NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

TELEMETRY SYSTEMS ANALYSIS AND DESIGN

by

William K. Ham

December 2000

Thesis Advisor: Brij Agrawal

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY ***(Leave blank)***

2. REPORT DATE
December 2000

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE :
Telemetry Systems Analysis and Design

5. FUNDING NUMBERS

6. AUTHOR(S)
Ham, William K.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(maximum 200 words)***

The Navy has a valuable opportunity to improve its own products and operations efficiency by showing its future leaders and designers how to design effective and viable telemetry, tracking, and commanding (TT&C) systems, and their operation. One system is the FLTSAT military communications constellation of spacecraft, one of which has been a static display at the Naval Postgraduate School (NPS) until June, 2000. The primary objective was to make this spacecraft operational and thus provide a new operational spacecraft laboratory for other NPS students. This thesis may also be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

14. SUBJECT TERMS
Space Vehicles, Other (Communications)

15. NUMBER OF PAGES
174

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

TELEMETRY SYSTEMS ANALYSIS AND DESIGN

William K. Ham
Lieutenant, United States Navy
B.S., Texas Tech University, 1993

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ASTRONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2000

Author: William K. Ham
William K. Ham

Approved by: B. N. Agrawal
Brij Agrawal, Thesis Advisor

Alfred N. Sorensen, Second Reader

Max F. Platzer, Chairman
Department of Aeronautical and Astronautical Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The Navy has a valuable opportunity to improve its own products and operations efficiency by showing its future leaders and designers how to design effective and viabletelemetry, tracking, and commanding (TT&C) systems, and their operation. One system is the FLTSAT military communications constellation of spacecraft, one of which has been a static display at the Naval Postgraduate School (NPS) until June, 2000. The primary objective was to make this spacecraft operational and thus provide a new operational spacecraft laboratory for other NPS students. This thesis may also be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENT

The author would like to acknowledge those individuals who provided their support throughout the production of this thesis. Thanks to both Brij Agrawal and Alfred Sorensen for their guidance and expertise. Thanks to the NPS engineers, David Rigmaiden and Edward Nath, whose time and talents were much appreciated in making FLTSAT operations a reality. Special thanks to the Naval Satellite Operations Center engineers, Edward Grucza and Doug Lawrence, whose help expedited the establishment of FLTSAT satellite operations at the Naval Postgraduate School (NPS). To my wonderful children, and the simple joy they brought when things seemed so complicated. Finally, to my lovely bride, Tippi. Her undying support is the key to my success, and she is the center of my inspiration.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. PURPOSE

This thesis may be used as a primer for the space engineering or space operations student regarding TT&C systems design. Great effort has been taken to document and discuss current design practices and standards adopted by DOD laboratories, test facilities, and operations centers. A TT&C system designed for a spacecraft incorporating all the traditional subsystems (payload, thermal, structural, power, TT&C, attitude control) is included.

B. RESEARCH OBJECTIVES

1. Primary Objectives

a. Apply current principles and design techniques to develop a Telemetry, Tracking and Commanding (TT&C) system for a small spacecraft incorporating as many traditional subsystems as possible (payload, thermal, structural, power, TT&C, attitude control).

b. Recommend appropriate hardware and software compliant with current DOD telemetry standards.

c. Document current practices and principles for designing spacecraft telemetry systems in a reference tool for use by other space systems students.

d. Demonstrate integration of TT&C control software with the FLTSATCOM spacecraft in the Space Systems FLTSATCOM Laboratory, contingent upon successful power up of the spacecraft. This would result in active communications with the spacecraft and possible future use as a hands-on student laboratory.

2. Secondary Objectives

a. Explore various compression techniques to improve telemetry data rates.

b. Explore innovative designs used in experimental spacecraft.

c. Investigate design limiting issues from both the engineering perspective and the operator perspective.

C. THESIS OUTLINE

I. INTRODUCTION

II. BACKGROUND

III. DATA ACQUISITION

- A. Optical Transducers
- B. Strain Transducers
- C. Thermal Transducers
- D. Position Transducers
- E. Data Acquisition Systems

IV. COMMUNICATIONS

- A. Modulation
- B. Link Design
- C. Demodulation
- D. Timing and Synchronization

V. TELEMETRY FRAME CONSTRUCTS AND STANDARDS

- A. Basic Frame Structure
- B. Current Standards: Inter Range Instrumentation Group
- C. Packet Telemetry

D. Future Techniques: CCSDS

VI. COMMANDING

A. Fundamentals of Commanding

B. ISCS Software for FLTSATCOM at NPS

C. Hardware Configuration at NPS

D. Software Configuration at NPS

E. Commanding Operations at NPS

VII. TT&C SYSTEM FOR A SPACECRAFT

A. Introduction

B. Requirements

C. Trade Studies

D. Final Design

D. EXPECTED BENEFITS OF THIS THESIS

There are several applications for this product. Any engineering team involved in a satellite design project, may find it a suitable baseline for the TT&C subsystem. The content could be formulated into course notes for implementing a course on TT&C system design, currently no course is offerred at the Naval Postgraduate School on this subject. Additionally, the successful implementation of active communications with the currently inoperable FLTSATCOM spacecraft in the Aerospace Engineering Building, has far reaching implications. Such a project not only provides opportunity to demonstrate the importance of operator interface to engineers, which is often forgotten in the design process, but also provides a platform for future students to conduct research or laboratory work. It is also possible that a future course may develop from this work, which may become at least an optional elective for future students of engineering systems design.

THIS PAGE INTENTIONALLY LEFT BLANK

II. BACKGROUND

A. INTRODUCTION TO TELEMETRY, TRACKING AND COMMANDING SYSTEMS

Spacecraft design incorporates many different disciplines. All of which contribute to the success of the mission for which the spacecraft is designed. All are equally important, in that if one was less important it would have been removed from the design process ages ago since every subsystem has mass, and mass is the main expense. One subsystem, however, has special consideration. Without it, other subsystems could not operate to carry out the mission. Additionally, it is the only link the operator or designer has to the spacecraft once it is on orbit. The Telemetry, Tracking and Commanding (TT&C) system is the central nervous system of any spacecraft, and also serves as the primary input and output for all the other subsystems. An introduction to the main functions of the TT&C system is in order: communications, data acquisition, system operations (commanding), and data/command storage.

Communications is the best place to start. After all, it is the only means by which we can do anything to the spacecraft once on orbit. Through highly reliable communications equipment and techniques, ground resources may communicate with the spacecraft whenever allowable. Why not at any time? Simply stated, an operator may not be able to see the spacecraft at any time. Ground resources are limited by dollars. That is, it may not be economically feasible to construct enough ground stations to ensure visibility to the spacecraft all the time. This is especially true for low altitude satellites. Additionally, the spacecraft may be in an attitude that is not optimal. A tumbling spacecraft requires communication with the ground to be recovered, therefore, communications must be possible from any orientation. This is usually acieved by strategic placement of antennas in the nadir and anti-nadir directions of the spacecraft. Such antennas are usually low power to achieve the requisite four pi steradian coverage, or communication from any direction. Thus the communications subsystem must be very reliable to ensure every opportunity to talk to the spacecraft is effective, which may only be a span of five minutes. Similarly, the reverse is true. For the operator or engineer, it is just as important for them to hear what the spacecraft has to say. After all, a reaction to a situation can only be initiated after knowledge of the situation has occurred. Thus the means by which the spacecraft understands what is happening to it while on orbit is important as well. This mechanism is the onboard processor and any peripheral components utilized to make these assessments. The processor is the director of all other subsystems to ensure the mission is successful. Certainly the operator or engineer tells the processor what to do, but really the processor is the one that carries out the orders while on orbit. It is clear that computer communications is essential to successful system design.

The interdisciplinary nature of TT&C systems contributes to the complexity of the design problem. Since most engineers tend to focus on one area (attitude control, guidance, structures, thermal, etc.), few can effectively describe interaction among them all. Previously the interactive nature of the TT&C system was outlined. It communicates with everything: other subsystems, itself, and the operator. This is depicted in Figure 1. An analogy is in order: for a person to be able to speak about several different topics, or even to be able to speak to several different types of professionals (doctors, lawyers, engineers, school teachers) they must have a rudimentary knowledge of that which they speak. This is not unlike the TT&C system designer and by extension, the system to be designed. To understand thermal data, the system must understand the difference between values that are acceptable and unacceptable. The same is applied to attitude control data. An understanding of something implies a knowledge base from which to draw from. For a TT&C system, this knowledge base is the software. It provides the thinking capacity for the spacecraft. It can facilitate comparison of actual values with a database of known acceptable values. And when a problem arises, the software can tell the processor to execute a series of safing commands which will configure the spacecraft in a known state until help arrives in the form of commands from the ground. To understand the data, however, data must exist in the first place. This brings to light the means for collecting data: the data acquisition system. This is probably the most overlooked component of the TT&C system. Most design texts speak of the sensors or transducers, which measure the stimulus, and the transponders, which transmit the data to the ground. The step in between is just as critical. This is the feet, if you will, that get the information from sensed value to communicated values. Not only is it important to understand this process, but it is critical to properly determining the TT&C system resource requirements (processor speed, data storage capacity, downlink bandwidth).

The thinking mechanism, the software, was only briefly mentioned, and requires greater attention. This is the means by which the processor decides to do something or to not do something. Operating the spacecraft requires being able to conduct several functions successfully while it is out of view of the operator. Some of these functions include maintaining proper attitude, ensuring adequate power profile, calculating ephemeris data, storing telemetry data, and maintaining the proper thermal environment

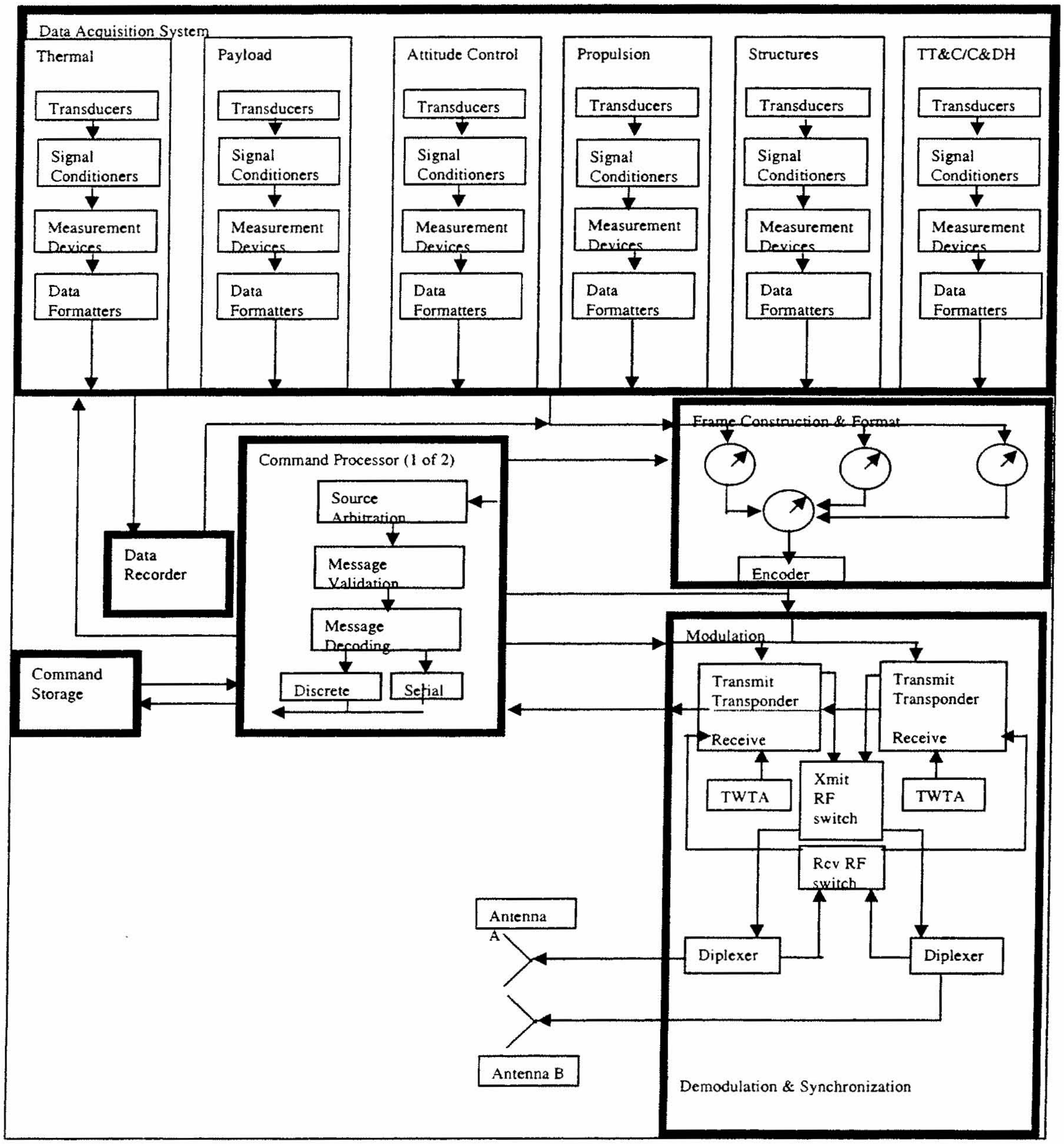

Figure 1. Overview of a TT&C System

[Ref. 1]. All these require decisions which must be made via software. Software is an interesting problem in itself. It has become a primary driver in system development costs, and is considered by many to be a subsystem all its own [Ref. 1]. Because software is so nebulous, large margins are used in estimating the costs and size [Ref. 1]. Software is one of the few things that can actually be changed after launch. This said, a limited scope will be explored. Key concerns include understanding what functions must be performed, and estimating the amount of memory to store all the software required for system operation. The former so proper size of the processor in terms of speed can be assessed. Thus all required instruction executions can be completed. The latter so enough memory can be planned for onboard the spacecraft.

Recall that a spacecraft is not able to communicate with the ground operator 24 hours per day. Ground stations, are the primary reason for this constraint [Ref. 1]. This is a critical and fundamental concept to understand in the system design. An old adage lends a great deal of insight here: 'If a tree falls in the forest, and no one is there to hear it, does it make a sound?' When a spacecraft is out of view, it does still operate. Temperatures still rise and fall, voltages continue to supply power to components, and problems do occur. So what action does the operator take when the satellite comes into view, and finds the spacecraft in a non-nominal health status? Typically it is desirable to know when the change occurred, since it is not likely that the spacecraft was left in this configuration when it was last viewed. So the system must be able to play back some portion of health data since the last time the spacecraft was in view. Play data back requires that it must have been stored in the first place. Thus a data storage unit is required to facilitate this main function. Along the same line of thinking, invariably it is necessary to have the spacecraft do something like perform a payload operation, or perform something health related when it cannot be viewed from a ground station. To do this, the onboard processor is the agent that will carry out the task. Carrying out the task requires that the processor look for the specific action or file at a predetermined time for execution. Thus the processor must have some storage buffer where it can find these actions, command storage. It is important to realize that with at least a rudimentary understanding of how the spacecraft will be operated, adequate flexibility can be designed into the system. This understanding can be obtained by observing missions which are similar and have already been deployed, or by specifying certain absolute requirements from an operational point of view. Both are techniques used in practice. When considering the significance of the TT&C system, and its relevance to mission success, its critical nature to the spacecraft design is plain to see. It is with this mindset that the resulting research into TT&C systems and how to design them is now presented.

THIS PAGE INTENTIONALLY LEFT BLANK

III. DATA ACQUISITION

One of the primary objectives of any TT&C system is to collect output data from spacecraft components [Ref. 5]. Collection of the data requires that we know what is being collected and how it is measured. The transducer converts one form of energy, temperture, force, or pressure into another, typically electrical voltage because it is easily measured. Generally, we want the transducer to measure some phenomena which may be occurring on our spacecraft: temperature of a component, presence of the sun in a sensor, whether a thruster is on, etc. Transducers are the means by which we collect the data we desire. Several transducer types are avaliable to the design engineer, and a few of those most often will be introduced.

A. OPTICAL TRANSDUCERS

An optical transducer converts luminous information or phenomena into a measureable electrical voltage or current [Ref. 2]. These transducers typically respond to a broad range of spectral frequencies. Therefore, to gain adequate spectral resolution, spectral filters are employed. A few applications of these devices include: sun sensors, earth sensors, electronic cameras [Ref. 1]. The physical phenomena that make these devices work is the photoelectric effect. There are two classes of optical devices: point photoelectric devices and area photoelectric devices. Point devices consist of photomultiplier tubes, phototransistors, photodiodes, and photocells. The mose complex of these is the photomultiplier tube. Area photoelectric devices are often called Charge Coupled Devices (CCD) [Ref. 2].

1. Photomultiplier Tube

These devices are used to measure very faint levels of light through a very limited aperture. The sensitivity provides for measurements of as little as a few photons per second. This device does not work well when saturated with a bright source. Because very faint levels of light are difficult to measure accurately, the device is constructed of multiple stages of photoelectric material resulting in a cascade of electrons at the final stage which is measureable as current. The stages of photoelectric material, called dynodes, are the key to the operation of this device. Electrons are acclerated through each stage where a collision with other photoelectric material occurs at the end of the stage. Thus more electrons leave the stage than entered the stage. As many as ten dynodes are used in the typical photomultiplier tube. High voltage power supplies are required to drive the tubes to ensure a potential difference across all the stages of approximately 1000V. [Ref. 2]

Photomultiplier tubes are characterized by three things: quantum efficiency, dark current, and fatigue properties. Quantum efficiency refers to the number of photons actually detected by the device [Ref. 2]. Response curves displaying quantum efficiency versus wavelength are generally obtained through the manufacturer and are non-linear. Such curves typically display a disproportionate response at particular wavelengths, thus the tube is chosen based on its response curve at the wavelength of interest. Dark current is a description of the tube's intrinsic noise level when not illuminated [Ref. 2]. This current is largely due to thermal excitation, and can be reduced to some degree by active thermal control. Fatigue is a property in all tubes which results in a change in output current while under a consistently bright load. It often manifests as a 'drift' in output current over time. Closing the aperture for a short duration, or cycling the aperture often will help to prevent fatigue in most cases. This property and dark current are especially damaging during extended calibration periods where precise measurements are required [Ref. 2].

2. Phototransistors, Photodiodes, and Photocells

Unlike the photomultiplier tube, these devices are used to measure incident light when the source is much more bright, such as a heavenly body that is relatively close to the detector eg. Sun or Earth for a Low Earth Orbiting (LEO) spacecraft. The measurement is produced in a discrete fashion. The response curve for these devices is generally logarithmic over several decades of illumination, thus giving them a linear plot on a log-log graph. The output current is generated in the transistor or diode when the light is present. These semiconductor devices change electrical states at the P-N junction in the presence of light [Ref. 2]. Photocells, on the other hand, change the cell material's resistance when light is present.

3. Charge Coupled Devices

CCDs are configured in arrays of photosensitve detectors. Both linear arrays and two dimensional arrays are often used. Each detector is essentially a storage device which stores charge based on the incident number of electrons over a sample duration [Ref. 2]. Once the duration is complete, the charge is released to a buffer. This transfer of charge can be measured as a voltage which is proportional to the intensity of the incident light. For an array, each detector voltage is sampled in sequence not unlike retreiving data from a memory array. Applications for the CCD array are found in imaging payloads as well as high speed tracking systems [Ref. 2].

B. STRAIN TRANSDUCERS

Whenever a force or pressure measurement is desired, typically the best way to obtain this is observing the material which is undergoing stress due to the force or pressure. Materials will undergo a certain amount of elastic deformation when a force is applied to them. This strain can be measured via a transducer that is attached to the material itself. Two types of transducers are generally used for this measurement: strain gauge and piezoelectric crystal.

1. Strain Gauge

Strain gauges have been widely used in engineering projects for generations. These are simple devices that exploit a material's well known resistivity property. Physical construction of a strain gauge, or strain rosette, consists of a wire or metal foil attached to a thin paper or plastic backing which facilitates bonding directly to the surface whose strain is to be measured [Ref. 3]. When the material stretches along the axis of the grid, the length of the wire changes, and thus a change in the resistivity occurs. Recall that resistance is given by the following equation:

$$R = \frac{\rho \cdot L}{A} \qquad \text{Equation 1}$$

where ρ is the intrinsic resistivity of the wire, L is the length of the wire, and A is the cross-sectional area of the wire.

Unfortunately, if the wire stretches along the perpendicular to the grid axis, no change in resistivity occurs. So to make measurements in this direction, the gauge would need a second foil, whose axis is perpendicular to the first. This is not widely used in practice. Industry typically uses the 45° rectangular rosette consisting of three foils, the center foil sandwiched between two side foils at 45°, or the 60° equiangular rosette also consisting of three foils separated by 60°. Figure 2. depicts these rosettes. From these configurations, not only can extensional strain be measured as in a single gauge, but shear strain can also be measured, often referred to as multi-gauge. [Ref. 3]

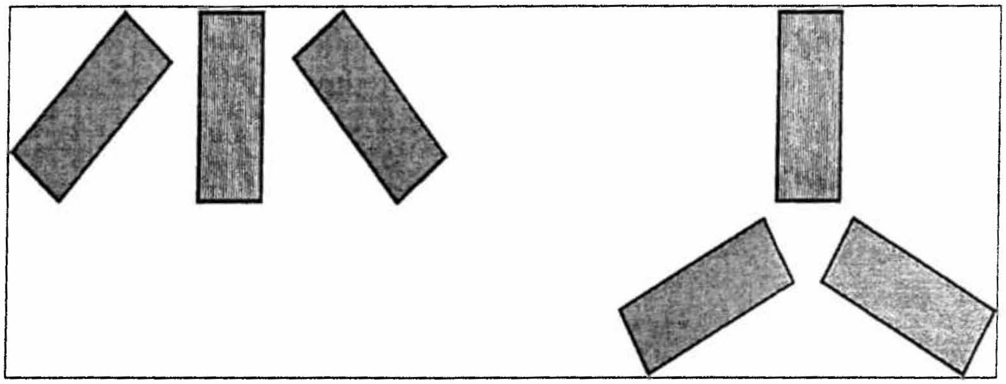

Figure 2. 45° Rectangular Rosette and 60° Equiangular Rosette After Ref. [3]

2. Piezoelectric Gauges

Piezoelectric materials react to transient changes in the crystalline structure of the material. When a crystal is compressed, a voltage is produced across the material. This voltage will dissipate if the acting force remains constant. Thus instantaneous measurements are only possible for actively moving materials. Vibrational displacements are the primary measurements these gauges are used for. The output for these gauges is linear over a large temperature range, making them attractive for space applications. Also, the crystals output fairly large voltages, on the order of milivolts, which enables them to be utilized without too much signal conditioning.

C. THERMAL TRANSDUCERS

A second class of devices that exploit the resistivity property of a material are the thermal transducers. Here the principal that the resistance of the device changes with temperature is at play. Three types of transducers are in widespread use: resistance temperature detectors (RTDs), thermocouples, and thermistors. Of the three, the RTD is the most linear.

1. Resistance Temperature Detectors

The most common material used in RTDs is platinum. In general the temperature-voltage relationship is given by an equation of the following form:

$$R_T = R_0 \cdot (1 + \alpha \cdot T) \qquad \text{Equation 2}$$

where R_T is the resistance at temperature T, R_0 is the calibrated resistance, and α is the coefficient of resistance change in units of Ω/Ω/°C where Ω is the unit of resistance in ohms. This is a general relationship, and the coefficients change depending on the material used. A more exact relationship with platinum, and that is found in most modern labs, utilizes a 20th order polynomial [Ref. 2]. Actual implementation of the RTD employs the two or three wire Wheatstone bridge as depicted in Figure 3.

2. Thermocouples

This commonly used device is based on the principal described by the Seebeck effect: every junction of two dissimilar metals will produce a potential difference across the junction [Ref. 2]. This voltage is not constant, but is a function of the material types and temperature. Advantages for using thermocouples include: greater resistance to damage, ease of manufacture and placement, larger operating range. The Seebeck effect not only provides the means for temperature measurement, it also provides the single most significant disadvantage [Ref. 2]. Because every dissimilar metal produces a potential difference, probes, inputs, and sockets contribute to this voltage. Separating these contributors from the voltage of interest requires a great deal of added design complexity. Additional powered equipment to maintain isothermal blocks for the two metals are generally required, which contributes to the complexity of the system design.

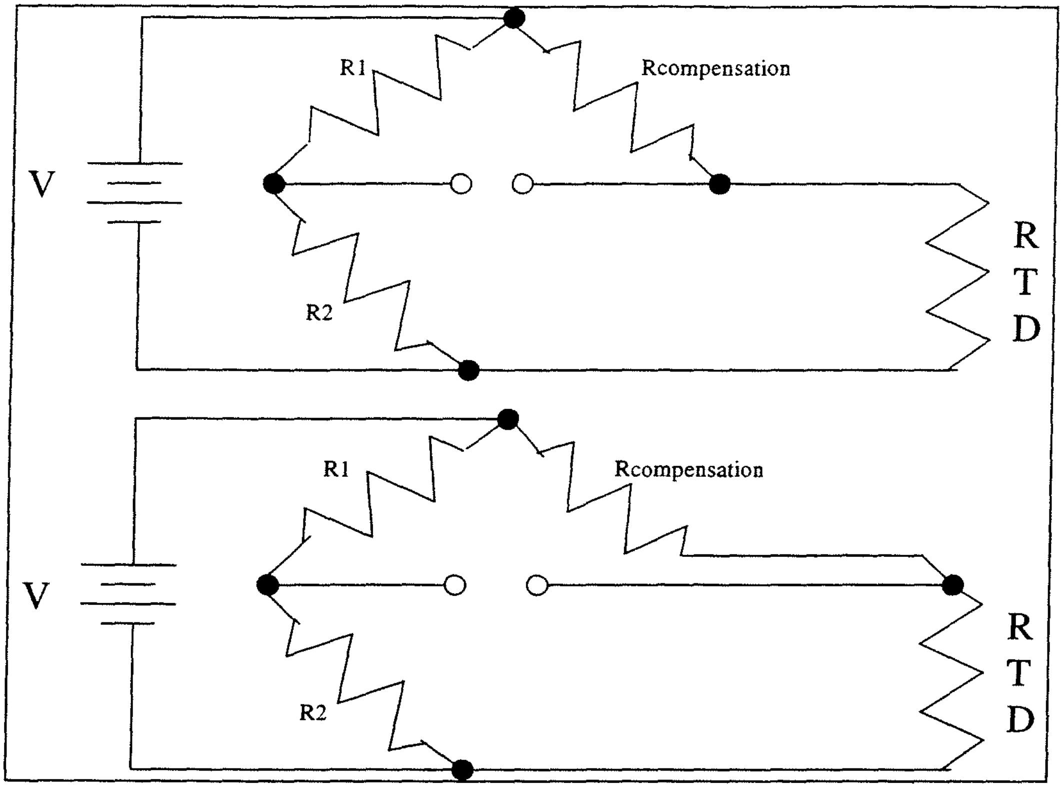

Figure 3. Common RTD Measurement Configurations After Ref. [2]

Another disadvantage is the nonlinearity of the operating characteristics. Successfully implementing these devices requires proper signal conditioning, careful placement of measurement leads, and for adequate resolution, reliably reading measurements on the order of microvolts.

3. Thermisters

This is a semiconductor device that must be maintained below the maximum operating temperature and not subject to much mechanical stress [Ref. 2]. It has a very steep negative slope coefficient, which allows much more resolution in small temperature changes. The following equation can be used to obtain resolution on the order of 0.04°C over a 100°C temperature range:

$$\frac{1}{T} = A + B \cdot \ln(R) + C \cdot [\ln(R)]^3 \qquad \text{Equation 3}$$

where A, B, and C are constants specific to the device, and T is temperature in K [Ref. 2]. This device is also implemented in a Wheatstone bridge circuit as in the RTD.

D. POSITION TRANSDUCERS

While moving parts are typically undesirable in a spacecraft design, it is sometimes unavoidable. Accurate position is very important on a spacecraft when implemented. For example, the solar wings are pointed to the sun to ensure power to the spacecraft payload and bus. Some type of motor is necessary to rotate the wing shaft to maintain sun pointing. Knowledge of this position accurately can mean the difference between the batteries being in a charging state or discharging state. For a LEO spacecraft, an error can lead to drastic results, as the batteries are charged and discharged every orbit. With this significance in mind, there are two basic types of position sensors: resistive measurements and optical sensors.

1. Resistive Distance Measurements

The most inexpensive device is, in general, not the most accurate either. The same truism applies to resistive distance measurements. These devices are potentiometers that are mechanically coupled to the displacement of interest [Ref. 2]. As the displacement increases, so does the resistance in the potentiometer. Voltage drop across the potentiometer is proportional to the displacement at any time. As observed in the temperature measurement devices, resistance is subject to change with temperature. The solar wing drive motors we discussed previously are also typically at a location that is in direct line of sight of the sun, which heats the potentiometers while in view. Thus the resistance changes depending on whether the spacecraft is in sunlight or in eclipse. Resistance dependence on temperature is one of the disadvantages of these devices, as well as the nonlinearities associated with the drive motor [Ref. 2].

2. Optical Distance Measurements

An optical sensor is usually used to get very precise measurement results. Often these sensors are used to measure rotary displacement and may be found in applications such as antenna pointing or telescope positioning. A binary encoded disk is placed concentric to the rotating shaft (see Figure 4.). When the shaft turns, the disk does also, changing the code. A string or bank of photodiodes and photo detectors are placed just

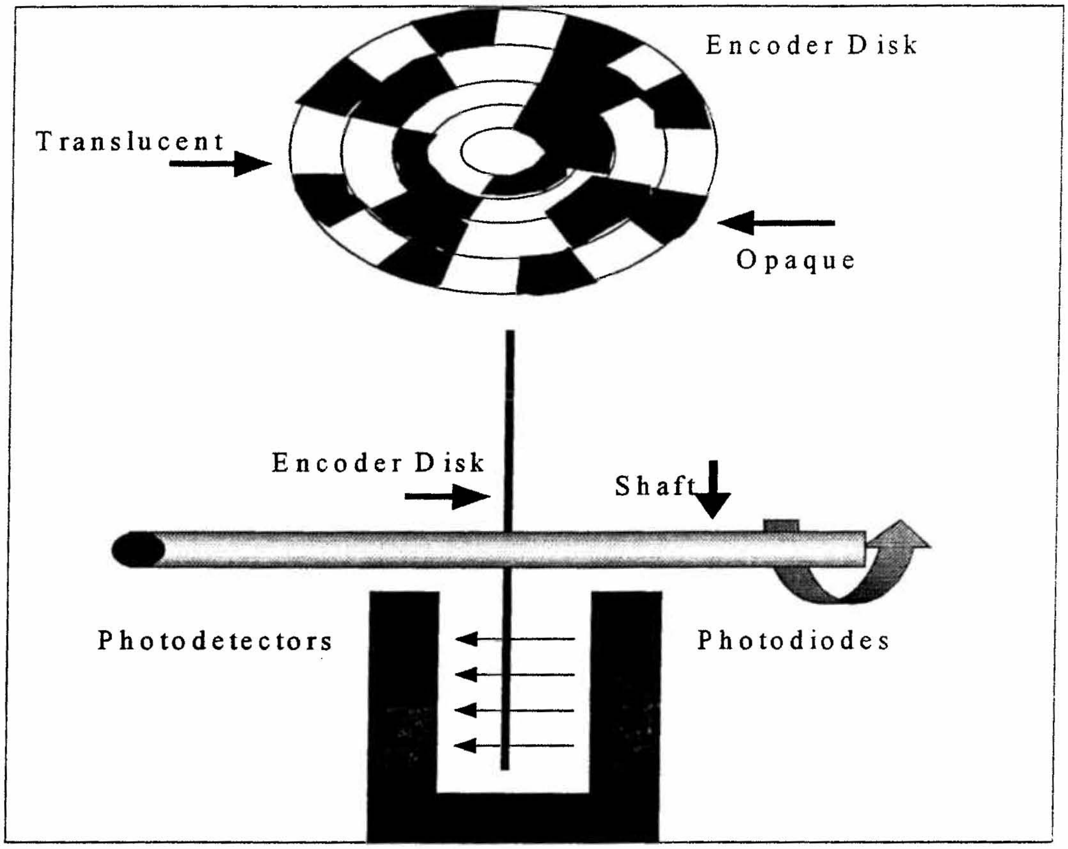

Figure 4. Optical Shaft Encoder After Ref. [2]

underneath the disk along the radius of the disk. As the code rotates, the alternating translucent and opaque sections of the disk, allow the light source to transmit through the disk to the photodetectors. Position angle is determined from the binary code sampled through the photodetectors. Higher resolution is obtained by adding more code rings. [Ref 2.]

E. DATA ACQUISITION SYSTEMS

Sensors such as the CCDs or thermisters provide the means by which phenomena are measured. From these sensors, voltage or current is generated in proportion to the stimulus. This voltage or current signal must now be processed to provide data for further analysis by the operator or even the onboard processor. Once analyzed, it will then become information. The process of converting signals into data is called data acquisition. Data acquisition is often taken for granted when describing the overall system, however, it is fundamental to a successful design. Data acquisition systems are found in all spacecraft, and are generally configured with a redundant counterpart. Sometimes referred to as Telemetry Encoder Units, Digital Telemetry Units, or Telemetry Data Units they all serve the same purpose: convert measured signals to data [Ref. 15]. The basic parts of a data acquisition system will now be presented.

1. Multiplexers

Spacecraft have many different sensors onboard. To get the data from any sensor, each individual sensor output must be connected to a common set of hardware that can observe the desired signal. Multiplexers are analog or digital devices that combine several independent lines of data to a single output line (see Figure 5) [Ref. 16]. These

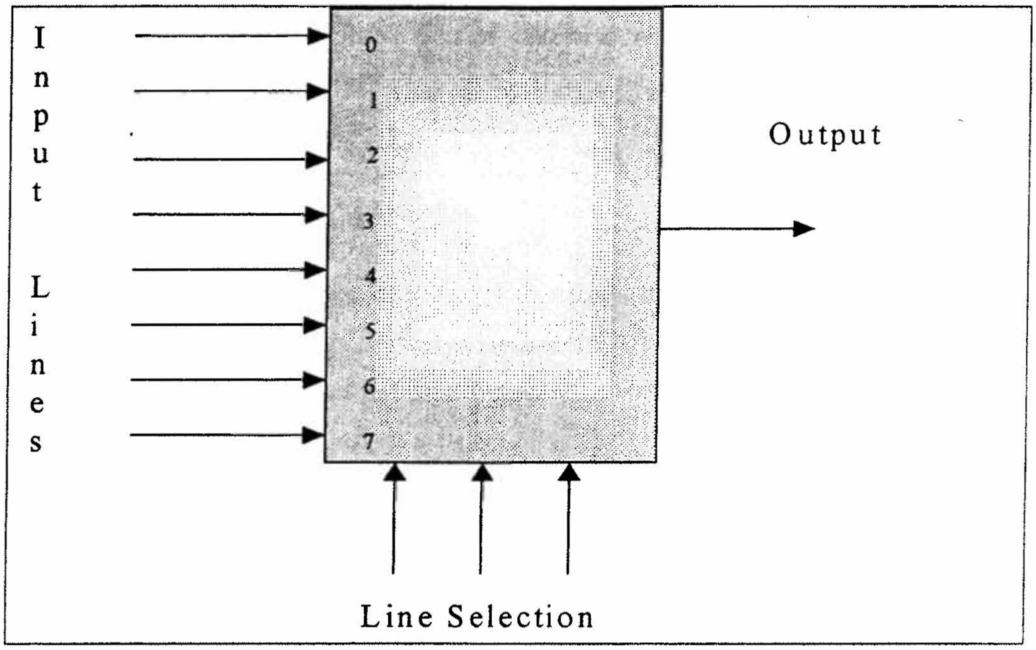

Figure 5. Eight Line Input to One Line Output Multiplexer

input lines share the single output line. An input may pass its signal to the output line only when selected. This is achieved by selection line input on the multiplexer as well. The line selection is easily controlled with the binary decoding relationship:

$$L = 2^n \qquad \text{Equation 4}$$

where L is the number of input lines, and n is the number of selection lines. A separate device keeps track of which input line is next to pass its signal to the output line. As a line selection example, the first line in Figure 5 would be selected to pass its signal to the output if none of the selection lines were active, eg. 000 = 0. If only the first two selection lines were active, 110, then line 6 would be active. Multiplexers can have any number of inputs, the only requirement being that adequate number of selection lines be included to select all the inputs [Ref. 16].

2. Sample and Hold Circuits

Once the signal channel is selected by the multiplexer, the signal passes to a sample and hold circuit (SAH) as appears in Figure 6 [Ref. 2]. These circuits track the incoming signal and when commanded, hold the last value for a predetermined amount of time. Then the circuit returns to the track mode and repeats the process. Sampled values are stored in an integrating/storage capacitor until released. Due to imperfections in the electrical devices used in SAHs, they are rated by several characteristics. Speed of signal

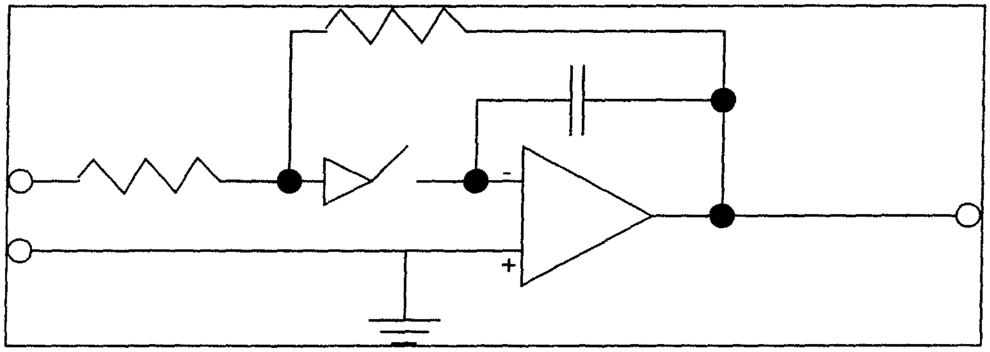

Figure 6. Sample and Hold Circuit Configuration After Ref. [2]

acquisition is the primary means of rating these circuits [Ref. 2]. This is the time required for the capacitor to charge to full value and remain within a specific error band. Average circuits will acquire a voltage in a ±10V range within 0.01% within several hundred nanoseconds to one microsecond [Ref. 2]. Hold mode droop is a second characteristic. It describes the drop in voltage over a specific time period of the held value while in the hold mode [Ref. 2]. Values for good SAH circuits range between 0.01μV/μs to 100μV/μs [Ref. 2]. Aperture delay is the time from when the hold is commanded to the time the switch is electrically open, thus storing the value. This defines how close to the desired instant the hold is executed. Typical values for this quantity range between under 100 nanoseconds to a few nanoseconds [Ref. 2]. Aperture jitter is the variation in aperture delay from sample to sample. Values of a few nanoseconds to 100 picoseconds are common [Ref. 2]. Interestingly, this value can limit the maximum frequency that can be sampled. Maximum frequency is given by:

$$f_{\max} = \frac{1}{T_A \cdot \pi \cdot 2^{n+2}} \qquad \text{Equation 5}$$

where T_A is the aperture jitter time, n is the number of bits used for quantization in the analog to digital conversion. [Ref. 2]

3. Analog to Digital Converters

The final process to convert a signal to data is the conversion of the analog sample to a digital sample. Analog to digital converters (A/DC) come in many different forms and current technology provides for implementation on a single chip. The configurations most often used in spacecraft design will be presented.

a. Successive Approximation ADC

The operating principal is to synthesize the input signal within the converter itself, then use this replica to cancel out the input signal (see Figure 7). This ADC is designed to perform the quantization within n clock cycles, where n is the number of bits in the output value. Each clock cycle, the ADC adds a fraction of the fullscale value to the previous value. The resulting sum is compared to the input sample voltage. If the sum is less than the input, this last fraction is retained otherwise the last rejected. Typical conversion speeds for 18 bit converters are on the order of 1 to 3 μs [Ref. 2]. Serial and parallel outputs are also selectable depending on the manufacturer. Additionally, the range of precision is also selectable from 8, 10, or 12 bits.

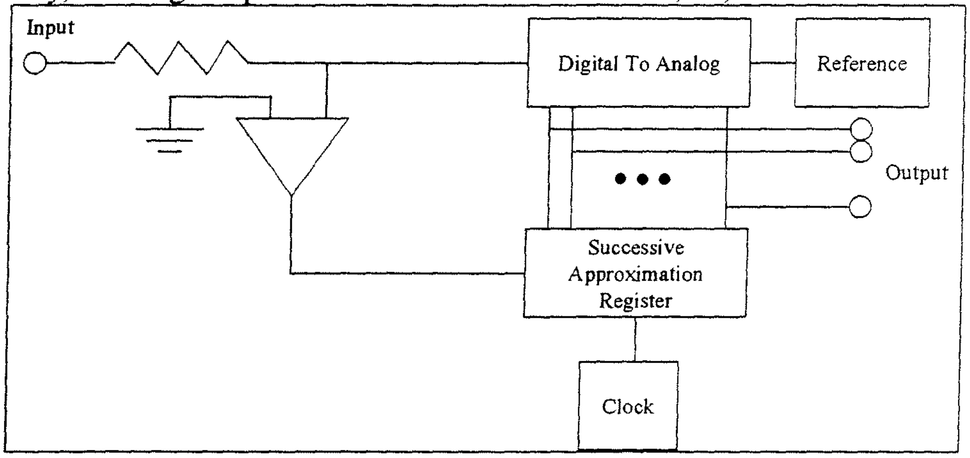

Figure 7. Successive Approximation ADC After Ref. [2]

b. Parallel ADC

These devices are used most often in high speed applications such as video processing because it allows a complete conversion in a single clock cycle [Ref. 2]. The larger number of circutry components is the key to this device. A series of operational amplifier comparators, a precision voltage divider circuit, and a decoder make up the configuration of this device (see Figure 8). The comparators respond high if the input signal is above the voltage drop at the divider network node. This technique allows eight bit conversions to be executed at 20 million sample per second rates[Ref. 2].

The first step in any communications system is to have data to communicate. The data acquisition system collects, formats, and organizes spacecraft data that must be communicated. Each of the subsections in this chapter described the necessary components for generating spacecraft data. Transducers convert the phenomena of interest into a measureable signal. An analog multiplexer combines several channels into a single output. The single output channel is then sampled by the sample and hold circuit. Finally, the sampled signal is converted to a digital value and sent to an output buffer for further analysis or transmission. A summary slide is in order which ties these components into a system (see Figure 9).

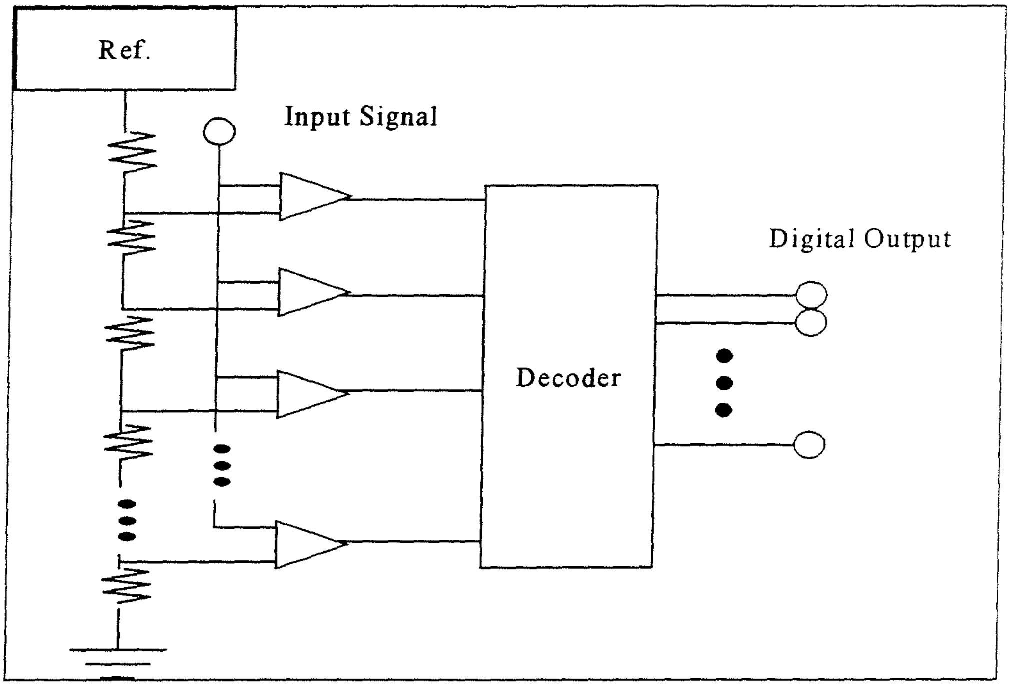

Figure 8. Parallel ADC After Ref. [2]

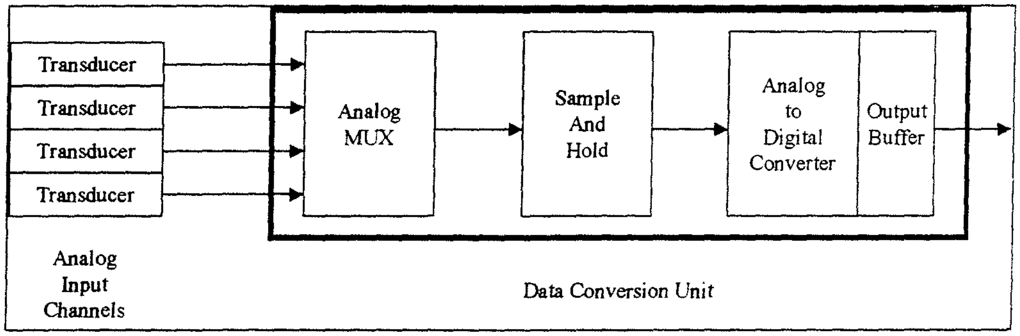

Figure 9. Data Acquisition System After Ref. [2]

THIS PAGE INTENTIONALLY LEFT BLANK

IV. COMMUNICATIONS

Sending and receiving data is the essence of communications. Data is collected and organized by the data acquisition system. Now that data exists, the transfer of that data must be completed. Data communication is performed by the transponder in the spacecraft [Ref. 16]. To ensure successful communications, several decisions must be pre-arranged. Just as though two people were speaking together, language and volume must be compatible. If the two are speaking different languages, they do not understand each other. If one of the two is speaking too softly, the other does not hear anything. And finally, if one person becomes distracted and loses their train of thought, they typically miss some of the conversation. They have simply lost their place in the discussion, and must get back on track with the flow of ideas being expressed. All these ideas can be adapted for spacecraft communications as well. Language can be thought of as modulation. Volume can be thought of as power, and the link budget is a tool used to ensure the power level is not a risk of being too low. Finally, timing and synchronization provide a means for the ground segment to keep track of where the spacecraft is in its communication flow [Ref. 4]. Because the receiving end of the communication system is typically the more critical, all illustrations refer to it, however, it is not difficult to simply put the same illustrations in reverse to derive the transmitting end of the system.

A. MODULATION

Modulating a signal requires several choices to be made. Each is a fundamental part of the communication system design. An important aspect, which must be decided early on is the frequency selected which will ulitmately carry the data. This is also termed the carrier frequency [Ref. 4].

1. Frequency Selection

Many different media for communications exist, however, radio frequencies are most often used in spacecraft TT&C design. Specifically, radio frequencies (RF) in the microwave range from 1000 MHz to 40 GHz are used due to the acceptable transmittance of the Earth's atmosphere for these frequencies (eg. transmittance ≈ 1). Beyond 40 GHz, atmospheric water, oxygen and other molecules severely degrade the transmittance through the atmosphere [Ref. 17]. Frequencies below 1000 MHz are severely affected by ionospheric scintillation, resulting in distortion in amplitude and phase of the signal. Also, the high degree of confidence required for satellite comand and control prescribe the use of RF wavelengths versus shorter wavelengths (eg. optical (lasers), infrared). When designing the TT&C communications subsection, it is useful to know whether any pre-existing ground segment will be used to operate the spacecraft. If this is the case, the frequency band used will already be defined. Table 1 displays uplink and downlink frequencies used for some currently available satellite control networks [Ref. 1]. With the range of frequencies defined, one part of the language has been decided on.

Modulation of the RF carrier frequency is the actual mechanism of communicating information over a TT&C link. Digital communications, the most widely used communications technique in use today, utilizes a finite symbol set or alphabet. In the case of binary modulation the alphabet set consists of 1 and 0.

Table 1. Existing Satellite Network Uplink/Downlink Frequencies After Ref. [1]

Network	Uplink (GHz)	Downlink (GHz)
Air Force (AFSCN)	1.76 - 1.84	2.2 - 2.3
NASA Deep Space (DSN)	2.025 - 2.120 7.145 - 7.190	2.2 - 2.3 8.4 - 8.5
Intelsat/COMSAT	5.92 - 6.42 14.0 - 14.5	3.9 - 4.2 12.2 or 17.7
Tactical Data Relay System (TDRS)	2.1064 MA* 2.025-2.12 SA** 13.775 SA**	2.2875 MA* 2.2 - 2.3 SA** 15.0034 SA**

MA* - Multiple Access, 20 simultaneous users

SA**- Single Access

Modulation, however, must be analog, because the communications media require it. So the techniques employed in modulation are a way to produce digital results using analog techniques. Analog signals, sine and cosine, are used in such a way to obtain a digital representation by exploiting their characteristics. Two different frequencies, for example, can be used to represent a bit one or a bit zero. Manipulation of the phase of a sinusoid is also a good option. That is, when the phase changes by 180°, we can interpret the change as a change to a different bit. The frequency method is much easier to implement, giving it a large degree of robustness, but it has limits in performance [Ref. 16]. Implementing phase detection hardware is much more complicated, but yields greater performance. Figure 10 displays the more common modulation types used in satellite communications and their associated wave forms.

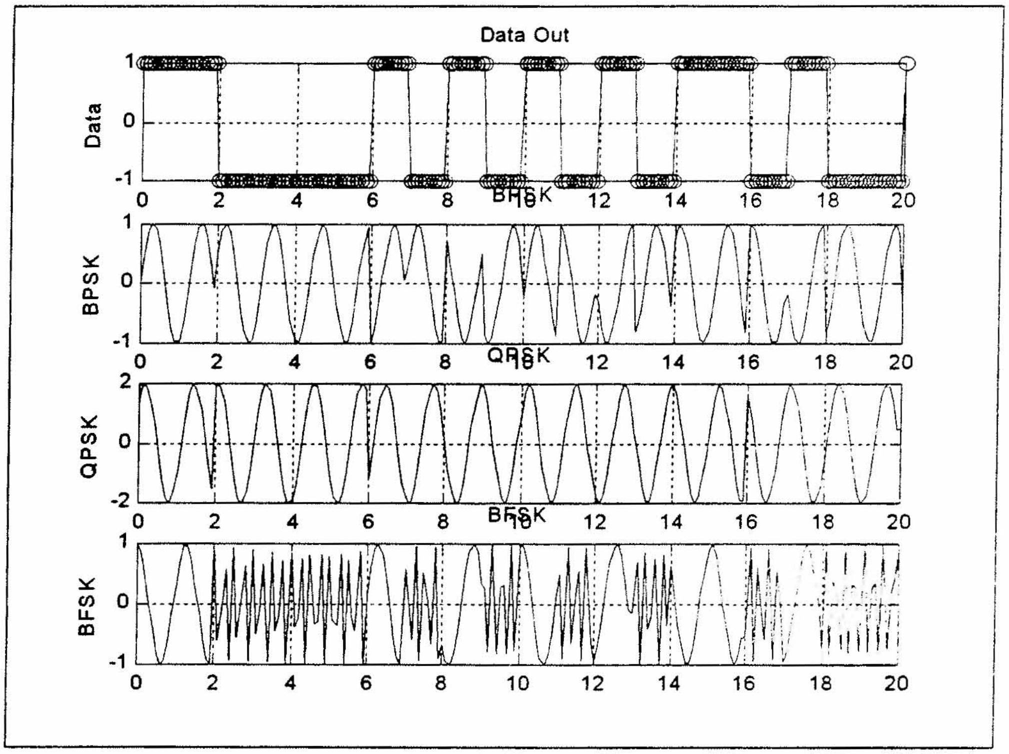

Figure 10. Common Modulation Waveforms in Satellite Communications

2. Bit Error Rate

Digital communications system performance is rated according to the probabililty of making an incorrect decision for any bit being received [Ref. 4]. This probability of bit error, P_B, is a measure based on the statistics of the bit stream given the probability of a bit one, probability of a bit zero, probability of choosing bit one given a bit zero was sent and

$$P_B = P(s_1)P(s_2 \mid s_1) + P(s_2)P(s_1 \mid s_2) \qquad \text{Equation 6}$$

where s_1 is symbol one or bit one, s_2 is symbol two or bit zero, $P(s_1)$ is the probability of a bit one, $P(s_2|s_1)$ is the probability of choosing bit zero when bit one is sent. Note that when the channel is symmetric, or when the probablility of a bit one is equally likely to be a bit zero, and that the probability of symbol one given symbol two is the same as its complement, then the equation simply becomes:

$$P_B = \frac{1}{2}P(H_2 \mid s_1) + \frac{1}{2}P(H_1 \mid s_2) = P(H_2 \mid s_1) = P(H_1 \mid s_2) \qquad \text{Equation 7}$$

3. Noise

The statistical nature of the calculation is a direct result of the noise from the transmission channel. Noise is by nature random, and subsequently is unpredictable. Since noise is added to the signal at the receiver, its random effects must be accounted for, thus each detection of the signal becomes a random variable. In most cases, the noise can be considered a Gaussian random variable [Ref. 4]. That is, the noise has a probability distribution function that is described by a gaussian distribution which is defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-\frac{u^2}{2})du \qquad \text{Equation 8}$$

where Q(x) is the complementary error function or co-error function and is commonly used to describe the probability under the tail of the Gaussian distribution. The co-error function is not evaluated in closed form, and typically tables or approximations are used to evaluate its arguments. One such approximation is valid for the argument greater than three (x>3) and is written:

$$Q(x) \approx \frac{1}{x\sqrt{2\pi}} \exp(-\frac{x^2}{2})$$ Equation 9

Note, for most analysis with noise, the random variable is taken to be zero mean and unit variance. Then adding the average power provided by the bit one or bit zero simply changes the mean of the random variable. Bit one drives the mean positive and bit zero drives the mean negative (we implement bit one as positive voltage and bit zero as negative voltage in the receive equipment). [Ref. 4]

4. Signal to Noise Ratio

One final definition is the Signal to Noise Ration (SNR). This is simply the a comparison of how much signal power exists relative to the noise power. For understanding, more signal power ensures less liklihood of making an error when deciding whether bit one or bit zero was sent. Typically this quantity is described as the energy in one bit divided by the energy in the noise for the same time interval (Eb/No). This can be shown with the following equations:

$$\frac{S}{N} = \frac{2 \cdot Ac^2}{N_o \cdot T_{bit}} = \frac{2 \cdot Ac^2 \cdot T_{bit}}{N_o} = \frac{2 \cdot E_{bit}}{N_o}$$ Equation 10

where Ac is the amplitude of the transmitted signal typically in volts, Ac^2 is the power of the transmitted signal, No is the noise power in one bit period typically in volts^2/Hz, T_{bit} is the duration of one bit period typically in seconds, and 2 is a coefficient used to simplify calculations. [Ref. 4]

The primary measure of performance for digital communication systems is the probability of bit error (P_B). Comparative analysis shows that it is desirable to have the lowest P_B for a given SNR. Figure 11 displays the plot of the various P_B versus Eb/No.

In practice, a system is designed by choosing a modulation scheme that meets the required probability of bit error. For example, most communication systems require P_B to be at least 10^{-5} for quality communications, or one bit in error for 100,000 bits transmitted [Ref. 4]. Recall that Eb/No was derived from the signal power. This directly affects transmitter power. Greater Eb/No requires greater transmit power. For a satellite

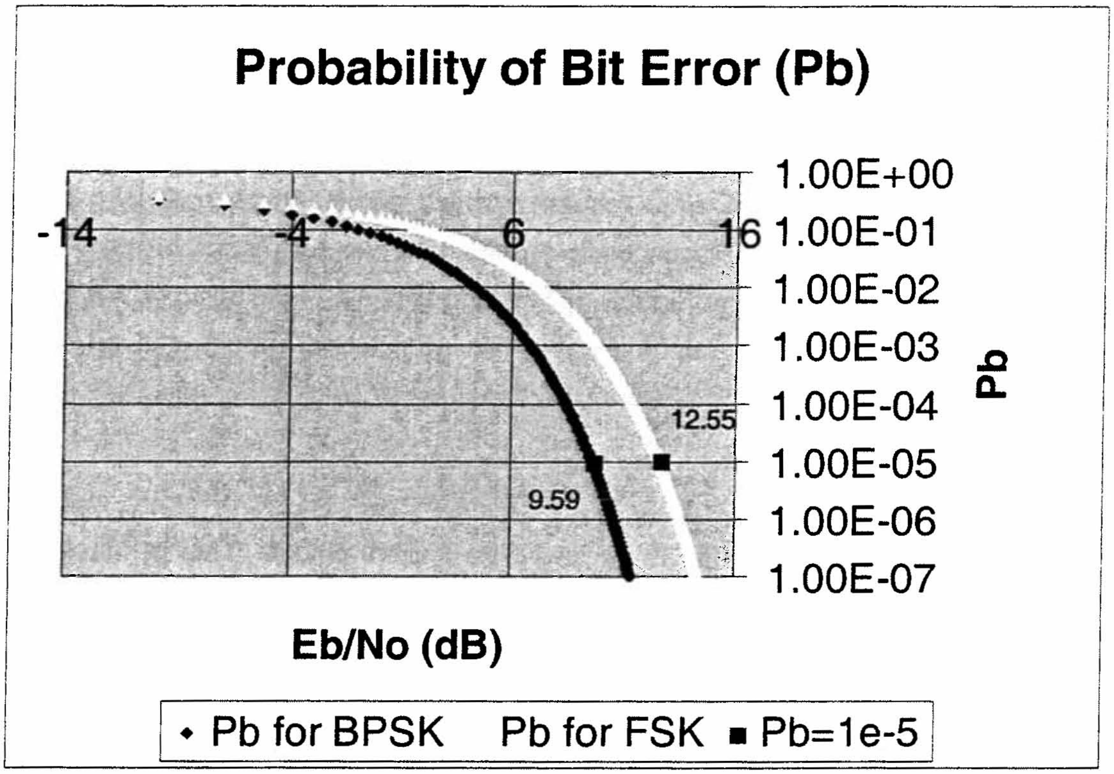

Figure 11. Probabitly of Bit Error (P_B) vs. Eb/No for Various Modulation Schemes

power onboard the spacecraft is a valuable and limited commodity. Good design strives to minimize the required transmitter power while maximizing the robustness. Choosing BPSK, since it requires the least Eb/No we have:

$$P_B = 1 \cdot 10^{-5} \Rightarrow \frac{Eb}{No} = 9.59dB \qquad \text{Equation 11}$$

Table 2 provides information regarding modulation schemes chosen by common satellite communications networks [Ref. 1].

B. LINK DESIGN

Explicitly defining the communication link characteristics comprises the essence of the link budget design. This calculation defines the system communication performance in tabular format, and is an essential element in any communication system

Table 2. Modulation Schemes for Common Communication Networks After Ref.[1]

Network	Uplink Modulation	Downlink Modulation
AFSCN	FSK	PCM/BPSK/FSK
DSN	PSK/FSK	PCM/PSK/PM
TDRS Cross-link	QPSK/Spread spectrum	QPSK/Spread spectrum

FSK = Frequency Shift Keying BPSK = Bi Phase Shift Keying PM = Phase Modulation

PCM=Pulsed Code Modulation QPSK = Quadrature Phase Shift Keying

design [Ref. 1]. This tabular calculation is an alternate representation of the link equation:

$$M[dB] = EIRP[dBW] + \frac{Gr}{T}\left[\frac{dB}{K}\right] - \left(\frac{E_{bit}}{No}\right)_{rqrd}[dB] - R\left[dB - \frac{bits}{\sec}\right] - \kappa\left[\frac{dBW}{K-Hz}\right]\cdots \quad \text{Equation 12}$$

$$\cdots - Ls[dB] - Ld[dB]$$

where bracketed terms are units, EIRP is the effective isotropic radiated power, Gr is receiver antenna gain, T is receiver temperature, $(Eb/No)_{rqrd}$ is defined by the modulation scheme chosen, R is bit rate, κ is the Boltzmann constant (228.6 dB), L_s is the path loss, and L_o is the implementation loss [Ref. 4]. Note that all terms are in decibels which is determined from the following equation:

$$X[dB] = 10 \cdot LOG_{10}(x) \quad \text{Equation 13}$$

1. Effective Isotropic Radiative Power

Considering any transmitter/receiver pair, an initial assumption of an ideal isotropic radiator is made. This source transmits RF uniformly over 4π steradians. Power density at some distance d from this source is directly proportional to the transmitted power, and is written:

$$p(d) = \frac{P_{transmit}}{4 \cdot \pi \cdot d^2} \quad \text{Equation 14}$$

where $P_{transmit}$ is the transmitter power, and d is the distance from this radiator. Placing this radiator at the focal point of a parabolic curved plate or dish will change this power density such that the concave side of the dish concentrates the flux in one direction. The increase in power due to the concentrating effect of the concave dish or directive gain is described by :

$$G = \frac{\text{maximum power intensity}}{\text{average power intensity over } 4\pi \text{ steradians}} \qquad \text{Equation 15}$$

This relation can be utilized to describe a radiator, which if isotropic, would have power EIRP:

$$EIRP = P_{transmit} \cdot G_t \qquad \text{Equation 16}$$

Additionally, the antenna gain, G, is related to the antenna effective area by:

$$G = \frac{4 \cdot \pi \cdot A_{effective}}{\lambda^2} \qquad \text{Equation 17}$$

where λ is the wavelength of the carrier frequency, and the relation only holds for $A_{effective} >> \lambda^2$. [Ref. 4]

2. Receiver Sensitivity

This quantity has been defined as the receive antenna gain divided by system thermal temperature (K). It is a good description of sensitivity for two reasons. Since thermal noise is the primary noise source limiting the satellite link it is designed to be as small as possible. Due to mass and pointing limitations, the antenna gain is also bounded. Thus for a given antenna size, and thus fixed power flux density, the only way to increase receiver sensitivity is to decrease system thermal noise. This is typically done with low noise amplifiers located directly on the back of the antenna. Additionally, by defining this quantity in two terms, Gr and T, system tradeoffs can be made with a great deal of flexibility. [Ref. 4] .

3. Bit Rate

Simply the rate at which data will be transferred across the link. Note that if any forward error correction coding is used, this quantity will be reduced. Intuitively, the link equation shows that when bit rate is increased, total margin is decreased. Thus all else being equal, there is less liklihood of bit errors with slower data rate.

4. Boltzmann Constant

The Boltzmann constant is defined as $1.38*10^{-23}$, or –228.60 dBW/K-Hz, and is a direct result of the definition of thermal noise power:

$$N = \kappa \cdot T \cdot W \qquad \text{Equation 18}$$

5. Path Loss

Free space path loss is given by:

$$L_s = \left(\frac{4 \cdot \pi \cdot d}{\lambda} \right)^2 \qquad \text{Equation 19}$$

This is the loss proportional to distance squared suffered by electromagnetic radiation. Note, this loss is inversely proportional to frequency, however, the atmospheric transmittance bounds the highest frequency to approximately 50 GHz. This is the largest loss to account for in the margin calculation [Ref. 4].

6. Other Implementation Losses

Smaller losses exist, and are important for accounting purposes. Imperfections in filter design (2-4dB), rain attenuation of the signal (2-3.5dB), polarization losses (0.25dB), and pointing losses (3-5dB)are typical of this combined value. Typical values range from 12 to 15 dB [Ref. 4].

7. Margin

Margin is the be all end all of the link budget design [Ref. 4]. All system trades should produce at least 3dB of margin for conservative design. When all loss and gain terms are known well, it may be possible to have a margin of exactly 3dB. Otherwise something greater than 3dB is common.

8. Power Flux Density

For the spacecraft downlink, this term is limited by Federal Communication Commission law. This quantity is limited to −148dB per 4KHz channel or less. If this value is exceeded, special permission must be requested from the FCC to ensure minimal interference with other RF users when operating.

C. DEMODULATION

Once modulated and carried across the channel, the modulated data must be demodulated. Hardware known as the receiver is used to perform this action. In general, a correllator element followed by an integrator are found in today's receiver structures. This allows sufficient recovery of a baseband waveform which is then sent to a comparator for conversion to TTL levels by a comparator amplifier. Specific receiver structures are required depending on the choice of modulation. BFSK will be presented, followed by the BPSK receiver.

1. BFSK Receiver Structure

Since BFSK utilizes two tones to transmit information, two banks of correlators are required to demoduate the signal. One bank, with both an inphase and quadrature phase for noncoherent BFSK, appears for each tone. For one bank, and each phase, the incoming signal is heterodyned with a replica of one of the tones.

The resulting signal, which has a component at baseband or $f_c=0$ Hz, and a component at $f_c=2f_c$, is sent to an integrator. The integrator has a low pass filter characteristic which removes the terms above one bit rate, such as the terms at twice the carrier frequency, and passes the baseband term. Due to the lack of phase knowledge, a square law detector is used to recover the baseband signal. The equations depicted carry out the mathematical expresions for the correlation demodulator. Figure 12 shows the noncoherent BFSK receiver in graphical format. Once baseband is recovered, the signal is sent to a comparator which simply converts the received voltage to a stream of square pulses at ±1 volt.

$$s(t) = \sqrt{2}A_c \cos[(2\pi f_c \pm \frac{\Delta f}{2})t + \theta_0] + n(t)$$

note that n(t) is Additive White Gaussian Noise

$$r(t) = s(t) \cdot 2\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= 2\sqrt{2}A_c \cos[(2\pi f_c + \frac{\Delta f}{2})t]\cos[(2\pi f_c + \frac{\Delta f}{2})t + \theta_0] + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= \frac{2\sqrt{2}A_c}{2}\{\cos[(2\pi f_c + \frac{\Delta f}{2} + 2\pi f_c + \frac{\Delta f}{2})t + \theta_0] + \cos[(2\pi f_c + \frac{\Delta f}{2} - 2\pi f_c - \frac{\Delta f}{2})t - \theta_0]\} + \cdots$$

$$\cdots + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

$$= \sqrt{2}A_c \cos[(2\pi 2f_c + \Delta f)t + \theta_0] + \sqrt{2}A_c \cos(-\theta_0) + 2n(t)\cos[(2\pi f_c + \frac{\Delta f}{2})t]$$

Integrating this expression removes the $2f_c$ term and the f_c term as long as $f_c >> R_b$, note that θ_0 is a uniform random variable $[0, 2\pi]$.

$$X(t) = \frac{\sqrt{2}A_c}{T_b}\int_0^{T_b}\cos(-\theta_0)dt = \frac{\sqrt{2}A_c}{T_b}\cos(-\theta_0)\int_0^{T_b} dt = \sqrt{2}A_c\cos(-\theta_0)$$

which gives a single term at baseband which will then be squared and compared.

2. BPSK Receiver Structure

Since BPSK modulation associates a bit one with one phase, and bit zero with another phase, the receiver requires phase coherence. Unlike the BFSK receiver which does not require any knowledge of the carrier phase, phase coherence, or precise knowledge of the carrier phase, requires additional circuitry which complicates the hardware. Phase knowledge can be obtained from a phase locked loop circuit or Costas loop which aquires and tracks the phase [Ref. 16]. Once attained, the resulting signal is heterodyned with a replica of the carrier frequency. This heterodyning generates a signal with terms at baseband and at $2f_c$, not unlike the BFSK receiver since both use correlator demodulator structures. An integrator then removes the term at $2f_c$, due to its low pass filter nature, and the baseband signal is passed to a comparator for conversion to the stream of square pulses. Figure 13 shows the graphical structure of the BPSK receiver.

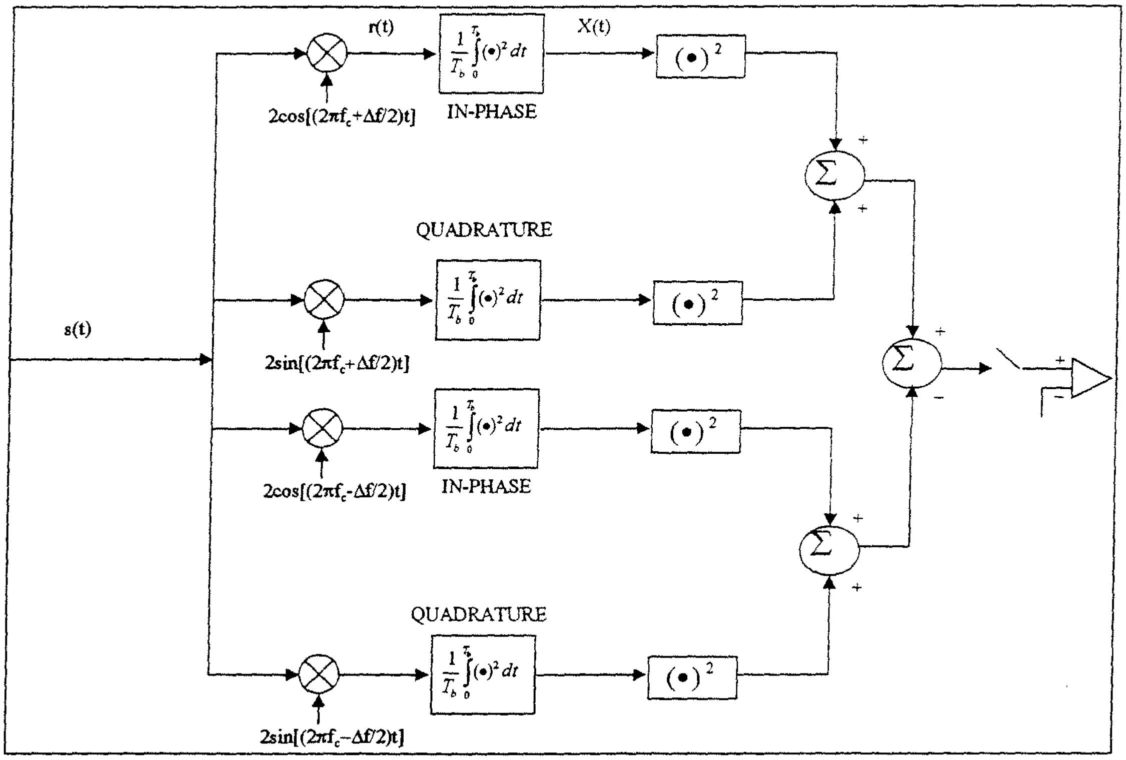

Figure 12. Non-Coherent BFSK Receiver Structure

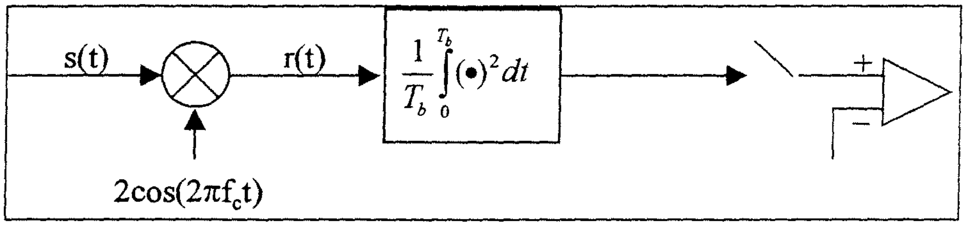

Figure 13. BPSK Receiver Structure

D. TIMING AND SYNCHRONIZATION

The transmit side of any communication system always knows what data it is sending, what frequency it is utilizing, what the phase of the carrier is, and where in the data frame structure the transmitter is, but the reciever does not have knowledge of any of this. Each of these items must be deduced at the receiver itself, from the signal it is receiving. Additionally, any time the transmitting side is reset, perhaps if the spacecraft payload experiences an anomaly recovery, or if the ground station is reinitialized, or even if the communications link fails, all this information must be re-established. Of primary importance is: establishing bit synchronization, and establishing frame synchronization.

1. Bit Synchronization

Before any data processing can begin, the receiving system must be slaved to the payload clock. That is, the data stream must be demodulated from the carrier, by the receiver hardware, and the data stream must be identified relative to a timing signal from the spacecraft. The generation of this timing signal is the most critical function of the bit synchronizer [Ref. 2].

a. Clock Extraction Circuits

In general, a synchronized timing or clock signal that exactly transitions with the beginning of a data pulse is desired. Ideally, this should happen as soon as data is received by the bit synchronizer, even when a string of all ones or all zeros occurs. This does not usually happen. Generally, some amount of synchronization time must occur and depending on the type of clock extraction circuit used, the clock signal may get lost.

Open loop extraction circuits are the primarily found in practice. Since no feedback information from previous symbols is taken into account for current clock rate or transition time extraction. They are easily implemented, and provide adequate clock signals as long as the data does not appear as long strings of ones or zeros. Figure 14 shows the structure of an open loop clock extractor. As can be seen in the figure, an image of the data stream delayed by half a bit period is correlated with the data stream. Heterodyning the two signals produces another random bit stream which is characterized by a discrete harmonic at integer multiples of the data rate [Ref. 2]. The bandpass filter isolates this harmonic and passes the harmonic signal through a hard limiter which produces the clock pulse. If the data has a long string of ones or zeros, the heterodyning produces no new bit stream, and therefore no integer multiple harmonic. Thus the clock signal vanishes, also known as loss of lock, until the bit stream alternates ones and zeros again. [Ref. 2]

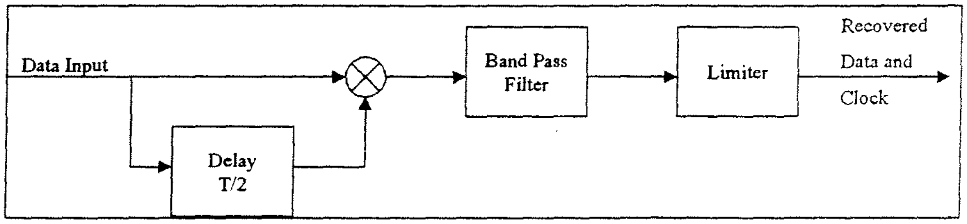

Figure 14. Open Loop Clock Extraction Circuit After Ref. [2]

Closed loop extractor circuits require feedback information to provide the clock rate and transition time. The clock signal is much more robust than that generated by an open loop circuit, however, at the expense of complicated hardware involved and additional time required to initially lock onto the clock signal. Typically, a phase locked loop circuit is used to produce the clock signal. Figure 15 shows the structure of a closed loop clock extractor phase locked loop. The clock signal, generated as the output of the voltage controlled oscillator (VCO), is sped up or slowed down by the difference in two signals. The two signals are generated from the integration over a single bit period. An

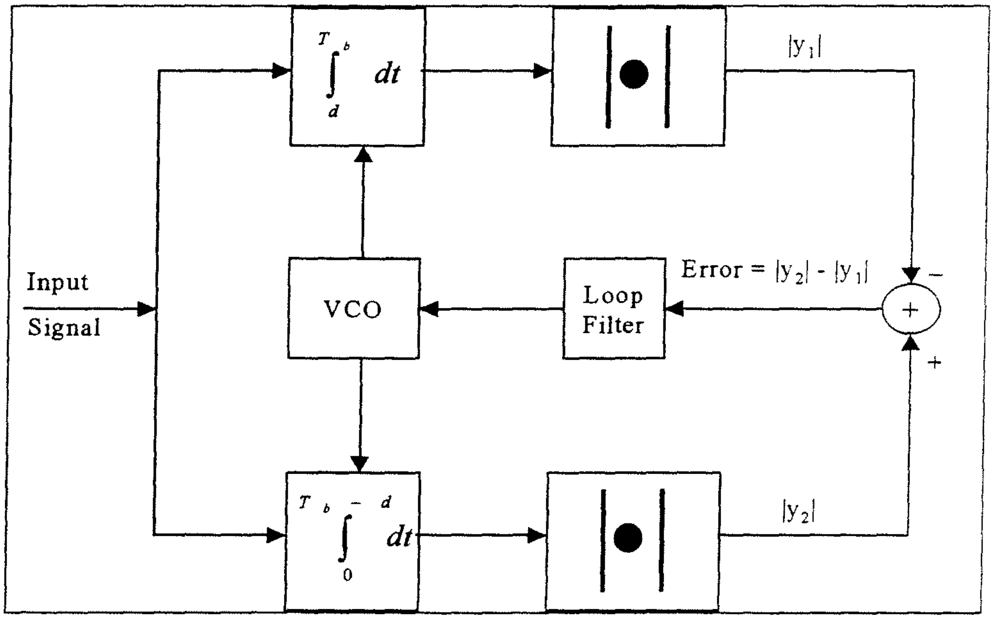

Figure 15. Closed Loop Data Synchronizer After Ref. [4]

example is in order. Data is sent to two integrators, each integrates over a fraction of a bit. The integrations are staggered within the single bit period such that the start of the first integration until the end of the second integration is exactly one bit period. The absolute values of the integrations are then subtracted and the difference used to drive the speed of the VCO output. If the one integration is larger than the other, a control voltage is generated which appropriately increases or decreases the VCO frequency. This change in VCO frequency affects the integration time of the integrators. If both integrations exactly match, then the VCO is synchronized to the data stream.

b. Data Scramblers

Often interleavers or data scramblers are employed in commercial bit synchronizers to prevent long strings of ones and zeros from occurring. This facilitates employing the open loop extractors with no added complexity. If the data is derandomized at the receiver, it had to be randomized at the transmitter. Thus the randomization of data had to be designed into the system from the beginning. In practice the randomizer is simply a series of shift registers and modulo two adder circuits, see Figure 16, that generate a pseudo random noise (PRN) bit stream when an input is applied. The input is the data stream. Note, the resulting bit stream is pseudo random, not expressly random. That is, the sequence can be recovered with the appropriate shift register/modulo two adder combination. This would not be possible if the resulting stream were expressly random.

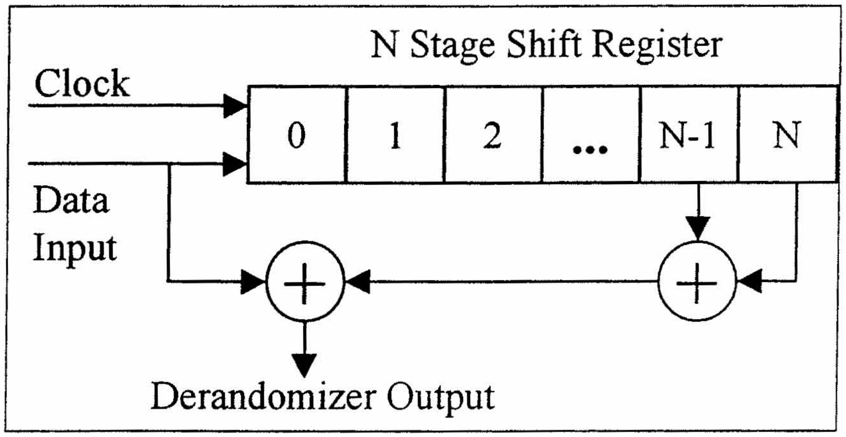

Figure 16. Data Derandomizer Circuit After Ref. [2]

2. Frame Synchronization

Frame synchronization requires the receiving system to acquire the spacecraft's data structure. Without first achieving bit synchronization, frame synchronization (frame sync) is not possible. Three states are typically executed to achieve frame sync: Search, Check, Lock.

a. *Search State*

Searching consists of correlating the beginning of a minor frame or packet to a particular synchronization marker. This marker is generally a binary word of alternating zeros and ones specifically chosen for its statistical correlation properties. Specifically, the marker must have very low correlation sidelobes, or low values when the word is correlated with a time shifted version of itself [Ref. 4]. The word is also repeated at a specific rate or interval. The receiver correlates the incoming data stream with the known synchronization marker over several intervals, depending on the length of the frame marker, to ensure the correct pattern has been found. If the marker is very short, as in systems where a continuous flow of data is present, the number of intervals will be large, translating into a longer acquisition time. Longer length markers facilitate short acquisition times, but increase the amount of overhead in the bit stream. Thus a sacrifice in data rate is required. Long markers are typically required where data traffic is not continuous, or is bursty. Table 3 shows some typical sequences, known as Willard sequences, which have low correlation sidelobes.

Table 3. Willard Synchronization Code Words Ref. [4]

Code Word Length [bits]	Sequence
1	+
2	+ -
3	+ + -
4	+ + - -
5	+ + - + -
7	+ + + - + - -
11	+ + + - + + - + - - -
13	+ + + + + - - + - + - - -

b. Check State

Checking consists of locating where in the data structure, major frame, the synchronizer currently is. Considering the case of packet telemetry, this amounts to identifying the packet counter. In a major frame, this is finding the current value of the subframe identifier (SFID) or minor frame number. Once the SFID is located, a check is made to ensure the SFID is incrementing appropriately. If not, the synchronizer will revert back to the search state for reacquisition. If the SFID is incrementing, then frame sync is completed, and the synchronizer moves to the lock state. Note that while in the check state, the synchronization word is still correlated for proper repetition rate and correlation value. Also, while in the check state, commutated and supercommutated data can begin to be processed. This is because this type of data is identified by their relative postions from the SFID. Subcommutated data is identified by specific SFID and its relative position from the SFID, thus it cannot be processed yet. [Ref. 2]

c. Lock State

Once lock is acheived, the SFID location is known as well as the value. This knowledge allows all data to be processed, and the matrix structure of the major frame can now be filled in. Lock state checks include recognizing the synchronization word and its repetition rate, and that subframe ID increments properly. If any one of these parameters is anomalous, the synchronizer will revert back to the check state. If the link is lost entirely, it may revert back to search state for reacquisition. [Ref. 2]

THIS PAGE INTENTIONALLY LEFT BLANK

V. TELEMETRY FRAME CONSTRUCTS AND STANDARDS

Data structure is as important as the means for getting the data to the desired location. Previously, data collection and transmission were presented. However, the ground station, in the case of satellite operations, must have some way of knowing what data is being transmitted. Receiving a long string of numbers does not provide any means for interpreting these numbers. Therefore, some method must be applied to structuring the data into a fashion which allows the receiving station to parse the values into meaningful information. Standard formats which have been previously agreed upon by various users with respect to a group of ground facilities allow interoperability and at the same time can reduce costs. Costs are reduced when several manufacturers develop hardware which comply with the format and thereby increase the supply of available hardware.

A. BASIC FRAME STRUCTURE

The simplest form to arrange data in is a large matrix of values. Each data slot, or matrix entry, is assigned to a specific sensor or data source. This basic structure is often called a frame of data. The entire collection of rows and columns compose a major frame, while the individual rows of data are called minor frames [Ref. 15]. Each minor frame, or row, is made up of a fixed number of words, which are generally a collection of eight or sixteen bits [Ref. 2]. Each minor frame will be made up of a fixed number of bits as well. The first word of each minor frame is usually a synchronization word, which provides a means for the receiver to correctly parse the values being transmitted [Ref. 4]. Major frames are always constructed of an integer number of minor frames. Thus far, each parameter is assumed to be sampled once per minor frame, and so the major frame consists of only a single minor frame. That is, all the data is called commutated data. Actual systems, however, often have some sensors sampled more often than others as well as some sampled less often. Supercommutation refers to data that appears in a single minor frame more than once per minor frame, and is often sampled at a multiple of the minor frame rate [Ref. 15]. Subcommutation refers to data that appears less frequently than the minor frame rate. In general subcommutated data is a submultiple of the minor frame rate [Ref. 15].

Subcommutation and supercommutation require that a specific frame be identified from the data stream so that accurate identification of the data is completed by the ground station. Typically this is done by assigning one column in the matrix to be the frame identification marker (ID) or subframe ID. There can be any number of minor frames per major frame, however, some standards limit the total number available. An example of a major frame is shown in Table 4. Each row of data is transmitted from left to right, and at the end of a row, the next row is inserted consequently placing the rows one behind the other in time. This concept for data transmission is also known as time division multiplexing (TDM), which prescribes a specific time slot to a specific data item.

Table 4. Telemetry Frame Format After Ref. [3]

Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1
• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •	• • •
Synchronization Word	Frame ID	1	2	3	...	Super Comm	...	N-1

B. CURRENT STANDARDS : INTER RANGE INSTRUMENTATION GROUP

Airborne systems implemented telemetry systems long before space systems, and therefore the standard for telemetry frame formats was first originated by military range/test facilities [Ref. 15]. The Inter Range Instrumentation Group (IRIG) is a body consisting of members from each of the Department of Defense (DOD) range facilities which provides guidance for operating policy and procedure to ensure each range facility is interoperable with the others. This action attempts to reduce ground system costs by assuring similar hardware interfaces for each system with the ground/test station. The IRIG standard for telemetry systems is IRIG 106.B and can be found on the internet at the Range Commanders Council homepage or via the International Foundation for Telemetering homepage. A brief summary of the highlights of IRIG 106. B will be presented, however, a detailed examiniation of the document should be made to answer specific questions.

1. Type I Format

A fixed format, called Type I, allows only a fixed minor frame length and no greater than 512 words per minor frame. The word length can be four to sixteen bits per word. While words of different lengths may coexist within the same minor frame, the word length in any position must remain constant. Additionally, 256 minor frames are allowed per major frame, and the maximum bit rate is prescribed at five megabits per second, minimum of ten bits per second. Words are not allowed to be fragmented and format changes are also not allowed. Asynchronous formats and independent subframes are also prohibited. The transmitted bit stream must be continuous and must have adequate transitions to ensure continued bit synchronization. The bit rate is not to deviate from the nominal bit rate by more than a tenth of a percent, and the jitter shall not exceed a tenth of a bit interval relative to the expected transition time. This transition time is derived from the average bit period of the last 1,000 bits. The synchroniztion word must be at least 16 bits, but no longer than 33 consecutive bits. A major frame is defined to be the number of minor frames necessary to complete one sample of every parameter. A frame count word is recommended in each minor frame which must be a natural binary count corresponding to the associated minor frame number. Even with these prohibitions and restrictions, most telemetry systems can be successfully designed. However, some complicated systems may require some additional flexibility. Thus a second type of format is available. [Ref. 15]

2. Type II Format

The type II format requires concurrence of the range involved to ensure interoperability with resident hardware, or to arrange for acquisition of supporting hardware. In essence, everything that was prohibited or fixed in type I is now allowed or may be variable in type II. Table 5 displays a comparison of the type I and type II specifications.

Table 5. IRIG Type I and II Telemetry Specifications After Ref. [3]

Parameter	Type I	Type II
Data bits/Words per minor frame	≤ 8192 bits or ≤ 512 words	≥ 16384 bits or ≥ 512 words
Minor frame length	Fixed	Variability allowed
Fragmented words	Not allowed	Allowed (up to 8 segments)
Format changes	Not allowed	Allowed
Asynchronous formats	Not allowed	Allowed
Bit rate	> 10 bps but <5 Mbps	> 5Mbps
Independent subframes	Not allowed	Allowed
Supercomm spacing	Uniform in minor frame	Even as practical
Data format	Unsigned binary	Other allowed
Word length	4 to 16 bits	16 to 64 bits

C. PACKET TELEMETRY

Packet communication techniques have been widely developed in the computer communications industry. Several formats have developed with one particular format finding wide use today: Transmission Control Protocol / Internet Protocol (TCP/IP). Each transmission format has a basic structure with specific requirements for each field, however all have a general structure which appears in Table 6. Packet communications has developed out of the need to support multiple users while efficiently using a limited amount of bandwidth, or transmission spectrum. Applying this concept to telemetry systems is the newest area of development in the telemetering field. As seen previously,

Table 6. Basic Packet Structure

Field	Contents
Primary Header	Version number / Source / Destination / Packet Count / Pckt Length
Secondary Header	Acknowledgement / Data Field Length / Options
Data Field	Data
Trailer	Error Check Code (CRC)