (Eq. 4.16) under the null hypothesis, is chi-square with (N-1) degrees of freedom per measured property. (2), (3), (8) Under neighboring alternative hypotheses the distribution is noncentral chi-square of noncentrality, 2S $H_{r\ell}$ (2), (8) Eq. (4.16). It is essential for us to determine: "How large is large?" By examining some of the properties of the chi-square distribution of 2S H(S), for large S we can obtain some insight how to proceed.

The mean and variance of H(S) are

and,
$$\overline{H(S)} = \frac{N-1}{2S} \tag{4.43}$$

$$\overline{[H(S) - \overline{H(S)}]^2} = \frac{N-1}{S} \tag{4.44}$$

Thus, for large samples the ratio of the number of states to the number of samples is important as far as statistical stability is concerned. It therefore appears that by taking N greater than two, for example N = 5 (as we have chosen), in our measurements we can find the value of S for which the asymptotic distribution is applicable. Since only the ratio is significant, we should be able to extrapolate the results obtained for these parameters for any value of N. For measurement purposes we have chosen random variables that are distributed according to arc-sine, rectangular and Gaussian probability densities, since these have typically different shapes. In the curves shown the number of quanta per random variable is N = 5, and the sample numbers used are S = 64, S = 127.

Fig. 4-2 and 4-3 are curves of the empirical distribution functions. The odd-numbered curves represent the null hypothesis whereas the even-numbered ones contain the theoretical distribution under the null hypothesis, along with empirical measurement for the alternative hypothesis. The curve are self-explanatory. For practical applications, it is apparent that the chi-square fit under the null hypothesis is adequate. For the alternative hypothesis, the theoretical noncentral chi-square distribution was not computed. It does appear, however, that the distribution under the alternative hypothesis

and,
$$\overline{H(s)} = \frac{N-1}{2S} \qquad (4.43)$$

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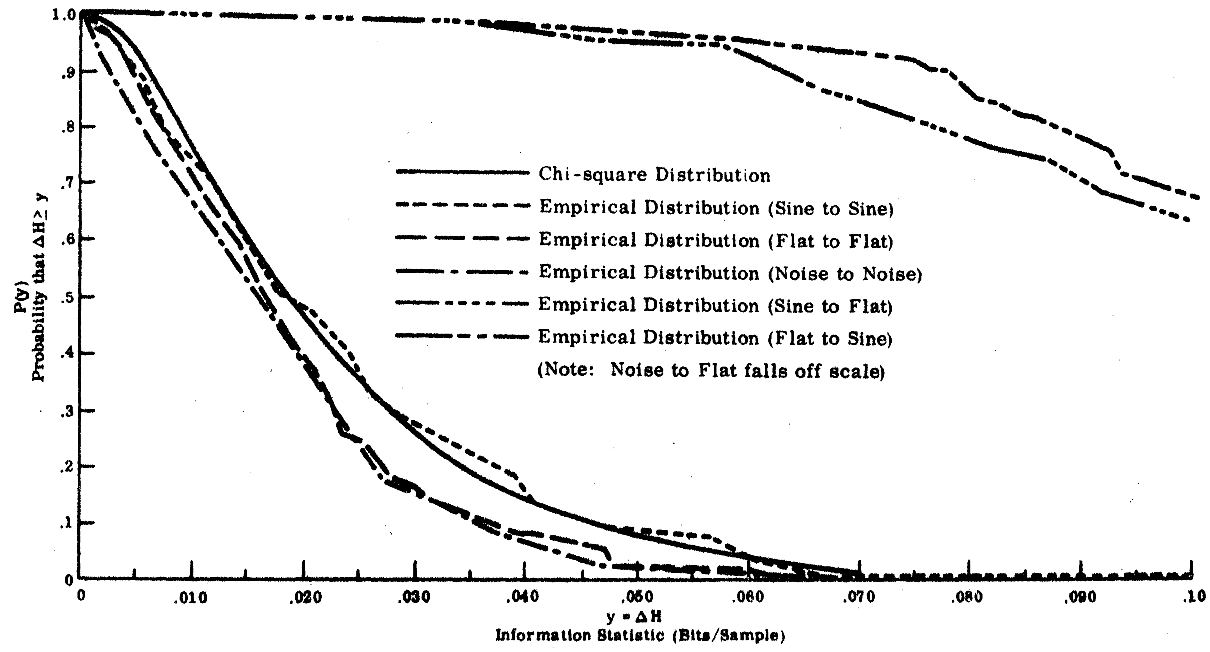

Figure 4-3

Probability Distribution of
Information Statistic
Null Hypothesis: N=5, S=128.

is a shifted version of the null hypothesis distribution. As expected, the greater the ratio of number of quanta-to-sample size, the smaller the confidence interval or the closer the fit which can be obtained for a given confidence level. Similar results were obtained for N = 8 and S = 63, 127.

4.3 Some Further Important Properties of the Observation Theory

In this section we will discuss briefly some important properties of the theory developed which have not been discussed previously.

4.3.1 Other Information Measures

There are modifications of the fundamental measure given by Eq. (4.16) which have similar properties. These measures are also positive and have an asymptotic distribution which is chi-square. Two such measures have been studies in (2), (8), and are of the form,

$$J_{rk} = \sum_{j=1}^{K}\sum_{i=1}^{N}\left[\lambda_{ijr}\log\frac{\lambda_{ijr}}{\lambda_{ijk}} + \lambda_{ijk}\log\frac{\lambda_{ijk}}{\lambda_{ijr}}\right] \tag{4.45}$$

$$L_{rk} = \sum_{j=1}^{K}\sum_{i=1}^{N}\tfrac{1}{2}\left\{[\lambda_{ijr}\log\lambda_{ijr} + \lambda_{ijk}\log\lambda_{ijk}] - \frac{\lambda_{ijr}+\lambda_{ijk}}{2}\log\frac{\lambda_{ijr}+\lambda_{ijk}}{2}\right\}$$

$$= \sum_{j=1}^{K}\sum_{i=1}^{N} 1/2\left\{\lambda_{ijr}\log\frac{\lambda_{ijr}}{\frac{\lambda_{ijr}+\lambda_{ijk}}{2}} + \lambda_{ijk}\log\frac{\lambda_{ijk}}{\frac{\lambda_{ijr}+\lambda_{ijk}}{2}}\right\} \tag{4.46}$$

If $\{\lambda_{ij}\cdot k\}$ represents statistics which have been measured previously and $\{\lambda_{ij}\cdot r = \lambda_{ij}\cdot(S)\}$ represents statistics which have been measured presently, J_{rk} or L_{rk} can be used as criterion for deciding if both measurements have come from the same distribution with a predetermined confidence interval and confidence level. Eq. (4.45) is a sharp measure while Eq. (4.46) is not. When a good sample is available, Eq. (4.16) is preferable.

4.3.2 The Adaptive Structure of the A Posteriori Probability Measure

It can be shown (1) that Eq. (4.11) has an "adaptive" structure in the sense that the probability of the state Λ_r based on independent measurements $\Lambda(S)$ is the a priori probability for the next or (S+1)th measurement. The a posteriori probability for Λ_r after (S+1) observations is, simply,

$$\xi\{\Lambda_r;\Lambda(S+1)\} = \frac{\left[\dfrac{\xi(\Lambda_r)\,P\{\Lambda(S);\Lambda_r\}}{\sum_{j=1}^{M}\xi(\Lambda_j)\,P\{\Lambda(S);\Lambda_j\}}\right]P(z_{S+1};\Lambda_r)}{\left[\dfrac{\xi(\Lambda_1)P\{\Lambda(S);\Lambda_1\}}{\sum_{j=1}^{M}\xi(\Lambda_j)P\{\Lambda(S);\Lambda_j\}}\right]P(z_{S+1};\Lambda_1)+\ldots+\dfrac{\xi(\Lambda_k)\{\Lambda(S);\Lambda_k\}}{\sum_{j=1}^{M}\xi(\Lambda_j)P\{\Lambda(S);\Lambda_j\}}\;P(z_{S+1};\Lambda}$$

$$= \frac{\xi\{\Lambda_r;\Lambda(S)\}\,P(z_{S+1};\Lambda_r)}{\sum_{j=1}^{M}\xi\{\Lambda_j;\Lambda(S)\}\,P(z_{S+1};\Lambda_j)} \qquad (4.47)$$

4.3.3 Geometrical Interpretation of Decision Procedure Using Information Statistic -- Clustering

The problem of concern to us can be given another interesting and precise interpretation.(5) Consider a set of probabilities $\{\lambda_{i\ell}\}, \{\lambda_{jr}\}$ and the measurements $\{\lambda_i\}$, i = 1,2,...,N. If we take an arbitrary $\varepsilon > 0$ such that $|\lambda_i - \lambda_{i\ell}| \leq \varepsilon$, i = 1,2,...,N, defining a region Ω, then after S observations of the statistics with probabilities $\{\lambda_{ir}\}$, the probability that the empirical measurements $\{\lambda_i\}$ will cluster about $\{\lambda_{ij}\}$ in the region Ω is given by

$$p\{|\lambda_1 - \lambda_{1\ell}| \leq \varepsilon, \dots |\lambda_N - \lambda_{N\ell}| \leq \varepsilon\} = \exp\{S[-\sum_{i=1}^{N} \lambda_{i\ell} \log \frac{\lambda_{i\ell}}{\lambda_{ir}} + O(\varepsilon) + O(\frac{\log S}{S})]\} \quad (4.48)$$

Thus, for every distribution $\{\lambda_i\}$, i = 1,2,...,N, the conditional probability clustering about one of the other previously observed distributions falls off exponentially with S and depends on the information statistic and the size of the region. This gives us the large sample distribution of obtaining the conditional probabilities of the alternatives. Reference (5) treates the entire problem of interest here rigorously and in great detail.

4.4 Application of Theory--Important Examples

In this section the application of the theory to the following problems is discussed:

(a) Complete Observation--Gaussian Process

(b) Complete Observation--Gaussian Spectral Process

(c) Incomplete Observation--Message Compression (Adaptive Coding)

(d) Application of theory to pattern recognition.

The first is a well-known, important problem to which the solution is well known. It is important that the theory developed yield the well-known results in this important special case.

The second process is important since the measurement of spectra of random processes is always encountered in applications such as communications, seismology, applied physics, etc.

The third application(4) is important from the practical point of view in such a new area as space telemetry. Systems of this type are automatic observing systems since the human observer, not being on-the-spot, can exercise only moderate control over the measurement procedures. Furthermore, he cannot exercise any control over the preparation of the actual phenomena, which he can often do in the laboratory.

Pattern recognition is a problem receiving much attention at the present time. The fundamental problem here is defining a set of efficient transformation operators or measurable properties for a given class of patterns. This is generally accomplished empirically, a perfectly valid method and often the only available approach. It is at this point where the observation theory developed here comes into play.

4.4.1 Example of a Complete Specified Information Process Gaussian Case

We postulate that the coordinates $\{C_{jr}\}$, j = 1,...K, of the process were chosen so that they are statistically independent. Since each is quantized to N levels we can specify a waveform by specifying a quantum level for each coefficient. This is equivalent to assigning a volume element in the observation space, one for each of the M signals. The coordinates $C_r = \{ C_{jr} \}$ specify a signal $f_r(t)$ which is a member of the class. We assume that it is known a priori that the sensor output will generate one of the M-specified signals. It is required to detect which signal is present.

For a Gaussian process, we have

$$\lambda_{ijr} = P_r(x_{ij})\,\Delta x \tag{4.49}$$

where $P_r(x_{ij}) = \frac{1}{\sqrt{2\pi}\,\sigma_{jr}} \exp\left\{-\frac{1}{2}\left[\frac{x_{ij}-C_{jr}}{\sigma_{jr}}\right]^2\right\}.$

σ_{jr} = RMS VALUE OF THE j^{th} coordinate of the r^{th} signal,

x_{ij} = i^{th} quantum level of the j^{th} coordinate.

(4.50)

Substituting Eq. (4.49) and (4.50) into Eq. (4.15) yields,

$$s\sum_{j=1}^{K}\sum_{i=1}^{N}\lambda_{ij}\left[\log\frac{\sigma_{j\ell}}{\sigma_{jr}} - \frac{1}{2}\left(\frac{x_{ij}-C_{jr}}{\sigma_{jr}}\right)^2 + \frac{1}{2}\left(\frac{x_{ij}-C_{j\ell}}{\sigma_{jr}}\right)^2\right] > \log\frac{\xi(\Lambda_\ell)}{\xi(\Lambda_r)} \tag{4.51}$$

Expanding out the quadratic terms in Eq. (4.51) and grouping terms according to the indices gives

$$\sum_{j=1}^{K} \log \frac{\sigma_{jl}}{\sigma_{jr}} + \sum_{j=1}^{K} c_j^* \left[\frac{c_{jr}}{\sigma_{jr}^2} - \frac{c_{jl}}{\sigma_{jl}^2}\right] + \frac{1}{2}\sum_{j=1}^{K}\left\{\left(\frac{c_{jl}}{\sigma_{jl}}\right)^2 - \left(\frac{c_{jr}}{\sigma_{jr}}\right)^2\right\} > \log\frac{\xi(\Lambda_l)}{\xi(\Lambda_r)} \qquad (4.52)$$

where,

$$c_j^* = \sum_{i=1}^{N} \lambda_{ij} x_{ij} \qquad 4.53)$$

The measurement C_j^* is a maximum likelihood estimate of the coordinate C_j. Because of general discrete formalism, the X_{ij} are constant values which depend on the quantum grid of the measurement apparatus, while $\{\lambda_{ij}\}$ are empirical probabilities. The generality of our theoretical model is demonstrated by this problem. For the special case of a white Gaussian process (6) with signals of equal energy, the usual expressions for correlation detection are obtained.

It is informative to investigate the clustering property of the information statistic shown in Eq. (4.48). To demonstrate this property, in Eq. (4.53), let $\lambda_{ij} \rightarrow \lambda_{ijl}$ hence, $C_{ij}^* \rightarrow C_{ijl}$. For the case of white Gaussian noise, the left side of Eq. (4.52) becomes,

$$d_{lr}^2 = \frac{1}{2}\sum^{K}\left[\frac{c_{jl} - c_{jr}}{\sigma}\right]^2 \qquad (4.54)$$

where $d^2_{\ell r}$ is clearly the ratio of the distance between the signals to the mean square noise. Substituting into Eq. (4.48), we have

$$P\{|\lambda_1 - \lambda_{1\ell}| < \epsilon \ldots |\lambda_N - \lambda_{N\ell}| < \epsilon\} = \exp\{S[-d^2_{\ell r} + O(\epsilon) + O(\frac{\log S}{S})]\} \tag{4.55}$$

Eq. (4.55) gives the probability that a measurement of a set of coordinates in additive white Gaussian noise will cluster about the coordinates of a signal which is a neighbor of the true signal. It is clearly shown that, for a given clustering region, the probability that the measurement will fall in the neighborhood of the false signal goes to zero exponentially in the number of measurements. The theory represents a general measure of clustering; it goes over to the usual Euclidian measure in certain applications.

4.4.2 Measurement of Spectra of Noise Processes

We will assume that we have a band-pass Gaussian process whose spectrum we wish to measure. The bandwidth W is subdivided into K sub-bands Δf such that the noise is, for all practical purposes, flat across Δf. Hence, the output of each narrow band filter can be considered a white Gaussian process. The probability density of the output of a square-law detector is Rayleigh distributed such that,

$$\lambda_{ijr} = \frac{1}{2\sigma^2_{jr}} \exp\left[-\frac{1}{2} \frac{x^2_{ij}}{\sigma^2_{jr}}\right] \Delta x \tag{4.56}$$

where,

$x_{ij}^2 = x_i^2(\omega_j)$ = output of square-law detector of j^th^ filter and,

$\sigma_{jr}^2 = \sigma^2(\omega_{jr})$ = mean square power output of j^{th} filter when r^{th} signal is present.

Also

$$K = \frac{W}{\Delta f} \quad = \text{number of filters} \tag{4.57}$$

$$S = \frac{T_0}{T} \quad = \text{number of samples per filter output} \tag{4.58}$$

$$T = \frac{1}{2\Delta f} \quad = \text{time interval between samples}$$

T_0 = post detection integration time.

Substituting Eq. (4.56) into Eq. (4.15), and combining terms yields

$$S\sum_{j=1}^{K}\log\left(\frac{\sigma_{jl}}{\sigma_{jr}}\right)^2 - \frac{S}{2}\sum_{j=1}^{K}\left(\frac{1}{\sigma_{jr}^2} - \frac{1}{\sigma_{jl}^2}\right)\sum_{i=1}^{N}\lambda_{ij}x_{ij}^2 > \log\frac{\xi(\Lambda_l)}{\xi(\Lambda_r)} \tag{4.59}$$

Let

$$[\sigma_j^*]^2 = [\sigma^*(\omega_j)]^2 = \sum_{i=1}^{N}\lambda_{ij}X_{ij}^2 \tag{4.60}$$

Eq. (4.60) represents a maximum likelihood estimate of the power at the output of the j^{th} filter. Once again, X_{ij} represents a fixed quantum level and λ_{ij} is the measurement.

An equivalent expression for S in Eq. (4.58) is,

$$S = \frac{T_0}{T} = 2\Delta f\, T_0 = \frac{2WT_0}{K} \tag{4.61}$$

In Eq. (4.43) and (4.44), we have shown that the fluctuation in the measurement of the information statistic, is

$$\overline{[H(s)-\overline{H(s)}]^2} = \frac{N-1}{S} \tag{4.62}$$

Then,

$$\sigma^2_{\Delta f} = \frac{N-1}{S} = \frac{(N-1)K}{2WT_0} \tag{4.63}$$

represents the mean-square fluctuation per filter output. Eq. (4.63) is an extremely important relationship for measuring spectra of random processes and finding the spectral law which fits the measurement. The term $2WT_o$ represents the total number of independent observations made of the spectrum and (N-1)K represents the total number of resolution elements in the measurement apparatus and hence in the measured spectrum. It is quite clear that the total number of observations must be substantially greater than the total resolution in the spectrum if the spectral lines are to be statistically stable. Also, note that the statistic of Eq. (4.10) is sharp in the sense that unpredicted line spectra can easily be detected. This model applies equally as well to the case where undesired noise is added to the random process. In this case, the power in each line is a combination of the wanted signal power and the unwanted noise power.

4.4.3 Message Compression

Adaptive coding is a message compression procedure which is a compromise between the most efficient coding (when the source statistics are completely known) and maximum entropy coding (straight transmission) when the source statistics are unknown. In an adaptive coding procedure, past statistical measurements are used for coding future measurements. The coding procedure is continuously monitored to determine its efficiency and whether a change in the procedure is required. For this procedure to be efficient, the sensor output statistics must be quasi-stationary. Hence, in order to code adaptively, it is essential to define a decision rule of adaptation which depends on past measurements and which will be useful for future measurements. As long as the decision rule is known at the transmitter and receiver, and as long as it is defined on past measurements, the receiver will always know when the sender has switched the coding. The theory developed here is applicable to this important problem. The theory of adaptive compression is presented in detail in reference (4).

4.4.3.1 Measure of Coding Efficiency

The adaptive coding process requires a measure of the efficiency of a particular coding procedure which can then be used for the purpose of determining when a new procedure is to be adopted. The statistical estimates used to determine a change in the coding procedure should preferably be useful for the purpose of generating the new code. (This property should actually be required of all adaptive processes.) Such a measure, which is important in coding as well as in decision processes, exists.

Let, $\{p_i\}$ be the true probabilities of occurrence of sequences $\{X_i\}$ and let $\{q_i\}$ be the probabilities of occurrences of sequences $\{Y_i\}$. If the $\{Y_i\}$ do occur and a code is used whose symbol lengths are proportional to $(-\log p_i)$, (the optimum code for the $\{X_i\}$), then the excess number of bits required for the i^{th} sequence is simply

$$\delta_i = \log_2 q_i - \log_2 p_i = \log_2 \frac{q_i}{p_i}. \tag{4.64}$$

The average number of bits per sequence in excess is simply

$$\Delta H = \sum_{i=1}^{N} q_i \delta_i = \sum q_i \log_2 \frac{q_i}{p_i} \geq 0. \tag{4.65}$$

In the case where the statistics are unknown a priori, straight transmission can be used. This is a case of maximum entropy; that is, $p_i = \frac{1}{N}$ for all i. After the measurement of S realizations, it is decided that the best estimates of the $\{q_i\}$ is $\lambda_i(S) = [n_i(S)/S]$, where n_i is the number of occurrences of the i^{th} sequence out of the number of measurements S. Then, the initial excess is simply

$$\begin{aligned} \Delta H_1 &= \sum_{i=1}^{N} \lambda_i \log_2 \lambda_i N \\ &= \log_2 N + \sum_{i=1}^{N} \lambda_i \log \lambda_i . \end{aligned} \tag{4.66}$$

If $\Delta H_1 \geq \Delta H_0$, the coding used (i.e., straight transmission) is inefficient and we now code according to $p_i = \lambda_i$. If $\Delta H_1 < \Delta H_0$, we continue with straight transmission. The new measurement is then

$$\Delta H_2 = \sum_{i=1}^{N} \lambda_i \log \frac{\lambda_i}{p_i} \geq H_0 \tag{4.67}$$

For samples of reasonable size S, it can be shown that ΔH has a chi-square distribution of N - 1 degrees of freedom for the null hypothesis and noncentral chi-square for neighboring distribution where the noncentrality is the excess.[2] This permits a simple calculation for the specification of confidence intervals and confidence levels.

For quasi-stationary processes it is essential to investigate the sensitivity of the excess measure ΔH. In Figure 4-4 this is shown for the binary case when

$$\Delta H = \lambda \log \frac{\lambda}{p} + (1-\lambda) \log \frac{1-\lambda}{1-p} . \tag{4.68}$$

Note that zero excess always occurs when the coding matches the statistics. Also note that for $\lambda = 0.5$, the case of maximum entropy (or straight transmission) for all values of $p > 0.5$ or $p < 0.5$, there is an expansion in the coding in excess of that required for straight transmission. Also note that

$$\Delta H(\lambda, p) = \lambda \log_2 \frac{\lambda}{P} + (1-\lambda) \log_2 \frac{1-\lambda}{1-P}$$

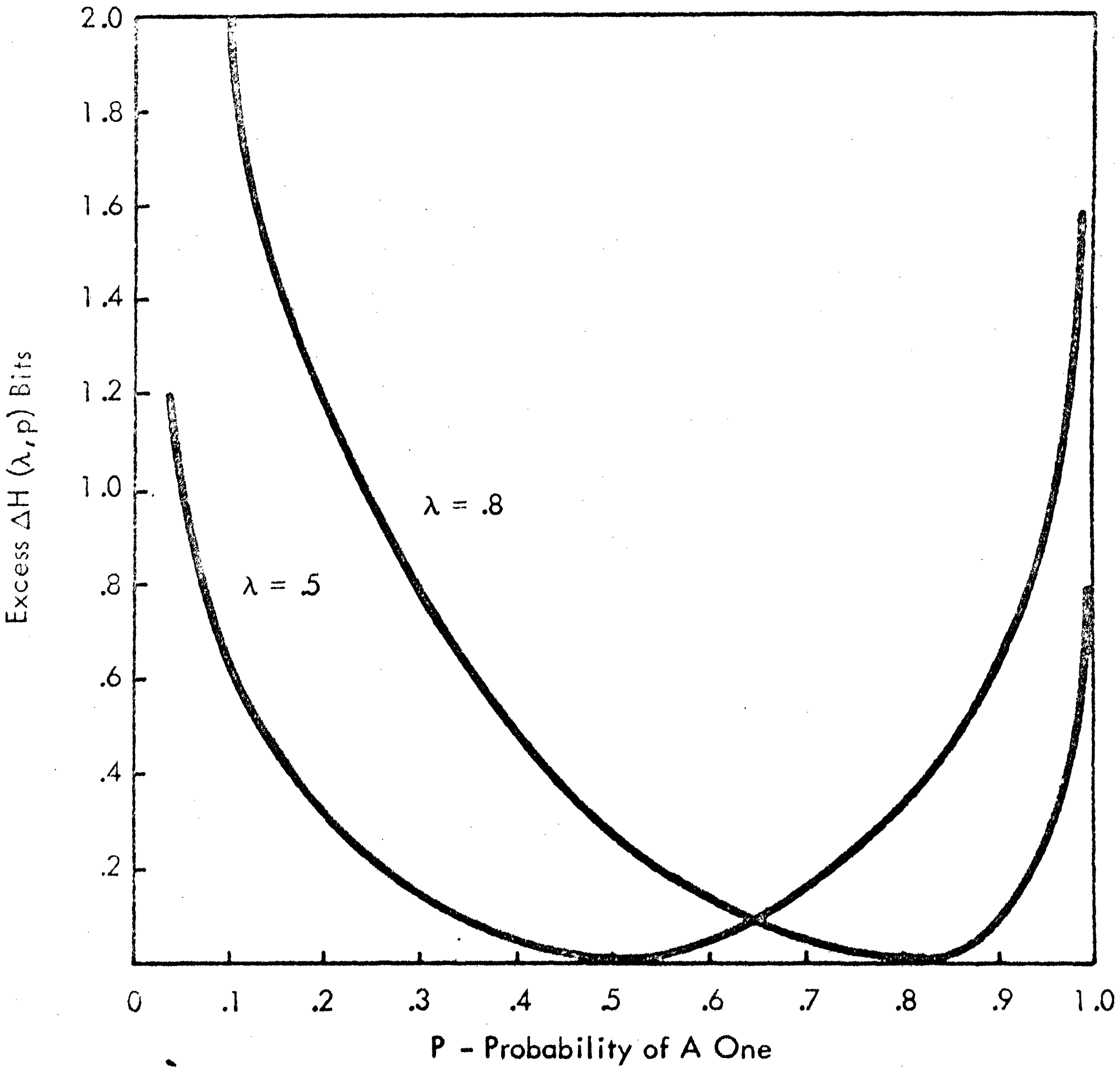

Figure 4-4: *Excess Bits When Code is Derived from Probabilities P and the True Probabilities Are λ*

the excess curves are fairly flat in the neighborhood of the minimum. Hence, precise knowledge of the statistics is not essential to achieve reasonably optimum efficiency. Thus, the statistical estimates $\{\lambda_i\}$ need not be precise and can therefore be measured from a sample of relatively small size. We can, therefore, conclude that an adaptive system should guard only against violent changes in the statistics, since the coding is not critical for relatively small ones. This conclusion should hold for the multistate case as well since, as seen from Equation (4.64) $\{\delta_i\}$ can take on positive and negative values and, hence, the average can be small. (Note, however, that this average is always positive.)

4.4.4 Pattern Recognition

The general theory developed here is applicable to recognition of patterns as well. (By patterns we mean various classes of figures such as written or printed letters, objects, human faces, etc.) The difficult problem in pattern recognition is to define a set of efficient measurement properties, for example, the transformation operators of this theory. In general, this type of information is obtained empirically and intuitively. For each class of objects, in conjunction with some insight as to the important properties, a set of measurements is defined. In general, the results of measurement should be invariant with respect to certain transformations, particularly translations and rotations. In this manner only meaningful characteristics in a pattern are used to distinguish one pattern from another. It seems to us, that for the specification of the measurable properties for the many complex problems encountered, we will continue to resort to intuition and empiricism. Furthermore, we will be forced to limit outselves to classes of patterns that have a common structure (i.e., human faces, printed letters, handwritten letters, etc.) In certain very special cases the underlying physical process will be sufficiently well understood to be described mathematically. In such cases the transformation operators can be specified. At this point "patterns" commonly called signals such as encountered in radar, communications, etc., which are generated by physical sources, (the physics of which is well understood), can be and in fact are described mathematically and for these optimum measurements can be defined. The first two problems discussed in this section belong to this class. In this case we have shown that the theory yields optimum results.

The information theory which we have developed is applicable to pattern recognition once the transformation operators have been defined whether empirically or mathematically. The theory then permits a consistent evaluation of the defined measurements. In fact, it puts a certain amount of order into defining the transformations and suggests some of the general characteristics of the transformations which should be used (such as invariance, independence, etc.).

4.5 Conclusions

We have presented a unified approach to the problem of representing information systems, on known and partially known signal environments, which shows clearly the arbitrary and the non-arbitrary operations. It was not shown that the theory developed is the only one possible, but it was demonstrated that it has a sufficient number of properties which a theory of information systems should have. The fact that we have constrained ourselves to a first order statistical representation does not make this a first order theory. The first order distribution is specified corresponding to a set of well defined physical properties, a principle which was shown to be optimum in special cases concerned with Gaussian processes. Actually, we are forced into this situation by the real life fact that the measurement of joint statistics requires extremely complex apparatus, extremely large amounts of data and extremely long measurement times. Information systems can seldom be described precisely mathematically.

We have shown how to estimate a priori probabilities (when this makes sense) and based on these how to decide which events are significant and which could have resulted from statistical fluctuations.

The statistic which was used for decision purposes is asymptotically chi-square distributed. We have shown experimentally the degree to which the asymptotic results can be used to predict performance confidently. Unless bounds are available for asymptotic results, which is not the case here, it is essential to find the point of departure empirically.

Finally, it would certainly be desirable to apply these concepts to space systems synthesis redundancy removal and pattern recognition, as examples, and to obtain detailed data as to system performance and behavior. With the theory as a mathematical framework for designing experiments in these areas and the programmed digital computer as an experimental tool for evaluating the properties which have been chosen as significant for recognition purposes, a consistent scientific approach results for studying, synthesizing and optimizing information systems.

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Section 5

SYSTEMS ANALYSIS

The methodology and mathematics of system analysis will play an important part in the day-to-day activities on the study. In the ensuing paragraphs, the problems of system analysis are considered in general and as applied to the particular requirements of the proposed study. The tools of analysis, especially computer programs, are discussed and their applicability to the present study indicated.

The recommendation of an optimum approach must rest upon an intensive comparison of candidate subsystem and system concepts relative to an established set of criteria. The criteria must be given a ranking or weighting so that the overall performance of the techniques or systems under scrutiny can be evaluated and compared.

The criteria which will serve as a basis for the selection of an optimum approach recommendation are grouped as follows:

Operational Criteria
System Performance Criteria
Implementation Criteria
Cost Criteria
Subsystem Criteria

5.1 System Criteria

5.1.1 Principal Operational Criteria

- Accommodate wide variety of missions
- Load sharing with remote computers
- Ease of a priori and a posteriori programming
- Handling unanticipated situations

5.1.2 Principal System Performance Criteria

- Reliability
- Efficient utilization of communication channel parameters
- Adapt so as to maintain prescribed error rate
- Graceful degradation with time in orbit

5.1.3 Principal Implementation Criteria

- Optimum balance—weight, size, power
- Modularity and redundancy
- Minimum of distinct modules
- Interconnective factors
- Is technology required within time frame?

5.1.4 Cost Criterian

- Is the configuration prohibitively costly?

5.2 System Optimization

System optimization is the determination of the parametric values which, when integrated, produce a system optimum with respect to the evaluation criteria. In practice, a near optimization is frequently effected by varying the system parameters to obtain the most satisfactory compromise with the established criteria.

Two principles govern the approach to obtaining an optimum system:

- It must lead to an optimum overall design, rather than locally optimal subsystems.
- It must not optimize on the basis of only a subset of the set of criteria.

Our approach to the problem of system optimization is characterized by these basic tenets:

a. The system -optimization program must utilize all available techniques to achieve its goal within the given time frame.

b. While the study must be approached with an open mind, the experience and engineering judgment of the team members should be fully utilized to eliminate unpromising approaches and to narrow the range of variability of the system parameters. (Extremely important!)

From a purely mathematical viewpoint, the optimization of a system ordinarily requires the maximization of a complicated function of many variables subject to a set of constraints. If the problem can be formulated appropriately in this manner, then sophisticated mathematical techniques such as linear programming, can be utilized to obtain a (mathematical) optimum. Unfortunately, it is frequently impossible to determine the functional relationship to a sufficient degree of accuracy to justify this approach.

An additional complexity in optimizing a system is that there are usually important criteria of a non-quantifiable or even intuitive nature which are not easily reckoned with by mathematical procedures. Furthermore, the relative weightings of the criteria may vary as time progresses, and information of an extra-system nature is added to the decision process. For example, economic forces not foreseen at the time a study is undertaken may later have a critical bearing on the final choice of a system design.

In the final analysis, human judgment, backed by engineering fact, plays the ultimate role in the choice and optimization of the system. The most useful systems analysis aid to this human decision process is the system tradeoff between two parameters.

Tradeoffs

From a purely mathematical viewpoint, the achievement of meaningful tradeoffs between two system parameters ordinarily involves an iterative process. Consider the function $f(x,y)$, giving performance as a function of the system parameters x = bandwidth and y = active sensors. If we cannot determine the function $f(x, y)$ explicitly its maxima must be determined by assumptions as to the analytical nature of the function, by the use of a computer, or by experimentation. Two difficulties are immediately evident. First, x and y may not be independent variables, and any determination of x and y maximizing $f(x, y)$ may be subject to some constraint of the form $g(x, y) = C$. Secondly, the changes in x and y necessary to maximize $f(x, y)$ may, if x or y are related to other parameters, affect other functions previously maximized, thus necessitating a compromise in the system design. For example, the number of sensors activated may vary as the system bandwidth is varied, giving rise to a relation $g(x, y) = C$. In turn, the variation of bandwidth ordinarily affects the choice of a modulation technique for fixed test-tone-to-noise ratio.

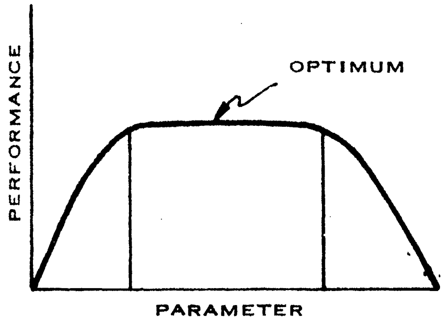
To overcome the aforementioned difficulties, the tradeoff procedure must assume the form of an iterative process. This process terminates when a system meeting the design criteria has been obtained or when an externally imposed time limitation on the optimization process has been reached.

Before making tradeoffs or giving detailed design specifications, the sensitivity of parametric inputs to the system must be examined in detail with regard to the desired output. This in-out relation is the key to translating the theoretically optimum system into hardware requirements.

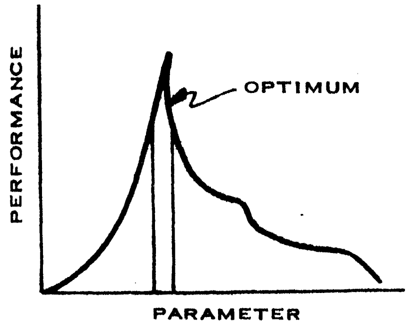
The range of parametric sensitivity is illustrated graphically in Figure 5-1. Curve 1 illustrates the case in which there is little input sensitivity and the curve has a broad maximum. This is desirable. Curve 2 illustrates the opposite extreme of severe parameter sensitivity. Here it is most unlikely that the optimum can be reached in the final design. Curve 2 also illustrates the importance of choosing a sufficiently small sampling interval so that sharp peaks and dips on the curve are not smoothed. Curve 3 is self-explanatory, representing a situation wherein the limitation in performance is caused by hardware inadequacies. Presumably, a technological breakthrough is required to improve performance. Nevertheless, the system designer has little difficulty locating the maxima in this case. Curve 4 illustrates the pitfalls of a curve with local maxima and inflection points. Finally, Curve 5 represents the possibility of a design parameter to which the system is insensitive and which can be eliminated from consideration in the optimization process.

Tradeoff curves will be prepared as a portion of the overall effort. To keep the number within reason, there will be a constant effort to exploit parameter dependencies and to utilize those parameters which are properly sensitive.

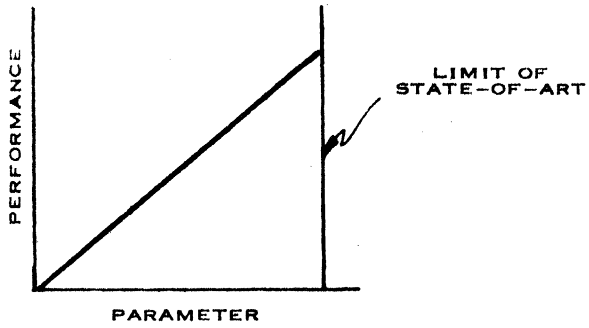
Consider the trade-offs involved in data compaction. Since the computer will play a major role in this area, it is reasonable to assume that an adaptive data compaction technique will be considered. Among the potential advantages of adaptive data compression are reductions in transmission time or bandwidth,



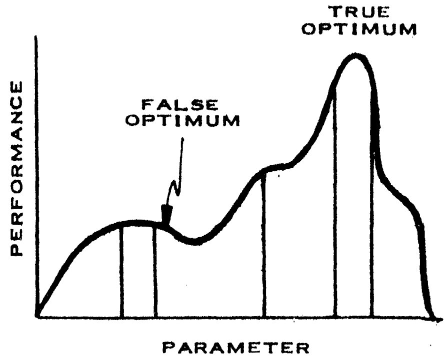
CURVE 1



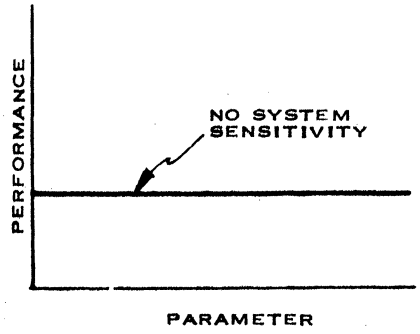
CURVE 2



CURVE 3



CURVE 4



CURVE 5

Figure 5-1. Representative Tradeoff Curves in power or error rate, and in storage requirements. The compression ratio actually obtained C_R is here defined as the ratio of the average number of bits required to represent a message at the compressor input to the average number of bits for a message at the compressor output. Then the transmission time required, for the same bandwidth, can be reduced to T/C_R or, alternatively, the bandwidth can be reduced to W/C_R. It is often desired to save weight by reducing the power required to transmit the (compressed) data from space; since the thermal noise is directly proportional to bandwidth, the signal power can be reduced to S/C_R without changing the S/N ratio.

Another important consideration is the improvement in bit error rate that can result from compression. It is well known that for many digital transmission systems the bit error probability decreases exponentially with signal energy*. If the same time were used to transmit the compressed bits, the new signal energy would be C_R times the old. It follows that the probability of a correct decision can be made exponentially proportional to C_R.

This last result is very significant. Because of the removal of some redundancy from the telemetered data, it is desirable to decrease the bit error rate, each bit now being important. Since an exponential improvement in error probability results from an increase in signal energy, some of the

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*See, for example, "Theoretical Comparision of Binary Data Transmission Systems," Cornell Aeronautical Lab Report No. CA-1172-S-1, AD 148 803, May 1958; or A. J. Viterbi, "On Coded Phase-Coherent Communications," Tech Report No. 32-25, JPL, August 15, 1960.

compression can be used to increase the signal energy and obtain the desired reliability, and the remainder can be employed to reduce the time, bandwidth, or power required for transmission.

To illustrate IBM's approach to exploiting the tradeoffs available among the system parameters, assume that the most significant factor in the design of the spaceborne compression system is the minimization of the total spacecraft weight. The spacecraft power source is assumed to be a fuel cell which provides approximately 10 watts per pound of spacecraft weight.* The amount of weight saved by a reduction in the power required to transmit a compressed message depends, of course, upon the nominal operating point for the power supply; this in turn depends upon the nature and duration of the spacecraft mission. Rather than exploit the full compression ratio to reduce signal power, the energy per bit could be increased to reduce the error probability, and the remainder of the compression benefits could be employed to reduce the power and thereby the weight penalty. Some additional equipment would be necessary to implement the compression processing; this would require a certain weight allocation and reduce the overall reliability of the spacecraft equipment. It might be desirable to design some redundancy into the system so as to regain the "lost" reliability (again at the expense of more weight), but in any case the equipment penalty associated with the compression process must be considered. Unlike ground-based compression

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*C. G. Peattie, "A Summary of Practical Fuel Cell Technology to 1963," Proceedings of the IEEE, May 1963, pp 795-806.

equipment, where the more subtle redundancies in the input signals can be considered when maximizing the compression, there is an extremely important tradeoff that must be exploited for spaceborn compression equipment between the weight and power required to obtain each additional increment of compression and the advantages (e.g., weight reduction) that this additional compression provides.

An important part of IBM's approach is the consideration that will be given to the equipment estimates for the spacecraft system. Design tasks will be pursued throughout most of the study, beginning with preliminary analyses to aid in the initial selection of promising multiprocessing concepts. After preliminary investigations have been conducted into the suitability of various configurations, block diagrams will be evolved to the extent necessary for estimates of weight, reliability, power consumption, volume, cost, etc. An attempt will be made to simulate the key concepts of the selected configurations within the scope of the program. Those concepts that look most promising after the simulation tests will be examined thoroughly, and estimates of the equipment penalties—reliability, etc.—will be made.

Another factor that will influence the recommendations of the study team will be the modularity that can be achieved for the various configurations. By utilizing techniques and equipment that are generally applicable to common classes of data, some degree of standardization for the spacecraft equipment can be obtained. Then, depending upon the mission requirements, a significant portion of the system can be designed from existing, proved modules.

5.3 The Computer As A Tool For System Analysis

We believe that the computer when properly utilized, is an invaluable aid in the synthesis and analysis of satellite systems and subsystems. Over a period of several years, we have developed a series of programs on contract and in-house projects, which have immediate application to the proposed study (pictures, guidance and control, coding, communications, etc.). Judicious application of these programs to the solution of problems not amenable to analytical techniques, and to the development of tradeoff relations will assure a thorough investigation of all the areas of interest within the time frame and manpower allotted for the study.

5.3.1 Automatic Synthesis

Computer programs for system synthesis can be grouped into two categories: those that employ rigorous mathematical programming techniques and those that are based on heuristic optimization procedures. In terms of ensuring an optimal solution, mathematical programming is to be preferred. However, there are two practical considerations that limit its use: many problems cannot be stated in the form required for the mathematical program, and, frequently, the mathematical program requires too lengthy computer running times. Very often, heuristic procedures can be programmed to run quickly, and while there is no guarantee that a truly optimal solution will be obtained, in many cases there is reasonable assurance that the resulting solution will be sufficiently optimum for practical purposes.

5.3.2 Linear Programming

Mathematical programming problems are concerned with the efficient use or allocation of limited resources to meet desired objectives. These problems are characterized by the large number of solutions that satisfy the basic conditions of each problem. The selection of a particular solution as the best solution to a problem depends on some aim or overall objective that is implied in the statement of the problem. A solution that satisfies both the conditions of the problem and the given objective is termed an optimum solution.

One very special subclass of mathematical programming problems consists of linear programming problems. A linear programming problem differs from the general variety in that a mathematical model or description of the problem can be stated, using relationships which are called "straight-line" or linear. The mathematical statement of a linear programming problem includes a set of simultaneous linear equations which represent the conditions of the problem and a linear function which expresses the objective of the problem. There are a variety of allocation or assignment problems which have some similarity to some portions of the vehicle system design problem. In the assignment problem, there are a number of individuals, machines, etc., to be assigned to perform a set of jobs. Each individual i has a given rating c_{ij} which measures his effectiveness in doing job j. An individual can be assigned to only one job. If x_{ij} represents the assignment of the i^{th} individual to the j^{th} job, (x_{ij} = 0 or 1), the linear programming formulation is then:

Maximize

$$\sum_{i,j} c_{ij} x_{ij}$$

Subject to

$$\sum_{j} x_{ij} = a_i \qquad i = 1, \ldots, m$$

$$\sum_{i} x_{ij} = b_j \qquad j = 1, \ldots n$$

where a_i is the number of persons of type i available and b_j is the number of jobs of type j available.

Assume

$$\sum a_j = b_k$$

The assignment linear programming algorithm can be employed directly to the problem of determining the optimal sampling rate of n sensors given a certain bandwidth available for transmitting this data to earth.

This sampling rate and thus the multiplex pattern will change as the environment changes so that optimum usage is made of the available bandwidth.

The linear programming technique will be investigated as a potential method for system synthesis on this study.

5.3.3 Heuristic Programs

The usual approach to heuristic programs is to decide how one would perform the synthesis if he were doing it manually and then to write a computer program to implement it. Since a manual approach to synthesis often requires the use of engineering judgment instead of the use of a mathematical expression that exhaustively tries all possible solutions, the heuristic program almost always carries the synthesis procedure just so far. At that point, the system designer examines the results of the program, decides if they look satisfactory, and guides the next computer runoff if the design does not appear sufficiently optimal.

An illustration of a heuristic approach is the program ASSIGN, which was developed in the IBM Federal Systems Division in connection with investigations of random-orbit satellite communications systems. The objective of the program is the same as for the linear programming assignment problem discussed above: assign connections to single-access satellites so as to maximize over time the total number of connections satisfied, and minimize the severity of the handover problem. The chief reason for using the heuristic approach was based on computer running-time considerations. Where the ASSIGN program performed an assignment in 0.12 second of IBM 790 computer time, the linear program required an average of 9.7 seconds. The solutions obtained by either method were comparable in terms of optimality. In general, the heuristic program follows a logical procedure in which the most critical links are assigned first to the most suitable satellites. Whenever the process finds that a particular link cannot be satisfied because all satellites within view of the link terminals are already assigned to more critical links, the program enters a subroutine which reassigns one of the more critical links to some other satellite if a certain intuitive criterion is met.

5.3.4 Other IBM Computer Programs for System Synthesis and Analysis

Besides standard computer routines for linear programming, IBM has developed special computer programs which are available as tools for system analysis on the proposed study. Programs are available for the evaluation of spread-spectrum modulation techniques, for the evaluation of RADA-type modulation techniques, and for the evaluation of error-control techniques.

Section 6

PROGRAM OUTLINE

IBM proposes a 15 man-month effort for this program plus 20 hours of System/360 Model 40 time. The assigned personnel have the background and experience in all the major areas of this proposal. They have published papers in this and related areas, some very recently. A paper in the area of satellite communications has been presented recently at the AIAA Conference in Washington, D. C. One entitled "Adaptive Digital Satellite Transmission Ground Terminal Design Considerations" by H. Najjar, R. D'Antonio, and H. Blasbalg et al deals with the design of advanced digital satellite communication's terminals.

Another paper entitled "An Adaptive Digital Data Collection and Telemetry Space Terminal" by H. Najjar, R. D'Antonio and H. Blasbalg has been accepted for presentation and publication at the 1966 "Aerospace and Electronics Systems Convention" Washington, D. C., October 3-6, 1966. This paper shows how an on-board computer can be used to monitor sensor activity and to derive an optimum rule of multiplexing. This paper is directly applicable to some of the tasks in this proposal. Both of these papers demonstrate experience which is certain to be valuable for studying multifunctional satellite communications links.

This project will be performed at the IBM Center for Exploratory Studies in the Satellite Communication Technology Department. Management here is both technically active and competent in the areas of the proposal and can supply both guidance and consultation during the course of the program. Most important, management's interest in this area will ensure that the program will receive proper attention.

IBM is proposing computer simulation as a tool in this study. The related experience clearly shows that computer programs have been used and exist for TV picture compression techniques, data compression, communications systems studies and system optimization. The challenge here is to identify and simulate the key multiprocessing concepts without exceeding the scope of the program.

Finally, IBM believes that technical competence and experience are the key ingredients for successful performance on this complex program. The resumes and experience of all those who will be associated with this program show that it will be successfully completed.

This section contains a comprehensive task outline plus a phasing chart. The phasing chart shows the major tasks according to task number. The program is subdivided into three phases; Computational Requirements, Admissible Multiprocessing Configurations and Evaluation of Admissible Multiprocessing Configurations. The effort is almost evenly divided among the three phases.

Phase I, shown in the Program Plan, is a comprehensive study which will relate the computational requirements to the subsystem parameters. This section draws heavily on the years of experience of the IBM personnel assigned to this project who have been working in such fields as adaptive telemetry, satellite communications, computer controlled communication, adaptive coding, data and picture compression, special and general purpose computers, etc. Without this background the tasks outlined in Phase I would normally require several man-years of effort rather than the 5 man-months recommended here.

Phase II, is concerned with the selection of several multiprocessing configurations for study which satisfy the computational requirements and the operational factors stated in the RFP. An understanding of the factors and their effect in the multiprocessing configurations is essential. In addition to studying multifunctional satellite configurations this phase studies the configuration of the Ground Control Facility and the overall communications link capacity. A method of ordering multiprocessing configurations by weighting the importance of the operational factors will be studied here.

Phase III, defines criteria for evaluating the admissible multiprocessing configurations. A computer simulation will be used as a tool during the evaluation.

Figure 6-1 is a graphic representation for the phasing of this study. The phasing chart is keyed to the program outline which follows the illustration.

Program Outline

Phase I—(3.5 months; 5 man-months)

1.1 Define Overall Multi-Functional Satellite System

- 1.1.1 General functional diagrams of subsystems
- 1.1.2 General functional diagrams of Ground Control Facility
- 1.1.3 General functional diagram of communications systems
- 1.1.4 Develop general information flow diagram
- 1.1.5 Develop functional block diagram of overall systems
- 1.1.6 Develop meaningful computation criteria

2.1 Subsystem Functions

- 2.1.1 Checkout (pre-launch and in-flight)
  - 2.1.1.1 Logical definition of telemetry functions
  - 2.1.1.2 Information flow within subsystems
  - 2.1.1.3 Subsystem block diagram
  - 2.1.1.4 Checkout functions interaction with special purpose processor

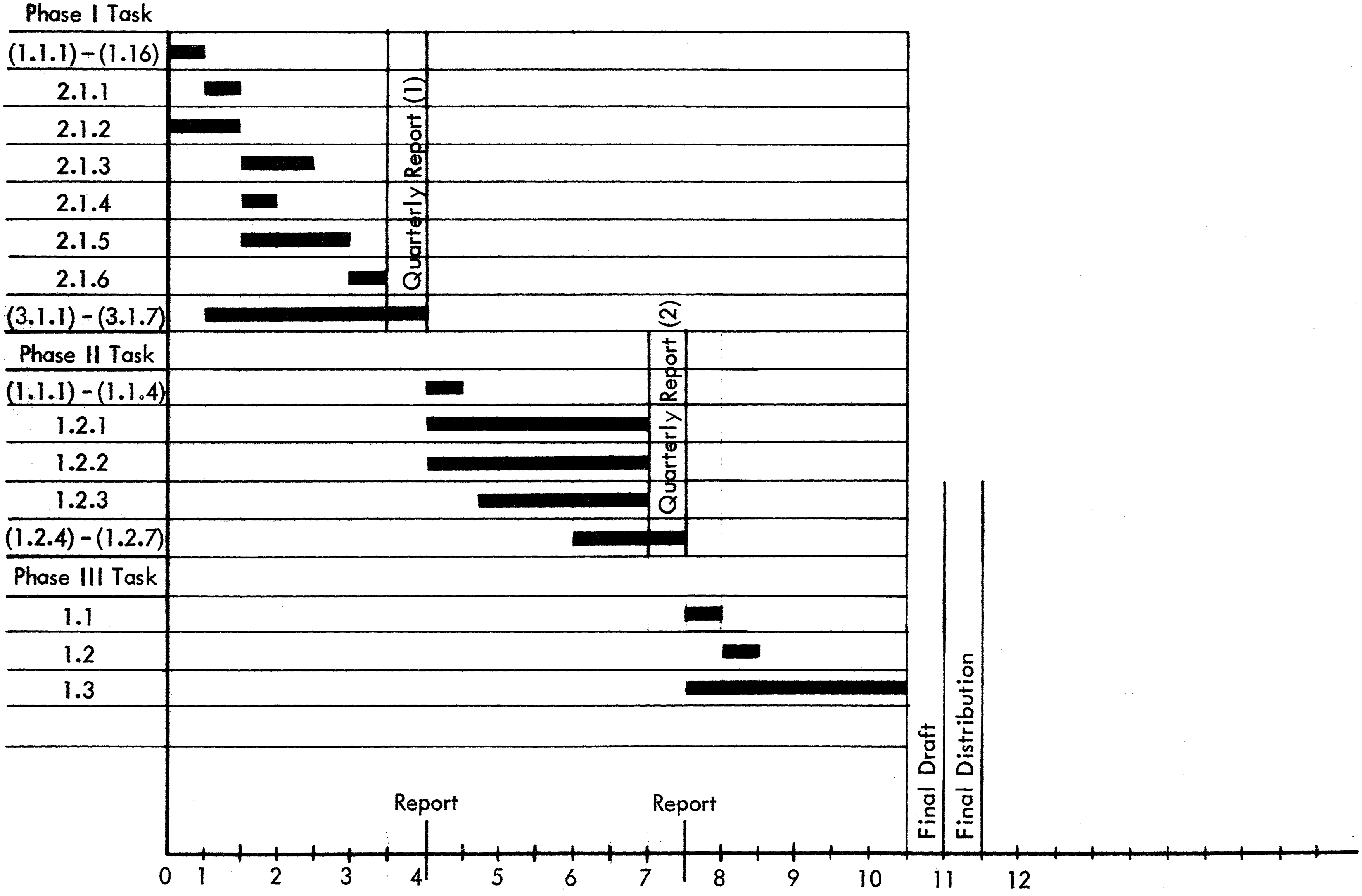

Figure 6-1. Phasing Chart

- 2.1.1.5 Specify functional parameters and bound the parameters
- 2.1.1.6 Relate computational requirements to parameters
- 2.1.1.7 Obtain computational requirements for bounded subsystem

2.1.2 Communications and Telemetry Modulator/Demodulator

- 2.1.2.1 Specify criteria for selecting admissible modulation schemes
- 2.1.2.2 Select optimum modulation scheme
- 2.1.2.3 Synthesize block diagram of optimum modulator/demodulator
- 2.1.2.4 Channel monitoring and adaptive control of communications
- 2.1.2.5 Adaptive coding against channel disturbances
- 2.1.2.6 Communication subsystem interaction with special purpose computer
- 2.1.2.7 Synthesize on-board communication subsystem
- 2.1.2.8 Specify functional parameters and bound the parameters
- 2.1.2.9 Relate computational requirements to channel parameters
- 2.1.2.10 Obtain computational requirements for bounded parameters

Phased Array Antennas

- 2.1.2.11 Define a phased array for future multifunctional satellite
- 2.1.2.12 Define antenna functions
- 2.1.2.13 Beamforming controlled by processor
- 2.1.2.14 Specify functional parameters and bound parameters
- 2.1.2.15 Relate computational requirements to parameters
- 2.1.2.16 Obtain computational requirements for bounded subsystems

2.1.3 Navigation Guidance, Control and Stabilization

- 2.1.3.1 Mathematical formalism of navigation, guidance and control
- 2.1.3.2 Mathematical formalism of stabilization problem
- 2.1.3.3 Detailed description of processor for these functions

2.1.3.4 Specify functional parameters and bound them

2.1.3.5 Relate computational requirements to parameters

2.1.3.6 Obtain computational requirements for bounded system

2.1.4 Operations or Sensors

Pictures

2.1.4.1 Identify classes of pictures of interest

2.1.4.2 Calculate raw information in a picture in parametric form

2.1.4.3 Study of picture processing techniques

2.1.4.3.1 Contour extractions

2.1.4.3.2 Image sharpening

2.1.4.3.3 Other approaches

2.1.4.4 Picture processing by a computer

2.1.4.5 Specify functional parameters for pictures and bound these

2.1.4.6 Relate computational requirements to parameters

2.1.4.7 Obtain computational requirements for bounded subsystem

Low Data Rate Sensors

2.1.4.8 Classify other (than pictorial) sensors

2.1.4.9 Specify information theoretic parameters (bandwidth, number of levels, sampling rate, etc.)

2.1.4.10 Specify useful sensor operations (spectra, distributions, curves, table, etc.)

2.1.4.11 Relate sensor parameters to operations and bound parameters

2.1.4.12 Relate computational requirements to parameters

2.1.4.13 Obtain computational requirements for bounded system

2.1.5 Data Handling

2.1.5.1 Define adaptive sampling, multiplexing, and channel selection operations on selected sensor parameters

2.1.5.2 Show block diagram of above controlled by processor

- 2.1.5.3 Relate data handling parameters to operations and bound parameters
- 2.1.5.4 Relate computational requirements to parameters
- 2.1.5.5 Obtain computational requirements for bounded system
- 2.1.5.6 Develop algorithms for deriving optimum sampling and multiplexing programs from sensor data

2.1.6 Energy Management

- 2.1.6.1 Relate energy requirements to each bounded subsystem
- 2.1.6.2 Identify energy management procedures and parameters
- 2.1.6.3 Define processor functions for identified procedures
- 2.1.6.4 Relate control parameters to operations and bound them
- 2.1.6.5 Specify computational requirements for control parameters
- 2.1.6.6 Obtain computational requirements for bounded parameters

3.1 Definition of Overall Satellite Computational Requirements

- 3.1.1 Obtain total computational requirements in parametric form
- 3.1.2 Obtain total computational requirements for bounded system

Example

- 3.1.3 Identify and select a representative multifunctional mission
- 3.1.4 Develop Time-Line and identify subsystem parameters
- 3.1.5 Relate computational requirements to parameters
- 3.1.6 Compare example to bounded parameter computational requirements
- 3.1.7 Evaluate parametric model developed in previous section

MULTIPROCESSING CONFIGURATION

Phase II (3-5 months, 8 man-months)

1.1 Define and Study Significance of Operational Factors

1.1.1 Reliability

Diagnostic capability

Fault isolation and corrective procedures

- Reconfiguration (modules, programming)
- Memory protections
- Computational back-up

1.1.2 Flexibility and Adaptability

- Optimum allocation of computations
- Accommodate diverse missions
- Load sharing with remote computers
- Ease of a priori and a posteriori programming

1.1.3 Hardware Realization

- Optimum balance (weight, power, size, cost, etc.)
- Redundancy, complexity and reliability
- Modularity - repetition of simple functions
- Connectivity

1.1.4 Hierarchy of Mission Control

- Handling unanticipated situations
- Reconfiguration program vs hardware
- Differing needs for different priority tasks

1.2 Multiprocessing Configuration Satisfying (1.1) and (3.1)

1.2.1 Combine processor junctions defined in Phase I and a central computer

1.2.1.1 Define information flow from processor to computer and back

1.2.1.2 Study PN-Switching as a means of rapid access from processors to computer

1.2.1.3 Develop supervisory program concepts

1.2.1.4 Reconfiguration concept by means of programs derived from measured data

1.2.1.5 Reconfiguration concepts by re-interconnecting modules

        - 1.2.1.6 Flow chart multiprocessing system for bounded system
        - 1.2.1.7 Flow chart multiprocessing system for selected mission
    - 1.2.2 Ground Control Facility (GCF)
        - 1.2.2.1 Instruction of GCF with multi-functional satellite
        - 1.2.2.2 GCF as switching center for multi-functional satellites in orbit.
        - 1.2.2.3 GCF as back-up for on-board computer
        - 1.2.2.4 Load sharing between one or more GCF's and computer
        - 1.2.2.5 Communications link capacity requirements for (1.2.2.3) (1.2.2.4)
        - 1.2.2.6 Trade-off between on-board processing and link capacity
        - 1.2.2.7 Define optimum overall multi-functional satellite system
    - 1.2.3 Repeat (1.2.1) and (1.2.2) with subsystem functions represented by multiple special purpose processors of low capacity
    - 1.2.4 Select and identify several new and most promising multi-processing configurations
    - 1.2.5 Rate each configuration in accordance with factors described in (1.1)
    - 1.2.6 Assign preference scale for each factor
    - 1.2.7 Preliminary choice of admissible configurations

<u>Phase III (3-5 months, 2 man-months)</u>

<u>Evaluation of admissible multiprocessing configuration</u>

- 1.1 <u>Systems Criteria</u>
    - 1.1.1 Develop principle operational criteria
    - 1.1.2 Develop system performance criteria
    - 1.1.3 Specify implementation criteria
    - 1.1.4 Estimate cost of various configuration
- 1.2 <u>Determine Optimum System</u>
    - 1.2.1 Vary system parameters
    - 1.2.2 Optimize with respect to all criteria
    - 1.2.3 Perform trade-off studies

1.3 Use computer for systems design and simulation

- 1.3.1 Determine best simulation technique
- 1.3.2 Develop simulation programs
- 1.3.3 Debug and run simulation
- 1.3.4 Analyze results of simulation

Section 7

PROJECT PERSONNEL AND CONSULTANTS

The project as it is proposed will require the services of four key technical personnel. It will be performed under the overall direction of Dr. H. Blasbalg, Manager of the Satellite Communications Technology Department. Dr. R. D'Antonio will be Project Manager, and Mr. H.F. Najjar and a senior associate programmer form the remainder of the IBM team. In addition, the project will use the consultant services of personnel drawn mainly from within the Center for Exploratory Studies. The consultants will include but not be limited to Dr. D. C. Ross, Manager of Communications Systems, CES; Dr. J. P. Rossoni, Manager of Cambridge Advanced Space Systems, CES; Dr. G. W. Johnson, Computer Control System Manager, Cambridge Advanced Space Systems, CES; and Dr. H. D. Mills, Manager of Computer Mathematics, CES. The resumes of these project personnel and consultants follow.

PROJECT PERSONNEL

H. BLASBALG (Overall Direction)

Dr. Blasbalg is Satellite Communications Technology Manager in the Communications Systems Department. Prior to this he was Manager of the Digital Satellite Transmission Department in IBM's Engineering Laboratory.

Dr. Blasbalg received a BEE degree (1948) from the College of the City of New York, an MSEE degree (1952) from the University of Maryland, and a Doctor of Engineering degree (1956) from the Johns Hopkins University. From 1948 to 1951, Dr. Blasbalg was an engineer with Melpar, Inc., working on a multiplex pulse-time-modulated communications system, voice channel compression, and other applied information theory projects. From 1951 to 1956, he was a research scientist with the Johns Hopkins University Radiation Laboratory. During this time, he was project leader of the signal analysis and signal analyzer group working on problems on electronic countermeasures. He also worked on statistical detection theory, automatic observing systems, and communications theory.

In 1956, he became a member of the Research Division of Electronic Communications, Incorporated. He was research scientist and technical director of theoretical and experimental work on automatic observing systems applied to electronic intelligence problems. He has also worked in statistical communication theory, meteor-burst communications, radar detection and estimation problems, secure communications, and other problems in these and related areas.

Since joining IBM in 1961, Dr. Blasbalg has worked in the use of pseudo-random sequences of large WT product for asynchronous communications systems. The preliminary analysis, the design, and the fabrication of the two RANSAC models took place under Dr. Blasbalg's general direction. Dr. Blasbalg holds many of the basic patents for the pseudo-noise techniques utilized in RANSAC. Dr. Blasbalg was also project manager of the Improved

Communications Satellite Modulation Techniques for NASA and on TV picture compression for the Army. In 1964, Dr. Blasbalg participated in an Institute for Defense Analyses Summer Study on multiple-access satellite communications.

He has published a number of papers on statistical detection in communication theory and contributed a section of signal analysis to the Department of Defense book on Electronic Counter-Measures. A few of the publications that are pertinent to this study are:

"A Logarithmic Voltage Quantizer" Trans. PGEC, 1955, Proc. of WESCON, Computer Session in 1954.

"The Relationship of Sequential Filter Theory to Information Theory and Its Application to the Detection of Signals in Noise by Bernoulli Trials," PGIT, Volume 1, IT-3, No. 2, June 1957.

"Transformation of the Fundamental Relationships in Sequential Analysis," Annals of Mathematical Statistics, Volume 28, No. 4, December 1957.

"Sequential Detection of a Sine-Wave Carrier of Arbitrary Duty Ratio in Gaussian Noise," PGIT, Volume IT-3, No. 4, December 1957.

"On the Application of Fourier Orthogonal Filters," Proc. of the Eastern Conference on Aeronautical and Navigation Electronics," Baltimore, 1958.

"Experimental Results in Sequential Detection," PGIT, Volume IT-5, No. 2, June 1959.

"Message Compression," PGSET, Volume SET-8, No. 3, September 1962 (Co-author).

"A Statistical Theory of Automatic Observing Systems," Second Symposium on Adaptive Processes.

"Auto-Correlation Function of a Gaussian Process Through a Linear Quantizer," to be published in Proceedings of the IEEE Professional Group on Information Theory.

R. A. D'ANTONIO (Project Manager, 6 months)

Dr. R. A. D'Antonio received a BSEE from the University of Rhode Island in 1956, an MSEE from Syracuse University in 1961, and a Ph.D. from the University of Rhode Island in 1965.

He joined IBM as a Junior Engineer in 1956 and during the next two years performed system tests and diagnostic programming for the SAGE computer. In 1958 he was transferred to the Research Laboratory and for the next year and a half designed computer systems incorporating error-detection logic. In 1959, he was assigned to Advanced Display Development where he did research on advanced display systems for the military and developed special-purpose display processors. In 1961 he was assigned to Communications Systems where he developed techniques for reducing to practice, the theory of coding for error control using polynomial codes. This work led to the development of the FLEXECODER. Later that same year, he left IBM on an educational leave of absence and in 1963 he was awarded an IBM Resident Study Fellowship. While at graduate school, he did research in stochastic processes in underwater communications, and lectured in information and switching theory. Since his return he has worked in the areas of digital beam forming, matched filters and error control. He has recently been working in the field of digital satellite communications, in particular, multiple access, satellite electronics, ground terminal design and telemetry systems. He is presently applying pseudo-noise techniques to satellite and deep space systems. He is the author or co-author of several papers on switching theory, underwater and satellite communications, and holds two patents.

Dr. D'Antonio is a member of Sigma Xi, Phi Kappa Phi, and the IEEE.

H. F. NAJJAR (4.5 months)

Mr. Najjar obtained a General Certificate of Education in mathematics from the University of London (1954) and a BSc in electrical engineering from the University of Wales in 1957. While in England, he worked with the South Wales Electric Company and B. T. H. Company. From 1957 to 1959, he was a reserve officer in the Iraqi Army in charge of a radio transmitting station, and was responsible for the maintenance and operation of four 100 Kw transmitters. Upon the completion of military service in 1959, he enrolled in the Electrical Engineering Department of the Johns Hopkins University where he obtained an MS degree in 1961. While at Johns Hopkins, he was appointed a junior instructor in the EE department from 1960 to 1961, where he taught networks and instrumentation and advanced measurements.

In the summer of 1960, he worked for Bell Telephone Laboratories on the development of protective circuitry for transistorized telephone equipment from foreign potentials. Upon completion of the MS degree requirements, Mr. Najjar joined Stromberg-Carlson Company where he did system reliability studies and logic design of electronic switching. While at Stromberg-Carlson, he also taught mathematics in the Applied Science Department of the Rochester Institute of Technology. He then joined Honeywell Electronic Data Processing Division where he worked on the development and design of different control systems interfacing the H200 series and communication facilities. He developed single and multichannel systems capable of operating with both full-duplex and half-duplex lines. While at Honeywell, he did graduate work in switching theory at the Massachusetts Institute of Technology.

Since joining IBM, Mr. Najjar has worked on adaptive digital multiplexing techniques for satellite communications. In particular, multiple access, satellite electronics, ground terminal design and telemetry systems. He is presently applying pseudo-noise techniques to satellite and deep space systems.

Mr. Najjar is a member of IEEE and an associate member of Sigma Xi, and has published several papers in his field.

SENIOR ASSOCIATE PROGRAMMER (4.5 months)

The third member of the project team will be assigned upon award of contract. His training and experience will qualify him for the program writing and simulation tasks necessary to support this study.

CONSULTANTS

G. W. JOHNSON—Navigation, Guidance and Control, Stabilization

Dr. Johnson obtained his BEE from Rensselaer Polytechnique Institute and his MS and Ph.D. degrees from the University of Connecticut. From 1950 to 1956, Dr. Johnson served as Instructor and Assistant Professor of Electrical Engineering at both the above institutions where he taught courses in Feedback Control Theory. He also taught as a part-time associate professor of electrical engineering at the graduate extension of the University of Alabama and is currently a lecturer at the Northeastern University Center for Continuing Education.

He was a consultant to the N. W. Kellogg Company in 1952 and 1953, performing analytic and analog computer studies of rocket engine control dynamics. From 1954 to 1956, he was a consultant to the Emerson Electric Manufacturing Company, performing analytic studies for airborne fire control systems. He performed summer research from 1954 to 1956 for the IBM Airborne Computer Laboratory, concerning analytical studies of digital bombing and navigation systems. In 1956, he joined the IBM Space Guidance Center in Owego, New York, remaining there until 1962. He conducted research studies and served as principal investigator in the areas of: ballistic missile flight control, hypersonic and orbital inertial guidance, control of nuclear power systems, craft-oriented inertial navigation systems, and design of digital accelerometers. From 1962 to 1964, Dr. Johnson served as the principal technical consultant to the engineering facility of the IBM

Space Guidance Center in Huntsville, Alabama, where his studies were in the areas of Liapunov stability for non-linear control systems and evaluation of optimal guidance systems using the "maximum principle" of Pontriagin.

At present, Dr. Johnson is computer control systems manager with the Cambridge Space Systems Department, Center for Exploratory Studies. He has served as a reviewer for numerous books and technical journals in the field of Automatic Control theory and he is the holder of a patent on a digital accelerometer.

H. D. MILLS —Multiprocessing, Multiprogramming

Dr. Mills obtained his B.S. in 1948, M.S. in 1950, and Ph.D. in 1952, all in mathematics, from Iowa State University. During this time he was also an instructor in mathematics and consultant in mathematical physics. Dr. Mills also did graduate research at Universität Zurich. In 1952 he became an instructor in mathematics at Princeton University. Two years later he went to work for the General Electric Company as a consultant in operations research and synthesis. In 1957, he became an adjunct associate professor in the Graduate School of Business Administration of the New York University, and a research associate in mathematics and economics at Princeton University. During this time, he served as a consultant to the Market Research Corporation of America. This position led to his appointment as President of Mathematica, a subsidiary of the Market Research Corporation of America, a position which he held for three years, from 1958 to 1961.

In 1961, he became a Member of the Technical Staff, Advanced Military Systems, Radio Corporation of America.

Dr. Mills joined the IBM Federal Systems Division as Manager, Systems Analysis, Advanced Planning Department, in 1964. In 1966, he became Manager of the Computer Mathematics Department for the IBM Center for Exploratory Studies.

Dr. Mills has many publications to his credit, among which are the following:

"Marginal Values of Matrix Games and Linear Programs," Annals of Mathematics Study 38, edited by H. W. Kuhn and A. W. Tucker, Princeton, 1956.

"Integrating Operations Research into a Business," Journal of the American Society for Quality Control, May 1956.

"Organized Decision Making," Naval Research Logistics Quarterly, 1957.

"Equilibrium Points in Finite Games," Journal of the Society for Industrial and Applied Mathematics, June 1960.

"Smoothing in Servo Processes," SIAM Review, April 1961.

"Marketing as a Science," Harvard Business Review, September-October 1961.

"Inventory Valuation—An Analytic Technique," Journal for the Institute of Management Sciences, October 1961.

He was an honorary fellow in mathematics, Wesleyan University, 1962. He was a member, National Science Foundation Committee for Mathematics in Industry and Government, 1955-58. He is a member of American Mathematical Society, Mathematical Association of America, Society for Industrial and Applied

Mathematics, Institute for Mathematical Statistics, American Statistical Association, Econometrica, Association for Computing Machinery, Sigma Xi.

D. C. ROSS—Multiprocessing

Dr. Ross obtained his BSEE in 1946, and MSEE in 1949, both from Purdue University, and a Ph.D. in engineering from Johns Hopkins University in 1964. His doctoral thesis was entitled "Vector and Tensor Algebra of Signals Applied to Satellite Navigation." Dr. Ross has been with IBM since 1953 in engineering, systems and management positions in the Federal Systems Division. At present, he is Manager of Communication Systems, Center for Exploratory Studies.

Prior to joining IBM, he was employed full time as Instructor of Electrical Engineering at Purdue University (1946 to 1951) and the United States Military Academy (1951 to 1953). During this period he was also engaged in part-time graduate study at Purdue and Columbia. While at Purdue, he designed electric control circuits for the 350 Mev Synchrotron and served as consultant to the Aircraft Control System Project. Dr. Ross' first assignment in IBM was in systems planning of the prototype SAGE computer. Later, he directed the system design of the production models. Other assignments at the Engineering Laboratory at Kingston, New York, included: Manager of Systems Engineering, Manager of the Air Traffic Control Project, and Manager of Technical Planning.

Two patents have been issued to Dr. Ross as sole inventor: a magnetic storage system, and an automatic position-telemetering system for aircraft and other vehicles. He was co-inventor of a group of patents pertaining to the input/output, buffer-storage and digital data transmission subsystem of SAGE.

Dr. Ross is a member of Eta Kappa Nu, Sigma Xi, Tau Beta Pi, Institute of Electrical and Electronics Engineers, Society for Industrial and Applied Mathematics, American Association for the Advancement of Science, and other professional societies. As an adjunct Lecturer in Engineering at The Johns Hopkins University, he has worked with Professor W. H. Huggins in developing a graduate course in signal theory. He has served as a member of the National Joint AIEE-IRE-ACM Computer Committee, vice-chairman of the Computing Devices Committee of AIEE, and delegate to the Radio Technical Commission for Aeronautics. Papers by Dr. Ross include:

"Vector and Tensor Algebra of Signals Applied to Satellite Navigation"
The Johns Hopkins University, Baltimore, 1964
AD 603 775

"Orthonormal Exponentials"
Proceedings of the National Electronics Conference
XVIII, October 1962, pp 838-849

"A Digital System for Position Determination"
IRE Transactions on Space Electronics and Telemetry
Vol. SET-5, No. 1, March 1959, pp 42-46

J. P. ROSSONI —Navigation, Guidance and Control, Stabilization

Dr. Rossoni, Manager of the Cambridge Advanced Space Systems of IBM's Center for Exploratory Studies, obtained his Ph. D. at the University of Bologna (Italy) in 1950. His experience in the field of astronomy includes Yale Star Catalogue calculations at Watson Laboratory; evaluation of proper motion of stars in galactic cluster M-37, for Stockholm Observatory, Sweden (work performed at Watson Laboratory); and instructor of programming techniques for solution of scientific problems, Watson Laboratory, Columbia University. Since 1957, he has assisted in developing computer programs, systems, and methods for machine solution of satellite-tracking problems. In the past year, Dr. Rossoni served as consultant to the National Academy of Sciences as a member of the Panel on Tracking Data Analysis, investigating the accuracy problem of electronic tracking systems at the DOD missile ranges. He is IBM satellite program coordinator at the Smithsonian Astrophysical Observatory, and a member of the American Institute of Aeronautics and Astronautics (AIAA).

E. M. RUTZ-PHILIPP

Dr. Rutz received the D. Sc. with highest honors in applied physics from the Technical University of Vienna in 1946. She directed applied research at Emerson Research Laboratories in propagation phenomena, microwave antennas, microwave solid-state devices and other components, and CW/FM systems. Before coming to the United States, she did research work for Siemens and Halske in Berlin and Vienna in electro-acoustic transducers, microwave tubes and circuits. At the University of Darmstadt and Aachen, she directed research on microwave circuits.

Since joining IBM in 1961, Dr. Rutz has been responsible for a number of research and development projects in space antennas, microwave switching circuitry, millimeter-wave systems and solid-state devices. She has provided key technical support to the IBM Federal Systems Division project at NASA Huntsville on the Saturn Instrumentation Unit. Dr. Rutz is a member of the technical staff of the Center for Exploratory Studies and will consult as required on the proposed study in the areas of antennas and propagation.

Section 8

ORGANIZATION AND FACILITIES

Organization

The IBM Federal Systems Division is composed of four operating centers one of which is the Center for Exploratory Studies (CES), (Figure 8-1). CES was created in February 1966 as the Advanced Technology arm of the Federal Systems Division. The mission for the Center is to serve the Federal Government and contribute to FSD's thrust in advanced technology by:

1) Identifying long-range trends in the technological environment and embarking on necessary investigations.
2) Selecting, initiating, and carrying exploratory development programs through to demonstration of technical feasibility. (With the establishment of feasibility the programs will be transferred to the appropriate center within the Federal Systems Division.)
3) Facilitating the transfer of techniques and ideas between the centers of the Federal Systems Division, between the Federal Systems Division and other divisions of IBM, and between IBM and the Federal Government for maximum exploration of technological advances. An implied benefit, consistent with the objectives of the Federal defense and space establishments, is to obtain maximum utilization from defense/space technology.

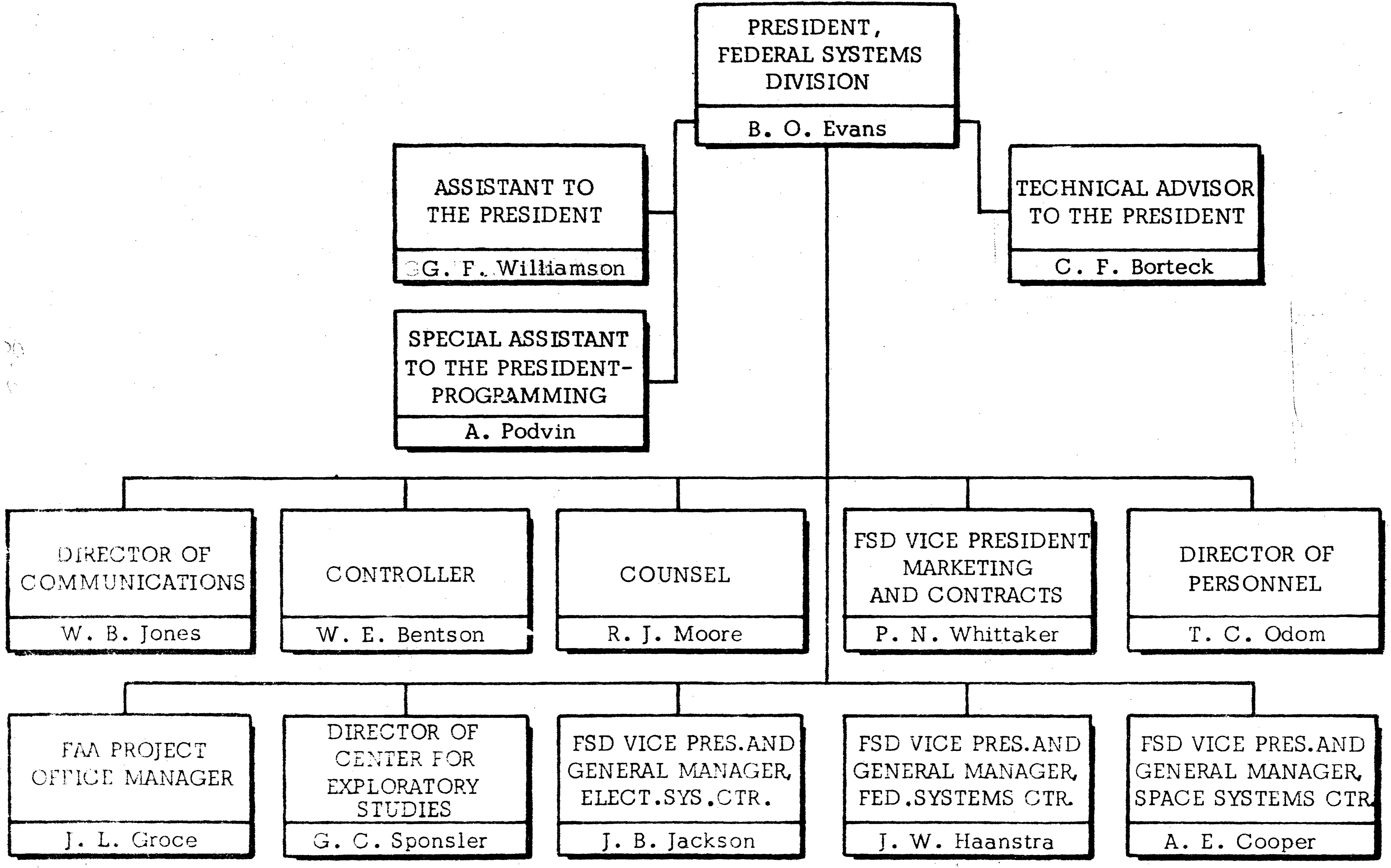

Figure 8-1. FSD Organization

Three of the five departments in CES will be involved in this study. (Figure 8-2). The Communications Systems Department will perform the proposed work with consultant services from the Computer Mathematics and Cambridge Advance Space Systems departments. The purposes of CES Communications Department are to conduct exploratory studies and feasibility model development in the following areas:

Digital Satellite Transmission

Adaptive Deep-Space Telemetry

Pseudo-Noise Modulation Techniques

Department personnel have designed an adaptive digital satellite ground terminal that interfaces with AUTODIN under contract to the U. S. Army Satellite Communication Agency. A feasibility model of a pseudo-noise communication set called RANSAC (Random Access Noise-like Signal Address Communications) was developed and successfully tested over SYNCOM III. RANSAC uses digital circuit technology to generate and receive complex noise-like signals. Optimum phase-locked techniques are also being developed which are applicable to a variety of future space communications systems requirements. Work is also in progress on the development of adaptive space telemetry concepts for future manned and unmanned space flights. The key here is an on-board digital processor which controls information flow within and external to the vehicle. Details on this and other IBM experience are included in the section on Related Experience.

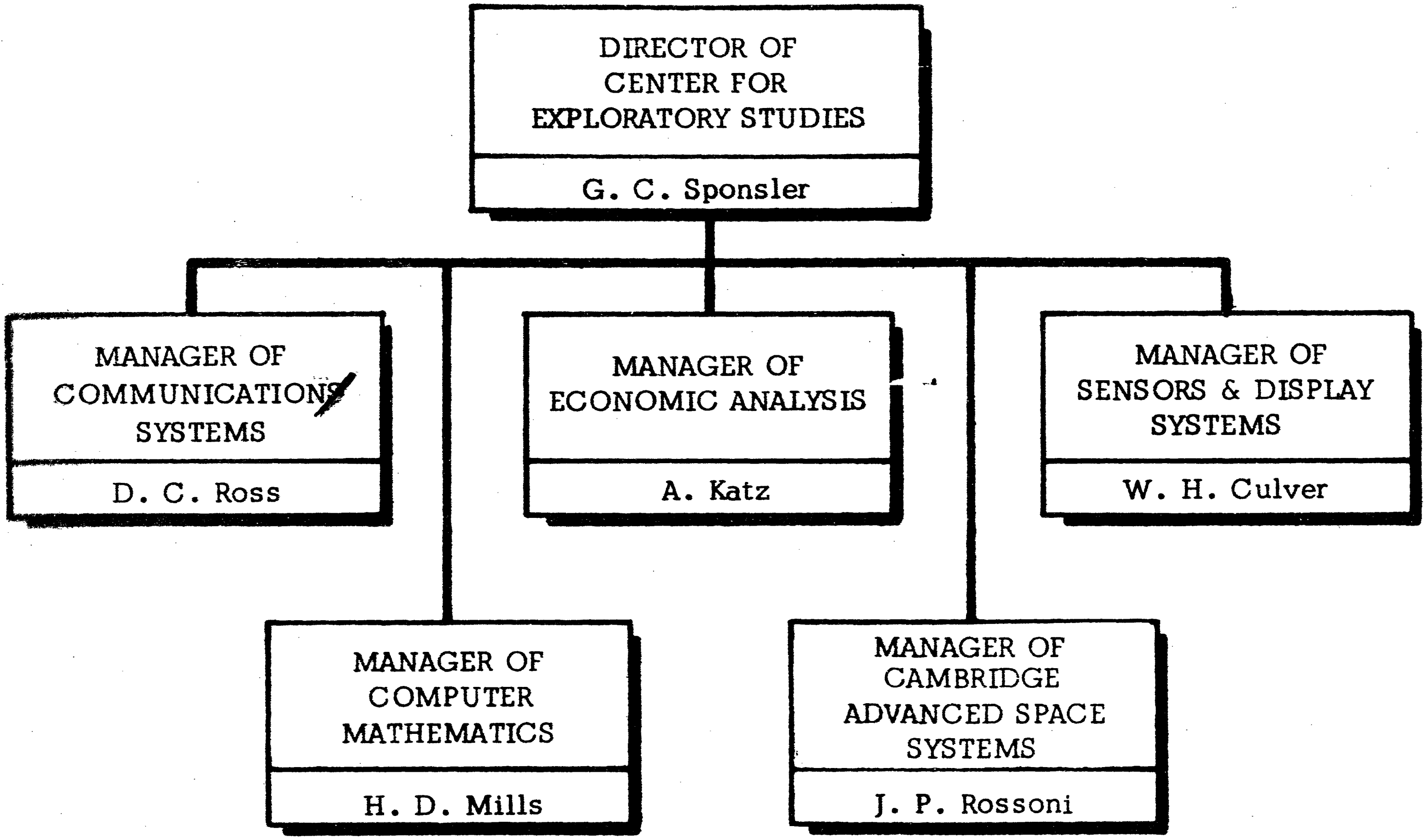

Figure 8-2. Center for Exploratory Studies

In some respects the proposed task will be a Center activity rather than one solely confined to the Communications Department. The skills and talents of personnel in the Computer Mathematics and Cambridge Advanced Space Systems departments will be required because this project involves space-borne electronic systems and advanced concepts in information processing. Some of the exploratory research performed by the Computer Mathematics Department is concerned with:

1) Evolutionary systems for data processing (ESDP) which is a machine-directed documentation process.
2) Mathematical computation such as automatic numerical problem solving, round-off error analysis, finite algebra macro operations, and error-free computation methods.
3) Machine architecture studies, including micro-programming, look-ahead logic, and virtual memory design.

Exploratory research in the Cambridge Advanced Space Systems Department includes:

1) Space trajectory analysis and related celestial mechanics problems.
2) Geoid determination from satellite observations.
3) Mathematical problems related to rocket guidance and control for Saturn IB and Saturn V.

Facilities

IBM will perform the proposed study effort at its Rockville facilities which are headquarters for the Center for Exploratory Studies. Within this facility there is substantial office space for study personnel and for NASA personnel who will be visiting the project. This building also contains adequate conference facilities.

The project will require time on an IBM System/360 which is located at FSD headquarters in Gaithersburg, Maryland, about ten minutes from the Rockville facility. Also located at Gaithersburg are the expanded facilities of the Engineering Laboratory. These facilities include substantial electronics testing and measuring devices as well as significant communications research equipment. The Engineering Laboratory is engaged in developing a host of communications and special purpose data processing equipment and performing specific research tasks. The latter include testing random-access modulation devices for the Army satellite program, pseudonoise modulation technique development and error-detection and forward-error-correction development and testing. If required, these substantial facilities of the Engineering Laboratory are available for use by study personnel.

Within the Washington area, IBM has a technical library consisting of 52,000 books, technical reports, and bound magazines as well as 300 technical publication subscriptions. About half of these publications are concerned with communications and space technology. Supporting these

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Within the Washington area, IBM has a technical library consisting of 52,000 books, technical reports, and bound magazines as well as 300 technical publication subscriptions. About half of these publications are concerned with communications and space technology. Supporting these library facilities are the IBM technical libraries of the Research Division, the Electronic Systems Center, and the Advanced Systems Development Division.

Section 9

RELATED EXPERIENCE

IBM has had considerable experience in many areas which relate to this study. As evident elsewhere in this proposal, personnel and consultants have worked in many fields and the aggregate of their experience provides a significant technical base upon which they are qualified to perform the work proposed.

IBM's experience in the areas encompassed by the proposed study is corporation wide, spanning a period of many years. The most relevant experience of the Federal Systems Division in these areas is summarized in Table 9-1. This table indicates the IBM interest and competence in modulation and detection, error control, adaptive techniques, multiple-access techniques, and other relevant disciplines.

Six areas of IBM experience are discussed in additional detail because of their pertinence to the work scope discussed in this proposal.

A. Adaptive Digital Communication
B. Adaptive Compression Telemetry Techniques
C. Coding Theory and Error Control
D. Multiplexing
E. Pseudo-noise Modulation
F. TV Techniques and Systems

A. ADAPTIVE DIGITAL COMMUNICATIONS

US Army Satellite Communication Agency
Contract No. DA-043-AMC-01407(S)

The concepts and the design for an adaptive digital satellite transmission ground terminal which interfaces with the DCS Net have been

Table 9-1

SUMMARY OF IBM RELATED EXPERIENCE

	NETWORK CONTROL AND OPERATIONS	MODULATION AND DETECTION	ERROR CONTROL	ADAPTIVE TECHNIQUES	SYNCHRONIZATION & ASYNCHRONIZATION BUFFERING & TRANSMISSION	A TO D CONVERT	TDM	HANDOVER	MULTIPLE ACCESS—SPREAD SPECTRUM & TDM	DCS INTERFACE
IRAD—RANSAC (RANDOM ACCESS NOISE SIGNAL ADDRESS COMMUNICATIONS)		X							X	
IMPROVED COMMUNICATIONS SATELLITE MODULATION TECHNIQUES (NASA), CONTRACT NO. NAS 5-3544	X	X		X			X		X	
IRAD—MINIATURE DIGITAL MATCHED FILTER MODULE		X	X	X						
ADAPTIVE ERROR CONTROL, CONTRACT NO. RADC AF 30(602)-3603			X	X						
IRAD—ADAPTIVE LINK DESIGN			X	X						
AN ENGINEERING INVESTIGATION OF THE DESIGN AND INSTRUMENTATION OF THE ERROR CORRECTING CODES—RADC AF 30(602)-2[illegible]			X	X						X
DCA AREAS COMMUNICATION CONTROL CENTERS CONTRACT NO. SD-115	X				X	X				X
IRAD—MULTIPLE ACCESS MODULATION TECHNIQUES STUDY		X		X			X		X	
IRAD—MULTIPLE ACCESS SYSTEMS FOR COMMUNICATIONS	X	X		X					X	
AUTOMATIC ALTERNATE ROUTING STUDY CONTRACT NO. DA 28-043-AMC-00-166(E)	X		X	X					X	
RADAS (RANDOM ACCESS DISCRETE ADDRESS SYSTEM) CONTRACT NO. DA-36-039-AMC-00-146(E)	X	X	X	X		X			X	
AIRBORNE RANGING AND ORBIT DETERMINATION SYSTEM (AROD)CONTRACT NO. NAS 8-4098		X		X	X	X		X		
MANNED SPACECRAFT COMMUNICATIONS CONTRACT NAS 1-2974, NAS 1-3612, NAS 9-1688		X	X		X	X				
REAL-TIME COMPUTER COMPLEX AND RELATED SYSTEMS—CONTRACT NO. NAS 9-996					X	X		X		
MERCURY PROJECT NAS 5-1376, NAS 5-2940, NAS 5-3406	X	X	X		X	X				
SPACE FLIGHT OPERATIONS FACILITY CONTRACT NO. 950-727 JPL	X		X		X	X				
MARSHALL SPACE FLIGHT CENTER - DATA CENTER CONTRACT NO. NAS 8-2040	X				X	X				
COMMAND POST COMMUNICATIONS-TERMINAL ANALYSIS CONTRACT NO. AF 19(628)522 CCN NO. 1	X					X	X			X
COMMAND CONTROL SYSTEM PROJECT 473L CONTRACT NO. AF 19(628)576; AF 19(628)3444					X	X				X
WS-239 A PROJECT (GLOBAL IR SENSOR TRACKING SYSTEM)			X		X	X				
474L BMEWS CONTRACT NO RCA GX 9-947661-96-Q96					X	X				X
SPACE DETECTION AND TRACKING SYSTEM CONTRACT NO. PO 8-88166 BENDIX					X	X		X		X
ORBITING ASTRONOMICAL OBSERVATORY			X		X	X		X		
ERROR CONTROL SYSTEM DESIGN—U.S. NAVY ELECTRONICS LABORATORY			X							
ERROR CONTROL SYSTEM DESIGN—GEMINI DIGITAL COMMAND SYSTEM			X	X						
ERROR CONTROL SYSTEM DESIGN—NASA RANGE INSTRUMENT CONTROL SYSTEM			X	X						
ERROR CONTROL SYSTEM DESIGN FOR FORT MONMOUTH			X							
ERROR CONTROL SYSTEM DESIGN FOR NASA BERMUDA-GODDARD LINK CONTRACT NO. NAS-5-3486			X							
ERROR CONTROL SYSTEM DESIGN—NASA UNIFIED S-BAND SYSTEM			X							
IRAD—ERROR DETECTION-FRAMING SIMULATION			X	X						
ERROR CONTROL SYSTEM DESIGN AND FABRICATION—LAUNCH TRAJECTORY DATA SYSTEM GEMINI-APOLLO CONTRACT NO. NAS 9-996			X	X						
ERROR CONTROL SYSTEM DESIGN FOR APOLLO MISSION SIMULATOR (NASA) CONTRACT NO. NAS 9-996			X							
IRAD - INTEGRATED COMMAND CONTROL FOR UNMANNED SCIENTIFIC SATELLITES	X							X		
IRAD - COMPUTER CONTROL OF MILITARY COMMUNICATIONS SWITCHING	X									X
IRAD - MANNED GUIDANCE AND CONTROL SYSTEM STUDIES, PHASE II					X	X				
IRAD - ESTABLISHMENT AND REFINEMENT OF TRACKING ESTIMATES								X		
IRAD - ANALYSIS OF DATA COLLECTED BY SCIENTIFIC SATELLITES					X	X				
IRAD - SPECIAL SPACE COMMUNICATIONS SYSTEMS STUDY	X	X		X						
IRAD - SIMULTANEOUS SURVEILLANCE OF OBJECTS IN HETEROGENEOUS ORBITS								X		
IRAD - ADVANCED DIGITAL CONTROL THEORY FOR REENTRY VEHICLES								X		
IRAD - SPACE COMPUTATION TECHNIQUES								X		
IRAD—SOLID STATE RF CIRCUITS FOR SPACE NAVIGATION SYSTEMS		X								
IRAD—ASSESSMENT OF ROUNDOFF AND TRUNCATION ERRORS			X							
IRAD - SPECIAL DEVICES AND COMPONENTS									X	
ERROR CONTROL SYSTEM DESIGN FOR AADS-70S, CONTRACT NO. RAYTHEON P.O. 71-3501 BC-005		X	X		X	X				
IRAD - ADVANCED SIGNAL DETECTION AND IDENTIFICATION STUDY TASK NO. 6161		X		X						
ADAPTIVE DIGITAL SATELLITE COMMUNICATIONS TECHNIQUES CONTRACT NO. DA-28-043-AMC-01407(E)	X	X	X	X	X	X	X	X	X	X

developed to meet DCS operational requirements. The inputs to the ground terminal consisted of standard data rates, non-standard data rates as well as analog voice signals. The adaptive digital satellite transmission ground terminal system satisfied the requirements for AJ, multiple access and the DCS Input-Output characteristics.

The adaptive digital terminal consisted of three subsystems:

- Adaptive digital multiplex-demultiplex subsystem.
- Adaptive control, error control and satellite channel monitoring.
- Ground terminal modem and multiple access.

Several techniques of combining and decombining (mux. -demux.) bit streams were studied. It was shown that the techniques lend themselves to a modular approach and the combining was organized so that the highest priority messages survive when the channel degrades. Two other integral parts of the adaptive digital multiplex subsystem were studied, the Format computer and the Input-Output Interface Units.

The functional design of the combiner-decombiner provides the flexibility to permit combining bit streams having rates which are multiples but nonsynchronous with respect to each other. Start-stop teletype inputs can be accommodated as well as bit streams that have non-multiple rates with respect to the other bit streams being combined. All of this is made possible by an input/output interface device, which performs retiming of input bit streams when required, or converts bit streams with nonstandard rates into ones in which each rate is standard and the sum of the decomposed standard rates is equal to the input nonstandard rate.

Techniques for channel monitoring, adapting, anti-jam modulation, and satellite multiple-access were investigated. An adaptive pseudonoise modulator-demodulator was specified and designed as a result of these investigations.

Dr. H. Blasbalg was the project manager and Dr. R. A. D'Antonio and Mr. H. Najjar were principal contributors to this project.

B. ADAPTIVE COMPRESSION TELEMETRY TECHNIQUES

NASA
Contract NAS 9-4618

IBM is presently under contract to NASA to investigate and develop adaptive-compressive telemetry techniques for PCM telemetry transmitted from manned spacecraft. This investigation includes the analysis of actual data tapes in order to classify or categorize the data by prescribed characteristics such as power spectrum. Evaluation of compression algorithms is performed by simulating the applications of the technique to specific data. This evaluation includes algorithms presently in use or known, and algorithms that were developed under contract.

The output of this contract will be a preliminary design of an Adaptive-Compressive Telemeter. Results to date indicate that all compressive techniques may be performed with the use of a special purpose digital computer (digital filter). The digital filter will not only perform the compression algorithms on the multiplexed data, but will also control the recombining and buffering of the data for retransmission.

Optimum Multiplexing Techniques Study
U. S. Army Satellite Communications Agency
Contract No. DA28-043-AMC-01567(S)

Working under contract to the U. S. Army Satellite Communications Agency, Ft. Monmouth, N.J., the Engineering Laboratory is designing an adaptive twelve-channel multiplexer for use in ground terminals of the Initial Defense Communications Satellite System.

The desire for an adaptive communications satellite system arises from the need to achieve efficient use of satellite down-link power. Hence the adaptive part of the system must trade bandwidth for pre-detection signal-to-noise ratio. The adaptive multiplexer changes the pre-detection signal bandwidth, and therefore the post-detection bandwidth as well, by adding or dropping input channels to be multiplexed. The adaptation matches the information rate to the transmission medium as a function of the time-varying signal-to-noise ratio in the system.

Prior to choosing an approach for implementation, several alternatives were evaluated analytically to find the most efficient combination of modulation and multiplexing techniques. The selected technique is frequency division multiplexing of single-sideband channel signals, with frequency modulation of a carrier by the multiplex signal. The total multiplex system design includes channel sensing elements for adaptation and a digital-logic control system.

Two mil-spec full-duplex adaptive multiplexers incorporating these design features are scheduled to be delivered in early 1967.

C. CODING THEORY AND ERROR CONTROL

IBM's capability in error control has evolved from initial work on internally sponsored studies. These studies led to the design and fabrication of the FLEXECODER, a laboratory device for on-line testing, evaluating, and demonstrating a wide variety of codes for error detection, correction, and retransmission. This device then became an integral part of the error-control program for the design and fabrication of hardware tailored to meet the individual error-control requirements of users and designers of digital data transmission systems. The program has been continually supported by research on internal projects and government contracts. Actual studies, designs, and fabrications which have been performed under this program are described in the following paragraphs.

Dr. R. A. D'Antonio was a principal contributor to this project.

Adaptive Coding Techniques
Rome Air Development Center
Contract AF30(602)-3603

This investigation was performed to determine how redundant coding and modulation techniques can optimally be used for reliable digital data transmission. In the preliminary phase the various redundancy forms were examined to determine which were applicable, how they should be applied, and their relative merits. Channel statistics were surveyed and compared with models. Techniques for relating models to error patterns and codes to channels were investigated. The amenability of channels and feasibility of techniques also were investigated.

In the analytical phase, systems were specified to match real channels and their performance analyzed and compared. The associated problems of implementation and cost were also investigated.

In the verification phase, computer programs were run to simulate real channels (based on the survey in the preliminary phase) and error-control techniques. This computer analysis verified and supplemented the mathematical analysis.

Dr. R. A. D'Antonio was a principal contributor to this project.

Error-Correction Sets

An internal project is underway to fabricate error-correction encoder and decoder units in the latest IBM technology (solid logic) to be used for test and demonstration purposes. The first units fabricated are being shipped to various locations throughout the United States to be evaluated. These Error-Correction Sets apply advanced polynomial coding techniques to provide forward-acting error-correction capability in transmitting digital data.

These units provide significant performance improvement over comparable units through employment of a code structure which enables the decoder to sense whether clustered or random errors have occurred in an incorrect message and to adapt its correction process to the type of error pattern present.

An Engineering Investigation of the Design and Instrumentation of Error Correcting Codes
Rome Air Development Center
Contract AF 30(602)-2958

This contract involved a wide range of error control studies from March 1963 to March 1964. Among these were:

1. Recurrent burst-error-correcting codes
2. Variable redundancy codes
3. Residue codes
4. Decoding Bose-Chaudhuri-Hocquenghem codes
5. Analysis and comparison of error-control techniques
6. Design of error-control systems
7. Adaptive error-control system
8. Experimental verification and other studies.

D. MULTIPLEXING

IBM's across-the-board experience in multiplexing systems include:

- The contract with the U. S. Army Satellite Communications Agency entitled "Adaptive Digital Satellite Communications Techniques" is directly applicable to this problem. Multiplexing techniques were considered in this study.
- The Fort Monmouth RADA contract during which IBM performed systems analysis and optimization using techniques readily applicable here.

- The NASA Modulation Techniques study, during which a substantial portion of the analysis required to produce an Optimum Approach Recommendation as well as some of the design required for the Functional Design Plan were performed.
- The design, building, and testing of pseudo-noise multiplexing equipment.
- The Institute for Defense Analyses study on Multiple-Access Satellite Communications.

During the past few years, this interest has focused on the application of these disciplines to the improvement of techniques for communication through satellite repeaters. These efforts, including contracts for the Armed Forces, DCA, and NASA, and tasks in the IBM Independent Research and Development program, have culminated in the development of the RANSAC transceiver for the experimental study of multiple-access communication satellites.

The most recent and significant tasks performed by FSD in areas relevant to the proposed study are detailed in the following pages. Reference to Table 9-1 reveals that these projects, of which five are presently active, span a range of topics relevant to the study. Of equal importance, the personnel proposed for the present study have taken a leading role in many of these projects and will bring this knowledge and experience to the study.

Multiplexing and Error-Control Equipment for STRATCOM

A system has been designed for the U. S. Army Strategic Communications Command for multiplexing a number of data channels for transmission over a single high-speed transmission channel with forward error correction. The multiplexer combines data from many input teletype channels having diverse bit rates, into a synchronous bit stream. Each output channel of the demultiplexer provides data and timing output which is the same as the data and timing presented to the input channel of the multiplexer.

The synchronous bit stream output from the multiplexer is encoded, utilizing the latest advances in the theory of coding for error correction. An adaptive decoding procedure is included which modifies the correction procedure between burst correction and random error correction as appropriate. The guard space required for burst correction is only slightly more than the correctable burst length.

Dr. Blasbalg, Dr. D'Antonio, and Mr. H. Najjar did the design on this system.

Asynchronous Multiplexer

IBM has recently submitted a proposal to the U. S. Army Electronics Command for the design and fabrication of an asynchronous multiplexer. IBM incorporated several unique features into the initial designs for this system, some of which are:

- A realistic but simple 120-channel traffic simulator
- Counter outputs for evaluation of freezeout rate
- Variation of threshold for external coding
- Optional delay bit identification
- Amplitude quantization of 5, 6, or 7 bits
- Optional use of companding

This unit is designed to be a laboratory tool in evaluating and optimizing external coding multiplexers. It achieves flexibility for this purpose by providing appropriate controls and switches to permit the user to vary all appropriate parameters.

Frequency and Time Division Multiplexing (Contract Nos. AF30(602)-2600 and -3086; RADC)

IBM has developed a new type of frequency-division multiplexing for the Air Force. It involves a unique sampling modulation-demodulation technique coupled with a generalized method of resonant transfer. A complete set of equipment with provision for 12 analog audio channels has been built and is being tested.

One variation of the arrangement results in integrated frequency-division multiplexing and time-division switching which offers particularly striking advantages with respect to simplicity and possible economic savings. These savings stem from the fact that the so-called mux equipment is eliminated in such applications.

Technical details of the equipment developed in the Engineering Laboratory are described in a professional paper:

> "A Unique Technique for Frequency Division Multiplexing, and the Integration of this Method with Time Division Switching," Paul M. Thrasher, Tenth National Communications Symposium, Rome, N. Y., 1964.

E. PSEUDO-NOISE MODULATION

RANSAC (Random Access Noise Signal Address Communications)
(IRAD Project; Period of Performance: 1/64 - 12/65)

RANSAC is a code-division multiplex VHF radio employing digital techniques to provide multiple-access communications for a variety of operational conditions. RANSAC provides exceptional capability in satellite multiplex communications and anti-jam/anti-spoof communications. The RANSAC principle is adapted to short-range tactical communications and ranging and identification devices.

RANSAC is an asynchronous system employing pulsed pseudo-noise modulation and digital-matched-filter techniques. A theoretical analysis of multiple-access communications has indicated that RANSAC possesses several important advantages over more common communication techniques when employed in space applications:

a. CCIR quality
b. Improved operation with both strong and weak stations
c. Handover problem with asynchronous orbits simplified

d. More effective use of available satellite power

e. Compatible with TDM

f. Advantage of pulsed modulation systems relative to peak power

g. Compatible with concept of communication system with no central control station

h. Immune to nonlinearities and other distortions (e. g., AM-PM conversion and hard limiting)

i. Simplified design with hard limiting in satellite

j. Reduced RFI problems because of spreading power over a broad band

k. Amenable to frequency hopping.

Experiments were performed with RANSAC over real communication channels to demonstrate the degree to which the measured performance agrees with that obtained from the theoretical studies outlined above.

In addition, a theoretical study design and development program has been initiated which will lead to the development of a laboratory model of an R-F phase-locked pseudo-noise modulation-demodulation device applicable to anti-jam secure communications as well as to commercial satellite links.

Dr. H. Blasbalg initiated the program which led to this task and directed it during the initial phases of work.

Improved Communications Satellite Modulation Techniques (NASA) (Contract No. NAS 5-3544; Period of Performance: 10/63 - 8/64)

This contract was for the investigation of modulation techniques suitable for random-access communications via a Syncom satellite. The study considered the complete spectrum of modulation techniques, and, in many cases, the analysis was extended to include the specification of system configurations and parameters to obtain a more realistic evaluation. SSB-FDM was used as the standard reference system for quantitative comparisons of two types:

a. Comparisons based on communications channel parameters

b. Comparisons based on the operational flexibility and the implementation complexity of various modulation techniques.

The study was divided into two phases. The major goals of the first were:

a. Specification of system configuration, system parameters, performance requirements, and criteria for selecting candidate modulation techniques

b. Selection of several candidate modulation techniques for more detailed study during the final phase of the program, and preliminary specifications of a system design based on these techniques

c. Analysis of special devices.

A major effort was expended on the application of PN (pseudo-noise) techniques, since this technique appears to be extremely attractive but has received little attention for nonmilitary systems. Criteria for choosing the optimum PN technique were developed, and the effect of hard limiting in the satellite receiver was investigated. PN multiplexing was explored in detail during the first phase, and continued to receive attention during the last phase with emphasis on two techniques:

a. PN modulation with matched filter reception

b. PN modulation with correlation-locked reception.

The final phase of the study was concerned with the optimization of the systems and techniques postulated in Phase I. Specifically, the study compared the PN configurations with selected conventional techniques. It was determined that matched-filter reception utilized channel capacity more efficiently than correlation-locked reception, although the latter requires less hardware.

Three principal types of satellite signal processors were identified: transparent, compound modulation, and detect-and-remodulate. It was determined that conventional modulation techniques can function effectively with a communication satellite in a multiple-access mode. As a result PCM/TDM-PCM/TDM was evaluated, and its good performance in the signal-to-thermal-noise ratio analysis, the simplicity of the satellite repeater, and the requirement for accommodating both small and large stations isolated this technique as a valid candidate for further study.

Dr. H. Blasbalg was the project manager.

Miniature Digital Matched-Filter Module (MDMFM)
(IRAD Project; Period of Performance: 1/65 - 7/65)

The primary objective of this project is the development of a MDMFM suitable for use in military applications of pseudo-noise and digital-matched-filter techniques. In addition, the feasibility of using an MDMFM in error-control applications where size and weight are important factors is being studied.

The MDMFM consists of N flip-flops wired as a shift register with an N-input Kirchoff adder attached. Based on preliminary studies of a variety of applications, N should be at least 16. If the MDMFM is to be made of a single hermetically sealed thin-film substrate, provision must be made for 2^N different ways of connecting the N flip-flops to the Kirchoff adder. However, separating the shift register and the Kirchoff adder leads to a large number of external terminals on each thin-film substrate. Reconciliation of these conflicting requirements is one of the major objectives of the project. Also, operational and logistical considerations of each major application must be taken into account in choosing the optimum value of N.

The thin-film technology currently being developed at IBM's Owego facility is being used as a basis for the development of an MDMFM suitable for applications involving any shifting speeds up to a limit of the technology (e. g., 5 Mc) and any width-time (WT) product by cascading the proper number of MDMFM's. A wide variety of applications are being studied and reduced to a common set of specifications necessary for a single MDMFM design. Comparison with non-IBM technologies are being made.

Dr. H. Blasbalg initiated the program in asynchronous pseudo-noise modulation.

DCA Area Communication Control Centers
(Contract No. SD-115; Period of Performance: 12/61 - 5/63)

Under contract to the Department of Defense, IBM provided special equipment, design, fabrication, and testing; integration of special and standard equipment in a test facility; complex operational programs and diagnostic programs; training; installation and maintenance; and project management for the four DCA Area Communication Control Centers.

Three Area Centers and the National Center underwent final programming checkout and became operational early in the second quarter of 1964. The area centers receive, possess, and store status information sent from message switching centers around the world. The messages containing data on circuit and traffic status are in the format prescribed by DCAC-55-5. Once the message has been processed, the data in the message is used to update large, active, and historical files stored in on-line random-access disk files.

When data in a file or a collection of events represented by several entries exceeds a predetermined norm, a display change is formulated. These changes are reflected on large wall-type electronic displays. The displays provide the center status supervisor with an overview of the facility and service status of the DCS in his area.

The Area Communication Control Centers provide DCA with a significant improvement in its capability to monitor and control the DCS on a day-to-day basis. They also provide complete and reliable historical data through which

DCA management directs the evolution of the DCS to meet the changing communication needs of government.

Multiple-Access Techniques
(IRAD project; Period of Performance: 1/63 - 12/63)

The purpose of this research and development project was to examine the techniques applicable to multiple-access communications systems. The following areas were studied:

a. Design and development of basic random-access, signal-address communications subunits

b. Integration of subunits (in the laboratory) for testing the feasibility of multiple-access concepts

c. Investigation of optimum signal design using coding theory and Boolean multiplexing in multiple-access systems.

A result of this program the development of a digital matched-filter communication system using pseudo-random noise-like address signals having large bandwidth-time products.

This task also included a theoretical and experimental study of phase-coherent spread-spectrum modulation, suitable for extremely long-range communications in a hostile signal environment. This effort was an out-growth of the previous studies of wide-band asynchronous communication systems using pseudo-random noise signals. An output of this task was the design of a digital delay-lock discriminator using a digital shift in a feedback loop. Because it can provide very precise synchronization, this device has application in the areas of HF communications, satellite communications, and command and control. Synchronization is accomplished by correlating the received pseudo-random reference signal with a locally generated replica.

Dr. H. Blasbalg was the technical leader for this task.

Multiple-Access Systems
(IRAD Project; Period of Performance: 1/64 - 12/65)

IBM's program in Multiple-Access Systems has included the investigation of requirements and the development of designs for a variety of applications. In addition, comparative analyses of various implementation techniques were made using analysis and computer simulation. These analyses included comparison of the RADA-type TF matrix and pseudo-noise addressing schemes. As a result of this work, preliminary system designs were developed, and conclusions drawn with regard to the applicability of various multiple-access techniques (RANSAC, in particular) in each of the most important areas of application.

Preliminary systems work was completed in 1964 in each of the following areas: Communications Satellites and Survivable Communications, Post-Attack Command and Control Systems, Limited-Range Tactical Multiple-Access Systems, and Ranging/Identification Systems. More detailed analysis and design work in these areas was accomplished in 1965.

This project made extensive use of data obtained from the experimentation conducted in 1965 with the RANSAC equipment, and used this data to derive the trade-off curves needed to verify previous analysis and design decisions.

Automatic Alternate Routing Study
(Contract No. DA 28-043-AMC-00-166(E); Period of Performance: 7/64 - 6/66)

In July 1964, work was begun on a contract with USAERDL (Fort Monmouth) to study all possible methods for the automatic routing of calls and messages in the Post-1970 Field Army Switched Digital Communications System. The ARMATS contract is for a period of two years and involves considerable use of operations research techniques, including simulation, linear programming, and probability theory. Results of the study will be data pertaining to the performance, complexity, and cost of each routing method considered. These results will be combined with results from three parallel studies that are under USAERDL auspices to form the basis for the overall system design of the Post-1970 System.

The Study involves two categories of analyses: those supporting general problem areas and those related to the specific routing methods under consideration. Included in the first category are the classification of possible routing methods, the development of a powerful general-purpose simulator for large networks (LANES) and the analysis of problems of "ring-around-the-rosie," network status reporting, and subscriber code translation.

The second category of analysis is repeated for each routing method. First, a detailed logical description of the routing method is developed, then a simulation model of the method is constructed and exercised. While simulation analyses are being performed, mathematical and engineering analyses are also published. System performance is measured in terms of percent-lost calls for both normal and partly destroyed networks. Engineering estimates are made of the cost and complexity of implementing each of the routing methods.

RADAS
(Contract No. DA 36-039-AMC-00146(E); Period of Performance:
4/62 - 3/64)

RADAS is the U. S. Army's acronym for Random Access Discrete Address System, a self-organizing radio communication system linking all units of an army division simultaneously over a common channel. The problems of implementing RADAS arise primarily from the mutual interference of many users on a common channel, and the strategic and tactical demands of an army divisional communications system.

As associate subcontractor to Motorola, Inc., in the development of RADAS, the IBM Communications Systems Department was responsible for computer simulation, operational and environmental analysis, and systems analysis. In addition, the IBM Communications Systems Department supported Motorola in the area of technology evaluation and development.

The IBM simulation task on the RADAS contract provided technical support in three general areas:

a. A digital computer program for the reduction and presentation of deployment and traffic data

b. Simulation programs that served as tools for system analysis and design by providing relative measures of performance for candidate system designs

c. A simulation program that depicted the actual performance of the selected system operating in a realistic tactical environment.

The IBM Systems Analysis Group had the responsibility for ensuring the validity of the data generated and the methodology employed in synthesizing RADAS. This group also formulated mathematical models of the communications processes peculiar to the RADAS concept.

To analyze effectively the problem of mutual interference in a RADAS, analysts at the IBM Communications Systems Department developed probability models of the process by means of which desired signals were extracted from the multitude of signals co-existing in a RADAS environment. Using the techniques of modern statistical communications theory and information theory, these analysts determined the optimum combination of the system parameters (e.g., pulse shape and detection logic) of a RADAS.

Another part of IBM's contractual obligation was to design and fabricate a RADA System Synthesizer to measure the effect of pulse errors due to noise and interference in delta modulation. The pulse error measurements were related to data transmission errors and more importantly to audio signal-to-noise ration.

Airborne Ranging and Orbit Determination System (AROD)
NASA
(Contract No. NAS 8-4098)

A feasibility study of an Airborne Ranging and Orbit Determination System was completed with Marshall Space Flight Center. This system, operating at S-band, is intended to be a self-contained navigational system for space and launch vehicles making use of coherent ground transponders which retransmit response to radio signals continuously transmitted from the space vehicle. Range and range-rate are measured simultaneously from three ground stations. These stations are uniquely identified and located accurately. A worldwide ground network of such stations is contemplated for an operational system.

The two most important results of this study were performance curves relating measurement accuracies to equipment penalties and a detailed system design which represents an economical approach to an operational AROD configuration. Range and range-rate measurement standard deviations of approximately 3 M and 0.3 M/sec., respectively, are achievable by the representative system.

Under follow-on NASA contract MAS 8-11050, a phase-locked-loop investigation was undertaken involving experimental studies to reduce the tracking-oscillator noise, a comparative evaluation of different types of oscillators, and determining the feasibility of employing adaptive loop control as a function of signed parameters. Studies of computer requirements, oceanborne transponders, and system interfaces were also carried out.

Under the follow-on contract, IBM performed a study of angle-modulation techniques, including the use of pseudo-noise waveforms for application to the AROD test model which was then under development. The purpose of this study was to select, on the basis of comparative analysis, the modulation scheme, modulation parameters, and tracking receiver implementation that provide the most suitable system performance in terms of tracking accuracy, interference resistance, acquirability, and immunity to multipath effects. Concurrently, engineering models of phase-locked tracking filters employing integrated circuits and microminiature components were developed. Among the objectives of this effort was the incorporation of maximum loop adaptivity and inherent memory in the tracking implementation to afford rapid reacquisition following signal fades.

Manned Spacecraft Communications

IBM's Communications Systems Department has undertaken communications system design studies for several manned spacecraft programs. These studies were performed under contract to the Air Force and NASA, and under subcontract to the Douglas Aircraft Company.

IBM was responsible to NASA's Langley Research Center for the preliminary design of the Manned Orbiting Research Laboratory (MORL) Flight Electronics System (Contract NAS - 12974). During Phase I of this program, the Communications System Department specified a base-line communications subsystem which provided telemetry, television, command, and voice channels for spacecraft/ground station communications, and provided for data and voice links between MORL and Ferry and Resupply Vehicles.

As a result of the Phase I MORL program, NASA selected the IBM/Douglas team to continue into Phase II of the program (Contract NAS 1-3612). During this phase, IBM selected an optimized communications system reflecting additional data transmission requirements and based upon equipment trade-off studies. In addition to the selection of communications equipments, system specifications were prepared which incorporate maintenance, test, and checkout requirements. The configuration currently under consideration includes equipments in the S-band, L-band, HF, and HF bands.

The Communications Systems Department also had responsibility for preliminary system design and equipment trade-offs on the Manned Orbiting Laboratory—Zero G Program. This study was performed for NASA's Manned Space Center (Contract NAS 9-1688). The study included determination of the communications requirements for an orbiting laboratory with a crew of 94, the conception of a system to meet these requirements, and selection of the equipment configuration. Preliminary system specifications were prepared for a configuration based on a unified carrier system providing television, telemetry, and voice transmissions.

F. TV TECHNIQUES AND SYSTEMS

Improved Coding for Military Digital Television
U. S. Army Signal Corps
Contract No. DA 36-039SC-87338

The objective of this program was to study means of providing the U. S. Army with a more efficient method of transmitting TV picture information by reducing the channel capacity presently required for transmission of analog video signal or the direct digital version of the analog. During this study exact coding techniques were investigated along with approximation methods which exploit the psycho-physical characteristics of the human observer.

A particularly interesting and important approach to TV bandwidth reduction was the decomposition of a picture into two information components; line drawings (i.e. a sketch) and detail "fill-in" information. A mathematical model for extracting the contours from a picture was developed and programmed in a digital computer. A digitized picture was then processed by the computer generating a line drawing. This technique worked extremely well. Mathematical methods were then developed for filtering in two dimensions, the remaining picture component. At the receiver two dimensional interpolation techniques were used to resynthesize the components.

This program was under the direction of Dr. H. Blasbalg.

In addition to the foregoing, IBM has worked on many significant space projects such as Orbiting Astronomical Observatory, Gemini, Manned Orbiting Research Laboratory and Manned Orbiting Laboratory. CES personnel have presented to NASA a conceptual paper on a Computer Managed Laboratory (CML) and are now doing some in-house research related to CML and the Automated Biological Laboratory. In support of these efforts, the IBM Space Systems Center also has a pioneering program in space biomedicine.

Satellite Distribution of Television Programs
Ford Foundation

Technical support was provided to the Ford Foundation in their recent proposal to the FCC for a Broadcasters' Non-profit Satellite (BNS) system. Representative systems for the distribution of TV, programs to broadcast stations were considered.

The key problems investigated here is the potential interference between the TV distribution satellites and the existing common-carrier microwave relay network. A study was also made of the effect on system cost of the present restrictions on effective radiated power in the down-link of the proposed satellite system.