NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

A SYSTEMS ANALYSIS AND PROJECT MANAGEMENT PLAN
FOR THE PETITE AMATEUR
NAVY SATELLITE (PANSAT)

by

Markham K. Rich

September 1994

Thesis Advisor: I. Michael Ross

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 1994	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE A Systems Analysis and Project Management Plan for the Petite Amateur Navy Satellite (PANSAT) (U)	5. FUNDING NUMBERS
6. AUTHOR(S) Rich, Markham Kiker	
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)	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	12b. DISTRIBUTION CODE
Approved for public release; distribution is unlimited.	A

13. ABSTRACT (maximum 200 words)

The Petite Amateur Navy Satellite (PANSAT) is a communications satellite being developed at the Naval Postgraduate School by the Space Systems Academic Group. This thesis is the result of an investigation into all aspects of the project. Research, analyses, and recommendations were concentrated in the areas of engineering design, testing, orbital operations, and organization and management. The study identified the upcoming Shuttle to Mir flights as providing the most attractive orbital parameters for PANSAT operations. A systems analysis was conducted that attempted to develop and prioritize engineering design issues requiring more thorough investigation. The chief problem area discovered by this analysis was in the power production aspect of the Electrical Power System (EPS). PANSAT was determined to have a negative power margin under certain conditions, and an even lower power margin than previously believed under most conditions. It is recommended that the project make satellite development its principal objective (over education) to maximize the likelihood of success. Student participation in the project is the single greatest asset of the project, and it remains largely untapped.. Re-organizing the project to increase student involvement, within the constraints of the Space Systems curricula, will improve efficiency by easing extraneous requirements on an overtasked engineering staff, and thereby improve overall productivity.

14. SUBJECT TERMS PANSAT, Systems Engineering, Systems Management, Systems Analysis, Project Management, Small Satellites.	15. NUMBER OF PAGES 154
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18

A Systems Analysis and Project Management Plan
for the PetiteAmateur Navy Satellite
(PANSAT)

by

Markham K. Rich
Lieutenant Commander, United States Navy
B.S., University of Florida, 1983

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY
(SPACE SYSTEMS OPERATIONS)

from the

NAVAL POSTGRADUATE SCHOOL
September 1994

Author: Markham K. Rich

Approved by: I. M. Ross, Thesis Advisor

M. A. Cervi, Second Reader

R. Panholzer, Chairman
Space Systems Academic Group

ABSTRACT

The Petite Amateur Navy Satellite (PANSAT) is a communications satellite being developed at the Naval Postgraduate School by the Space Systems Academic Group. This thesis is the result of an investigation into all aspects of the project. Research, analyses, and recommendations were concentrated in the areas of engineering design, testing, orbital operations, and organization and management. The study identified the upcoming Shuttle to Mir flights as providing the most attractive orbital parameters for PANSAT operations. A systems analysis was conducted that attempted to develop and prioritize engineering design issues requiring more thorough investigation. The chief problem area discovered by this analysis was in the power production aspect of the Electrical Power System (EPS). PANSAT was determined to have a negative power margin under certain conditions, and an even lower power margin than previously believed under most conditions. It is recommended that the project make satellite development its principal objective (over education) to maximize the likelihood of success. Student participation in the project is the single greatest asset of the project, and it remains largely untapped.. Re-organizing the project to increase student involvement, within the constraints of the Space Systems curricula, will improve efficiency by easing extraneous requirements on an overtasked engineering staff, and thereby improve overall productivity.

TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

The Petite Amateur Navy Satellite (PANSAT) is a small spacecraft that is being designed and constructed at the Naval Postgraduate School (NPS). The project is primarily an effort of the Space Systems Academic Group (SSAG), with the invaluable support of faculty and facilities of the Departments of Aeronautical and Astronautical Engineering, and Electrical and Computer Engineering in particular, and other NPS departments in general. Design and development of the various aspects of the project are being conducted as a coordinated effort of the SSAG engineering staff and NPS students. Student contributions come primarily in the form of theses, formal group and individual class projects and directed study classes. Faculty contributions consist largely of the direction of student thesis research or projects, and consultant efforts.

1. PANSAT System Overview

The program consists of the design, development, launch and operation of an amateur radio band communication satellite. The PANSAT system therefore consists of the satellite, the ground station(s), and the personnel, software and procedures to conduct operations. It is anticipated that the satellite will be launched from the Space Transportation System (STS), a.k.a. Space Shuttle or simply shuttle. PANSAT's concept of operations (Figure 1) is to operate basically as an orbiting mail server or bulletin board service, providing store and forward, packet file transfer between ground users.

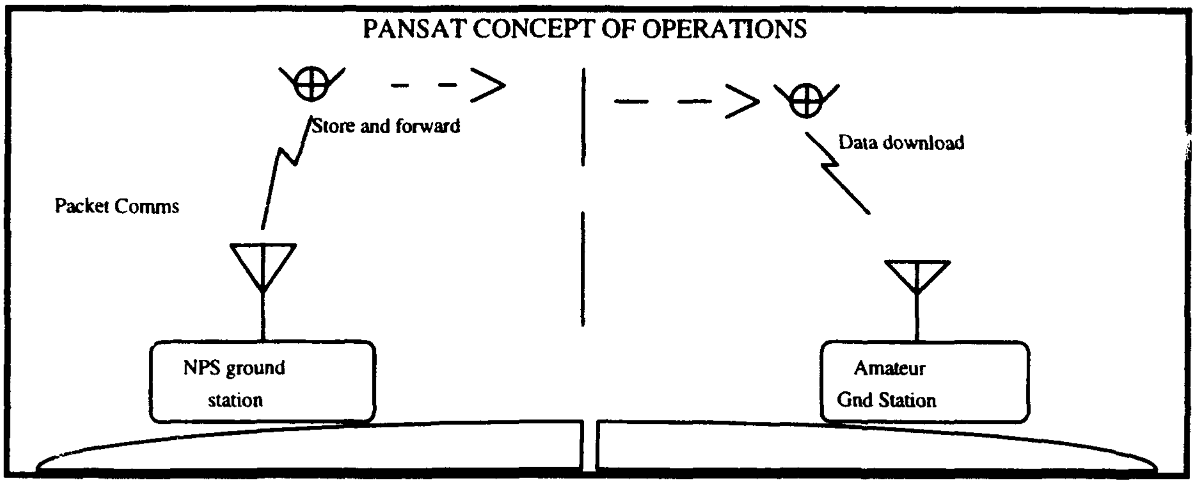

Figure 1: PANSAT Concept of Operations

a. Satellite Subsystems

The PANSAT satellite (Figure 2) consists of four subsystems: Spacecraft Structure, Electrical Power Subsystem (EPS), Digital Control Subsystem (DCS) and the Communication Payload. This relatively simple design does not include

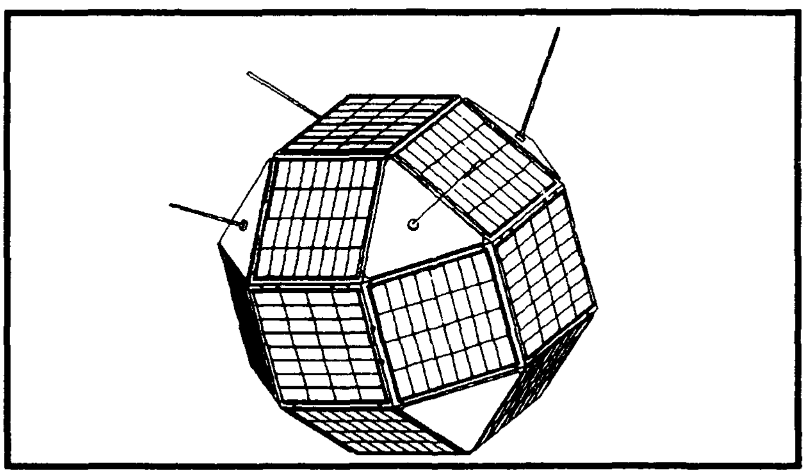

Figure 2: Depiction of the PANSAT Spacecraft

the traditional satellite subsystems of Thermal Control, Guidance Navigation and (Attitude) Control or Propulsion. The system was designed to minimize complexity and cost by addressing these subsystems in the most basic manner. By design, thermal control is passive. This issue will be addressed in Chapter II of this thesis. The spacecraft (s/c) has no attitude, navigation or guidance sensing, or control capability whatever, and as such its motion is referred to as "tumbling" even though this may not necessarily be an accurate description. The s/c's orbital dynamic motion has not as of yet been characterized completely. Additionally, the satellite has no propulsion capability, and as such its orbit is completely constrained to that of the launch vehicle (upon launch vehicle separation) and thereafter upon external forces, principally atmospheric drag. The satellite subsystems will be briefly described in the following section; however, they will be more thoroughly treated in the systems status and design analysis sections of this thesis (Chapter II).

PANSAT's structure acts, as does any s/c structure, as the principle housing and support mechanism for the s/c subsystems. The structure consists of a 26-sided polyhedral aluminum housing with 18 square and eight triangular sides. Of the 18 square sides, 17 will be mounted with solar cell arrays and the last square side will be used for the launch vehicle interconnect baseplate. Four of the triangular sides will be mounted with the antenna assembly, with the remaining four used for handling, electrical interface and battery venting (if required). PANSAT can be roughly approximated as a 19 inch (diameter) sphere.

The EPS is responsible for the generation and distribution of properly conditioned electrical power for satellite operations. PANSAT subsystems require 12 Vdc and 5 Vdc. The EPS is comprised of 17 silicon cell solar arrays for primary electrical power, two Nickel Cadmium batteries for backup power and electrical conditioning, charging and power regulating circuitry. *The current status of the EPS is an issue of some concern at this stage largely because of the uncertainty of s/c power consumption characteristics and requirements and ergo, an accurate power margin.*

The DCS acts as the Command and Data Handling subsystem and consists of two independent and identical sides for redundancy. Each side consists basically of a system controller, analog multiplexer and mass storage device. The DCS in its capacity as the Command and Data Handling subsystem of the satellite is absolutely critical to virtually every aspect of s/c operations. Specifically, the DCS is responsible for all s/c data handling, sensor measurements, communications, housekeeping functions and a significant percentage of power management functions. There are several design issues of significant concern that will be addressed in Chapter II.

The communication subsystem's primary operational mode is as a direct sequence spread spectrum (DSSS) system that operates in the 70-cm amateur radio band with 2.5 MHz of bandwidth and a 436.5 MHz center frequency. It is also capable of narrow band Binary Phase Shift Keying (BPSK) communications. The communications subsystem is in fact the mission payload and as such has traditionally been the subject of a significant portion of student input. Because of this fact, coupled with the rapidly changing technology of digital communications, the communications system design is somewhat less mature than other s/c subsystems. The antenna consists of four dipoles in a tangential turnstile arrangement mounted on the triangular structure plates providing near-omni-directional coverage and no greater than 10 dB nulls.

b. Ground Station

An integral part of the project is the simultaneous development of the command ground station to control PANSAT operations. Additionally, the development of a "Ham Kit" will be pursued in order to simplify access to PANSAT for amateur radio enthusiasts. This "Ham Kit" will be the basic hardware and software configuration necessary for communication with PANSAT.

The NPS station will operate as the principal ground station and will retain command authority through password protection and security measures. In its capacity as the command ground station, the NPS station will have the capability to upload commands, operating systems and other software, as well as files, and to download files and telemetry. Amateur ground stations will be able to up and download files and download telemetry.

c. Deployed Operations

Post launch operations will consist of operating system upload, on-orbit test and evaluation, system status determination, normal store-and-forward packet communication service, telemetry download, monitoring and evaluation, and special software uploads. The system will be considered to have achieved proof-of-concept when overall status determination is achieved and the system is capable of performing normal communications service at the specified Bit Error Rate of 10^{-5}.

2. PANSAT Project Development

The PANSAT project, initiated in 1989, was conceived as an educational tool for NPS based military officer students. The hands-on experience of design, development and operation of an actual space system was seen as a method of providing invaluable experience to Space Systems students. The applicability of educational enhancement is obviously not restricted to Space Systems students, but can be easily seen to apply to Astroronautical, Electrical and Computer Engineering and Science curricula. The goals of the PANSAT program [Ref. 1:p. 3], in order of precedence, have therefore evolved into the following:

- To enhance the education of officer students.
- To design, fabricate, test, launch and operate a small satellite.
- To demonstrate the feasibility of small satellites for supporting defense needs.
- To provide a valuable space asset to augment existing military communications in time of crisis.

The established order of precedence can easily be shown to be crucial to the funding support of the project. NPS is in the education business, not satellite construction. The SSAG, likewise is an educational support mechanism and not a competitive satellite construction facility. Funding support therefore can only be justified for PANSAT in that it provides enhanced educational experience for officer students. The last two project goals can only be considered as extraneous in that small satellites have already been demonstrated as worthwhile efforts for defense support, and that PANSAT's frequency assignment (amateur band), relatively short anticipated orbital lifetime and limited communications capabilities implies hardly any likelihood of being employed in any military supporting role.

B. STUDY OBJECTIVES

The project is currently entering what can be characterized as the most critical development stage to date. PANSAT completed a Preliminary Design Review (PDR) in May 1993, and an Engineering Design Review (EDR) in March 1994. The next logical steps in the development cycle will be a design freeze and subsequent Critical Design Review (CDR); these are anticipated to occur in late 1994. NPS has signed a Memorandum of Agreement with NASA that begins the process of securing a STS flight for PANSAT. This agreement will eventually lead to the manifest and launch of PANSAT from the shuttle via the Hitchhiker program. The project must now begin the crucial transition from design to product. This transition must begin soon and proceed smoothly in order for the project to fulfill upcoming commitments.

This thesis was conceived as a tool to provide guidance and direction to this critical stage of the project in order to improve all possible aspects of the program, ultimately resulting in the successful launch and operation of PANSAT.

1. Problem Statement and Development

Any project following a system's engineering approach must progress through development with regard to requirements and project goals. The case may be put forward that the project has already sufficiently fulfilled the primary goal of educational enhancement. It is, however, equally true that the educational impact could certainly have been much greater than it has been to this point. There are approximately 17 theses related to PANSAT currently in work and 20 theses have been completed since the project's inception in 1989. Ten of the completed theses were done in the last year alone. The complication to this picture comes when examining the project's second goal, that of building, launching and operating a satellite. The problem is simply that goals one and two are in direct conflict with one another in many ways. How can the project continue to provide educational opportunities and allow the program to be subject to student participation shortcomings (level of effort, quality, timing, completeness, etc.) and yet adhere to any realistic schedule? Documents have been signed and will be signed bringing commitments to the program. These commitments must be fulfilled for the project to have a viable future or any likely successors. So when does the SSAG team curtail educational support and begin in earnest the work of building a satellite communications system?

To this point the vast majority of PANSAT related theses have been engineering in nature. The SSAG supports the Space Systems curricula which consist of Space Systems Engineering and Space Systems Operations. In an ideal development cycle, the system design would be approached as an ideal source of thesis topics for Space Operations students; they would develop the requirements, the mission, candidate architectures and trade studies towards a system decision. Engineering students would then become the project focus as the design transitions from functional to physical and became thoroughly specified. Finally, the Operations side would return to the primary focus as the system transitions from fabrication to deployment and operations. PANSAT, however was initiated in a somewhat different, perhaps haphazard, manner.

PANSAT's development was initiated as a tool to enhance the education of Space Systems students by designing and developing a satellite. The type of satellite was determined by evaluation of the possible designs to which students could meaningfully contribute. At this point the design work began. As it turns out this is somewhat of a cart before the horse approach when compared to the "Systems Engineering" approach outlined above. This basic problem has subsequently led to many of the issues that will be examined in this thesis.

As a satellite communication system project, the organizational structure currently employed to carry out this effort can be characterized as insufficient, inefficient and unwieldy. The PANSAT engineering team has seven personnel working approximately full time and an eighth part time. The effort is insufficient in that a typical competitive space contractor would likely have in excess of 50 dedicated personnel to an undertaking of PANSAT's magnitude; fiscal commitments are of a similar magnitude less than typically found.[1]

The effort can be seen as inefficient in that the contributions of faculty and students are on a completely voluntary basis. What this implies is that the level of effort and area of contribution is not under any positive control. Thesis students can come and

[1]Personal Conversation with Dr. Rudy Panholzer, 10 June 1994.

go at will, and work on topical areas of their interest at the time that fits into their curricular schedule. Whereas there is nothing wrong in itself with this fact, it often does not coincide well with project priorities and timing. Likewise faculty contribution is equally difficult to influence, and is subject to the particular faculty member's ability to solicit sponsorship relative to the project. Few faculty have the financial or time availability or flexibility to contribute significantly without fiscal sponsorship and so.

The project is unwieldy with regard to the management issues involved in coordinating the engineering team's efforts with those of faculty and students. The project's biggest single difficulty may be that there is not currently in place any organizational structure to adequately obtain sufficient personnel support and to direct and coordinate the efforts of those personnel who are involved.

The purposes of this thesis, therefore, were to examine the above detailed concerns, to develop the issues to which these concerns lead, and to make recommendations that will ultimately lead to an improved development process and thereby to a system with a higher likelihood of success. With regard to this concept, the thesis will examine the PANSAT project from all feasible aspects, including but not limited to: engineering, testing, process, organizational, managerial and operational issues and decisions. To summarize, the end result of this thesis was intended to be (loosely) viewed and employed as a systems management guide. The "system" in this instance shall be defined in the System's Engineering sense as the sum of all those facilities, personnel, processes and components that are required in the design, fabrication, testing, deployment and operations of the PANSAT satellite and ground station.

2. Research Questions

The primary research question was: What are the critical current issues affecting the overall status of the PANSAT project and how should those issues best be addressed to carry the project through to the successful completion of its primary goals? Subsidiary research questions include:

- What is the current status of each subsystem of the project development structure?
- How does the project proceed through the next critical development steps of a design freeze and critical design review?
- What managerial, engineering, organizational and operational techniques and recommendations will best guide the project to a successful completion?

These questions outline the framework in which this thesis was initiated. Other issues naturally follow as solutions to the above questions are considered and will be posed and addressed in later chapters.

C. SCOPE OF THESIS

As a result of an informal program review conducted in April 1993, LT T.J. Sharps of the Space Technology division of the Naval Research and Development Command, the need for a PANSAT, Student Project Officer (SPO) was documented [Ref. 2]. That position was filled by the author in January of 1994, primarily as a stepping stone towards research for this thesis. Although there was no job description associated with this title, part of the scope of this thesis was to determine what role the SPO would play with regard to the PANSAT project.

The scope of this thesis was to address the issues outlined above and provide recommendations for the improved performance of the project in as many aspects as possible. Succeeding chapters will address the issues in the following manner: Chapter II will address engineering and design status and issues. Chapter III will address the status of the PANSAT testing program. Chapter IV will examine operational issues and concerns. Chapter V will concern management and organizational considerations and description of SPO activities and recommendations for future responsibilities. Chapter VI will provide conclusions, recommendations and set the stage for follow-up projects and theses. It was the intent of this thesis to emphasize issues and concerns that were determined not to have been adequately addressed or that remain unresolved. The final effort of this thesis was to prioritize those unresolved issues where possible, so that an efficient order of addressal could be pursued by future SPO's or other students.

II. SYSTEMS ANALYSIS

A. SYSTEM DESCRIPTION

1. Systems Engineering

This thesis in general, and this systems analysis in particular were approached from a systems engineering perspective. Systems engineering is defined as a process by which a stated need (objective) is transformed into a life cycle balanced set of product and process descriptions [Ref. 3:p. 2]. These descriptions are incrementally matured throughout the development of the system. They are used to plan and implement the development, fabrication, verification, deployment, operation, support, training, and disposal of the system.

This thesis will primarily deal with two of PANSAT's objectives (1) to enhance the education of officer students and (2) to design, fabricate, test, launch, and operate a small satellite. The PANSAT system, therefore, consists not only of the satellite, ground station(s), and the personnel and procedures that develop, fabricate, test, launch, and operate the satellite and ground stations, but also the personnel and facilities involved in all aspects of the education and training of the officer students associated with the project. This chapter will concentrate on that portion of the PANSAT system associated with the second objective; Chapter V deals more with issues associated with the primary objective.

2. Functional Description

A functional description of the satellite and ground station combination is best approached iteratively. On a large scale, the project is a satellite communication system that provides store and forward, packetized communications via spread spectrum amateur radio communications. The spacecraft receives packetized communications from a ground station, stores them in memory and re-transmits those messages at a later time to other ground stations. This overview now permits a more focused examination of the functionality of its components.

Within the satellite, a functional component description is now more easily described. Signals are received by the communications payload; the DCS (command and data handling) converts the signal format and stores the message for future re-transmission. The EPS generates and stores solar power, and provides conditioned power to the customer components within the satellite. The spacecraft structure supports, houses and provides protective enclosure (from the space environment) to all components; the DCS further provides control of all mission and housekeeping functions of the spacecraft. Similar, but less complex functionality can be defined for ground stations. A ground station transmits and receives signals via an antenna and transceiver system, while command and data handling are accomplished via a personal computer and a terminal node controller (TNC). These are the only ground station subsystems that warrant discussion.

B. PROJECT STATUS

The overall project status of PANSAT can best be described as mid-design phase. The project completed its PDR in 1993; however, upon examination of the significant design changes that have occurred since that time, it is readily apparent that the PDR was pre-mature. The most significant change since the PDR was with regard to the communications payload. The demodulator design was determined to be power, schedule, and cost prohibitive, and the communications payload was changed from analog to digital implementation. The EDR of 1994 saw the project closer to what would normally be considered to be the maturity of a project at the PDR stage. The design of PANSAT is complete and stable at the systems level and at the functional level for subsystems. The physical implementation of more detailed design work is currently ongoing.

Any status assessment of a project of this magnitude must be general in nature simply due to the number of components, subsystems and assemblies under consideration. The subsystem status sections of this chapter will, therefore, be largely non-specific. Particular components of significant interest for various reasons will be singled out for expanded discussion.

1. Spacecraft Structure

The basic spacecraft structure is a 26 sided polyhedron. Seventeen square sides provide mounting for solar arrays; the remaining square side is reserved to mount the launch vehicle interface. The remaining eight sides are triangular shaped, four will provide mounting for the communication antennae, and the remaining will provide handling, electrical (Hitchhiker) interface, and battery venting (if required). The remaining function of the structure is to provide component environmental protection, housing, and mounting. The next major step in the development of the spacecraft structure is the detailed design drawings to include, housing locations and dimensions, wiring locations, through holes and structural connectivity.

PANSAT's size can be roughly approximated by a 19 inch sphere. Early in its design stages the decision was made to forego any attitude stabilization capability, or even any attitude determination capability in the interest of reduced cost and complexity. The resulting design was determined to be the optimum design for solar power generation in the absence of spacecraft stabilization. The flat sides were chosen to provide ease of design and mounting for solar arrays. While it was not the intent of this thesis to second guess decisions beyond any possibility of reconsideration, the question of this choice for a basic structural design has to be raised in the event a follow on PANSAT becomes a reality. As will be developed later in this chapter, power is a critical consideration for PANSAT. The final power margin may in fact be negative, and many subsystem design options have been determined principally on the basis of minimizing power consumption. PANSAT's objectives have already been compromised in two ways. First, the original goal of using PANSAT as a platform for secondary experiments will not be met, except in terms of software upload experiments. Secondly, end performance will undoubtedly suffer given that power consumption will override other selection criteria. Additionally, this design requires an omni-directional antenna and the increased power requirement thereby incurred.

a. Status

The basic structure design has been completed and square panels have been fabricated for solar array mounting. Those panels/solar arrays are presently in the late stages of acceptance, qualification and functional testing. The current schedule calls for the basic design of the remaining plates, equipment housing, and most structural components to be completed in October 1994. Detailed design drawings, and fabrication for remaining plates, components, and subassemblies is scheduled from March to June 1995.

b. Issues

PANSAT will be deployed from the shuttle from a Get-Away-Special (GAS) canister. The separation method is via a mechanical spring that pushes the satellite out of the canister when commanded. The spring is attached to a pusher plate that touches the adapter on PANSAT. The spring is held depressed until desired, and the adapter is held against the pusher plate by a clamp. This clamp is pyrotechnically released and PANSAT is pushed out of the GAS can. Figure 3 shows the ejection mechanism as it appears after the Marman clamp has released and a payload has been ejected. A student thesis specifically addressing the launch vehicle interface adapter design will be completed in September 1994. This is an area of particular concern since early indications are that the adapter, which is permanently fixed to PANSAT, will shadow the solar arrays.

Another complexity decision was that individual solar arrays are pure series, which means that if a single cell is shadowed, it generates no current and that entire array generates no power. Again, the possibility seems to exist that under certain geometry up to four panels will be shadowed at a given time.

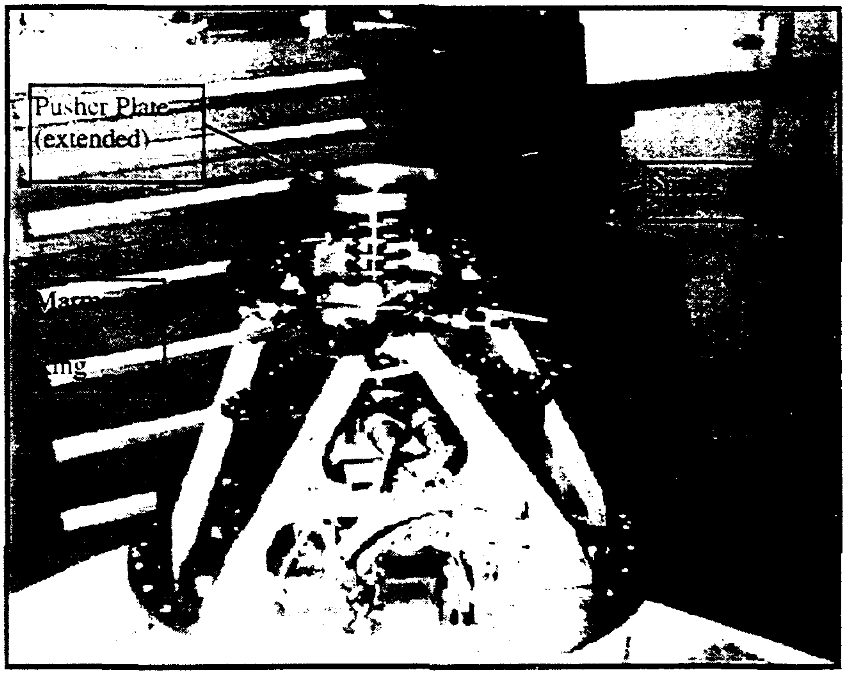

Figure 3: GAS Ejector Mechanism

The possibility has been raised of a modification to the adapter plate to reduce or eliminate shadowing of solar arrays [Ref.4:p. 84]. This may be the best option to eliminate shadowing, and is the subject of current research. The design that has been selected will eliminate direct shadowing (direct incidence), but off-angle shadowing has not been examined. The process by which a modification to a space qualified component must be fully understood, and carefully pursued. PANSAT will be integrated into the GAS canister by NASA Goddard Space Flight Center. The proper approach to modification is to specify exact requirements to NASA Goddard. The issue may then fall to one of funding.

Structural design progressed early and rapidly in the course of PANSAT's development cycle. For obvious reasons, after initial basic decisions were made, it was the simplest subsystem to develop. Progressively detailed design has slowed while other subsystems catch up in maturity. *It is symptomatic of many aspects of the PANSAT project that many different areas seem to occasionally stagnate while awaiting inputs from other areas.* This particular concern will be more thoroughly developed in Chapter V.

c. Recommendations

The adapter plate options include pursuing a modification of the anticipated adapter plate, flying with the plate as is, or obtaining an entirely new plate. At this point, there is some confusion with respect to what choices are available for adapter plates. Some documentation has been received indicating the possibility of the existence of different plate sizes. Confirmation of this possibility has not as of yet been obtainable. This question should be addressable through the CPR process, and should be pursued with the earliest iteration possible.

Follow on programs should perform more in-depth trade studies with regard to basic spacecraft structure. Specifically, is a relatively simple and inexpensive attitude control system (e.g., gravity gradient stabilization) a more attractive option? That choice would allow for a more directional antenna, and thereby reduced transmitter power; it would also provide the ability to design for more efficient solar power generation.

2. Communications Payload

The PANSAT communication subsystem is, due to the nature of the mission, the primary (and only) payload for the spacecraft. It is designed to be a simplex (single channel up and down link), spread spectrum, amateur band system. PANSAT will operate in the 70 centimeter (wavelength) band at a center frequency of 436.5 MHz with 2.5 MHz of bandwidth. The communication payload is in actuality a combination of the radio frequency (RF) subsystem and a portion of the DCS. Figure 4 presents a schematic view of side A of the RF subsystem.

The RF subsystem provides redundancy by employing two identical, separate and switchable sides (A and B). A side of the RF subsystem for a receiving signal begins at the antenna; the signal is then routed through a side (A/B) selector switch, a transmit/receive switch, and into a low noise amplifier (LNA). The boosted signal then is mixed with a 366.5 MHz local oscillator (LO) where the resulting difference of 70 MHz is filtered as the intermediate frequency (IF)[2]. At this point the IF is routed to the DCS, where it is down converted and sent to the analog to digital (A/D) converter where it is converted to digital data, then to the PARAMAX[3] demodulator where it is de-spread and demodulated. [Ref. 5:p. 24] A transmission is accomplished somewhat differently than a

---

[2]Briefing by Steve Huneke, for SS-4003, PANSAT Design Meetings, 26 July 1994.

[3]PARAMAX is a UNISYS Company.

pure reverse process. Data is prepared for transmission by modulating with a pseudo-noise sequence and then with a Bi-phase Shift Keyed (BPSK) modulator. The signal is then routed back to the RF subsystem where it is upconverted from IF (via the same LO) to 436.5 MHz, boosted through a high power amplifier (HPA) and then routed through the same switching to the antenna. The system can alternately be operated in simple BPSK modulation mode (un-spread).

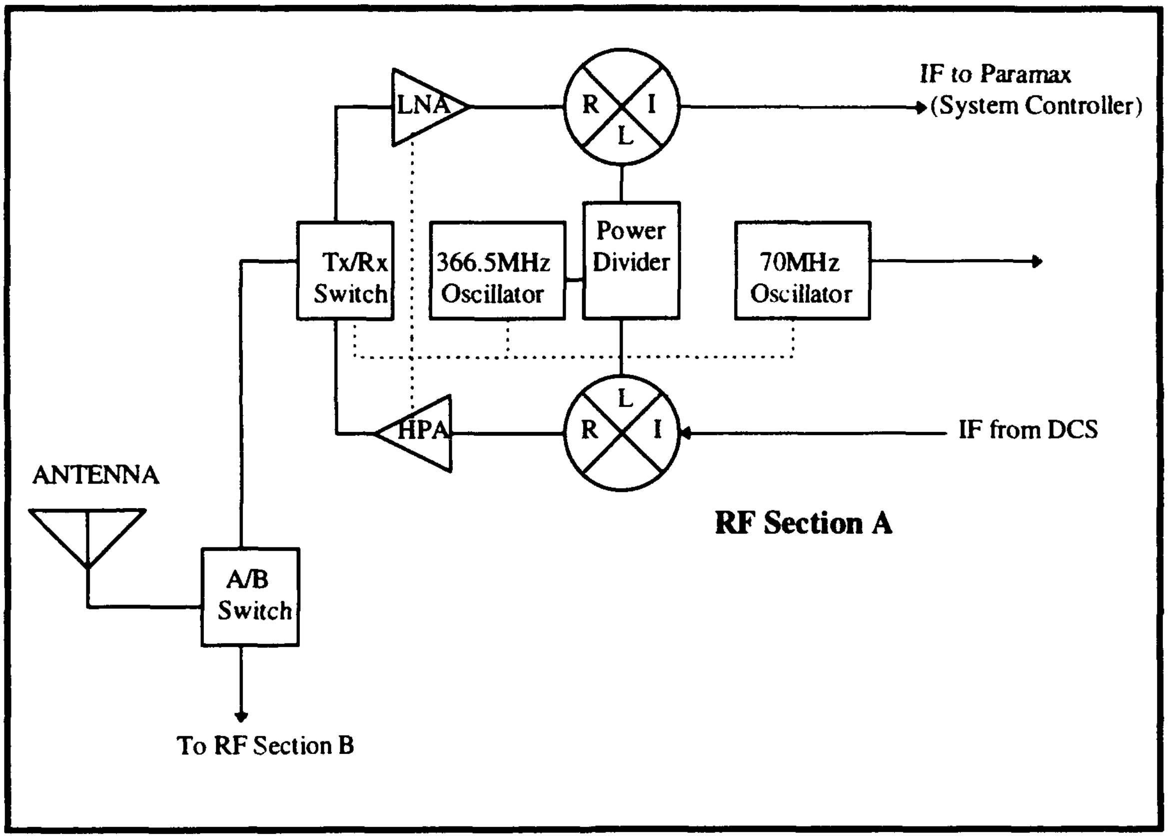

Figure 4: Schematic of RF Subsystem (Side A)

a. Status

Systems level design of the communication subsystem is complete and detailed design of the system is progressing. Brassboard development of the system is anticipated by October 1994, although the physical implementation of some detailed design aspects, such as the HPA and the A/B switch have not yet been satisfied. Student efforts are presently addressing these areas. In particular a detailed RF subsystem and RF/DCS interface design effort is scheduled for completion in September 1994. The results of this design work will likely change the above described signal processing in order to better realize redundancy and reliability requirements. What is anticipated is a switching network allowing either side of the RF to use multiple LO's, IF oscillators and amplifiers.

The PARAMAX demodulator is a design decision that warrants consideration from several aspects. This option provides state of the art, digital signal processing at greatly decreased power consumption, higher data rates and decreased complexity. The other option, until late 1993, had been an analog design developed by LT Arnie Brown [Ref 6]. It was subsequently determined that the demodulator design required by an analog system was too complex, large, and power hungry to be easily adapted for PANSAT.[4] At about the same time, research identified a digital off-the-shelf option which performed all required functions within power and size budgets. That item is the PARAMAX, PA-100 Spread Spectrum Demodulator.

b. Issues

The PA-100 seems to be the answer to many tough problems for PANSAT. There is a downside, however. The PA-100 was originally thought to be

[4]Personal Conversations with David Weiding regarding his thesis research findings, August 1994.

available in a Military Specification (MIL-SPEC) model, but that does not now seem to be the case. The option exists for the SSAG to purchase a production run for MIL-SPEC PA-100's but at a price of approximately $60,000 this option is apparently cost prohibitive. What then are the implications and risks of using a plastic PA-100? The known concerns are two-fold. *How will the chip stand up to the temperature and pressure extremes of space, and launch vibration and shocks? What effect will out-gassing have on the rest of satellite components?*

The brassboard demodulator should begin environmental and functional testing in September of 1994. This test sequence should resolve the first question of environmental sturdiness. The question remains about out-gassing and its effects on the rest of the spacecraft. A larger question with more far reaching implication is an immediate follow on as a result of these two. *What is the pass fail criteria for these tests and what options are available if the PA-100 fails?*

The anticipated antenna design for PANSAT was developed in 1991 by a thesis student. The resulting recommendation was for a tangential turnstile antenna in order to provide the nearest possible approximation of an omni-directional radiation pattern. [Ref. 7] The analysis performed met the criteria [Ref. 8:p. 4] of no nulls of greater than 10 dB. There was some concern given to polarization losses which could only be quantified statistically. This analysis used the entire PANSAT structure in the antenna model based on the relative size of PANSAT as compared to a wavelength (roughly .7 wavelengths). The results when the structure were included were significantly different from that of the antenna arrangement alone. That study was performed, however, without incorporation of the adapter as part of the structure.

c. *Recommendations*

The project has painted itself into somewhat of a corner with respect to the demodulator issue. There exists little or no corporate or research based knowledge of what likelihood a non-MIL-SPEC chip has of performing in an extended space environment. Will the subsystem's environmental testing be rigorous enough to determine potential shortcomings?

The next months of payload development are absolutely critical to the entire PANSAT project. The recommendations of this thesis towards reducing program risk are numerous:

- Thermal analysis must be accelerated to the point of an accurate thermal range for not only PANSAT but for the PA-100 location.
- Research for any lessons learned with regard to non-space rated chips in space.
- Develop fall back options for a demodulator design if the PA-100 does not succeed; these include investigation of adequate off-the-shelf radios and the purchase of MIL-SPEC PA-100 chips given the significant capital outlay.
- Develop pass fail criteria for environmental testing of the PA-100. Determine what level of out-gassing is acceptable and what is not.

A student is beginning thesis work in the area of antenna design. This should clarify that aspect of the communications system and allow for an increasingly accurate link budget. An antenna radiation pattern model including polarization effects will also satisfy some EMC testing issues that will be addressed in Chapter III.

3. Command And Data Handling

Command and data handling duties are performed by the Digital Control Subsystem (DCS). This critical subsystem coordinates the activities of the EPS, the RF communication subsystem, as well as the basic spacecraft operations and missions. The DCS functionally consists of three principal modules; a system controller, an analog multiplexer (MUX), and a mass storage unit. The current DCS design is redundant, providing identical A and B sides, similar to the RF communications subsystem. An integral part of the DCS is the Peripheral Control Bus (PCB), which provides the primary electrical interface for communication and control between the system controller and other DCS modules as well as the other spacecraft subsystems. [Ref. 9:p. 2]

The system controller module will house a M80C186XL processor, a serial communications controller, a counter timer, a peripheral interface, error-detection and correction random access memory (RAM), and programmable read only memory (PROM) as the principal digital controller. The input to the DCS from the RF communication subsystem is 70 MHz IF. The system controller therefore contains many RF communication components. The PARAMAX demodulator, analog to digital and digital to analog converters, quadrature downconverters, BPSK modulator, PN code generator, two low pass filters, and a band pass (IF) filter are all housed in the system controller module.

The analog multiplexer provides analog to digital conversion of temperature sensor data for telemetry monitoring and reporting. The mass storage unit provides four megabytes of volatile static RAM and 1/2 megabyte of non-volatile flash memory for data storage. This is the principal implementation of PANSAT's communication mission as a mail server. The mass storage is required to store packet information, transmission records, and telemetry history.

Switching between DCS sides A and B is accomplished via a watchdog timer. Normal operation of the DCS provides for periodic reset of the watchdog timer (interval TBD). If the watchdog timer counts down, this indicates a DCS malfunction and brings about a system reset. This will require operating system and software uploads from the command ground station and will switch spacecraft controller to the previously idle controller side. The watchdog timer is a component of the EPS.

a. Status

The development of the DCS hardware is, in general, in the breadboard phase. The analog MUX design is approaching prototype, and the system controller is tied in many ways to the RF communication subsystem development schedule. A complete system controller development board should be completed and ready for testing by early fiscal year 95. The system controller is the key module within the DCS and will appropriately receive the primary development effort in the near future. Implementation of the remaining two modules is nevertheless tied in many ways to that of the system controller. The design of system controller interfaces is ongoing. Interfaces have been defined but not specifically assigned.

The question arises of the necessity for redundancy in the design of the DCS. The majority of components within the DCS (with the notable exception of the PA-100 chip) are radiation hardened components, and therefore much more resistant of single event upsets. The need for error free operation of this critical system can not be overstated, however. Even considering the added complexity and expense of designing redundant sides into the DCS, it is a sound decision to provide this increased reliability.

b. Recommendations

The primary issue of concern for the DCS is software. As with any digital controller, software design and coding will make or break the system's ability to reliably perform its mission. It is absolutely critical to emphasize early and thorough testing in the subsystem's development cycle. The development of a spacecraft simulator is the most effective way to provide sufficient testing. A student thesis involving a simulator development on LabVIEW software is scheduled for completion in December 1994. This will only be the first stage in the development of the system. This is particularly true when the level of design that will be available as that thesis nears completion is considered.

The mechanisms for switching between sides A and B bear even closer and more thorough scrutiny. As the hardware and software designs solidify, it is essential to develop every possible scenario that could result in a system reset. As a system reset is currently defined, this is a drastic event with significant operational implications with regard to ground station requirements. Are there other conditions or non-catastrophic malfunctions that will cause expiration of the watchdog timer? If so, is it possible to do a less drastic DCS side switch, specifically, one that does not require a full operating system/software upload? What other malfunctions will cause a DCS shutdown?

As will be addressed in the next section, there is the distinct possibility that operational scheduling will be required to overcome power generation shortcomings. The simplest and most effective way of dealing with a potentially negative power margin is to minimize spacecraft power consumption while batteries are re-charged. Design decisions are now being made which may be affected by this eventuality. The ability to easily switch to a reduced power mode for specified time periods should be a DCS requirement. The most likely option for a reduced power mode is to switch the transmitter and receiver off or to standby. How quickly can these components be powered up to be ready for operation? What are the power consumption savings from this possibility?

4. Electrical Power Subsystem

The EPS provides primary electrical power in the form of 15.2 Volts dc generated from 17 silicon cell solar arrays, and secondary power from Nickel Cadmium (NiCd) batteries. In addition to solar arrays and batteries, the EPS consists of power conditioning electronics, distribution circuitry, temperature, current, and voltage sensors, and interfaces with the PCB. The EPS functional requirements call for an average minimum power of 21.5 Watts at 15.2 Vdc from the solar arrays at end of life (two year mission). A positive power margin is also a specified requirement. [Ref 8:p. 10]

The EPS contains the previously mentioned watchdog timer as a control and interface device for the DCS. This clock will effectively monitor DCS status and under normal operations be periodically updated. If the watchdog timer times out before being reset it will be indicative of a significant DCS malfunction and will cause a system reset. This reset will bring up the opposite side of the DCS. Many operations of the EPS are controlled by the DCS via the peripheral control bus. The principal power consumers in fact are the three modules of the DCS along with the transmitter and receivers. Other secondary consumers include power dissipated in isolation diodes and converters in the power generation side of the EPS.

a. Status

The particulars of the final EPS design remain in a pre-breadboard phase. The primary hold-up in many aspects of EPS and thereby spacecraft development is a battery selection decision. The final battery decision is likely by October 1994 at which time EPS designs will readily fall into place. A prototype EPS should be ready by early 1995. After the battery decision is made, extensive battery characterization tests will begin upon receipt, and these tests will fill in many of the missing details. There have been numerous power margin calculations over the development of the EPS. Finer power requirements are increasingly available from customer subsystem and component designs. With these data the PANSAT team believes the power margin to be approximately +10%. The issue of power margin is of critical importance to PANSAT for obvious reasons, not the least of which is that the results have significant impact on many other design issues throughout the spacecraft.

b. *Issues*

(1) Power Margin. Historically PANSAT's power margin calculations have been a source of confusion and debate. The latest calculations have been determined to be *energy margin not power margin.* While the energy margin may in fact be useful information, the accurate determination of power margins is a necessary first step to quantify system operations. The current calculations use solar cell voltage and current values corrected after discrepancies from the solar cell manufacturer were discovered. The average power available is then determined based on the results of a program written to determine the average effective illuminated area of PANSAT when rotated through 2π steradians with respect to the sun. This area was divided by the total area of the 17 solar panels to determine the percent of PANSAT illuminated. This average illuminated area was multiplied by the power generated by a panel normal to the solar incidence and the result was labeled as Average Available Power. This method is not sufficient because the power margin should be used to compare power generated versus power required under specific scenarios, not over a period of time. In other words, the average available power has little utility in this respect.

It was decided to develop power margins for specific scenarios to better understand the operational implications of the EPS design. Power generated in a given array is based on a basically constant array voltage and a current that varies with solar incidence angle. Each solar array consists of 32 solar cells connected in series. The cells have end of life performance of .478 volts and .282 amps. End of life array voltage is determined by:

$$\textbf{Array Voltage}_{eol} = \textbf{Voltage}_{eol}\textbf{/Cell} \bullet \textbf{\# Cells (series) - Wiring losses}$$

With an estimated .02 volt wiring loss the array voltage is therefore 15.27 Volts. The maximum power generated by any array is then given by:

$$\textbf{Power}_{max} = \textbf{Current}_{eol} \bullet \textbf{Array Voltage}_{eol}$$

which yields a maximum power per panel of 4.01 Watts. PANSAT's total power generated for a variety of sun orientations were calculated by the following formula:

$$P = \sum_i (V \bullet I \bullet \cos \theta_i) = \sum_i \text{Power}_{max} \bullet \cos \theta_i$$

where θ_i = solar incidence angle on illuminated panel i. Figure 5 shows the three specific orientations which were examined analytically, and the associated coordinate axes (X axis, not shown, is defined by the right hand rule). Solar incidence was assumed to be directly perpendicular to the figures (i.e., in the -X direction).

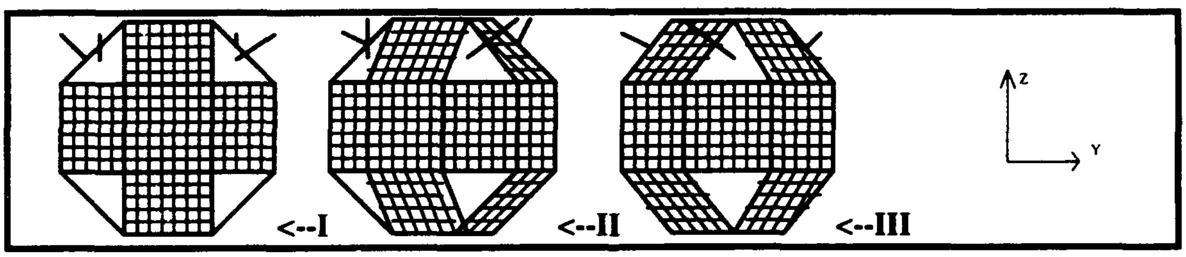

Figure 5: Orientations Analyzed for Power Margin

The power generated for orientation **I** was calculated based on one panel normal to the sun, and four panels having incidence angles of 45°. This yielded a power of 16.49 Watts. Orientation **II** involved a slightly more complicated calculation.

Solar incidence was assumed normal at the intersection of the two middle panels. Based on PANSAT's octahedral basic design all joint intersections are 45°, so the two middle panels have an incidence angle of 22.5°, the two adjoining panels (middle row) have incidence angles of 67.5°. The top and bottom panels' power calculations are more easily determined by considering two incidence angles (rotated about different axes) rather than a single incidence angle. The top and bottom panels that are just left of the middle have incidence angles of 22.5° (about Z axis) and 45° (about Y axis). Similarly, the remaining two panels have incidence angles of 67.5° and 45°. This yielded a power of 19.21 Watts. Orientation **III** incidence angles were calculated using the same methods as described above. Incidence angles were 45° for the two outer middle panels, and the four top and bottom panels had incidence angles of 45° about both axes. The power from this orientation was 19.01 Watts.

The initial implications of this analysis is that the power in general is directly related to the number of illuminated solar panels. More evidence of this was obtained by rotating orientation **II** 20° about the Y axis. This brings a ninth panel into view and when the incidence angles are adjusted, the power from this aspect is calculated to be 19.52 Watts. The complication to this analysis is that the presence of the base plate panel has not yet been considered. The worst case would be with orientation **I** with the base plate normal to the sun, the power generated here will be only 12.18 Watts. For orientation **II**, the effect of the adapter as one of the panels varies from a 3.98 to a 1.17

Watt reduction in power. For orientations **I** and **III**, the reduction varies from 4.31 Watts (normal plate) to 2.15 Watts.

Current power requirements are largely based on the EPS supporting the three DCS modules, and the receiver and transmitter. Additionally, the dissipated power in isolation diodes, current sensors, battery charging, as well as converter inefficiencies were included. The principal power consumers require 10.85 Watts, but due to EPS converter inefficiency of 75%, draws 14.47 Watts. The remaining dissipated power boosts the required power to 15.42 Watts. When comparing this requirement with the generation capabilities examined previously, it is apparent that PANSAT will operate on a negative power budget under some sun orientations. While full statistical analysis will be required to determine probabilities, the basic situation is relatively simple. Assuming completely random motion, the adapter panel will not be illuminated roughly 50% of the time. When this is the case, a positive power margin is a strong likelihood (i.e., no orientations could be determined with less than 16.49 Watts generated, this corresponds to a +6.3% power margin). Under most orientations where the adapter is illuminated, those conditions that are likely to have a negative power margin are when a relatively small number of panels are illuminated (e.g., orientation **I**) and the adapter is a panel of low incidence angle. The power rises rapidly as additional panels are illuminated; orientation I rotated through only 10° about the Z axis produces 17.3 Watts, a .8 Watt increase. It should be noted that the potential shadowing of additional panels from the base plate has not been considered in this analysis.

(2) Battery Selection. The battery design candidates have been narrowed to a choice of non-space qualified NiCd batteries, one consisting of F- cells, and one of D-cells. The overriding cost of space qualified batteries ($300,000) ruled this option out immediately, given budget limitations. The battery decision has narrowed to a trade off of performance issues. The F-cell has a capacity of 6.5 Amp-hours and a; the D-cell has a 5.7 Amp-hour capacity. [Ref. 4] Obviously, the higher capacity is desirable, but the question is what battery capabilities are required. One specific, answerable question is what is the required capacity of the battery and therefore the cells. Cell capacity requirements are based on eclipse power requirements [Ref 10:p. 89] and can be derived from the following formula:

$$\textbf{Required Energy} = \mathbf{P} \bullet \mathbf{t_d} = \textbf{Supplied Energy} = \mathbf{C} \bullet \mathbf{V_B} \bullet \textbf{DOD}$$

where: P = Required Power, t_d = Duration of eclipse, C = Capacity (required), V_B = Bus Voltage, and DOD = Depth of Discharge. Using a bus voltage of 12 Volts and 10% DOD, all that remains is a determination of required energy. The only eclipse power requirements are 14.47 Watts to converters to run the DCS and RF subsystems, and dissipated power (.32 Watts) in the battery isolation diodes. Eclipse time has been calculated to be approximately 40% per orbit, which equates to 36 minutes. Required energy therefore is 8.87 Watt-hours, but given a two battery system, the single battery requirement is half load and therefore 4.44 Watt-hours. Equating required energy and supplied energy and solving for **C** gives required capacity of 3.7 Amp-hours.

The battery design calls for a DOD of 10% to provide for the high cycle requirements imposed by PANSAT's low altitude orbit. A typical space NiCd battery cycle life versus Depth of Discharge curve can be approximated by:

$$\% \ \mathbf{DOD} = -30.74 \bullet \log_{10}(\ \#\ \mathrm{Cycles}/1.2\mathrm{x}10^5)$$

The number of cycles can be approximated based on 14 orbits per day for two years; this gives 10,227 cycles. This converts to a depth of discharge of 32.9%. Entering the 10% requirement into the formula yields a number of cycles equal to 56,738, which is more than 11 years. [Ref. 10:p. A-82] Does the charge performance differ significantly for the different type cells? Is the volume required for F-cells within the size limitations of the space allotted to the battery system?

c. Recommendations

A better analysis of power margin is warranted. A model generating power production considering attitude dynamics should be developed. Statistical evaluation of the resulting power margins will yield an energy margin and therefore better information about operational effects, and battery requirements. Pursuing the definition of reduced power modes will allow an improved energy margin by allowing operational adjustment of power consumption. These efforts are overdue. The current power margin by which the EPS design is proceeding, as was previously stated, is an energy margin. The power production prediction was based on a computer model that determined an average percentage of PANSAT illuminated. This percentage was converted to an average available power. The calculated average was 19.45 Watts. Utilizing the method described above, only one orientation examined was able to produce a power of this magnitude.

The algorithm and data used to produce the 19.45 Watt average power value were examined for possible error. The algorithm could not be debugged to determine accuracy, so the inspection turned to the data. The data output was effective illuminated surface area of solar panels for particular orientations. The methodology employed saw orientation **I** as the basic orientation. This orientation was rotated at 5° intervals through 90° about the z-axis. After each increment the satellite was rotated (6° incrementally) about the y- axis through 360°. The values for the three orientations considered manually above were compared to output data; in all three cases the resultant powers computed differed by less than .1 Watt. However, when the basic orientations were rotated about the y-axis, the results were drastically different. For example, orientation **III** was rotated through 11° and the resulting power was manually calculated to be 19.52 Watts. The power from the algorithm was 21.81 Watts, a difference of 2.3 Watts from an 11° rotation. This implies a rotation of only 11° which incurs a 10% increase in power (or surface area). The mechanics of this rotation simply do not agree with these results. That rotation brings an additional solar panel into view, but with an incidence angle of only 79°, this corresponds to .82 Watts. Of the seven panels already in view, five have higher incidence angles (i.e., lower power) from this rotation and only two have lower incidence angles (i.e., higher power). Another scenario was considered. Beginning with orientation **I**, a 45° rotation about the y-axis (Figure 6) gives the exact same view as orientation **III** rotated 90° about the x-axis (Figure 7, x-axis by the right hand rule). The rotated view in Figure 6 is given in the data as generating 23.22 Watts, but this has been shown to be identical to orientation III (rotated to no effect on power) which has been calculated manually and by the algorithm to generate only 19.01 Watts. *This clearly demonstrates a significant error in the algorithm upon which all prior power calculations have been based.* All possible scenarios have not been calculated manually, but the average power figure of 19.45 Watts is clearly too high, perhaps on the order of 2 Watts and almost certainly more than 1 Watt. This has significant implications on an already underpowered satellite.

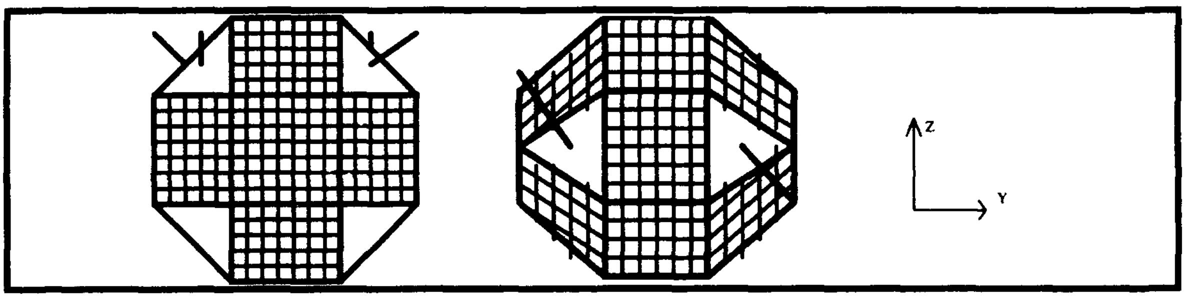

Figure 6: Orientation I and its 45° Rotation About the Y-Axis

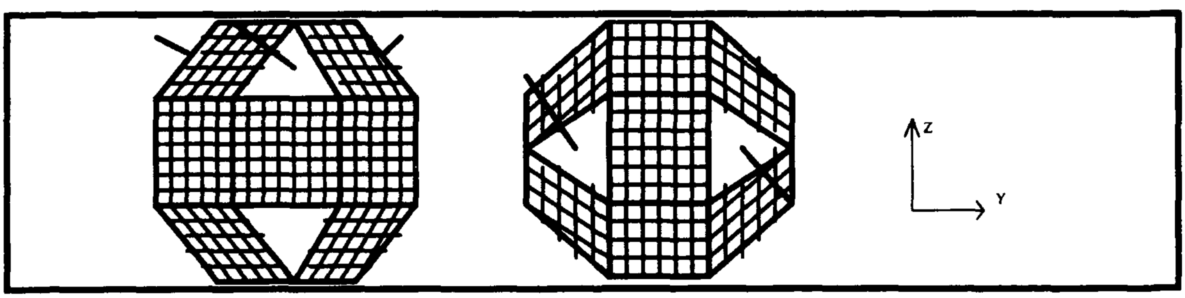

Figure 7: Orientation III and its 90° Rotation About the X-Axis

A thorough and complete review of the operational states of the spacecraft subsystems is absolutely essential. States that reduce power consumption enable operational plans that will overcome power generation deficiencies. The initial reaction of all subsystem coordinators to this question is that there are no lower power states available. From the DCS requiring at least standby power to all major components (of the operating side) to the requirement to continuously monitor sensor telemetry for battery charging circuits, the answer is universally negative. *This author is highly doubtful that there exist no available options for reducing power consumption from the basic state. It is strongly recommended that renewed effort be directed to this question.*

Considering the above calculations, it is recommended that a thorough trade study of the battery decisions be performed. Charge rate, volume and weight comparisons at a minimum should be considered along with the capacity for the best choice. The DOD issue also impacts the study. Is the DOD versus cycle life curve used above applicable to non-space rated NiCd's? If the answer is yes, then why design to such a restrictive limit? While the capacity of the D-cell is somewhat less, it is reasonable to believe this capacity is still more than sufficient to power PANSAT through eclipse. Furthermore, if the use of 10% DOD proves to be as conservative as is apparent, the choice of a lower capacity may be even more secure. As with all systems design issues, one decision impacts the next, which impacts the first, etc. With regard to this complication, in this case the order seems simpler. *An accurate model of power production should be the immediate high priority effort. Almost every other EPS issue hinges on these results.*

Another consideration for the power analysis is of course power consumption. *Are there any components not yet positively determined that are* *replaceable with lower power ones?* Specifically, is there an HPA that meets requirements that consumes less power than the current options? Is a lower power amp feasible with consideration to the link budget? Current link budgets typically consider a 5° or 10° minimum elevation in link margins. If PANSAT gets an orbital inclination of greater than 28.5° can realistic communication windows be achieved if the minimum elevation for a link margin went up to 15°? *In other words how much link margin is there to trade-off for lower performing RF components in order to help a beleaguered power budget?*

5. Thermal Control

Another of the design decisions made early on in the development of PANSAT was to design a satellite that could operate without active thermal control. This decision was reinforced as power budgets were examined and it became increasingly apparent that active control was a luxury that simply could not be achieved. Initial reports of the findings of a transient thermal analysis indicate internal temperatures for PANSAT should be maintained within the range of 0° C to + 40° C.[5] This range is well within the safe operating range of the electronic components. This is a significant benefit to the program as little backup was available if the analysis had not proved so benign.

The detailed results of the transient analysis must be examined in particular for one issue. The battery performance is very dependent on operating temperature, and it

[5]Peronal conversation with Dan Sakoda, PANSAT Systems Engineer, 4 Aug 1994.

requires a much narrower range than that given above. Therefore the ability to obtain and maintain an acceptable battery operating temperature has not yet been resolved.

It is unlikely that facilities will be made available for PANSAT to be able to perform a thermal balance test. The question should be asked though; how thorough a test is required in order simply to provide some validation to the thermal analyses that have to date driven PANSAT's thermal control system (or lack thereof). If there is a way to perform a less rigorous test than a fully developed Military Standard thermal balance test, every effort should be made to pursue that option.

6. Ground Stations

PANSAT ground stations under development fall under two separate categories. The command ground station will be located on the NPS campus; the particular location will be determined at a later date. The SSAG team is simultaneously developing the design for a generic "Ham Kit." The kit will be designed with two primary goals in mind, that of providing an amateur radio operator with all necessary hardware and software to communicate with PANSAT, and to do so at as inexpensive a cost to the amateur as possible in order to maximize participation.

The SSAG currently has an operating base station, routinely communicating with other amateur satellites, such as the OSCAR series. The components of the base station that will form the basis of the PANSAT command station are the transceiver, terminal node controller (TNC), and personal computer running packet communications software. The PANSAT station design and construction will involve adapting the current base station into one compatible with PANSAT. This implies the use of the satellite's modem, integrated into the TNC, a PANSAT optimized antenna, and the specific PANSAT software that is not available "off-the-shelf."

a. Command Ground Station

The design and fabrication of the command ground station are in many respects, either already in place, or fall largely under the domain of the communications subsystem or DCS development. The RF subsystem of the communications payload requires integration into the existing base station. Specifically, the spread spectrum, modulator and demodulator (PARAMAX) components must be integrated into the transceiver/TNC interface, the PANSAT antenna must be fabricated and mounted, and command and control software must be completed.

There are several operational issues which must be addressed as development proceeds. The Federal Communications Commission requires that a ground station maintains a log of all spread spectrum transmissions for a period of one year following the last downlinked entry. These station records must include sufficient information to enable the commission to demodulate the transmissions. An operations manual and guide must be developed as well as training procedures for ground station operation.

The integration design work is largely completed up to the breadboard stage. Further efforts are dependent on DCS and communication subsystem schedules. The ground station antenna [Ref. 7] design is that of a thesis student. The design of both the ground station and satellite have been completely based on one particular thesis that selected the antennae based on a simulation in 1991. Since fewer interdependencies exist for the ground station antenna the timing is less critical than for the satellite; however, the need for a physical model to validate the design certainly exists. Antenna acquisition or construction is scheduled for September 1994, with mounting in November. December should see the PARAMAX integrated into the ground station, whereupon the PANSAT ground station will be completely functional, and then operational after testing by early 1995.

b. Amateur Ground Stations

The decision to pursue the PARAMAX design had significant impact on the "Ham Kit" design. As the satellite design progresses it has become increasingly apparent that a separate, simple design for amateur radio operators is not feasible. The emphasis in this context is that the Ham Kit design is unlikely to be a separate one. The amateur radio operator must have a ground station which is almost identical to the command ground station in order to communicate with PANSAT. The principal difference will be in the form of software, specifically, command and control capability and security passwords that are only available to the command station. Whether or not an amateur utilizes the PANSAT recommended ground antenna design may impact the link viability. The reason the current design was selected was largely to minimize the probability of large polarization losses. More popular antenna designs for amateur satellite links suffer substantially greater polarization effects.

A final but important consideration in the development of the "Ham Kit" is adaptability. Specifically, the kit will be better received by the amateur radio community if it can be readily expanded or modified for use with other satellites and or systems.

III. SPACECRAFT TESTING

A group project completed in June 1994 for AA-4831, Spacecraft Systems II, examined, in detail, the issues involved in spacecraft testing as it specifically related to the PANSAT project. [Ref. 11] The author of this thesis was the project lead for that Test Plan Development project. That project consisted of the background research and an initial Test Plan framework specifically designed to the PANSAT project. The title for the group's report of findings was "PANSAT Test Plan". Unless specifically noted or otherwise referenced, the contents of this chapter will be drawn directly from the findings of the aforementioned project.

This chapter will address testing terminology, environmental, functional and operational testing issues and provide recommendations where feasible. This thesis is primarily concerned with the future of the project; therefore, past and ongoing testing will not be covered in this chapter.

A. TESTING OVERVIEW

1. Testing Terminology

Military Standard 1540B (MIL-STD-1540B) dated 10 October 1982 is very specific as to the required tests for any government spacecraft. Testing requirements and categories can be described in many ways, Environmental testing, Functional testing, Qualification testing, Acceptance testing, Developmental testing, and Operational testing.

It can be a daunting task in itself to organize a plan into logical categories and sequences. For this thesis the testing is organized in the following manner. The broadest and therefore, top level testing fall into one of three categories which describe the general goal of the test: Environmental, Functional, or Operational. Within Environmental testing, qualification or acceptance testing can be applied and will be used to determine testing levels. Development testing can be generally considered to be a subcategory of functional testing implying the design level at which the test occurs. Functional and Environmental testing are roughly aimed at determining how a particular component, subsystem or system conforms to specifications. Operational testing is aimed at evaluating how a whole system, or possibly significant subsystem, performs its intended mission in a typical operational environment.

a. Qualification Testing

Qualification test levels are usually specified as the design levels. These test levels are established to exceed the range of environments and stresses expected in any subsequent use. The expected environmental maximums are adjusted with a margin of safety to establish design levels. For vibration testing, these margins must further ensure that repeated acceptance, if necessary, will not jeopardize the integrity of the hardware. Qualification tests should validate the planned acceptance test program, including test techniques, test procedures, test environments, ground support test equipment, and computer software.

Qualification testing is associated with prototype equipment and as such has a somewhat limited application to PANSAT. Prototype components and subsystems should undergo normal qualification testing, but protoflight components should not be exposed to the full qualification extremes. The adjustments to qualification of space flight (protoflight) vehicle is as follows:

- Acoustic qualification shall be 3 dB above maximum predicted, but not less than 141 dB overall.
- Vibration levels shall produce vibration responses 3 dB greater than maximum expected.
- Thermal Vacuum shall have 4 cycles of temperatures 5° C beyond maximum expected.
- If optional thermal cycling is adopted as baseline, minimum temperature range of 60° C should be used for minimum 15% more cycles than acceptance testing stipulates.

b. Acceptance Testing

Acceptance test levels are the maximum expected environmental levels. This testing is generally associated with deliverable space flight equipment. Protoflight equipment should be tested to the amended qualification levels described in the previous section. Acceptance tests are intended to demonstrate the flight-worthiness of each deliverable item. Acceptance tests should demonstrate acceptable performance over the specified range of mission requirements.

c. Functional Testing

This required test verifies that the electronic, electrical and mechanical performance of the component meets the requirements. Electrical tests shall include application of expected voltages, impedance, frequencies, pulses, and waveforms at the electrical interfaces of the component, including all redundant circuits. These parameters shall be varied throughout their specification ranges over the sequence expected in flight operation, and the component output shall be measured to verify component performance. A functional test shall be conducted prior to and after each of the environmental tests.

d. Component Development Tests

The major portions of the development test series are conducted on breadboards and prototypes at the component and subassembly levels. The objective is early verification of the critical design concepts to reduce the risk involved in committing the design to qualification and flight hardware. Designs should be characterized across worst case voltage, frequency, and temperature variations at breadboard level. Functional testing in thermal and vibrational environments is normally conducted. For electronic boxes, thermal mapping in a vacuum environment may be needed to verify the internal component thermal analysis.

e. Component Qualification and Acceptance Tests

The space vehicle component qualification and acceptance test baseline consist of all the required tests specified below. The test baseline shall be tailored for each program. Each component that is acceptance tested as a component shall undergo comparable qualification tests as a component. In certain circumstances, required component qualification tests may be conducted partially or entirely at the subsystem or space vehicle levels of assembly.

f. Environmental Testing

Environmental testing is focused at determining a spacecraft's performance in the environments to which it will be subjected either in transportation, launch or operation. Vibration testing is aimed at vehicle transportation and launch. Thermal testing is aimed at on-orbit operations, launch and deployment. Radiation testing is aimed at the electromagnetic environments to which it will be exposed during transportation, launch and operations as well as the s/c's own radiation characteristics. Since a significant portion of this report is dedicated to development of environmental testing issues in general and specifically applied to PANSAT, it will not be further developed here.

2. Testing Philosophy

A testing philosophy is a logical approach to developing a coherent testing sequence. With regard to available assets, the entire range of possible testing should be delineated for consideration. The tests required by the Hitchhiker program should first be developed. The remaining tests would then be listed and analyzed for applicability. Those tests should be ranked in terms of their relative importance to PANSAT performance enhancement. This precedence list can be analyzed for each particular tests' impact on program cost and schedule. After this process, the remaining tests should be merged with the Hitchhiker required testing and analyzed for potential combinable tests.

The PANSAT testing philosophy, therefore, is to test for design verification and performance improvement while fullfilling Hitchhiker requirements. *Test selection* *and sequencing should be determined via a logical process yielding those tests that are the most worthwhile, not just the most do-able. The results of this testing sequence should be a qualified, reliable spacecraft vehicle, and therefore, a program with increased potential for success.*

B. ENVIRONMENTAL TESTING

1. Vibration Testing

PANSAT must be able to withstand the forces to which it will be subject throughout its lifetime. It must withstand the vibrational and acoustic effects of the launch vehicle. Additionally, the satellite will be exposed to the shock effects of engine ignition and shutdown, as well as the shock caused by pyrotechnic separations, ejection from the shuttle, and ground handling.

Vibration testing falls under the larger category of environmental testing. Some of the qualification test methods that can be performed on a spacecraft before flight qualification are: discrete force, below-resonant frequency sine dwell, sine burst vibration, sine sweep, random vibration, and transient (shock) testing. These rigorous qualification tests ensure that the space vehicle will survive its initial trip into space.

The random vibration environment imposed on the space vehicle components is due to the lift-off acoustic field, aerodynamic excitations, and transmitted structure-borne vibration. The maximum predicted random vibration environment is specified as a power spectral density, based on a frequency resolution of 1/6 octave (or narrower) bandwidth analysis, over a frequency range of 20 to 2000 Hz. A different spectrum may be required for different equipment zones or for different axes. The component vibration levels are based on vibration response measurements made at the component attachment points during ground acoustic tests or during flight. The duration of the maximum environment is the total period during flight when the overall amplitude is within 6 dB of the maximum overall amplitude. Where sufficient data are available, the maximum predicted environment may be derived using parametric statistical methods. The data must be tested to show a satisfactory fit to the assumed underlying distribution. The maximum predicted environment is defined as equal to or greater than the value at the ninety-fifth percentile value at least 50 percent of the time. Where there are less than three data samples, a minimum margin of 3 dB is applied to the prediction to account for the variability of the environment.

The sinusoidal vibration environment imposed on the space vehicle subsystems and components is due to sinusoidal and narrow band random forcing functions within the launch vehicle during flight, or from ground transportation and handling. In flight sinusoidal excitations may be caused by unstable combustion, by coupling of structural resonant frequencies with propellant system resonant frequencies (POGO), or by imbalances in rotating equipment in the launch vehicle or space vehicle. Sinusoidal excitations may occur during ground transportation and handling due to the resonant response of tires and suspension systems of the transporter. The maximum predicted sinusoidal vibration environment is specified over a frequency range of 20 to 2000 Hz for flight excitation and 0.3 to 300 Hz for ground transportation excitation. Where sufficient data are available, the maximum predicted environment may be derived using parametric statistical methods as described above. Where there are less than three data samples, a minimum margin of 3 dB is applied to the prediction to account for the variability of the environment.

The pyro shock environment is due to structural response when the space or launch vehicle electro-explosive devices are activated. Resultant structural response accelerations resemble the form of superimposed complex decaying sinusoids which decay to a few percent of their maximums in 5 to 15 milliseconds. The Maximum Predicted Pyro Shock Environment is specified as a maximum absolute shock response spectrum determined by the response of a number of single-degree-of-freedom systems using Q = 10. The Q is the acceleration amplification factor at the resonant frequency for a lightly damped system. This shock response spectrum is determined at frequency intervals of one-sixth octave or less over a frequency range of 100 to 10,000 Hz. Where sufficient data are available, the maximum predicted environment may be derived using parametric statistical methods as described above. Where there are less than three data samples, a minimum margin of 4.5 dB is applied to account for the variability of the environment [Ref 12:p. 64].

Pyro shock testing is not required for Hitchhiker payloads. In general, the high frequencies (100 - 10,000 Hz) are easily damped out over distances of 5 inches or more. The Hitchhiker payloads are sufficiently displaced from the pyrotechnic devices used to release the GAS canister release bolts, Shuttle SRB's and external fuel tank.

a. Requirements

Since PANSAT is less than 180 kg, vibration testing will be conducted in lieu of acoustic testing. The vibration test requirements are delineated in the Customer Accommodations and Requirements Specifications (CARS). Further details are specified in the Shuttle Orbiter/Cargo Standard Interfaces document, the General Environmental Verification Specification for STS Payloads, Subsystems, and Components manual.

(1) Equipment Integrity and Factors of Safety. Hitchhiker payloads require structural testing to 1.25 times the limit loads and positive margins of safety by analysis at 1.4 times the limit loads for ultimate failure modes (fracture and buckling). Analysis showing positive margins of safety at 2.0 times the limit loads and 2.6 times limit loads for ultimate failure modes may alternatively qualify the payload for Hitchhiker launch. [Ref 13:p.3-5]

(2) Vibration Frequency Constraints. Hitchhiker payloads are required to have a lowest natural frequency of greater than or equal to 35 Hz, idea' greater than 50 Hz. Predicted natural frequencies below 100 Hz require modal survey or sine sweep testing to verify, a recent analysis has a predicted natural frequency for PANSAT with internal components at 67.26 Hz, so the sine sweep test will be required.

(3) Random Vibration Test. Random vibration testing exposes a payload to the design level vibroacoustic environment. It is considered to be the most realistic test to simulate many actual environments. The typical frequencies used to excite the payload range from 20 to 2000 Hz. Due to the infinite number of frequencies within

the above bandwidth, the 20-2000 Hz bandwidth is subdivided into narrower frequency bands or lines. The smaller these new bands or "lines" are, the more in depth the testing. The determining factors rest with the tester's preference and the capability of the vibrational control system or shaker.

The energy focused on the payload at each of these frequencies will have a pulse that is determined randomly from a gaussian distribution about the determined test level. The amplitude level is limited to prevent failure and is specified in g^2/Hz. Dividing by the filter bandwidth yields normalized data, allowing plots with two different bandwidths to be directly compared.

When conducting random vibration qualification testing, the component is mounted to a rigid fixture through the normal mounting points of the component. It is critical that the mounting system be an accurate representation of the actual system, and that the system be rigid. Failure to do so could result in tremendous errors. Testing is done in each of three mutually perpendicular axes. The minimum overall test level for components weighing less than 50 lbs is 12 g_{rms} (root mean square). Components weighing more than 50 lbs are evaluated on an individual basis. Test duration time for each axis is determined by the greater of three times the expected flight exposure time to the maximum predicted environment, three times the component random vibration acceptance test time, or three minutes. New design equipment, such as PANSAT, must be tested to qualification levels. Qualification Random Vibration levels and spectrum are shown in Table 1.

TABLE 1: VIBROACOUSTIC QUALIFICATION LEVELS

Frequency (Hz)	ASD Level (g^2/Hz)
20	.025
20-50	+6 dB/octave
50-600	.15
600-2000	-4.5 dB/octave
2000	.025
Overall	12.9 g_{rms}

(4) Sine Vibration Test. The sine vibration test is used to identify the resonant frequencies. The lowest natural frequency must be equal to or greater than 35 Hz, and desirable to be above 50 Hz as stipulated in the Hitchhiker CARS. If the lowest cantilevered natural frequency is predicted to be below 100 Hz, then the natural frequency must be verified by either modal survey or sine sweep vibration.

Sine vibration testing exposes the payload to the design levels of the sinusoidal (or decaying sinusoidal) vibration environment. The vibration element is due to the sinusoidal and narrow band forcing functions of the launch craft during flight and during ground transportation. The sinusoidal excitations during ground transport are generated from the resonant responses from the transporter's tires and suspension. This test is most useful when testing for environments that have dominant narrowband frequency characteristics. Tests are conducted to see if the payload can not only withstand but operate in this environment. Sinusoidal vibration testing also verifies the natural frequency and determines if there are any resonant frequencies of the payload that should be noted. Lastly, this test is used to evaluate fixtures used in the testing.

The sine vibration test can be a sweep type test that sweeps across a frequency band or a dwell type test which dwells on a specified frequency. Sine vibration testing requires a minimum and maximum frequency, start frequency and direction, number of sweeps, sweep rate, and an acceleration profile. A good test sweeps the frequency band a number of times with changing sweep directions. Also, because the starting frequency and direction are of no consequence, the test can be aborted and started up again at the abort point.

Test levels are chosen to produce vibration responses equal to the maximum predicted flight environment plus a design margin. Structural response at resonant frequencies will be limited to prevent design limit loads from being exceeded. Careful consideration shall be given to resonance effects of the structure, adapter type, table control techniques, and location of control accelerometers. During the test, all electrical and electronic components will be energized and sequenced through all operational modes, unless operation would result in damage. Test duration for each axis will be the greater of three times the expected exposure to maximum flight environment, three times the acceptance test duration, or three minutes.

(5) Sine Burst Test. All launch loads for the Space Shuttle must be able to withstand the launch, operational, reentry and landing environments of the Shuttle without failure. The stated requirement is for structural resting at 1.25 times the limit loads, with positive margins of safety by analysis of 1.4 times the limit loads for all modes of failure. Qualification by analysis alone can be done if positive margins of safety can be

shown at 2.0 times the limit loads for material yield and 2.6 times the limit loads for ultimate failure modes. This is to be approved on a case by case basis, however, by GSFC. If analysis alone cannot qualify the spacecraft, a sine burst test or equivalent test must be performed.

(6) Transient (Shock) Testing. Transient testing is used for simulating short duration, high amplitude disturbances. Examples are impacts and stage separations (which involve pyrotechnic devices). Waveforms used in transient testing can be broken down into classical waveforms, shock spectrum synthesis, and field transients. Once again, the Hitchhiker requirements, as stated in the CARS, make no mention of transient or shock testing. More realistic vibrational tests have been developed which run two tests concurrently (e.g., sine on random and transient on random). While not required, these tests should be considered. If a later decision is made to launch PANSAT via means other than the shuttle, a new test plan will have to developed.

b. Proposed Plan

(1) Sine Vibration Test Plan. This test is required, since the lowest resonant frequency, based on analysis, is 67.26 Hz, [Ref 14:p.36] which is below the 100 Hz threshold for testing. The Sine Vibration Test consists of a low-level sinusoidal excitation, which will be swept from 20 to 2000 Hz. The test will be conducted three times, once in each axis for a duration of three minutes. This test will be used to identify actual resonant frequencies

(2) Random Vibration Test. This test will consist of excitation at frequencies between 20 and 2000 Hz. Since it is not practicable to test at all frequencies, a sampling of 1600 lines will be made. The energy level at each frequency is to be controlled to a level determined by use of the power spectral density plot found in the Hitchhiker Customer Accommodation and Requirements Specifications (CARS). The actual amplitudes will be random. This test will be conducted in each of the three axes. The shaker must be able to shake PANSAT with a force equal to the mass times the acceleration of gravity. PANSAT is on the order of 150 lbs; adding ten lbs for the fixture gives a total weight of 160 lbs. Therefore, the shaker must be capable of approximately 1280 lbs, based on a total weight of 160 lbs, and a Grms of 8. This precludes use of the MB Dynamics PM 500A shaker, which is capable of only 465 lbs. On the other hand, the Ling shaker is capable of up to 3000 lbs for sine sweep and shock testing, and 1500 lbs for random vibration testing. Therefore, the Ling shaker can meet the requirements. The Ling is capable of operations, but has not yet been qualified for use.

(3) Sine Burst Test. Presently, there is no plan to conduct any strength testing based on the high margins of safety obtained in analysis. Table 2 [Ref. 14] provides load vectors derived for a yield Factor of Safety of 1.25 and an ultimate Factor of Safety of 1.5.

TABLE 2: STRUCTURAL STRENGTH ANALYSIS

Load Case	Element #	Max. Stress (psi)	Avg. Stress (psi)	Smallest M.S.
X(9 g's)	155	2.911×10^3	5.17×10^2	11.37
Y(9 g's)	144	2.911×10^3	5.17×10^2	11.37
XY(9 g's)	145	3.005×10^3	4.99×10^2	10.98
Z(15 g's)	379	4.884×10^3	1.414×10^3	6.37
Combined	379	4.884×10^3	1.777×10^3	6.37

The smallest Margin of Safety (M.S.) is 6.37 (CARS requires only a positive M.S.). Although the specified limit loads do not meet the CARS stipulated Factor of Safety requirements of 2.0 times the limit loads for material yield and 2.6 times the limit loads for ultimate failure, the large Margins of Safety more than cover the reduced Factors of Safety. This analysis should be more than sufficient to satisfy strength testing requirements, and should be submitted to GSFC for approval in lieu of structural testing. [Ref 13:p. 3-5]

c. Unresolved Issues

MIL-STD 1540B stipulates that all electronics and electrical circuits be energized during testing, even if they will not be operating during launch. Monitors should be in place to detect failures as the electronics are sequenced through their operational modes. The exception to this is for equipment which would definitely be damaged by energizing during the test, but not in the operating environment. Presently, there has been no plan to energize circuits during vibration testing. It is recommended that this be changed to comply with the requirements of MIL-STD 1540B.

Because the structural analysis was conducted for factors of safety lower than that required, it is recommended that another analysis be done at the higher factors of safety to confirm positive margins of safety. While the high margins of safety appear to be more than sufficient, the analysis does not meet the actual requirements. Further, this waiver of strength testing based on analysis is currently on a case-by-case basis, the groundwork for which should be pursued for clarification.

Planned test duration for the different vibration tests is presently scheduled for three minutes. If the MIL-STD 1540B requirements are to be complied with, the test duration must be the greater of three times the expected flight exposure time to the maximum predicted environment, three times the acceptance test time, or three minutes. Three minutes may in fact be sufficient, but there is no evidence that any determination of flight exposure time has been made.

No plans for testing or analyzing the fixture for attaching PANSAT to the vibration shaker have been developed yet, since the fixture has not yet been designed. The present intent is to perform a modal analysis once a fixture has been designed and manufactured. It is important to get the fixture "right," in order to avoid large errors in vibration testing.

2. Thermal Testing

Spacecraft design consideration must be given to the temperature and pressure extremes imposed by the space environment. Thermal testing is primarily designed to evaluate component, subsystem and system performance in that environment. Internal temperatures ranging from 0°C to +40°C are anticipated for PANSAT's orbit. This estimate is based on separate steady stated and transient analyses that have been performed for PANSAT.

Thermal Vacuum testing exposes the component, subsystem or system to the predicted spacecraft environment. It is designed to evaluate the spacecraft's ability to withstand the temperature and pressure extremes of space. Thermal Cycling testing is designed to evaluate a spacecraft's ability to withstand the stresses imposed by temperature cycling imposed by orbit eclipses. Thermal Balance testing is designed to verify the thermal model (analysis) and therefore the spacecraft's thermal control system's ability to maintain s/c temperatures within acceptable limits.

a. Requirements

As is the case with other types of environmental testing, specific Hitchhiker imposed thermal test requirements are delineated in the Shuttle Orbiter/Cargo Standard Interfaces document and the General Environmental Verification Specification for STS Payloads, Subsystems, and Components manual. The Hitchhiker stipulated qualification level thermal testing requirements can be fulfilled by mathematical model analysis. These are the only hard thermal testing requirements per se for PANSAT; however, modified qualification level thermal cycling is a self imposed requirement for design validation.

b. Proposed Plan

The current plan for thermal related testing consists of component, subsystem and system level thermal vacuum and cycling tests. Thermal balance will be conducted on a time permitting basis, although no efforts to this point have been made to investigate the logistical implications of setting up a thermal balance test. Thermal vacuum testing will be conducted from -10° C to +50° C. Note this is in excess of the +/-5° level stipulated for protoflight level qualification.

Cost and schedule requirements dictate the test vehicle will also be used as the actual flight vehicle. MIL-STD-1540B mandates qualification test levels be diminished in level of intensity and duration if the test vehicle and spacecraft are the same. Additionally all component sub-assemblies tested in accordance with MIL-STD-1540B must have passed the component acceptance test baseline.

Prior to commencing the sequence it is assumed component level testing as certified by the production factory is valid, and that the assembly level tests will be completed, which will also verify the test data. Thermal testing in particular will consist of the thermal balance developmental test that serves to verify the thermal analysis and modeling of the space vehicle and component thermal design criteria.

(1) Component Thermal Acceptance Tests. The spacecraft components serve various purposes such as actuators, valves, batteries wiring harnesses and individual black boxes (such as transmitters or multiplexes). MIL-STD-1540B allows component acceptance test to be conducted at the subsystem level or space vehicle level of assembly. However, in order to maintain fault traceability, documentation of individual component level tests is required. Therefore component level testing should be conducted at acceptance levels to include the baseline thermal vacuum and thermal cycling test. A functional test will be conducted before and after each thermal test.

(2) Subsystem Thermal Acceptance Test. Subsystems are assemblies of functionally related components that perform one or more prescribed functions. Although not mandated by MIL-STD-1540B, thermal vacuum and cycling testing should

be conducted for deficiency or fault identification prior to assembly level tests. As with other testing, the level of test is determined on a case by case basis if the subsystem is flight equipment, prototype or protoflight.

(3) Space Vehicle Thermal Vacuum Qualification Test. This test demonstrates the space vehicle's ability to meet the design requirements under vacuum conditions and at temperature extremes which simulate those for flight plus design margin. A space vehicle, modified qualification level test procedure is described below:

- Conduct functional test for the entire vehicle to establish operating baseline.
- Reduce chamber pressure to 10^{-6} torr and power up on-orbit systems once at the low pressure level.
- Commence temperature cycle from ambient and reduce to the specified low temperature and lower an additional 5° C.
- Soak at low for 8 hr but do not allow the system to fall below the design limit.
- Raise the temperature to the specified high temperature and soak for 8 hr.
- Conduct four complete cycles at the maximum predicted orbital rate and conduct functional test after the last cycle.

(4) Thermal Balance Qualification Test. This test will verify the vehicle thermal analytical model and demonstrates the ability of the thermal control systems ability to maintain the vehicles specified operational temperature. Additionally this test verifies the adequacy of component thermal design criteria. The goal of thermal Balance testing is to match the vehicle thermal performance to +/-3° C of the predicted thermal performance. In order to simplify the test protocol thermal balance testing should be combined with thermal vacuum testing, if feasible.

c. *Unresolved Issues*

Thermal testing philosophy, as with other environmental testing, is geared towards fulfilling Hitchhiker requirements first, and secondly (but equally important) to ensure successful on orbit operations. The accurate characterization of temperature and altitude effects on PANSAT and its subsystems is critical to project success.

The NPS spacecraft test facility consists of one operational thermal vacuum tester that will accommodate component level testing only. Current plans call for the complete renovation of an existing albeit inoperative chamber that can house the entire craft for assembly level tests. Based on a preliminary search of an alternate facility and the accompanying transportation and user fees it is believed the best option is continue current plans to renovate the "large" chamber. This will give the added benefit of keeping all production and test "in house".

The principal question with regard to thermal testing is the status of system level testing that requires the large thermal vacuum facility in Halligan Hall. To date the PANSAT team has ball park figures of renovation costs for that chamber, but no funds securely in place to carry out the project. Adequate facilities are available at various nearby locations such as China Lake Naval Weapons Center. The issues involved in this possibility, however, have received no attention as of yet. Questions involved in this option include safe transportation of the space vehicle (how, where & structural stresses?), what exact facilities are available (i.e., no conflicting scheduling), what is the minimum desirable test sequence and how long would it take to complete, and how much would this transportation and test cost (TDY funding, transportation costs, facility charges, etc.)? The final issue in this vein is just how necessary is systems level thermal testing, or what risk is incurred by not testing? The question can be reduced to a slightly simpler one upon consideration [illegible] of off-sight testing. An additional consideration in this issue is the fact that funds spent to refurbish the Halligan chamber will result in a product that can be used more than once. On the other hand, once an off-sight test has been conducted, there will be no residual value to the investment Although the off-sight costs not yet been detailed, it would have to be significantly cheaper to warrant consideration unless time limitations forced this option. A trade study is warranted toward this end; however, until such a study is conducted conclusively *it is recommended that all available avenues be pursued towards determining exact costs to renovate and obtaining those moneys required to complete the project.*

3. Electromagnetic Compatibility Testing

Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI) Testing fall under the broader category of environmental testing. The three topical areas of primary interest in reference to EMC testing are frequency management, electromagnetic interference, and electromagnetic susceptibility. The general issues of frequency management are frequency assignment and maintaining transmissions to within the assigned frequency band. The assignment of transmission frequency of 436.5 MHz puts PANSAT in an Amateur Radio Band and as such brings about FCC related restrictions [Ref. 15] on power and bandwidth management. Electromagnetic Interference can be thought of as referring to electromagnetic emissions from PANSAT and their effect on the Shuttle Orbited and other payloads. EMI is also an important consideration in the design of internal subsystems and components to ensure avoiding adverse effects internal to the s/c. Electromagnetic susceptibility refers to the adverse effects which PANSAT may incur as a result of exposure to EM fields from environmental sources. This can refer to internal cause and effects of various electromagnetic components.

Electromagnetic Compatibility can be described as the ability of electronic equipment to operate in the intended operational environment without causing unacceptable degradation to other equipment, and without receiving unacceptable degradation from other equipment. [Ref. 16] Electromagnetic Interference is the degradation which is caused when either of the above conditions is not achieved.

The DoD categorization of EMC criticality is useful and instructive for all EMC applications, military or not. DoD describes three levels of EMC effects with respect to their potential damage type and degree. [Ref. 16] Category I involves serious injury or loss of life, damage to property or major loss or delay of mission capability. Category II involves degradation of mission capability, including loss of autonomous operational capability. Category III implies the loss of functions not essential to mission.

a. Requirements

PANSAT resides in a somewhat nebulous world with respect to requirements. It is a military supported project but one that is not subject to the standard

DoD requirements as are typical military space programs. The specific requirements that PANSAT is responsible to design, test, and document to are outlined in the Shuttle Cargo Standard Interface Control Document, ICD 2-19001, and the General Environmental Verification Specifications for STS Payloads and Components Manual (GEVS). Additionally PANSAT must meet further test requirements specifically for s/c which have their own transmitter. These requirements are primarily at the subsystems/component level and there is further requirement for a system's level test with all flight equipment in accordance with MIL-STD 1540B. These requirements basically provide for certification of non-interference of the payload with the Orbiter, and that the payload is not susceptible to interference from known Orbiter EM radiation patterns. The remaining requirements for PANSAT are self imposed. This is not to diminish the importance of the self imposed requirements as they relate directly and immediately to mission performance.

PANSAT has a frequency allocation of 3 MHz bandwidth from 435-438 MHz (as do all 70 cm band satellite control earth stations). Transmission power is limited to 611 Watts effective radiated power (1000 Watts EIRP). The 1/2 power point must maintain a minimum elevation of 10° above the horizon. [Ref. 15] Due to the nature of spread spectrum communications and PANSAT's low power, the only requirement requiring verification is likely to that of ensuring no power above noise outside of the bandwidth allocation.

The final EMC related requirement is a safety verification report which is detailed in the CPR and GEVS. This is part of an encompassing safety document required for STS payloads; the EMC portion deals with ensuring precautions to prevent radiation harm to other payloads, the orbiter and crew. As of this writing, there is no formal plan for PANSAT with regard to EMC testing.

EMI issues as applied to PANSAT fall into a variety of aspects all of which bear design consideration and testing. EMC of components and subsystems that make up the spacecraft is probably the most immediately applicable to PANSAT. Interference between subsystems can degrade or prevent operation of the s/c. EM field mapping of components will be conducted as construction progresses; this will also include the characterization of the effects of external fields on components. The external fields will be generated to simulate fields generated by other components and subsystems as well as the operational and orbiter environment.

The primary issues involved with EMC testing are:

- Requirement certification in order to obtain flight qualification aboard from Hitchhiker.
- Safety verification.
- Electromagnetic emissions control of components, subsystems and the system.
- Electromagnetic susceptibility control with respect to the orbiter environment.

In other words, EMC testing is all about ensuring no adverse effects on or from the launch platform and ensuring proper operation of the system in general and its electromagnetic components in particular through design and construction with EMC considerations.

b. Proposed Plan

Although PANSAT is not required to be tested to Military Standards, the procedures and considerations in MIL-STD-461, 462 and 6051 are not overly restrictive and should be followed unless it can be shown why a particular method is not reasonable or feasible. Quite simply, the procedures outlined are sound and practical and following them should enhance the reliability of PANSAT as well as provide a sound basis for requirements verification when the exact requirements become available. MIL-STD-462 lists the equipment required for particular methods the majority of which is readily available in the development lab.

The specific methods which are applicable to PANSAT components and subsystems are (at a minimum):

- CE03 Conducted Emissions, Power and interconnecting leads, .015 to 50 MHz
- CE06 Conducted Emissions, Antenna terminals 10 kHz to 26 GHz
- CE07 Conducted Emissions, Power leads, spikes, time domain
- CS01 Conducted Susceptibility, Power leads, 30 Hz to 50 kHz
- CS02 Conducted Susceptibility, Power and interconnecting control leads, .05 to 400 MHz
- CS03 Intermodulation, 15 kHz to 10 GHz
- CS04 Rejection of undesired signals 30 Hz to 20 GHz
- CS05, Cross Modulation, 30 Hz to 20 GHz
- CS06 Conducted Susceptibility, Spikes, power leads
- CS07 Conducted Susceptibility, Squelch circuits
- CS09 Conducted Susceptibility, Structure (Common Mode) Current 60 Hz to 100 kHz
- CS10 Conducted Susceptibility, Damped Sinusoidal transients, Pins and Terminals 10 kHz to 100 MHz

- CS11 Conducted Susceptibility, Damped Sinusoidal transients, Cables 10 kHz to 100 MHz
- RE01 Radiated Emissions, Magnetic field, .03 to 50 kHz
- RE02 Radiated Emissions, Electric field, 14 kHz to 10 GHz
- RE03 Radiated Emissions, Spurious and harmonics, radiated technique
- RS01 Radiated Susceptibility, Magnetic field, .03 to 50 kHz
- RS02 Radiated Susceptibility, Magnetic and electric fields, spikes and power frequencies
- RS03 Radiated Susceptibility, Electric field, 14 kHz to 40 GHz
- RS04 Radiated Susceptibility, Electromagnetic pulse field transient

System tests should be conducted to determine radiation patterns of the spacecraft to characterize all modes as this information will be a required test for Hitchhiker although permissible levels are not yet available. System EM susceptibility testing should be conducted after a system functional baseline test has been performed with a subsequent functional test following the susceptibility for evaluation purposes. Susceptibility testing can be accomplished in the radio frequency shielded enclosure simulating orbiter environmental characteristics. Radiation pattern characterization can be conducted in the ECE antenna lab for the full transmit mode and in the radio frequency shielded enclosure for idle/receive states.

c. Unresolved Issues

The principal issue yet to be resolved as detailed above is that of specific requirements determination. What are the exact deliverable requirements and associated timelines required for flight? A specific engineering plan for which of the above methods will be tested to and how to do that most efficiently so as not to duplicate unnecessarily.

The Shuttle Standard Cargo Interface Control Document, ICD 2-19001, was received in June 1994, as a direct result of inquiries arising during the AA-4831 project. That document is extremely large and will take considerable time for thorough review. Once all pertinent requirements documentation is obtained, the subsystem managers should familiarize themselves with all references in order to ensure compliance with any EMC issues.

C. FUNCTIONAL TESTING

1. Functional Testing Issues

Functional tests primarily serve three purposes. [Ref. 12:p. 30] The first is to verify that the mechanical and electrical performance of the space vehicle meet specification requirements. The second purpose is to verify that the space vehicle and all ground support equipment are fully compatible. Finally, the functional test validates all test techniques, as well as the software algorithms used in any computer-assisted command and data processing.

The basis for functional testing is the space vehicle functional requirements document. This document specifies the purpose (mission) of the vehicle, functional requirements for the components, subsystems, and space vehicle, and the acceptable performance limits. For PANSAT, these specifications can be found in the Functional Requirements (SSD-S-SY000) document.

The Mechanical Functional Test is designed to verify proper operation of all mechanical devices, valves, deployables, and separable entities. This test is to be conducted in the appropriate space vehicle configuration (launch, orbital, or recovery) for the tested component. Maximum and minimum limits of acceptable performance shall be determined with respect to mechanics, time, and other applicable requirements. Each mechanical operation will show positive margins of strength and torque margins. Additionally, the test shall demonstrate the ability of the components to operate in environments above and below specified operational limits.

The Electrical Functional Test is designed to verify the integrity of all electrical circuits, including redundant paths, by application of a stimulus and confirmation of a proper response. All commands are to be tested. This includes proper operation of thermally controlled components, commands requiring preconditioning conditions, and autonomously controlled functions. Additionally, a segment of this test shall be devoted to testing the space vehicle through a mission profile with all events occurring in the actual flight sequence as much as practicable. [Ref 12:p. 31]

2. Component and Subsystem Level Testing

The Hitchhiker Customer Accommodations & Requirements Specifications document does not specify requirements for functional testing. The two primary reference documents for functional testing requirements are the MIL-STD-1540B and the PANSAT Functional Requirements document.

Since PANSAT does not have solar array arms, a stabilization system, propulsion, or separable parts, there are no requirements for mechanical testing of these types of space vehicle components. Space vehicle mechanical testing, outside of environmental testing, is limited to verification of outer dimensions (to ensure fitting inside the Hitchhiker container), and compliance with the mechanical interface requirements. Mechanical testing of the ground station will be required to assess antenna pointing capability.

PANSAT systems to be electrically tested include the Communications, Telemetry & Telecommand, Command Ground Station, Electrical Power, Thermal, and Digital Control subsystems. While few of these systems have been built, the Functional Requirements document provides design specifications around which a test plan can be built.

In addition to the above test areas, testing to ensure proper compatibility between satellite and GSE, as well as software controlled functions, is a necessary part of the functional testing requirements. The following test requirements are derived from the PANSAT Functional Requirements document.

a. Communications Subsystem

The communications payload is a simplex, spread spectrum system operating in the amateur 70 cm band. It is the only means of communicating with the satellite. The communications payload utilizes a fully redundant design system capable of both spread spectrum and narrow band BPSK modulation on each unit. This payload will be processor-controlled by the DCS. Data will be synchronous, with one pseudo-noise (PN) code sequence length per bit of data. Specifications to be tested include:

- 9600 bps data rate, simplex
- 436.5 MHz center frequency

- 10^{-5} BER
- mutually exclusive redundant SS modems
- capability to switch to (unspread) BPSK
- omni-directional antennas, no greater than 10 dB nulls
- antenna noise temperature not greater than 290°

b. Telemetry & Telecommand

Satellite telemetry consists of required data points from sensors and vehicle operations that indicate performance of components and subsystems. Telecommands consist of those commands that relate to implementation of the store-and-forward capability and to the payload. Specifications to be tested include:

- error detection and correction (BER TBD)
- ability to switch to non-spread spectrum operation
- near real-time buffered telemetry data updated (1 cycle)
- periodic down-link of near real-time buffered telemetry
- telemetry format and data-types capable of changes via DCS and up-link
- stored telemetry for time history mail storage
- spacecraft telemetry & experiment data collected from subsystems and stored
- most recent TLM packet available for down-link
- accumulated TLM data stored in system mail memory
- capability to change frequency of telemetry data acquisition
- proper operation of various sensors

c. Command Ground Station

This system is to utilize PC-based data handling and requires testing of the following functions:

- software controlled Doppler compensation
- telemetry & telecommand up-link normal and contingency operation
- antenna elevation angle 1/2 power point not less than 10° above horizon

- maximum effective radiated power of 611 W (1000 W EIRP)
- record and document all SS transmissions
- antenna pointing functions within azimuth. and elevation required accuracy limits
- error detection and correction (BER TBD)
- receive and store raw telemetry
- process telemetry for temp. profiles and distribution
- process telemetry for power usage profiles by subsystem
- process telemetry for payload usage and performance profiles
- process telemetry for state of health data

d. Electrical Power Subsystem (EPS)

The EPS must properly regulate and distribute the electrical power needed by the PANSAT subsystems. Specific requirements to be tested include:

- 21.5 Watts at 15.2 Vdc (avg-min pwr, solar array at end of life)
- minimum subsystem efficiency of 60% power conditioning
- bus regulated at 12 Volts
- on-orbit battery reconditioning
- positive power margin
- 10% depth of discharge (DOD)
- 5 Amp-hr capacity
- sufficient power to meet specified power budgets
- controller/sw accept code and data changes via up-link

e. Thermal Subsystem

To ensure proper thermal control, the following temperature requirements for military specification parts are specified:

- MIL-STD-833 ICs within -55° to 125° C
- batteries 0° to 10° C nominal, -6° to 26° operational
- no more than five 5 W heaters at 10% duty cycle (per orbit)

f. Digital Control System (DCS)

The DCS is responsible for processing digital messages, managing the message buffer, maintaining an operational status log, and maintaining proper spacecraft operation. It must accept up-linked messages (source-to-destination, source-to-broadcast, and user-to-spacecraft), store them with associated information (source, destination, time of receipt), and down-link them to the appropriate destination. Specifications are as follows:

- proper message and data handling:
- communicates utilizing AX.25 protocol
- store packet data (memory address, size, header)
- logs record of transmissions
- manages message buffer
- four megabytes of dedicated data storage
- accept code and data changes via up-link
- NPS command station priority works
- watchdog timer causes proper switch to non-SS modem
- maintain satellite housekeeping
- generates and formats status messages
- updates latest telemetry data for down-link
- stores all telemetry data
- performs data bus control functions (polling subsystem controllers)
- monitors subsystems, detects faults and initiates
- recovery (reset or activate redundant unit)
- processes telecommand functions/routines
- stores daily passwords (recognizes and processes)
- battery backup functions (microprocessor, RAM, clock)

3. System Level Testing

The transition from subsystem to system level testing should be accomplished incrementally. A series of multi-subsystem tests should be performed to allow troubleshooting and fault isolation. The general design of the initial tests should be based on functional relationships rather than strict subsystem boundaries.

a. Command Ground Station Support Test

The functional performance of the Command Ground station should be tested initially during the development simply by communication with currently orbiting amateur satellites. An accurate assessment of all parts of the ground station except for that portion of the communication payload which is unique to PANSAT should be firmly in place prior to the payload incorporation.

b. Payload Test

A payload test will utilize actual transmissions of test messages between the s/c and ground station. Test messages will require PANSAT to receive, store, and retransmit data to verify all functions, at or above the required 10^{-5} BER. Communications will be established via cable or by RF antenna (during the later stages of functional testing). Signal strength of the transmitted signal will be varied to simulate tumbling of the satellite. Once communications are established with the satellite, a series of command functions will be exercised to test data exchange, storage, and down-link. The payload will be exercised in primary and secondary modes of operation. Input signal level should be varied to evaluate thresholds at which the s/c (and ground station) can no longer perform at the specified BER.

Modes and Status Test

This test is primarily aimed at verifying proper functioning of the EPS and DCS subsystems and their interrelationships. The test, in general, evaluates how the subsystems perform at the boundary conditions imposed by specifications. Typical issues for investigation by this test sequence are:

- Do the power generation and storage capability of the EPS perform as specified and is the properly conditioned power available to customer components/subsystems?
- Does the DCS accurately evaluate the EPS (and overall s/c) status and accurately transition the s/c into the required operational modes at the proper battery power levels?
- Do the reported telemetry points accurately reflect their environment?

d. Overall System Test

The final step in this process is to combine the above test sequences in order to verify the proper functioning of all elements of the system as they will operate during operations. *As previously mentioned, the final functional check should include an RF vice cable link.*

4. Unresolved Issues

Test equipment requirements need to be identified now, before subsystems are completed. Hardware may not be available or sufficient. There is concern over acquiring use of sufficiently large thermal vacuum chamber to test the assembled satellite. Another related concern is that while computer support systems are probably sufficient, the issue of available testing software needs to be addressed. Present functional test planning does not address testing of the ground station antenna. The EC department should be queried for availability and suitability of antenna test equipment. The EPS test does not address testing of the controller and associated software for acceptance of code and data changes via up-link. Only the message and data handling functions of the DCS are addressed. The functions of NPS command station priority, watchdog timer (switch to non-SS modem), battery backup, and housekeeping are overlooked. These functions are vitally important to satellite operations and need to be tested. An overall functional test plan has not been laid out as a coherent sequence. It may be possible to test multiple subsystems simultaneously, if enough sensors and test equipment are available.

D. OPERATIONAL TESTING

1. Operational Testing Issues

Operational Testing will be conducted to determine the effectiveness and suitability of the PANSAT system. Operational testing should focus on the performance of a system under typical conditions with typical users. Operational effectiveness is the degree of mission accomplishment of a system under realistic conditions. Operational suitability is the degree to which a system can be satisfactorily placed in normal operations, with respect to availability, reliability, maintainability, etc. Operational testing should be conducted as early as possible via simulations, breadboards, components or subsystems in smaller scale tests using the same approach. This should reduce project risk by the early identification or potential problem areas.

An effective operational test and evaluation plan addresses the issues of operational effectiveness, (e.g., Does it perform as intended?) and operational suitability (e.g., Is it satisfactory for field use?). Under the broad category of suitability, the questions of reliability, availability, maintainability, supportability and other 'ilities' need to be specifically addressed. As a part of the overall test and evaluation program, the operational testing portion should take on increasing importance as the system design solidifies and the program progresses from pre-production to production to deployment.

Operational testing performed before production can be referred to as Operational Assessments or as Initial Operational Test and Evaluation. [Ref. 16] This stage of test can be conducted on components or subsystems or only by simulation models depending on the progress of development. The emphasis at this point should be on determining the ability of the overall system to adequately perform in its intended role. It cannot be overemphasized that operational testing, especially at this stage should be designed with these guidelines rather than test for performance against technical specifications, i.e., duplicating development testing.

Testing that occurs after full production can be referred to as Follow-on Operational Test and Evaluation (FOT&E). The emphasis of FOT&E is the same as in earlier stages, now, however it is more likely for the entire system to be used in the testing rather than a combination of subsystems and simulations. This may be the first opportunity to actually test the system in a realistic environment with representative users. One caution that holds throughout operational testing, is that tests should be designed to generate data corresponding to carefully chosen Measures of Effectiveness (MOE) to better assist decision makers in evaluating the system and to perform trade off analysis. A common mistake is to gear tests towards the generation of easy to get and interpret data, (which may have little or no relationship to MOE's). Such tests are wasteful and need never have been performed.

DoD spacecraft testing generally is pursued along the same lines as the previously described testing methodology. Spacecraft by nature pose some unique problems which require special and specific addressal. The high cost of space system generally imposes the limitation of very small production numbers. Spacecraft systems are generally unique in many areas of design from any other spacecraft (except the relatively rare, identical spacecraft) Testing spacecraft in a realistic environment is generally physically impossible except for simulations until deployment. Last and most importantly, any opportunity for system modification is lost after deployment (and therefore before a full operational test), except for the ability to make relatively minor modification that has been built into the spacecraft, e.g., sensor adjustment, software uploads, etc. With these limitations in mind a generic spacecraft operational testing program simply does not exist. Testing programs have to be developed alongside the spacecraft with care towards the general principles outlined earlier, and with regard to some of the following considerations.

PANSAT's Operational Testing program currently consists of the "On-Orbit Operations Test Plan," a document in its infancy. Operational testing of PANSAT is relatively simple in concept. Operational testing plans should be gearing towards evaluation and verification of data and command transmissions. Considerations include, the communication link budget, the power budget, antenna characteristics, transceiver capabilities, ground station configurations and an amateur radio operator. Spacecraft responses to all possible commands and transmission errors must be evaluated for state determination. As previously noted, a major concern with spacecraft is state and or mode control. There must be sufficient consideration and testing to preclude the attainment of permanent undesirable states due to command, control or data transmission. Software testing is also a critical issue along those lines.

2. Operational Test Design

The On-Orbit Operations Test Plan currently addresses the following areas:

- Launch vehicle separation
- Initialization sequence
- Spacecraft orbit description
- Communication window description
- Ground station description
- Communication session description
- System performance specifications
- Experiment description
- Amateur radio usage
- Command and control

Based on this outline, the current document serves better as a framework for an operations plan than as a test plan. This is not necessarily a problem, however; the document should be developed as far as current design allows and from this detailed document, the test plan will be designed. The initialization sequence, communication session, and experiment description sections are the principal topics that will developed into an On-Orbit Operations test plan.

What has heretofore scarcely been addressed is how to conduct operational test on PANSAT prior to launch. To a limited extent, operational testing will be satisfied by slight modifications of (primarily) the systems level functional testing. To adequately complete operational testing prior to flight, it will be necessary to make extensive use of computer simulations of operations. Some of the typical operations that warrant testing via simulation will be described in the following sections.

a. Attitude Dynamics

Develop initial and increasingly detailed and accurate estimations of attitude dynamics based on the following:

- Detailed designs of PANSAT, with respect to component/subsystem location, physical characteristics, wiring , etc.
- Atmospheric drag, solar pressure and other external torques
- Any internal torques

These inputs should lead to approximate principal and secondary axes, Moments of Intertia (MOI), and thereby characteristics of attitude dynamics, or motion. *This quantification of the general descriptive term for PANSAT's orbit "tumbling" is an important critical first step in the development of follow on tests.*

b. Power Generation, Storage and Consumption

Attitude dynamics will then be combined with the environmental characteristics of the anticipated orbit to develop an improved model of power generation. Current efforts at developing a power budget have taken nominal conditions into account for power generation. This information, with component consumption characteristics, leads directly to an EPS storage and consumption model to better predict s/c operational performance. Operational performance here refers to how long the s/c can maintain specific states or operational modes.

c. Initialization Sequence

Once it can be accurately predicted what the capabilities of the s/c are to generate power, the initialization sequence can then be modeled. Various initial battery conditions, and environments will be inputs to the model which will predict time from launch (launch vehicle separation) until minimum power for communication is achieved. In other words, this is the best prediction, when combined with PANSAT's orbital elements, when the ground station will achieve communications with the s/c.

d. Operations Model

The above sequence of tests leads to the culmination of operational testing, which incorporates the functional test design given earlier. PANSAT is anticipated to have a negative power margin at worst and a very low margin power budget at best. The anticipated range is aproximately -20% to +21%, depending largely on the particular location of the baseplate with respect to the solar incidence angle. *The model* *achieved through the above described process should reduce the margin of error in the estimation and therefore lead allow the opportunity for operational decisions to compensate for design weaknesses.* Once a thorough EPS model, and therefore a highly accurate power margin, is available, scenarios can be developed for the state adjustment of the s/c to reduce the opportunity for (low) power induced problems. If PANSAT is below a specified power capacity the s/c lowers its operational status until that capacity is achieved. Similarly, if PANSAT is in a negative power budget orientation, lower the operational status of the s/c when it is not in a likely communication window. The s/c should be in its minimum power consumption state while not within a predetermined time of likely communications. Operate when approaching the continental United States, for example, and other land masses as the budget allows, but not over open ocean. Granted this limitation may exclude a few desiring users, but the only overriding operational concern is proof of concept. *There is no significant necessity to provide other the than minimum service to certify proof of concept.*

E. TESTING SEQUENCE

1. General Test Flow

The testing program for a spacecraft should begin in the earliest stages of design conception. Making "testability" a functional requirement early on sets the stage for a program that is readily able to evaluate status in any phase of development. The initial testing of most programs is developmental and functional in nature of components at the breadboard and prototype levels. The primary objective is early verification of critical design concepts. Early detection of critical design shortcomings provides the obvious benefit of correction at the easiest and least expensive level in terms of both cost and schedule. As testing progresses to the acceptance and qualification phases, the goals expand to that of a functional and environmental evaluation of the components, subsystems, or system. The standard sequence of a typical qualification test battery is: a comprehensive functional baseline test; EMC test: pressure; pyro shock; vibration; acoustic; thermal cycling; thermal balance; thermal vacuum; and a post sequence comprehensive baseline comparison functional test. Electrical and mechanical functional testing should be conducted prior to and after each environmental test, as well as during thermal and vibration testing. Some of the above requirements may be omitted as specific program requirements dictate.

2. PANSAT Test Flow

The flow of PANSAT testing should be basically along the lines of the typical spacecraft. Developmental testing of components and subassemblies to validate design decisions, followed by the above sequence of functional environmental, with the following omissions. Sine and Random vibration testing will be conducted in lieu of acoustic testing. Thermal testing will consist of thermal cycling and thermal vacuum testing. No efforts have been made to date to prepare for thermal balance due to the lack of available facilities. Figure 8 shows the general flow of a testing sequence. This is shown for a systems level test; however, the same flow can easily be applied at component, subassembly or subsystem level with minor omissions as the specific case warrants.

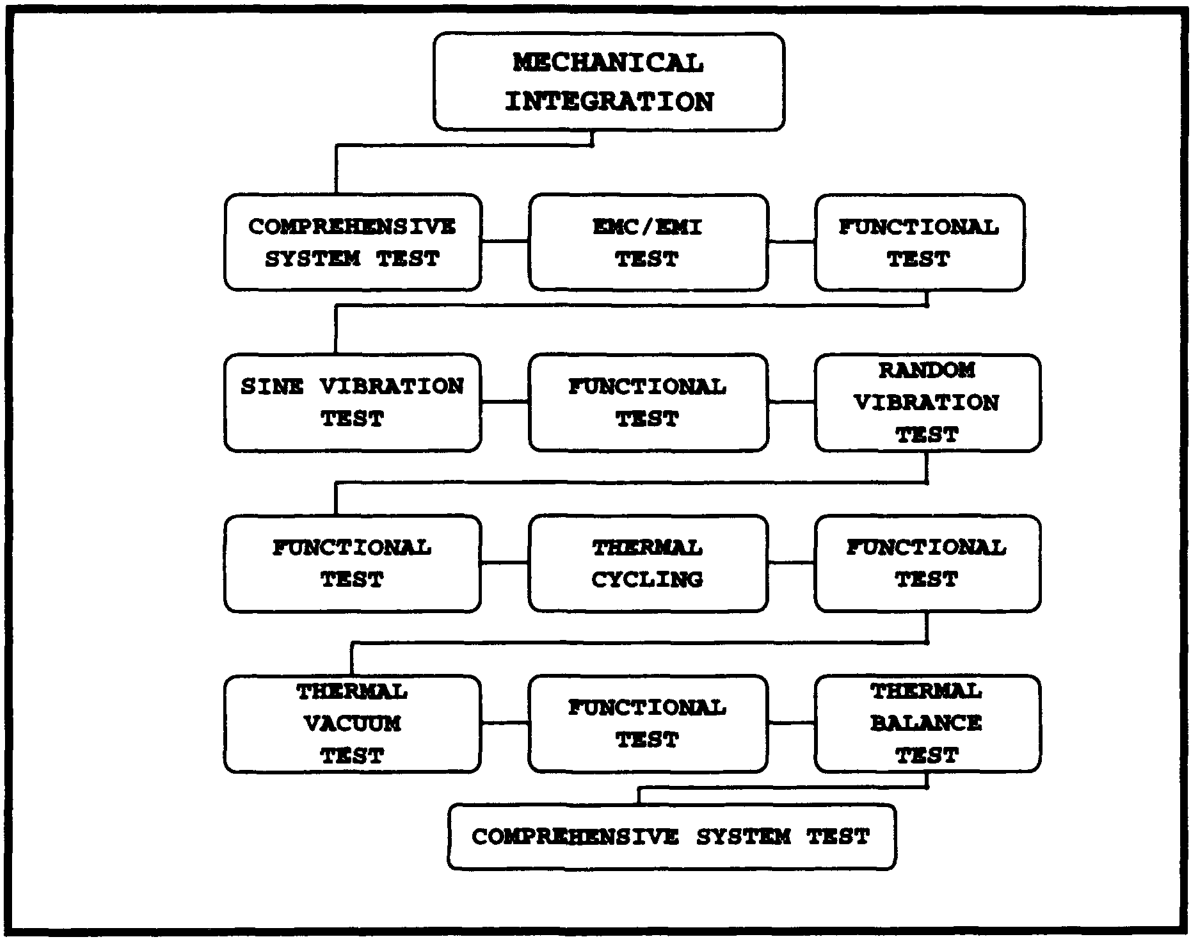

Figure 8: Test Sequence and Flow

Table 3 presents a brief summary of the proposed overall test plan. Thermal testing requirements can be satisfied by mathematical analysis but are still strongly recommended. Systems level thermal testing requires rehabilitation of an NPS facility. Thermal Balance testing has not been examined but should be pursued time permitting. EMC/EMI requirements can be satisfied at the systems level and are related to safety and launch vehicle interference and compatibility. Subsystem and component level testing is recommended for reliability purposes.

TABLE 3: SUMMARY OF PROPOSED TESTING

Test Type	Required *	Recommended	Notes
Vibration	Yes		Qualification
Strength (sine burst)	Yes **		Requires waiver to use analysis
Sine sweep	Yes		Verify natural frequency (> 35 Hz)
Random vibration	Yes		Realistic environmental simulation
Thermal vacuum	No	Yes	System/Subsystem/Component level
Thermal cycling	No	Yes	System/Subsystem/Component level
Thermal balance	No	Yes	System level
EMC/EMI	Yes	Yes	System/Subsystem/Component level
Functional		Yes	System/Subsystem/Component level
Operational		Yes	System/Subsystems level

* All requirements are NASA/Hitchhiker imposed.

** Can be satisfied by analysis on a case-by-case basis

IV. OPERATIONS ANALYSIS

A. GENERAL

The design and development of spacecraft operations, to this point in PANSAT's development, have largely been glossed over. There have been only two Space Systems Operations related theses completed on PANSAT to date, neither or which was more than generally related to specific operations analysis issues for the current design status of PANSAT. The emphasis of research with respect to this thesis was in the area of orbit design. Timing priorities of the upcoming Customer Payload Requirements Document dictated that this was an issue of more pressing concern than many other operational issues. With respect to other aspects of operations, research was limited to developing and prioritizing future areas of research. Pre-launch operations efforts in the short term should be lumped together under the general umbrella of an "Operations Plan", which should be a high priority. There are several inherent difficulties in developing an Operations Plan. Defining the scope of an operations plan is the first obstacle, not only in terms of what it should cover, but in what detail. Another stopping block, which has been highlighted as a lesson learned in previous research, [Ref. 11] is the difficulty in maintaining sight of the larger overall goal without becoming engulfed by details. The PANSAT team has little experience in this type of undertaking and the same certainly applies to the students involved to an even larger extent. When defining the contents of an operational plan, the tendency will be to overdevelop those issues that are well understood and simultaneously lose sight of the more urgent need simply to first scope the effort for completeness.

B. PROGRAMMATICS

With the signing of the Memorandum of Agreement (MOA) in April 1994, the iterative process of developing and finalizing the Customer Payload Requirements (CPR) document formally began. The purpose of the MOA was to define the relationships between the USAF Space and Missile Center/Space Test and Small Launch Vehicle Programs Office (SMC/CUL) and NPS on the terms and conditions for integration and flight of PANSAT on the Space Shuttle. [Ref 18:p. 1]

The relationship between SMC/CUL and NASA is that NASA/Goddard Space Flight Center (GSFC) is directly responsible for the overall Hitchhiker program. SMC/CUL is responsible to GSFC for the integration of experiments and or payloads into the Hitchhiker carrier for transportation onboard the Space Shuttle. The MOA delineates the relationships and responsibilities between customers (NPS for PANSAT) and the agency that transforms a payload into acceptable form for shuttle flight. The MOA initiates the process of the Customer Payload Requirements document that is an agreement between GSFC and the Hitchhiker customer to carry the customer's experiment onboard the shuttle via Hitchhiker. The CPR is a technically specific document formalizing the mutual responsibilities of carrying out that process. The end result of the iterative CPR process is ideally, a manifested experiment, which is then carried and launched from the Space Shuttle.

The implications of these two documents are significant to the PANSAT program in many ways over and above the obvious ones detailed above. As will be explored in much greater detail in Chapter V, the MOA to some extent and the CPR to a much larger extent effectively eliminate the viability of (significant) program delays for re-design, or cancellation as overall program management options.

C. ORBITAL DESIGN

If PANSAT were to obtain a dedicated launch vehicle and thereby become a primary payload, the strong likelihood exists of being able to achieve a near optimum orbit for mission employment. Orbital design could be pursued to the maximum capabilities of the launch vehicle. Notwithstanding the tremendous advantages offered by alternative launch options for PANSAT, the window of opportunity for utilizing launch vehicles other than the Space Shuttle has come and gone. The orbit problem then transitions from designing the optimum orbit to a series of simpler yet more difficult questions. The questions can be seen as more difficult simply by the fact that regardless of all else, the orbit for PANSAT is basically subject to the orbit of the Shuttle Mission on which it is flown.

The questions that need to be asked in order to perform an orbital analysis for PANSAT are as follows:

- What orbits are available to the launch platform (Shuttle)?
- What is the expected and or desired time frame of launch for PANSAT?
- What are the Shuttle Missions scheduled during PANSAT's launch window?
- What are the orbital parameters for the above Missions?

- What effect do the orbital parameters have on the mission performance of PANSAT?
- Is (are) there a preferred orbit(s) for PANSAT with regard to mission performance?
- How does PANSAT get on a mission to a preferred orbit?

For the purposes of this study, it was determined to proceed in the following manner. The process of orbital determination is a multi-step procedure that is designed to select an orbit which, while not optimal, is acceptable by those measures against which it will be judged. The initial task was to narrow the choices of possible orbits. After narrowing the possibilities, the task comes to measuring performance. The principle performance measures considered for this study were duration and frequency of visibility windows and orbital lifetime. Considered together, these factors present an excellent first cut at total lifetime communication opportunity, an easily justifiable measure of effectiveness for comparing satellite communication systems.

It should be noted again that the intent of the study was not to specify to a particular level of accuracy what those numbers would be, but simply to provide a basis for relative comparison. Obviously, the selection of the best candidate should not be made without due consideration of many other factors. The effect of altitude (ergo range and free space path loss) on PANSAT's link budget, qualitative examination of other aspects of passes, and the feasibility of being manifested on the preferred mission are some examples.

The most challenging step of the process was to analyze the performance data. Unless every performance measure pointed to a unique solution it would be necessary to determine a method for comparing results from different performance measures against each other. There are several Operations Research techniques available to do this, such as an Analytical Hierarchy Process, but these methods are basically heuristic approaches to quantify subjectivity. In any event these processes do not lend themselves particularly well in this scenario, with so many factors that cannot be quantified for numerical evaluation against several purely numerical measures. In the final result, extraneous factors were considered predominantly in the role of tie breakers.

1. Launch Platform Analysis

Since it is now obvious that the launch platform options have reduced to the Space Shuttle, or not flying at all, the process of launch platform analysis is somewhat simplified. The orbital capability of the Space Shuttle is most easily characterized simply with regard to altitude. The published maximum shuttle operational altitude is 400 nautical miles (740 Km). The maximum altitude is associated with flights only at 28.5° inclination. Orbital mechanics dictates that fuel required for inclination adjustment would decrease altitude capabilities of the Shuttle. Since the Shuttle orbits rarely approach the maximum operational altitude, the typical mission altitude of the shuttle cannot generally be considered to be affected by orbital inclination adjustments. PANSAT's development schedule targets a deliverable spacecraft by March 1996. The incorporation of a standard six months for payload integration places the initial launch window for PANSAT in the September 1996 time frame [Ref 18:p. 5]. This launch time frame is therefore an excellent point of origination for the examination of candidate Shuttle orbits. Table 4 [Ref. 19] shows Shuttle missions 81 through 91 along with their scheduled launch dates, inclination and altitude. The p[illegible]ter of altitude in Table 4 (and throughout the chapter) is, more precisely, semi-major axis minus average equatorial earth radius, given an orbit of zero eccentricity, i.e., perfectly circular. Since the missions considered typically have eccentricities on the order of 10^{-5} this substitution has negligible effect on accuracy and altitude is a much more concise term.

TABLE 4: SHUTTLE MISSION SCHEDULE

STS #	MISSION	LAUNCH	ALTITUDE	INCLINATION
STS-81	MIR-5	[illegible]	397km	51.6
STS-82	MIR-6	11/7/96	397km	51.6
STS-83	SPACEHAB	12/5/96	295km	28.5
STS-84	MIR-7	1/30/97	397km	51.6
STS-85	HUBBLE SVC 2	3/27/97	600km	28.5
STS-86	MIR-8	4/17/97	397km	51.6
STS-87	MTL SCI	5/30/97	350km	28.5
STS-88	MIR-9	6/26/97	397km	51.6
STS-89	μ-GRAVITY	7/31/97	400km	28.5
STS-90	MIR-10	10/2/97	397km	51.6
STS-91	SSF #1	12/4/97	407km	28.5

Table 4, therefore addresses the first four above steps in an orbital analysis for PANSAT, leaving an examination of how the candidate orbital parameters affect PANSAT's mission performance as the next logical step.

2. Principle Parameter Analysis

Based on evaluation of the data shown in Table 4, orbital analysis was performed on four candidate orbits. Parameters for the four orbits were selected based on the initial knowledge that higher altitude leads to both longer orbital lifetime and longer times in view or pass times, a need to compare the effect of changing inclination (given equal altitudes) on pass opportunities, and the need to compare the effect of a significant altitude change (given equal inclinations). This would lead to a group of orbits that would allow reasonable conclusions to be drawn from the data gathered. Based on these selection criteria, the orbits selected were a typical Mir, (Soviet Space Station) orbit, a projected orbit for Space Station Alpha (SSA), the Hubble Space Telescope (HST) orbit, and a typical Space Shuttle orbit.

The altitude selected for the Mir was 370 km. This number is intentionally conservative but may be closer to an actual PANSAT orbit than that of Mir itself when deconfliction is considered. Deconfliction here, means that PANSAT would not be put into an orbit with any possibility of close passes to Mir. Mir has a typical eccentricity of 6×10^{-4} and is in a 51.6° inclination orbit[6].

Space Station Alpha has been tentatively planned for a 28.5° inclination and 407 km altitude. Eccentricity was assumed to be approximately zero and assigned the same value as that of Mir.

The Hubble Space Telescope (HST) has inclination of 28.5, an eccentricity of less than 5×10^{-4} and altitudes of approximately 600 km. This altitude is significantly above a typical STS mission and the first repair mission was done when HST was at an altitude of 585 km. A conservative 570 km was used for the simulation altitude.

A fourth candidate orbit was analyzed. Called a 'generic' Shuttle orbit, the orbit had an inclination of 28.5 and an altitude of 370 km specifically to compare the

[6]NASA Two-Line Orbital Element Sets, World Wide Web, an INTERNET data source.

effects of inclination change on communication parameters against the Mir orbit, and to compare the effects of increased altitude against the SSF and HST orbits.

The software program TRAKSAT[7] was used as the principle analysis tool. TRAKSAT was selected primarily because of an analytical orbit evaluation mode it employs which enables the relatively rapid accumulation of large amounts of data for evaluation. The analytical mode basically predicts rise and set time of satellites versus a ground station. The controlling equation in the analytic mode is more difficult to solve but is required only once per orbit, rather than a typical Keplerian step by step orbital progression. The resulting benefit of the analytical mode is a tremendous increase in speed. A small accuracy loss (less than one minute error in rise/set time) is a small price to pay [Ref. 20].

The software program *LIFE4, Version 1.0*, was used as an estimator of orbital lifetime. Separate orbital lifetime prediction was being pursued by LT Dan Cuff in much more detail, [Ref 19] so the lifetime prediction part of this analysis was pursued not for exacting accuracy of numerous variables (e.g., solar cycle, magnetic field variations, launch dates, etc.), but for a general comparison of how altitude and inclination differences affect the lifetime taken one parameter change at a time. In this manner for both TRAKSAT and LIFE4 simulations, tradeoffs and comparisons were made possible.

TRAKSAT pass data and statistics were gathered from a simulation run covering a two week period from 7-16 September 1994 to approximate a possible mission

[7]TRAKSAT, Version three is a general purpose satellite tracking program distributed as shareware by Paul E. Traufler, AEROSPACE Corporation.

launch window. The four candidate satellite orbits were run against an NPS located ground sight which had a minimum useable elevation of 10°. The data was analyzed for average pass times, standard deviation of passes, and total number of passes for each satellite. LIFE4 simulations were also run to determine lifetime predictions based on a launch at the above date for each candidate orbit.

3. Comparisons

Table 5 summarizes the parameters of the four candidate orbits in the study. The eccentricity for all candidates was assumed to be near zero for approximate circular orbits but the programs required a non-zero value for input. The particular values of Mir and Hubble Space telescope's eccentricities were based on recent NASA generated two-line orbital element sets. The generic Shuttle and Space Station Freedom eccentricities were assigned to match Mir for comparison purposes.

TABLE 5: CANDIDATE ORBIT PARAMETERS

CANDIDATE ORBIT	ALTITUDE	INCLINATION	ECCENTRICITY
MIR TYPE	370km	i = 51.6°	$2x\ 10^{-4}$
GENERIC SHUTTLE	370km	i = 28.5°	$2x\ 10^{-4}$
HUBBLE SVC	600km	i = 28.5°	$6x\ 10^{-4}$
SPACE STATION ALPHA	407km	i = 28.5°	$2x\ 10^{-4}$

Table 6 shows the calculated pass statistics for the candidate orbits. The average duration of passes shows little significant difference for the orbits of similar altitudes. In fact, the 38% change in altitude from Mir to HST orbits, yields only a 26% increase in average pass duration. When standard deviations are considered, there is effectively no identifiable difference in pass durations for co-altitude orbits with differing inclinations, and no difference in co-inclination orbits with an altitude difference of 37 km. In short, with regard to pass duration (i.e., time in view or communication time) there is no significant benefit of a relatively small altitude increase.

TABLE 6: CANDIDATE ORBIT PASS DURATIONS

CANDIDATE ORBIT	PASS DURATION AND STANDARD DEVIATION
MIR	8 min 19 sec (σ=1m 21s)
GENERIC STS	8 min 13 sec (σ=54s)
HUBBLE SVC FLIGHT	11min 17 sec (σ=58s)
SPACE STATION ALPHA	8 min 37 sec (σ=1m 14s)

Table 7 gives the nominal orbital lifetimes of the candidate orbits. Examination of this data yields quite different results with regard to the value of not only increased orbital altitude, but increased inclination. When comparing the Generic Shuttle and Space Station orbits, a 10% increase in altitude yields a 55% increase in orbital lifetime. Similarly increasing the inclination of co-altitude orbits has a significant increase on lifetime. Again, it should be stressed that the orbital lifetime predictions are intended for comparison and not accuracy given the significant number of unchanged variables. What is noteworthy, is that depending primarily on the solar cycle, there is a significant increase in predicted orbital lifetimes in the 350 to 425 km altitude regime. Where this change occurs varies with solar and ballistic factors. Figure 9 shows the altitude decay history for the orbital life of a typical satellite, note the significant life increase for relatively small altitude increase above 400 km. This observation is confirmed, expanded and quantified by LT Cuff in his thesis.

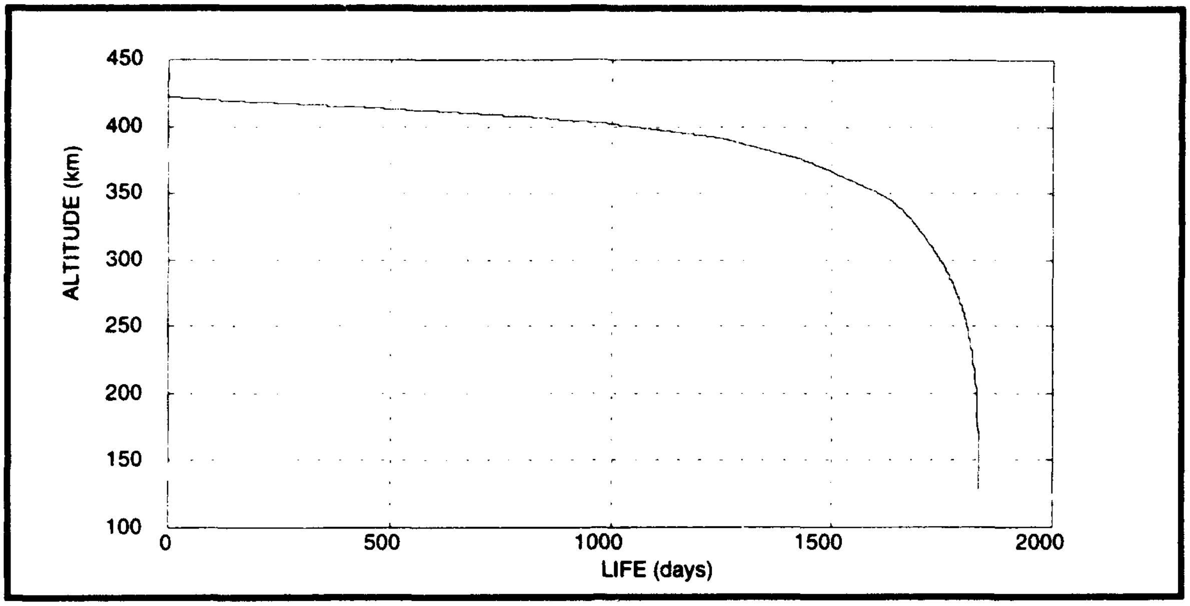

Figure 9: Typical Altitude Decay History

TABLE 7: CANDIDATE ORBIT PREDICTED LIFETIMES

CANDIDATE ORBIT	PREDICTED ORBITAL LIFETIME
MIR	776 days
GENERIC STS	664 days
HUBBLE SVC FLIGHT	10 + years
SPACE STATION ALPHA	1028 days

Table 8 presents the frequency of occurrence of passes for the candidate orbits. With regard to the expected number of passes per day, the higher inclination orbit is clearly superior. Additionally, the benefit of increasing inclination to 51.6° appears to be greater than that of an altitude increase to 600 km.

TABLE 8: CANDIDATE ORBIT FREQUENCY OF PASSES

CANDIDATE ORBITS	AVERAGE # PASSES/DAY
MIR	4.2/ day
GENERIC STS	2.7/day
HUBBLE SVC FLIGHT	4.1/day
SPACE STATION ALPHA	3.0/day

What then is the most logical way to interpret the somewhat contradictory results of the simulations, and how do factors affect the conclusions which result?

There were three significant differences in communication opportunities for the candidate orbits. The HST orbit has the longest average communication window of any candidate orbit. The Mir has significantly larger number of passes over PANSAT's projected lifetime than all orbits except HST. The HST orbit lifetime therefore would far outdistance any of the other orbits and provides more lifetime communication opportunity. This orbit would in fact yield far more life than PANSAT could gainfully employ, or for which PANSAT is likely to be operational in any event.

Over the calculated life of the orbits the Mir orbit would provide over twice the communication minutes as would the 'generic' Shuttle mission, and approximately 25% more communication minutes than the Space Station Freedom orbit. Note this is based on straight multiplication of mean pass time and expected number of passes (over the life of the orbit) and does not recompute pass statistics for orbital decay over the life of the orbit. If that were taken into account however the advantage would even further lie with Mir versus an equal altitude 28.5° inclined orbit since decreasing orbital altitude would affect communication more severely with a satellite whose inclination is significantly less than that of the ground station's latitude.

A sample run of the 'generic' Shuttle orbit yields the following thumbnail sketch of the effects. Based on the LIFE4 calculated orbital decay, after one year the altitude was estimated to be ~ 335 km. Based on this altitude, pass times for the same maximum elevation have reduced by about 20-25 sec. Fortunately, it appears that 28.5° is close enough to the NPS latitude to avoid overwhelming degradation of the communication opportunities until extremely late in the orbit's life.

4. Other Considerations

The key considerations affecting the analysis that have not been examined in detail will now be discussed. The line of sight visibility for NPS may be slightly greater than 10° in some directions due to terrain or obstructions depending on final ground station antenna placement. This would primarily affect the lower inclination orbits since that is where every pass would be in its entirety, but for a 51° orbit much fewer passes would be influenced by a directional terrain effect. For the above reasons, antenna tracking of higher inclination s/c is much more dynamic and susceptible to temporary loss of signal due to mechanical tracking errors. The likelihood of tracking errors; however, is less than that of low elevation obscuration exceeding 10° in some cases.

Political considerations may make the targeted launch window fairly restrictive. A second Hubble repair mission, Mir rendezvous missions and Space Station assembly flights seem to threaten extreme difficulty in making a manifest. Obviously with 6 Mir missions in the target window, this option may be the most achievable. If a launch date slide extends past a year, then more Space Station assembly flights become open. Owing to the extreme high visibility mission and high altitude, ergo lower payload capacity, the HST repair mission may in fact be unachievable.

5. Conclusions and Follow Up Studies

a. Mission Tradeoffs

The results of this study indicate that PANSAT should target the Mir missions as the most desirable. Given the influence on PANSAT operations of the solar cycle, [Ref. 19:p. 14] it warrants consideration with regard to mission preference. With regard to this factor the early Mir missions, STS-81 and 82, occur just prior to solar minimum and are the clear best choices. The communication advantage comes in the form of number of opportu .ies. With packet communications the length of a communication window does not limit the size or amount of data that can be transmitted as files can be transmitted over more than one pass. Moreover, experience with the current ground station at NPS has shown pass times of five to six minutes to be more than sufficient for nominal size file transfers at data rates substantially lower than those at which PANSAT will operate. So clearly, a higher frequency of passes directly converts into operational flexibility. Instead of there being a need to utilize every pass opportunity the ground station can be more selective and provide a logistically easier schedule. Additionally, during the critical immediate post launch period, four pass opportunities a day will be a significant advantage over two or three in initializing PANSAT and verifying status and operational capability. The higher inclination orbit offers less opportunity for terrain induced low elevation losses. Antenna tracking of higher inclination orbits is more dynamic but well within the capability of a ground station to perform, so this is not considered to be a significant factor.

A Mir rendezvous mission also achieves an altitude that is somewhat higher than a typical STS mission, which means that being manifested on one of the missions with no hard orbital requirements (STS- 83,87 and 89) brings about the distinctive possibility of an altitude of less than 370 km. As cursory lifetime analyses indicate, lifetimes severely shorten for even small altitude reductions below approximately 400 km. A higher inclination orbit offers less communication degradation with orbital decay as a considered factor.

The HST would offer a significantly longer lifetime, but one that is unnecessarily long for PANSAT's mission. The extreme altitude of this mission lowers the payload capacity and therefore makes it a more competitive manifest. The additional 200 km also implies an additional free space path loss (FSPL). The particular amount of increased FSPL will vary with geometry. The additional loss is minimized to 2 dB at low elevation and reaches a maximum of almost 4dB when directly overhead. The maximum occurs at a point that is well within the link margin but the additional 2dB loss occurs at the point of minimum link margin.

A secondary option should be to pursue mission assignment on the Hubble service flight, STS-85, in order to maximize lifetime, since as the schedule gets further away from solar minimum the orbital lifetimes decrease significantly. Space Station Alpha missions offer an attractive option due to the increased altitude (compared to Mir) but should be pursued only if PANSAT's schedule slides significantly and the HST service flight is not attainable.

b. Additional Questions

The results of the above study brought about some further issues in company with the ones that were addressed. If 51.6° inclination is better than 28.5°, what is the optimum inclination? If the Mir orbit is achieved, what will the operational schedule look like over time? Is there a need to specify orbital parameters other than orbital altitude, eccentricity and inclination?

(1) Optimum Inclination. The study detailed above strongly indicates that, with respect to number of communication opportunities over a given period, an orbital inclination of 51.6° is clearly superior to 28.5°, given similar altitudes. Since frequency of communication opportunities has been shown to be the most desirable parameter to maximize, is there then, an optimum inclination with regard to this parameter? If there is an optimum inclination, and it can be determined, that inclination can be used in the CPR document as the desired inclination, and while it may not be feasible for PANSAT to be given that particular inclination, it would strengthen the case for specifying an acceptable range.

To examine this issue, a 60 day analysis period was simulated for orbits differing only in inclination, which ranged from 28.5° to 74°. The high end inclination was determined on the basis of a prior simulation with 90° inclination, this yielded fewer passes over time than the 28.5° orbit. Therefore, a first cut determined that performance versus inclination was not constantly increasing and apparently did have some maximum. A value of 74° was chosen as an estimate that would exceed the maximum. The results are presented graphically in Figure 10. Clearly the area of optimum inclination can be seen to be in the region between 36°and 51.6° inclination. As this simulation was primarily for narrowing down the range, further analysis is warranted. Intermediate results are not presented, but the inclination was similarly narrowed through a series of simulations, with the final range of inclinations narrowed to 44° to 48°. The results of this final simulation are presented in and Figure 11.

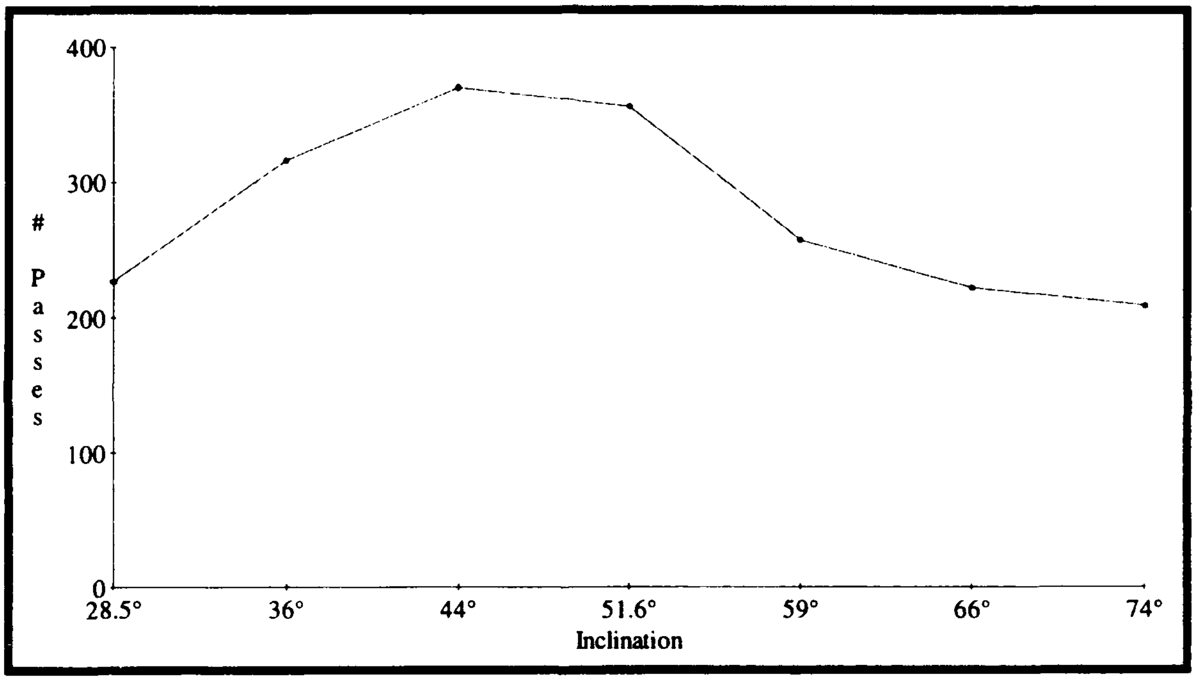

Figure 10: Optimum Inclination, Rough Estimate

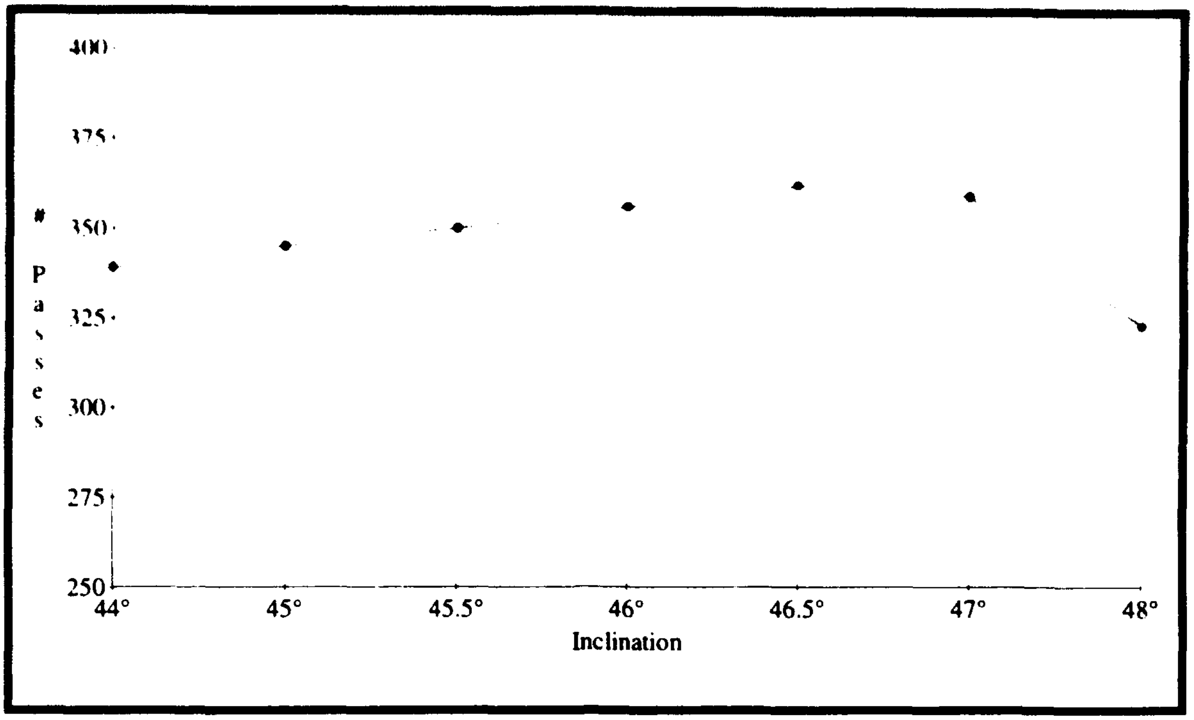

Figure 11: Optimum Inclination

The analysis indicates an optimum inclination of approximately 46.5°. Further examination of the issues involved yielded no positive conclusions as to where exactly this value comes from or how to have predicted it prior to the data analyses. However, the value does make intuitive sense given the following chain of reasoning. Where do communication opportunities arise for a ground station, satellite combination? The inclination should obviously be equal to or greater than the latitude of the ground sight (Monterey, CA ~ 36.6° north) to allow for passes when the satellite is rising from the ascending node and descending towards the descending node. Further, it should be close enough in latitude so that when the satellite's nadir point is at its inclination latitude the satellite is still in view of the ground station. Therefore the ground station's latitude and minimum elevation capability are determining factors. As the data bears out, an orbit with inclination somewhat greater than the latitude of the ground station is the best option.

(2) Mir Orbit Operations. What effect will achieving a near Mir orbit have on operations? Is there any evidence of periodicity with regard to the time of passes occurring? The typical day of operations with a satellite in a Mir type orbit has four passes. The passes generally occur in two sets of two, the sets being eight ve hours apart and the two within each set being approximately 90 minutes separated. The 90 minutes is indicative of the orbital period and passes on two subsequent orbital revolutions. The two sets of passes are indicative of a set as the satellite rises from the ascending node and a set as the satellite descends toward the descending node. With all the variables inherent to orbital motion, the periodicity question reduces to a search for a way to further examine the data.

If there were in fact periodicity, it would be primarily dependent on a limited number of variables. Motions of the satellite within its orbit, the earth's rotation, and orbital precession are the basic considerations for a first order analysis. Orbital precession will be the focal point of consideration due to the substantially greater time constant governing that variable in comparison to the constants governing the motion of the spacecraft within its orbit and the earth's rotation. Examination of the other two variables is beyond the scope of this analysis. Orbital precession (**$d\Omega/dt$**) is given by [Ref. 21:p. 210] the following equation:

$$d\Omega/dt = -1.5\,[J_2R^2/a(1-e^2)]\,M\cos(i)$$

where: $J_2 = .0010826$, R = Earth equatorial radius, a = semi-major axis, e = eccentricity, M = Mean motion,and i = inclination. Calculating this for Mir gives a value of -5.09°/day which implies a complete revolution or period of 70.8 days. This implies that over time, all times of the day will be available as passes. As inspection of the data indicates, the pass times on a given day are heavily weighted to a particular portion of that day approximately ten hours in length. Adjustment of the ten hour period containing the overwhelming majority of the passes likewise should occur on the same 70 day period. That adjustment should be slow to progress, which means that a particular communication window region will be the norm a substantial length of time.

The orbital precession calculation was primarily used as an initial approximation with which to design an analysis to bring out any evidence of periodicity. This analysis consisted of a simulation for a single satellite against the NPS ground sight over a 180 day period. Observations were counted for a day divided into two hour blocks to cover an orbital period. These counts were evaluated in ten day blocks in order to quantify progress in sufficiently small increments in comparison to the expected period. Histograms were then constructed for each ten day period, and evaluated for trends. The results, (Appendix, Figures 15-24) lend strong credibility to the argument for periodicity. The general shape of each histogram was remarkably similar, with virtually all observations occurring within a 12 hour block, with two spikes of significantly higher frequency blocks about six to eight hours apart. Subsequent histograms show the general reduction of pass times by approximately four hours in ten days. *This indicates a* *periodicity on the order of 60 days, close enough to 70 considering the approximations involved in the first estimate.* Further, when comparing histograms 60 days apart the similarity is generally even stronger, (Figure 12) with only minor count differences in some of the blocks.

As a final step in the analysis, another method of data analysis was employed to lend credibility to, or disqualify the above hypothesis of 60 day periodicity. The hypothesis now under consideration became: If there were periodic tendencies in the pass times, over the course of a period the probability of a sighting in a particular time block should be equal for all two hour blocks. To investigate this hypothesis, histograms of accumulated pass data were constructed for different lengths of the simulation, (Appendix, Figures 25-28) including, 60 days, 110 days, 150 days, and 180 days. The particular two hour block probabilities for the 150 day histograms varied from a low of ≅ .063 to a maximum of ≅ .11, which is also approximately equal to the expected probability or .083 +/- .02. The probabilities for the 110 day period varied from ≅ .065 to ≅ .095, a smaller range. The probabilities for the 60 day period varied from ≅.077 to ≅ .095, a smaller range still. Finally the probabilities for the 180 day period varied from ≅ .078 to ≅..088, easily the smallest variation.

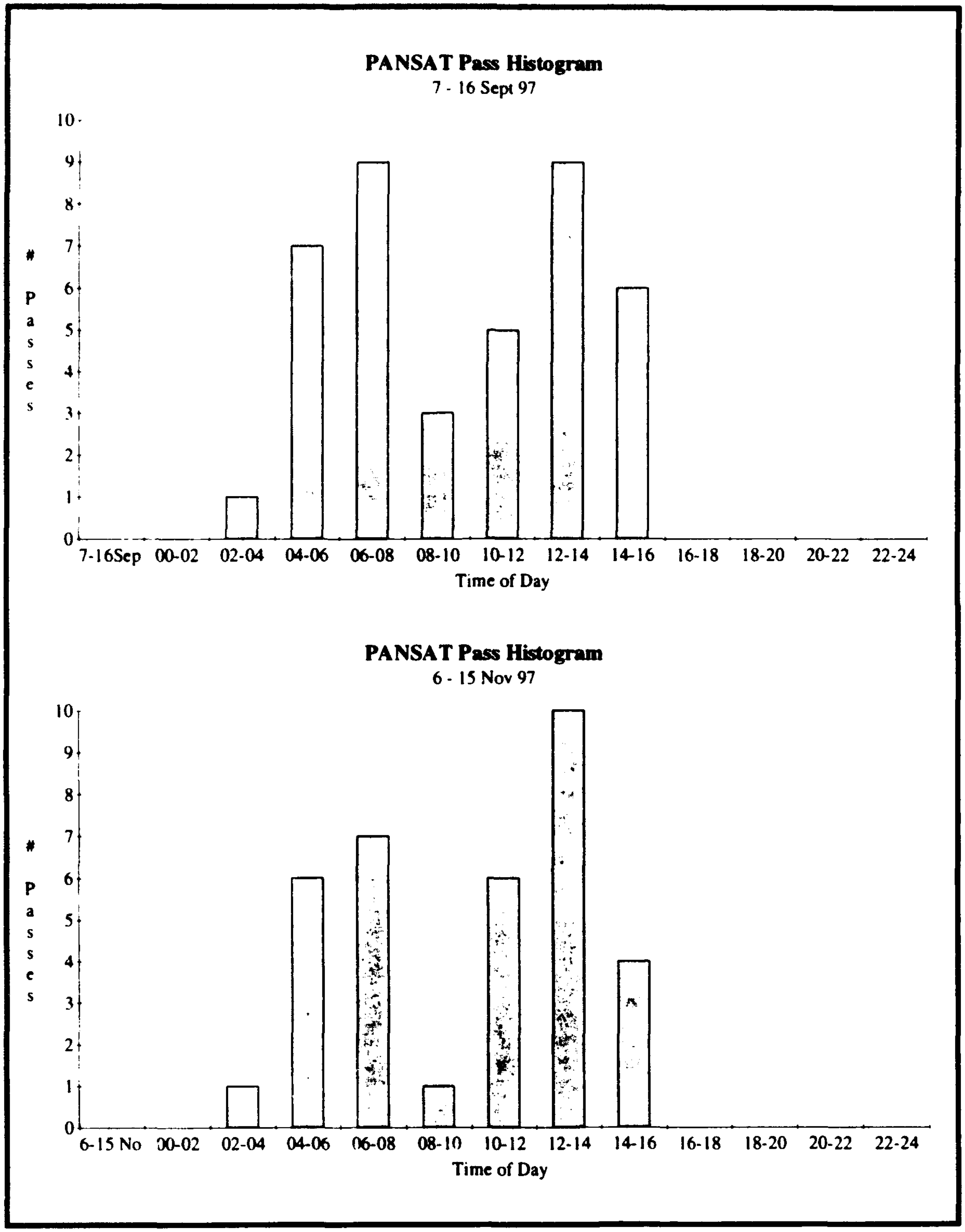

Figure 12: Comparison of Histograms

What then can be inferred from the ranges of probabilities encountered? If there were periodicity, then it would be reasonable to expect the probabilities for individual blocks to be closest to equal over a full period and increasingly so over integer multiples of full periods, and as the total number of observations significantly increased. The data bears this out; the 150 day sample, while drawn from a larger data set than most, is the farthest away from a full period and has the widest range of probabilities. The 110 day sample is closer to a full period and the range has reduced. The 60 day sample is at the expected period and the range of probabilities here is smaller still. Finally, the 180 day sample has the smallest range of probability variation and is an integer multiple of the expected period. *The facts clearly indicate periodicity of approximately 60 days.* If the reduced range of probabilities for the 180 day sample were purely a result of increasing numbers, then the 150 day sample would bear this out as well, but it does not.

D. IMMEDIATE OPERATIONAL CONCERNS

Research priorities with respect to operations should be to thoroughly develop the initialization sequence for the spacecraft, and define when and how proof of concept is achieved. What is the exact sequence of events that must occur to begin normal operations for PANSAT? These issues are in some ways critical to many other aspects of operations plans. The project has targeted a goal of two years on orbit. This fact has significantly impacted the project schedule in that two years is achievable by a launch in late 1996 through mid 1997 [Ref. 19:p. 49] due to the solar cycle. *This decision effectively imposes a true deadline, which is certainly a new consideration for the project.* If the proof of concept criteria were already established, the required on orbit time could be more realistically evaluated. Developing the initialization sequence should be an integral process with system design since it establishes subsystem interfaces and working relationships. Failure analysis is another area of high priority research. While telemetry design is already somewhat mature, designing fault identification into telemetry reporting has not been sufficiently addressed. The reverse engineering process of fault analysis can be made significantly easier if it is considered in the telemetry design phase.

V. MANAGEMENT AND ORGANIZATION

A key assumption in the development of this thesis was that the PANSAT project is subject to stringent fiscal limitations. What budgetary assets are available must be spread between salaries, research, test and fabrication equipment purchasing, parts and consumables purchasing, and operating expenses to name but a few. Of the incomplete list given above, the most significant fiscal commitment goes to the salaries of the SSAG, PANSAT staff. A further assumption of this thesis was that the analysis first would be conducted without regard to the possibility of increasing the SSAG staff. That possibility will be dealt with as a separate issue. In light of the above delineated assumptions, the only realistic approach to improving the overall development process becomes the examination of how the available personnel are being used to complete the project. In other words, what managerial strategy should be pursued to better match assets to requirements. The current organizational structure sees only the SSAG staff engineers physically within the project management's cognizance. Are there feasible steps that can be taken that will increase the effectiveness of faculty and student contributions to the project? Can these contributions be effectively matched to project requirements on a timely basis, thus enabling the staff to proceed to subsequent development areas?

A. ORGANIZATIONAL ISSUES

1. Tasking and Positions

As the only physically employed component of the development effort, the engineering staff will be the first focus of an examination of the project structure. The SSAG PANSAT engineering team consists of a project manager (PM), systems engineer, EPS engineer, DCS/communications coordinating engineer, ground station engineer, system master plan/testing engineer, DCS/communications design engineer, and a model maker/fabricator. Given their status as SSAG staff, all members of the engineering team have additional responsibilities and commitments outside of the PANSAT project. The above listing only gives titles and not responsibilities. The particular responsibility assignments are primarily coordinated by the program manager, and are not nearly so clearly defined. The systems engineer is also the lead engineer for structural subsystem development. The EPS and DCS/communications design and coordinating engineers are all involved in overlapping details of the EPS design, interfaces, DCS design and interfaces and communications payload development. The systems engineer and testing engineer handle overall project documentation and coordination with outside agencies in general.

The program manager maintains and updates a master project schedule via inputs from the engineering team with regard to subtask progress. More detailed work breakdowns are maintained by most members of the engineering staff.

2. Issues

There is no formal program plan. A program plan is an essential tool to develop the logical approach to, and the implementation and control of a program. The effective program plan should analyze program objectives and work required in light of cost and schedule estimations. The program plan [Ref 22:p. 2-1] should contain an overview, a technical summary, management approach, procurement approach, and budgetary and project control plans. These items are the basis of a well-organized project, and should be used as a starting point for increasingly detailed planning efforts.

The project manager for PANSAT has had, and continues to have significant difficulty obtaining adequately detailed schedule plans from subsystem coordinators. Certain aspects of development, largely due to greater student interest, have continually received more attention with regard to schedule and design development than have other areas. The result is that a macroscopic schedule has been generally arrived at and decided upon (perhaps by default) without sufficient detailed development of design concepts and associated schedules to ensure that the overall schedule can be met. A specific example of this issue occurred when a recent thesis recommended a late 1996 launch in order to achieve launch during favorable solar radiation conditions. The decision was thereby made to proceed with the project in order to meet that launch date. That launch date incurs the requirement for a fully operational PANSAT by early 1996 (six months prior to launch) for Launch Vehicle integration. In the opinion of the author, there is no firm evidence to support the prediction of a fully operational and tested satellite by that date.

The management plan for PANSAT consists of an expanded listing of subsystem coordinators, and the associated upper level tasks for which they are responsible. Beyond the basic subsystems, the areas covered also include software, spacecraft architecture and configuration, solar panels, testing, operations and documentation, and the high level responsibilities of the project manager and systems engineer. Under each of the coordinators for the above areas, specific responsibility is assigned for the upper level tasking. This work breakdown is a good initial guideline, but it is insufficient. The Naval Center for Space Technology (NCST) organizes a work breakdown structure (WBS) somewhat differently than does the SSAG. The top level work breakdown structure is organized at three levels. Figure 13 shows an (incomplete) top level WBS for a typical system. Level one is the program level, while the second level can best be described as principal tasks. The third levels are subtasks and subsystems. [Ref. 23:p. 2-5]

The second level of the work breakdown structure separates a project into the top level tasks of program management, systems engineering, subsystem development, software development, systems effectiveness, parts procurement and processing, spacecraft integration and test, test system development, and ground station development. Program management includes planning, control, contract management, and budgeting. Systems engineering includes system requirements definition, bread and brassboard systems engineering, and technical interface activities. The subsystem level breakdown of a typical systems engineering task is presented as Figure 14. Spacecraft systems effectiveness includes product assurance, reliability engineering, quality assurance, design analysis, and safety. Integration and test involves test planning, execution and analysis while test system development implies the hardware and software development associated with performing the testing. [Ref 23:p. 2-5] All other tasks are considered self explanatory.

It is readily apparent that the approaches to work breakdown structure taken by the SSAG and NCST are fundamentally quite different. Almost all of PANSAT's breakdown occurs vertically down a single level (Subsystem Development) of the recommended structure of the NCST model. Subsystem coordinators also perform subtasks horizontally across the NCST model, i.e., subtasks under other level two tasks than subsystem development. Subsystem coordinators procuring parts, developing test plans, and developing software are but a few examples. The reason for this disparity is simply the fact that personnel assets for an NCST type work breakdown structure do not seem to exist for the SSAG. *So while the organizational structure of the NCST model is not readily transferrable to a project of PANSAT's scope, the details of the work breakdown structure certainly are adaptable to PANSAT's organization.*

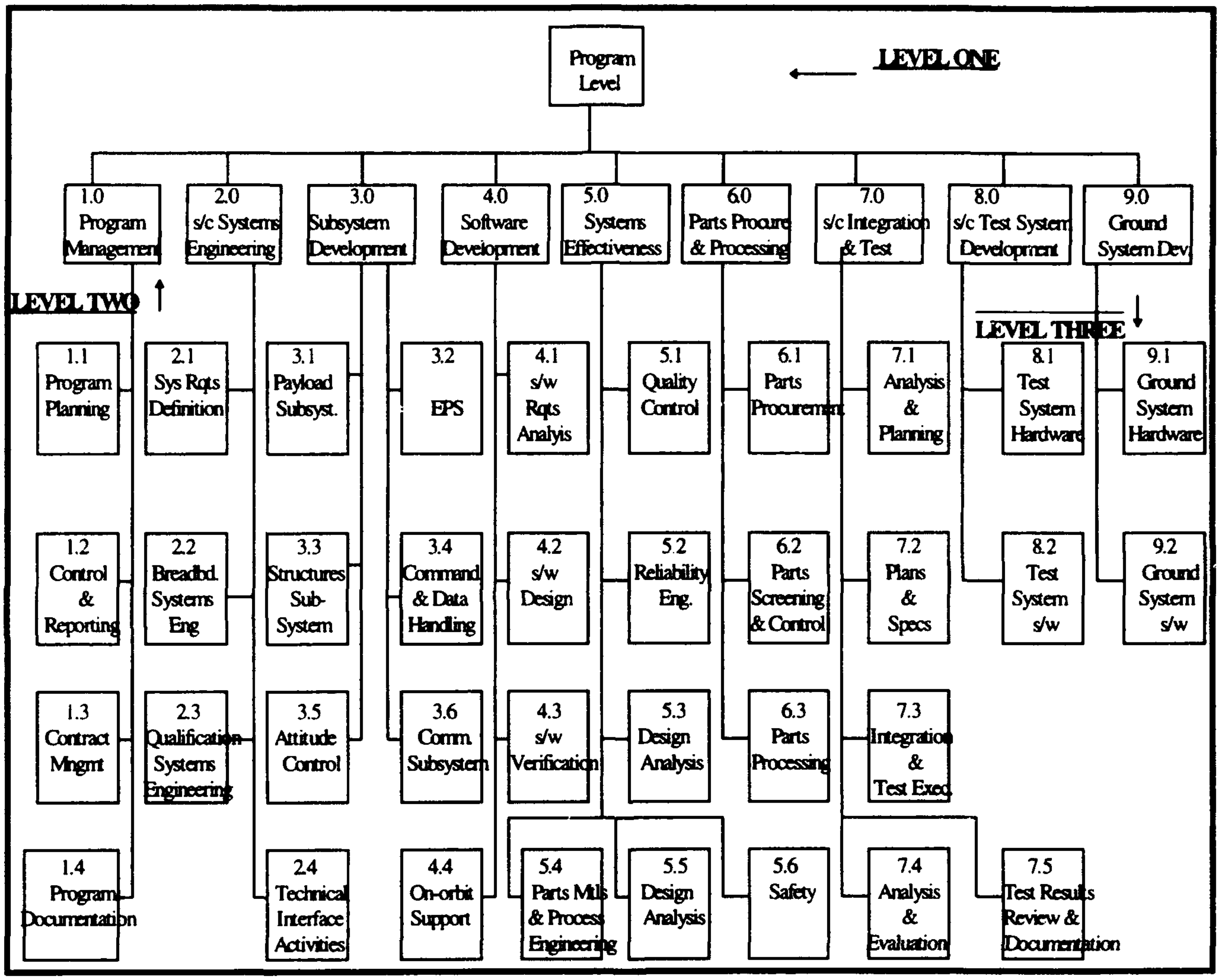

Figure 13: Typical top-Level Work Breakdown Structure

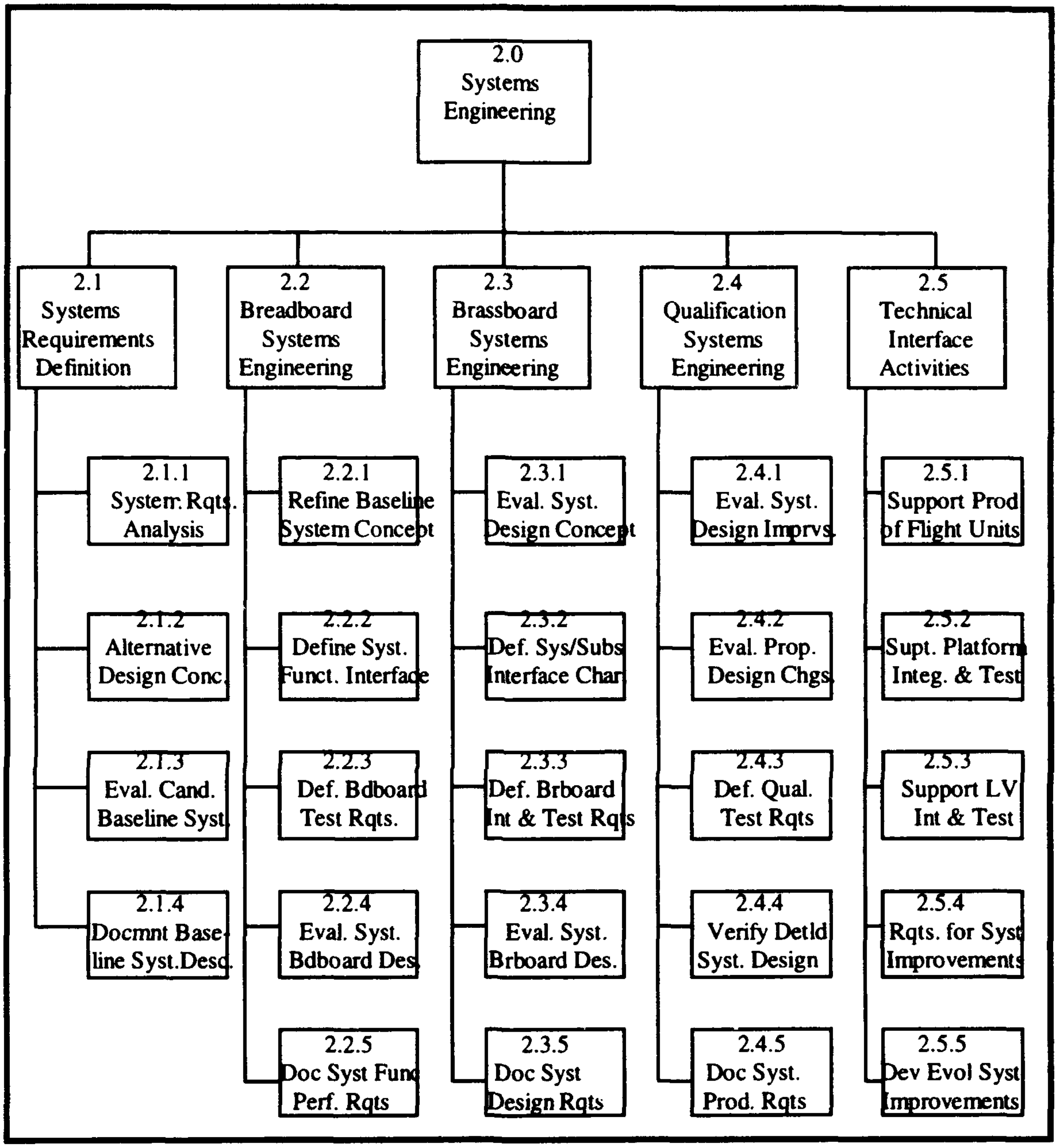

Figure 14: Sample Systems Engineering Work Breakdown Structure

3. Recommendations

The Naval Postgraduate School is not in the business of building satellites. It is therefore reasonable to seek additional direction and evaluation from a reliable and unbiased source. It is the recommendation of this thesis to reorganize the project along the lines of the Space Systems Division of the Naval Center for Space Technology at the Naval Research Laboratory. The first step in this will be the development of a formal program plan document. The development of a program plan is detailed in Reference 22.

The PANSAT work breakdown structure should be reorganized along the lines of the NCST model (modified to PANSAT specifics). Coordinators should be assigned to level two tasks; most personnel will need to assume responsibility for more than one top level task. If this system is adopted it will benefit the project in a number of ways. First, the probability of subtasks remaining unaddressed will be reduced because this model is simply more thorough than the SSAG model. The SSAG breakdown meanwhile should be used to assign lower level tasking to ensure that no previously noted tasks are omitted. Secondly, the adoption of a structure employed by a *proven spacecraft development* facility only makes sense in the absence of contradictory SSAG corporate knowledge. Additionally, the adoption of this structure increases the facility for outside program audits, examinations, and recommendations. Finally, this breakdown improves the work distributions and definitions of two critical team members, the PM and the systems engineer.

Among the recommendations that are implicit to the adoption of the NCST work breakdown structure, is the realignment of the duties of the PM and systems engineer. The PM should assume primary responsibility for program documentation. Coordinators should provide required documentation needs and requests that would be maintained updated and audited for completeness by the PM. Documentation of critical decisions and direction has plagued the project since its inception. Proof of this assertion is the near complete unavailability of trade studies, decision support documentation, requirements determination papers and the like. Student theses provide the primary documentation of project history. Electronic documentation of recently developed design details and decisions exists but doesn't cover the early stages of the program.

The systems engineering duties should be restructured along the lines of the classic systems engineer. [Ref. 3] This one position, due to the requirement of impartiality with regard to design compromises, should not be performed in conjunction with any other responsibilities with regard to PANSAT. Overall project design, development, and interface and integration management are too critical to the success of any project to risk their compromise by an otherwise tasked systems engineer.

B. PROGRAM MANAGEMENT ISSUES

As developed in the preceding sections of this chapter, a critical problem that continues to evade resolution is the issue of staffing. Specifically, there is simply not a large enough staff to complete all of the required details necessary to a successful program in the time before PANSAT's anticipated launch date. Unless the decision is made to take on additional engineering staff, if the project is to succeed, the slack must be taken up by some other physical asset. The only options available are to work smarter and faster, to purchase rather than develop hardwware and software where feasible, and to supplement the engineering staff with increased and improved faculty and student participation. What follows is an examination of how these options might be accomplished.

Faculty participation in the past has been marked by outcomes that fall well short of expectations in more than one case. Professors have withdrawn from project involvement for political reasons and of all project personnel are singularly beyond any management control and in some cases even influence.

1. Other Participants

a. Students

The single greatest resource available to the PANSAT project is the officer students, principally from the Space Systems curricula. To date this asset by any standard has been employed far short of its potential. Student participation is predominantly voluntarily, excepting the infrequent class with a PANSAT related project requirement (e.g., AA-4831 for the Space Operations Curriculum). Other participation largely consists of thesis research in the Space Systems Engineering, Electrical and Computer Engineering, and Space Systems Operations fields. Some additional participation in the form of directed study projects related to PANSAT also contribute; although not all student participation has any significant effect on the project.

Students in the Space Systems Operations and Engineering curricula are available in varying degree to participate in PANSAT. The operations curriculum has three unspecified elective slots in a normal course matrix. The student is allowed to choose an elective sequence to fit his or her needs and or wishes. The operations curriculum has several core courses taught by SSAG professors and a quarterly one hour Space Systems seminar; one class begins each academic year. The engineering curriculum has many of the same characteristics with the noted exception of no free elective openings in its matrix. The engineering curriculum, however, has two separate classes each academic year.

Student participation in the project could be significantly increased and improved in a number of ways. The majority of space systems students do not arrive with a pre-determined thesis. If the Space Operations class SO-31 (September 1994 graduates) is a representative one, the majority of students do not choose theses until they have been at NPS for nearly a year. Students not having selected a thesis by a predetermined time (e.g., the start of the third quarter) should be encouraged to select one from a list of topics that the PANSAT team has generated. This would certainly be a non-traditional academic policy, but it should be remembered that the students are first and foremost military officers, well versed in non-traditional requirements. This policy would quickly reduce the number of unaddressed topics for PANSAT, while expanding the bounds of academic enhancement. In addition to this thesis selection, all incoming space students should be exposed to the PANSAT project early on and encouraged to participate. Instead of being required to attend all SS-4000 (Space System Seminars), which are often beyond many first and second quarter students, they should attend SS-4003 (PANSAT Design Meetings). This could be done on a quarterly basis, i.e., SS-4000 for a quarter and SS-4003 the next. The design meetings can be easily restructured to provide an in depth introduction to PANSAT for early students. For students approaching or beyond thesis selection a separate course should be designed as an operations or engineering working group (depending on specific curricula). The opportunity for this course exists for all space students in the form of SS-4000. Additional opportunities exist for the operations students in that a sequence of (SS-4900) electives can be designed as an operations development sequence. These electives can be administered by SSAG instructors and consist of group and/or individual projects of timely importance to the project.

The author does not anticipate that the above proposals are likely to be well received initially; the academic mind set must, however, allow room for consideration for two reasons in particular. First, the proposal goes directly to improving project performance with regard to the two primary objectives. Second, there is an already significant, and ever expanding wish list of topics to be addressed prior to launch, and staff can not possibly address even the essential topics, let alone the "nice to know" ones.

b. Faculty

The difficulties of improving faculty input seem somewhat overwhelming. The nature of faculty participation is, like students, voluntary. Unlike students, however, there is no avenue for requiring additional participation, nor obviously does there exist the necessity to produce a thesis. The SSAG unlike other true academic departments has limited influence over even SSAG faculty, who are also associated with an academic department. Even after a faculty member has joined the project, there is nothing to prevent subsequent withdrawal at any time. The only way of increasing participation is to make it more attractive for faculty to participate. Research funding is the best, and possibly only way to accomplish this, except for those who are genuinely and deeply interested in the project itself.

In light of the inherent difficulties of managing faculty participation, direct reliance on additional faculty should be avoided by the SSAG staff. Students seeking thesis advisors should be the primary contact with any faculty not currently and actively involved in the project.

2. Decision Authority

How are decisions affecting the project made and what documentation exists of those decisions? This question is more difficult to answer than would reasonably be expected. The decision making authority for the project resides at any of three basic levels dependent upon the nature and potential impact of the decision to be made. The ultimate decision authority rests with the principal investigator and to a reduced extent with the project lead. Top level, high impact decisions are made at this level with full consideration of engineering staff input. The engineering staff has periodic Planning and Integration (P & I) Meetings to develop details either for top level decision or to decide second level items. Decisions at the second level do not typically affect top level system design per se, but rather how some requirement is fulfilled. This is done in the meeting climate to ensure full staff understanding of the issues and implications. The third basic level of decision rests with the subsystem coordinators and generally implies an issue that has no implications outside of that subsystem.

Documentation of third tier design decisions exists primarily in the form of a design log, available to the SSAG staff. Second tier decision documentation is via Planning and Integration Meeting minutes similarly maintained. Top level design decisions, primarily those made early in the project's life cycle, are, to the knowledge of the author, not maintained or available. The design log and P & I minutes document relatively recent decisions only. This lack of documentation of critical decisions made early on in the process makes project analysis infinitely more difficult. Word of mouth reasoning behind significant decisions has mandated countless hours of duplicate efforts on the part of more project participants than can reasonably be determined.

Decisions that have been made in the past should be reconstructed and fully documented with regard to what was considered, what was assumed, what was decided, what were the alternative choices, and the potential effects of the decision. Decisions made henceforth should be similarly documented and maintained in a sole source project design and decision log. If a decision cannot be documented, and the above reasoning completed in detail, that decision has not been sufficiently investigated. *Reconstruction of past decisions may seem pointless, but the potential avoidance of future duplicate work should be fully considered before dismissing this proposition.*

C. MANAGEMENT PLAN

The overriding intent of this thesis was to provide recommendations to the project in order to improve overall performance towards the successful fulfillment of stated goals. This section, as a management plan, is the forum for those recommendations. This plan can be divided into three logical areas. First, a review of project goals deals with how the project is proceeding towards those goals and with specific recommendations regarding those goals. Next, assessing the project's direction deals with fine tuning smaller scale considerations than overall goals. Finally, an examination of PANSAT would not be complete without developing a logical approach to the long term future of the project.

1. Project Goals

The PANSAT project is at a critical point in all respects. The decision has been made to proceed with a targeted launch window beginning in September 1996 through early 1997. This gives concrete end times to the project's schedule. Specifically, this schedule now requires a completely assembled and tested space vehicle ready for Shuttle Integration possibly as early as March, but more likely by the fall of 1996. This has serious implications to the stated goals of the project.

The primary goal of the project must now become what was previously secondary; that of developing, fabricating, launching, and operating a satellite communications system. The reasons for this are self evident. A project on a deadline can not afford the luxury of a flexible schedule. Student involvement by its very nature makes a flexible schedule an inescapable reality.

Educational enhancement is not necessarily curtailed by this fundamental change in approach; the manner of implementation, however, must be altered. Education must be pursued where available, but where it does not impact the project schedule. The most significant manifestation of this fact should be in the availability of the engineering team. *If the staff is to succeed in this undertaking, then satellite construction must be their overriding concern, to the exclusion of students.* This entails the necessity for students to fit into the staff's schedules and work on topics not intimately involved in the overall schedule. This is a hard reality and one that will require management's complete enforcement and support. It is directly against the charter of the SSAG to put students second but if the project is to succeed, PANSAT must come before all else. This aspect of the recommended policy may be more prove easier for the staff to implement than for management to openly support.

What are the alternatives to this fundamental change in philosophy for the project? The first option is to remain in the current approach of education first and giving effort to launch PANSAT less than total emphasis. This choice, while not necessarily doomed to failure, certainly lessens the likelihood of a successful launch. The third option is to admit before further commitment is made that NPS is not in the satellite production business, and that PANSAT faces insurmountable obstacles in making the launch window. This will leave the education of students as the primary concern of the SSAG. The problems with this approach are (1) the loss of funding support that would result from program cancellation, and (2) the difficulty in getting funding for a following project, since PANSAT would be seen as a failed program. While it is true that a large reason for the DoD based financial support of the project is due to its educational basis, the value of that education would be best demonstrated by a successful satellite launch and operation. This view shows that the two principal objectives of the program from its inception are inextricably tied, and that neither can be fully achieved without the other. In light of the above discussion, the only reasonable choice seems to be the realignment of primary and secondary goals. The time to begin the transition to a satellite production facility is past due.

2. Direction

If the decision is made to make the completion of the project the primary objective, what then are the details of that course of action? This decision requires the full support and commitment of all involved; lip service alone will not suffice to allow the engineering team to pursue their responsibilities adequately to the project. The potential impact of this action on students is significant but short term, and it can be easily managed to minimize the detrimental effects. This approach does not make student participation unwelcome; it does make the student more responsible for his or her own support. The largest effect may be in the type of projects that students will pursue.

The large majority of theses coming out of the PANSAT project thus far have been engineering in nature. As designs become increasingly detailed and fabrication begins, the opportunity for masters level engineering work decreases. At this stage, however, the opportunity is just beginning for operational theses. This aspect of the PANSAT project has received minimal attention to this point. *The operational aspects of the project are not only crucial to success, they are also the best ways to pursue continued education without adversely affecting the project's progress.*

There are still a large number of thesis opportunities in every aspect of PANSAT; however, the project-wide attitude is that these opportunities are well known. That is not the case; the available thesis topics are seen only after close scrutiny on the part of prospective students. The transition away from educational emphasis should begin with the subsystem coordinators' thorough evaluation of the tasks remaining. The result fits well into the previously recommended new work breakdown structure. This task description improves schedule knowledge and thereby not only allows a student better information as to available thesis topics but gives a concrete time frame during which the work must be completed. In this manner the subsystem coordinators and student can easily determine whether or not the student fits into the project. This underscores the fundamental change in approach; the student must fit into the project, no longer should the project have to find a place for the student. *The importance of thoroughness in the development of the task evaluation can not be overstated.* This identification of needs and schedule will be the principal connection between staff needs and student participation. *Student participation can be optimized by well-developed projects or squandered by half-hearted lists.*

The project has undergone two design reviews, both largely internal. Given the current development schedule, virtually every subsystem should be in, at a minimum, the detailed design phase by early 1995. *The project should solicit a thorough and encompassing critical review by an unbiased expert analysis team to be completed by March 1995.* One year prior to launch vehicle integration should be the latest acceptable time for such a review. The Naval Center for Space Technology (NCST) at the NRL has significant experience in space related projects of all size and complexity, not to mention projects on extremely tight schedules. If a team from NCST could be brought to NPS for a program review, the resulting insights could prove invaluable. *The teams unbiased evaluation should be given every consideration, even if that evaluation was that the project would not work.* This may be the latest time to cancel the project, were that decision to be made, without catastrophic repercussions.

Close examination of the PANSAT project reveals some critical management issues. Without citing examples, an overriding impression of the development team is that the complexities of detailed design are getting in the way of the bigger picture issues. There are numerous instances of designs put on hold awaiting details from another subsystem coordinator who is awaiting details from yet another, and so on. The problem of too much focus on details impeding the basic design is the domain of the systems engineer. Recent steps have addressed this issue, but constant attention to this phenomenon is warranted. *This reason alone is justification of the earlier recommendation that the systems engineer be relieved of all extraneous responsibilities.* The dual role as structures subsystem coordinator can possibly compromise the purpose of a systems engineer to coordinate, integrate and compromise to attain the best overall system. *The systems engineer and program manager must assume more demanding management styles; to this end they need the full and open support of the principle investigator and project lead.* The development team gives the general impression of reaching decisions based on personality and strength of argument. *The systems engineer and program manager simply need more basic authority, and it should be exercised.* In the months to come it will become a necessity to demand more from the team and that authority must be put in place now, before it is too late.

3. The Future

The ideal realization of the goals of PANSAT would be for its success to bring about a new more ambitious project. The lessons learned from this undertaking will enable a project of significantly greater scope to be pursued. The start of that future undertaking, however, should occur now. The SSAG has the unique opportunity to start the follow on project without affecting PANSAT. The key to this is in the approach to the system. Recalling discussions of some previous chapters, the project should begin with a team of Space Operations students. A design team determines and develops a mission need or requirement. That mission is evaluated and analyzed, resulting in a listing of functional (system) requirements along with candidate architectures. *The Space Operations core class, SS-4001 (Decisions and Space Systems), is a perfect forum for this effort.* Not only does this proposal fall directly in line with the course description but it has the additional benefit of being an in-place, (i.e., funded) course in the curriculum. The candidate architectures are analyzed by an engineering team for feasibility and the combined teams generate a candidate list of alternatives and recommendations. Along with the candidates is a refined list of functional requirements. The candidates are evaluated and a decision is made within the SSAG. A key consideration remains the inclusion of education as a principal goal of the project at this level. After a decision is made, the engineering design work converts the functional requirements into physical requirements and thereby also develops the selected candidate's architecture into subsystems and assemblies, etc. Since the operations team was involved from the start, operations can be addressed in the initial stages of the project in order to provide crucial supporting information for key design decisions, as well as to frame and/or perform trade studies towards those design decisions. It is worthy of mention that a critical difficulty in PANSAT's design freeze is the way the project works with functional requirements. The functional requirements document is an assortment of physical and functional. Further, the requirements document has been routinely altered to meet the physical design as it developed. This approach is fundamentally flawed. A system's functional requirements should define a systems purpose, intent and basic approach. It should not be an engineering design document. Additionally, such a document should not be altered to meet what can be built, rather, the functional and then physical requirements should have been adequately developed before design work got to this stage and changes to it should be the exception. ***In other words, the design should be worked to meet requirements, not vice versa.***

VI. CONCLUSIONS AND PASSDOWN

The future of the PANSAT program, as detailed in earlier chapters, hinges on many details of engineering design and fabrication, operations development and planning, and thorough testing. A failure on the part of any one of a large number of these details could prove catastrophic, and yet success will not even be ensured if every single one is adequately addressed. As with any complex systems development project, the interrelationships of all of these factors make it impossible to isolate and deal with any single issue at a time. This thesis raised a significant number of these issues that will require timely resolution in order for PANSAT to succeed. It is certainly true that there are a significant number of issues that have not been identified herein of equal or perhaps greater concern. *The single largest contribution of this thesis may, in fact, be the identification of the fact that there are not only significant identified difficulties with the project as it now stands, but that it is reasonable to assume the presence of unidentified potentially fatal complications.*

In the opinion of the author, the largest obstacle facing the project is the lack of organization and continuity in the design and fabrication effort. The organization of the team and project planning are unwieldy to carry off a project of this magnitude. The project would be better served to adopt a more military style hierarchical chain of command structure in order to increase accountability and responsibility. The goals of the project and design goals of individual subsystems need more focus and less experimentation. The time for considering new design possibilities has passed. The current design state must be dealt with in the most effective manner to put the pieces together and make the system work. The presence of students and faculty only complicate the dynamics of the organization. A more focused, better managed approach to handling these participants has become a necessity.

The electrical power production capability of PANSAT is one aspect of the engineering effort that has been a constant source of misunderstanding. Although the power shortcomings are expected to be manageable through operational methods, this thesis has highlighted a serious miscalculation with regard to how much power the spacecraft will produce. *Operational methods can only address situations that are fully understood; if status schedules are put into effect for PANSAT without knowing their full and complete implications a bad situation will only degrade.*

In the opinion of the author, the decision authorities for the project need to give serious consideration to the realistic chances for PANSAT being completed and ready for launch as it is currently scheduled. There seems to be an optimistic attitude regardless of the complications. The concern this raises is that the problems of which the project is aware may be correctable, but the problems that kill projects are the ones that are unforeseen until too late. The PANSAT project seems ripe with unforeseen problems; every investigation of one issue brings others to light that are often more serious.

PANSAT needs aggressive audits in two particular areas. *The overall system should undergo an independent critical design review by an agency such as NRL* in order to validate in house estimates of likelihood of success. *An audit of the testing program should also be solicited as this issue goes directly to meeting the requirements to be launched.* The results of these audits should be given every possible consideration. The cancellation of any project may be a more attractive alternative than pursuing a program doomed to public failure.

The engineering staff should be supplemented if at all fiscally possible. The largest two shortcomings of the PANSAT staff are in size (too small) and experience at the middle management level. *A space-experienced managing engineer would be the most beneficial single addition to the project.* The necessary ingredient that such an addition would provide is an ability to focus on the larger picture and to impart that focus to the development staff.

Follow-on tasking for future Student Project Officers (SPO) was one of the goals at the outset of this thesis. One obvious direction is to follow through on the specific recommendations proposed throughout the individual chapters of this report. The best initial task for the new SPO would be to carry through a new systems analysis within a few months of taking the position. This is considered essential in light of the fast approaching Critical Design Review and any external audits resulting from recommendations herein. The specific areas of interest will be by individual preference; however, in terms of chronological order, the answering of systems design questions and solidifying these issues should be the top priority. The next priority should probably be development of testing issues raised and a comprehensive test plan. For the most part, operational issues can be carried out without quite the same time criticality as the above topics, a notable exception being the need to establish coordinating activities with the Hitchhiker, GSFC, and NASA program offices. Ideally, an increase in student activities in these particular areas would allow the SPO to oversee and guide rather than personally undertake these efforts. A major obstacle when beginning this effort was the definition of the role of SPO. As the management structure of the project does not have any defined gaps in job description, the SPO has no readily identifiable role. Any new SPO must tailor the specific approach to their particular strengths and weakness, as well as to the strengths and weaknesses of the PANSAT project. *The best fit in the course of this thesis was determined to be as a more technical program manager and a less technical systems engineer. In other words the SPO should be versed in both jobs and attempt to bridge the gap between the two roles.* This would be the best application of the likely skills and ability of a new SPO and at a minimum is the best point from which to develop an individual role.

APPENDIX

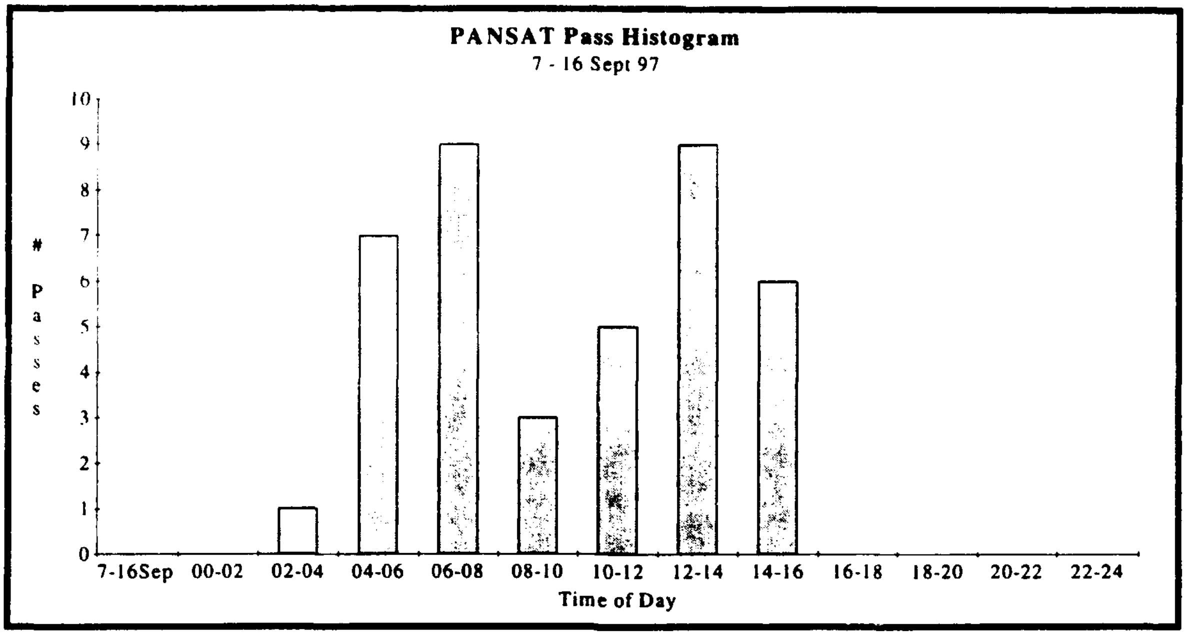

Figure15: Period One Histogram

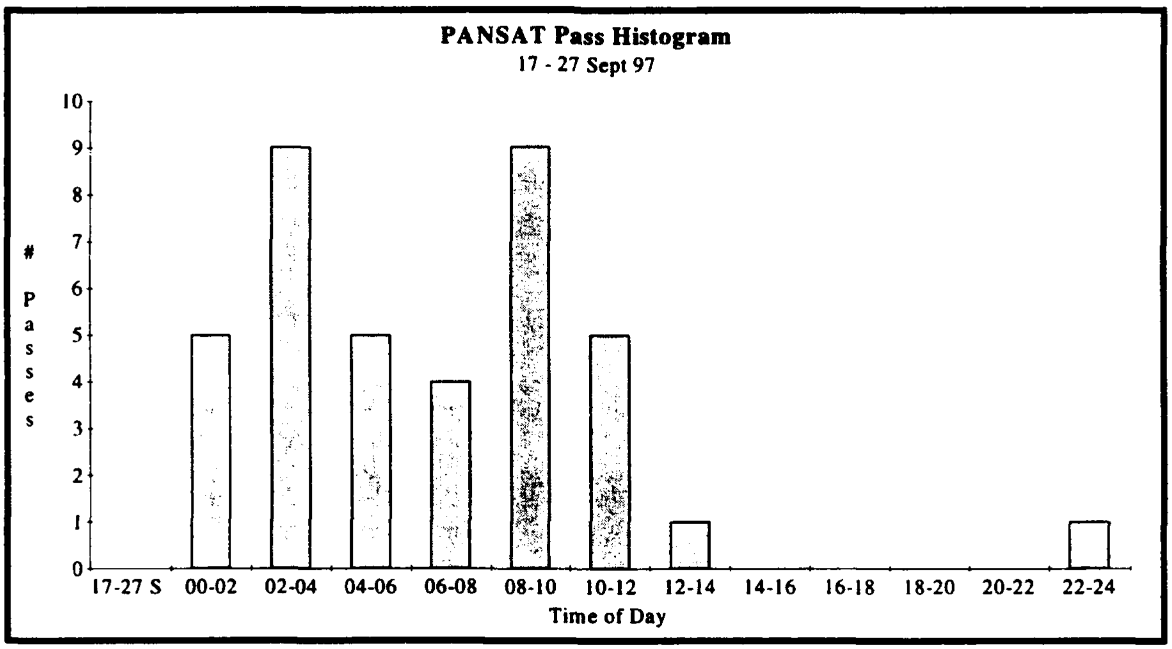

Figure 16: Period Two Histogram

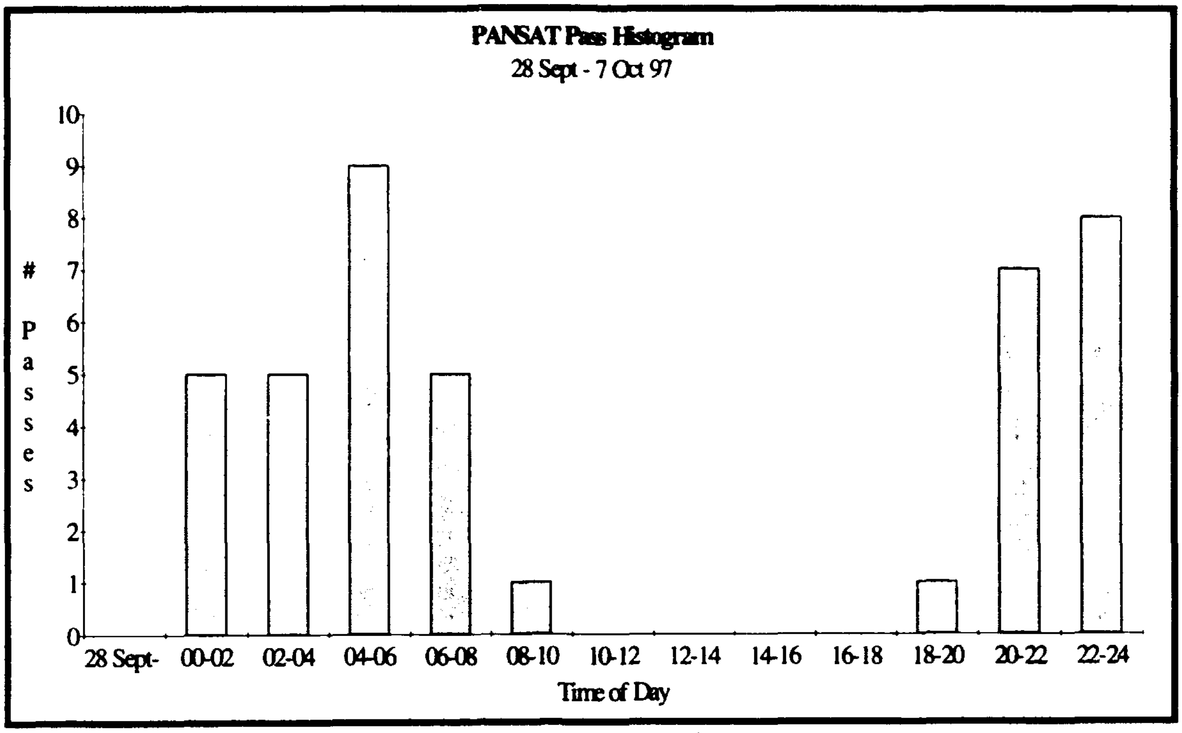

Figure 17: Period Three Histogram

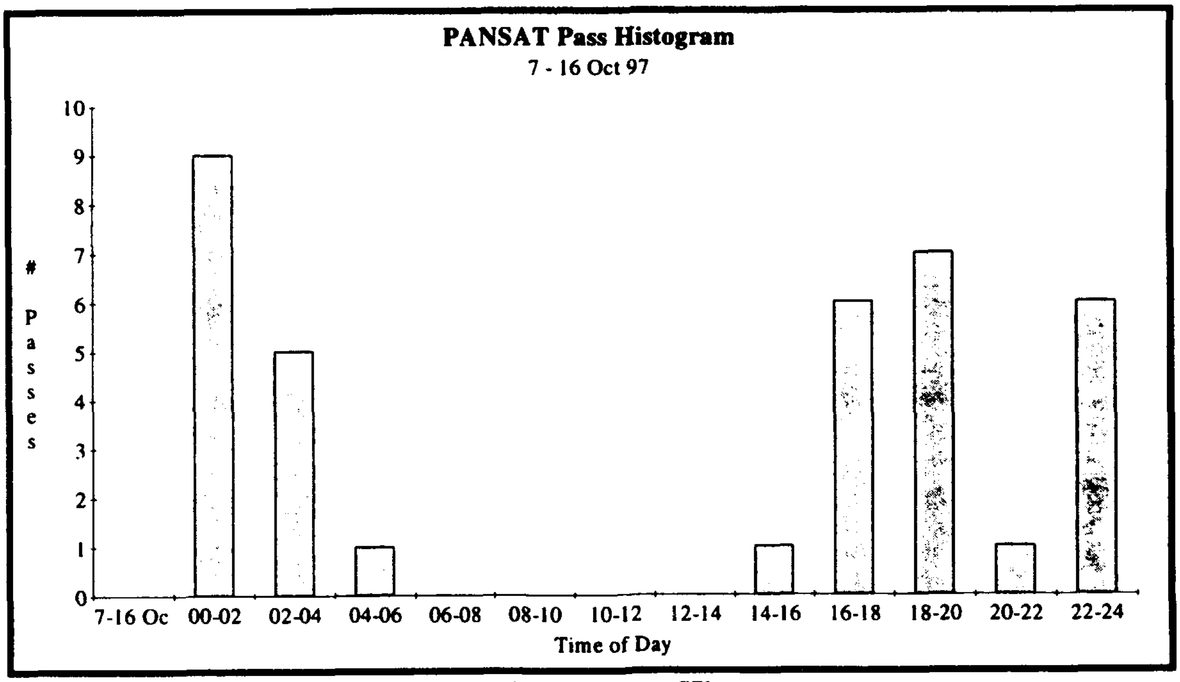

Figure 18: Period Four Histogram

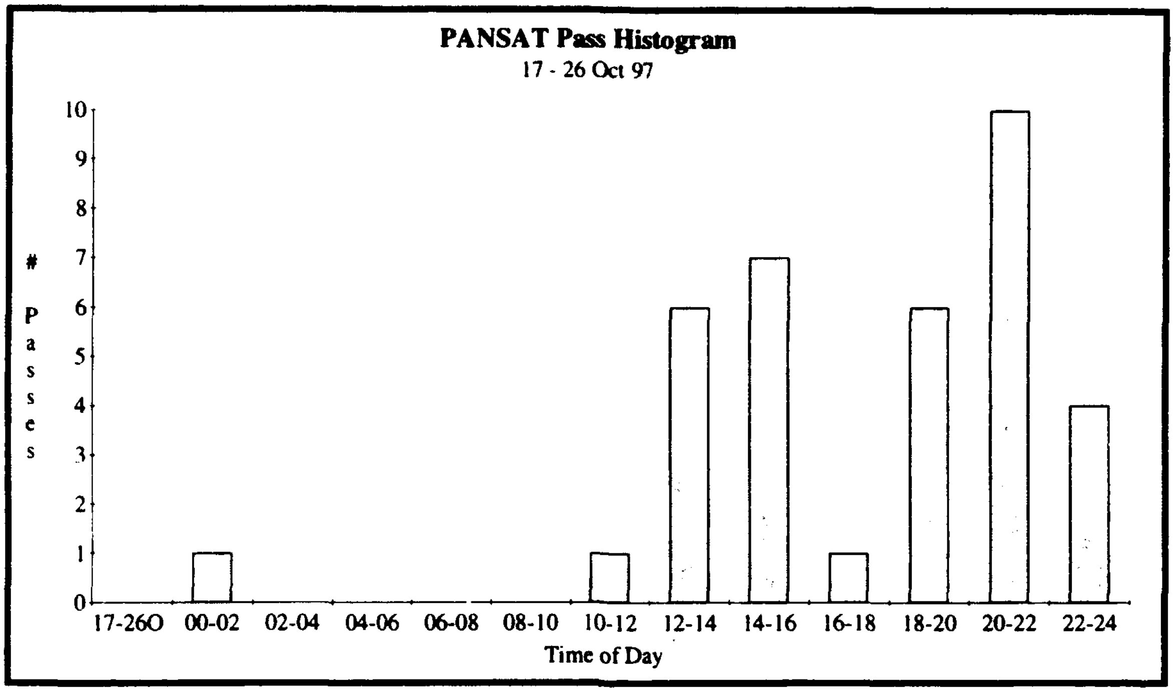

Figure 19: Period Five Histogram

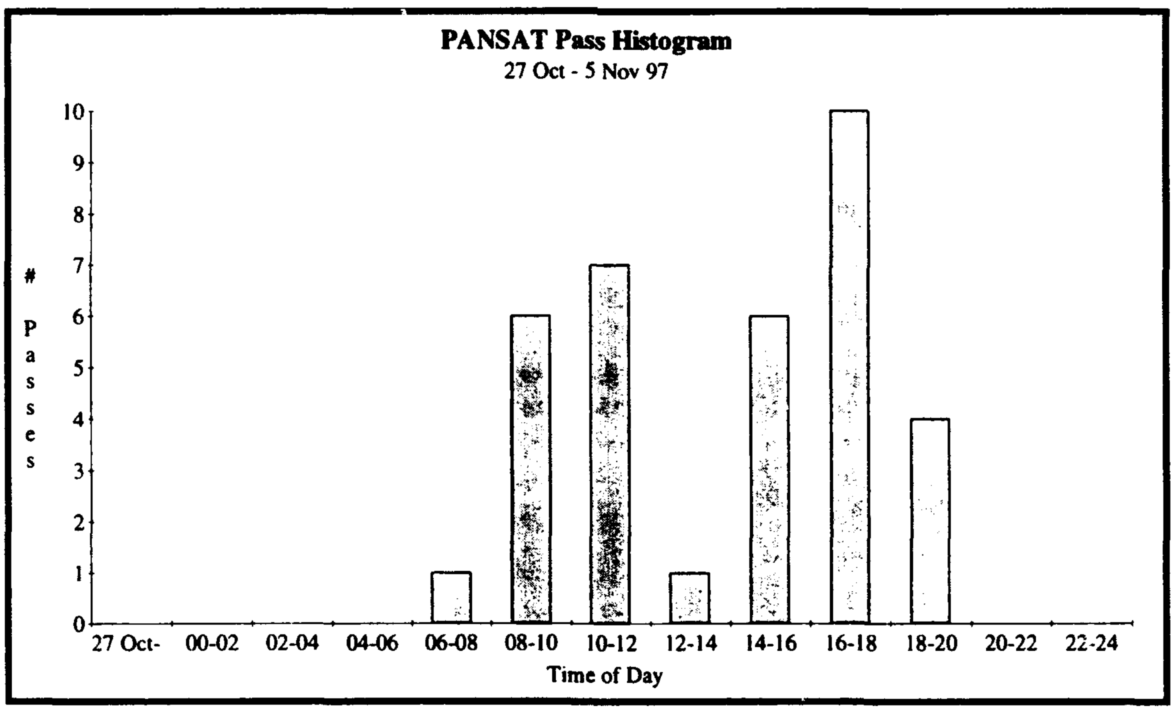

Figure 20: Period Six Histogram

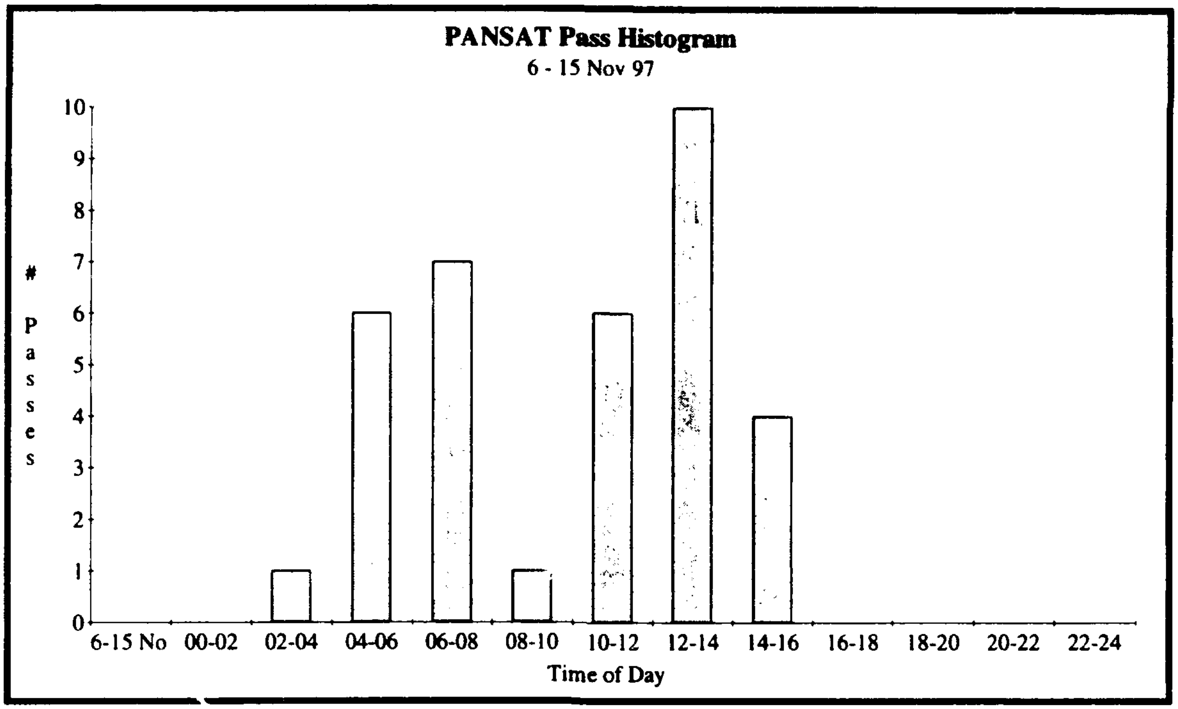

Figure 21: Period Seven Histogram

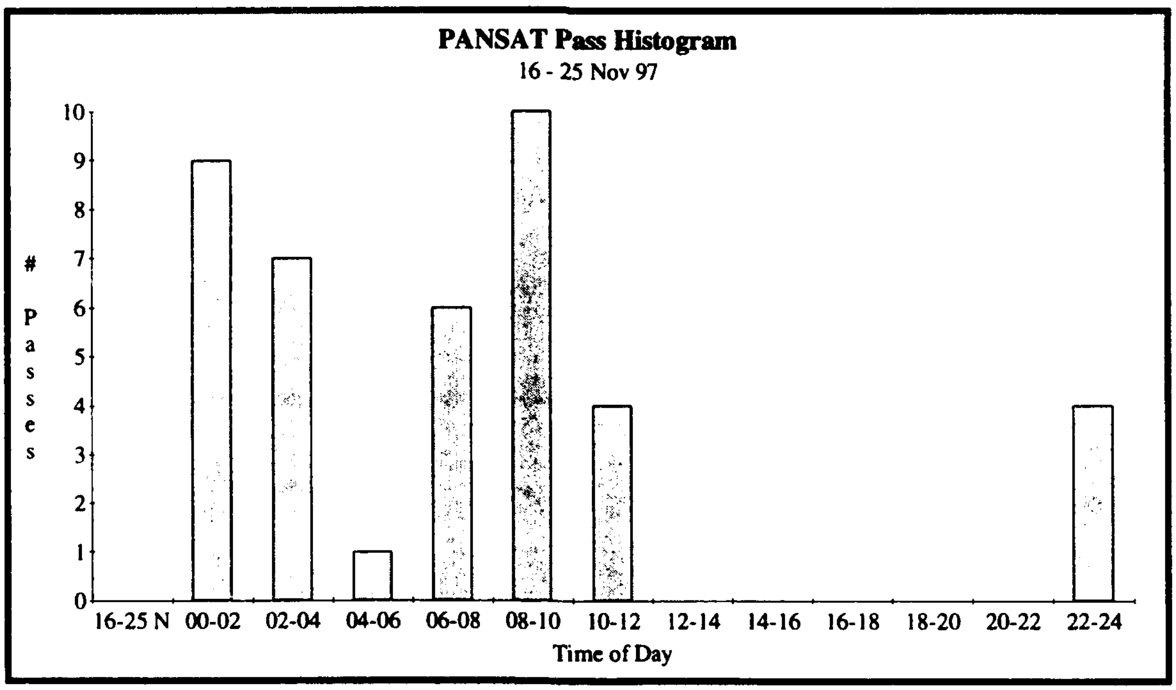

Figure 22: Period Eight Histogram

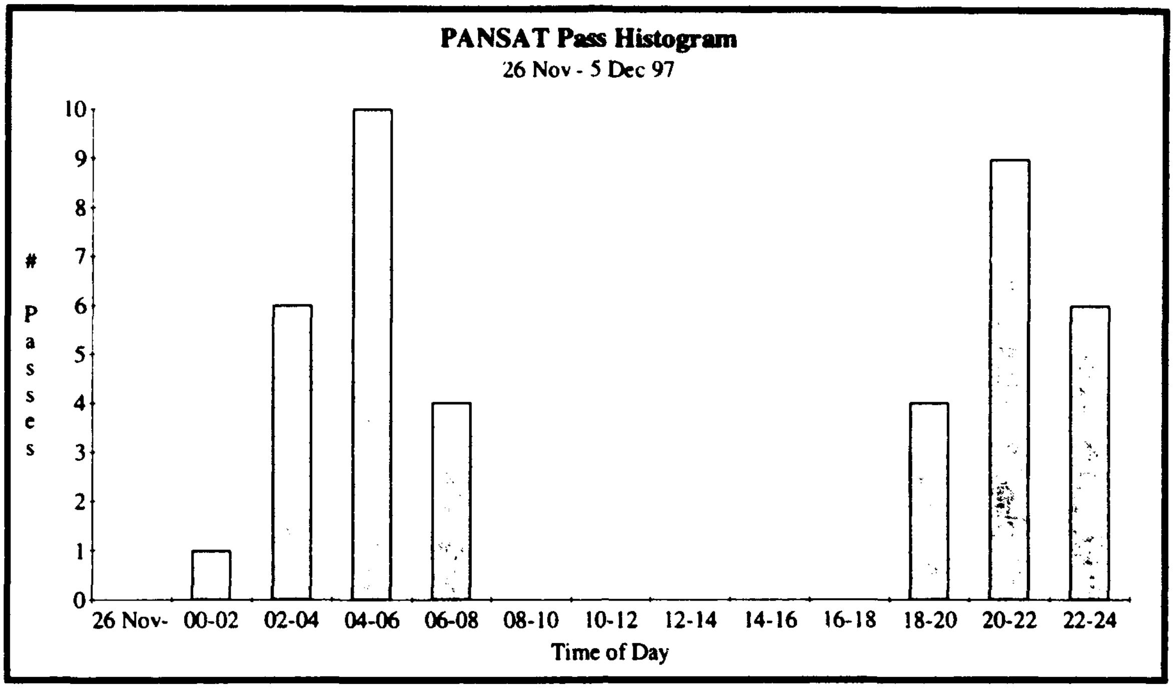

Figure 23: Period Nine Histogram

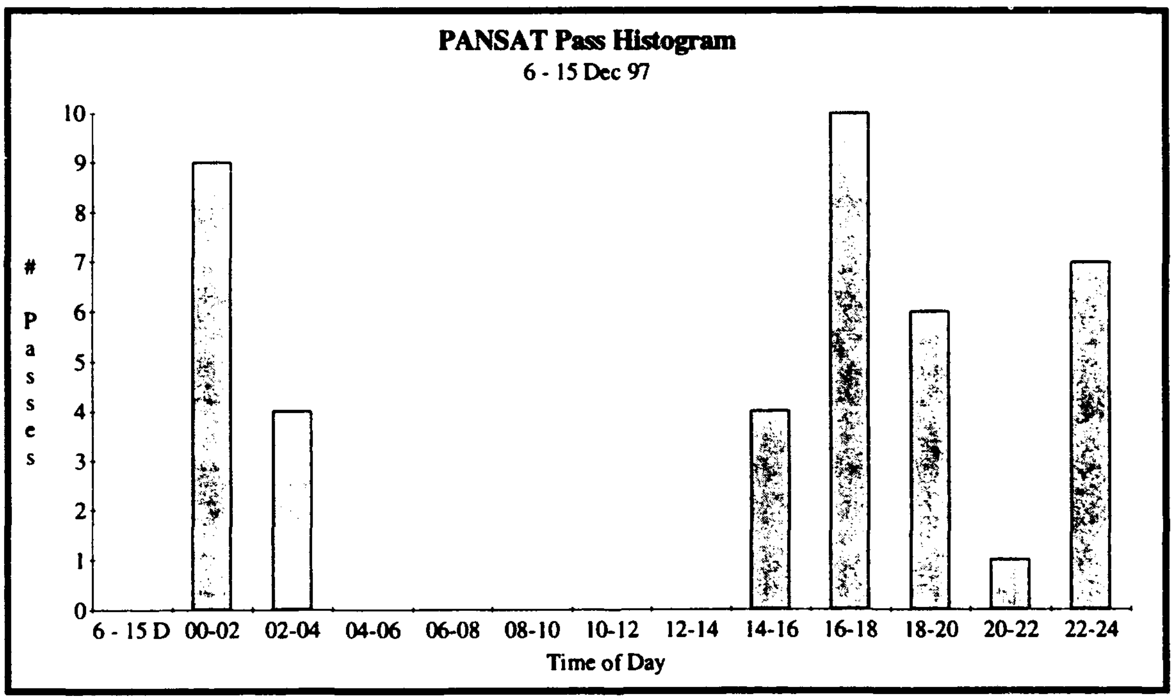

Figure 24: Period Ten Histogram

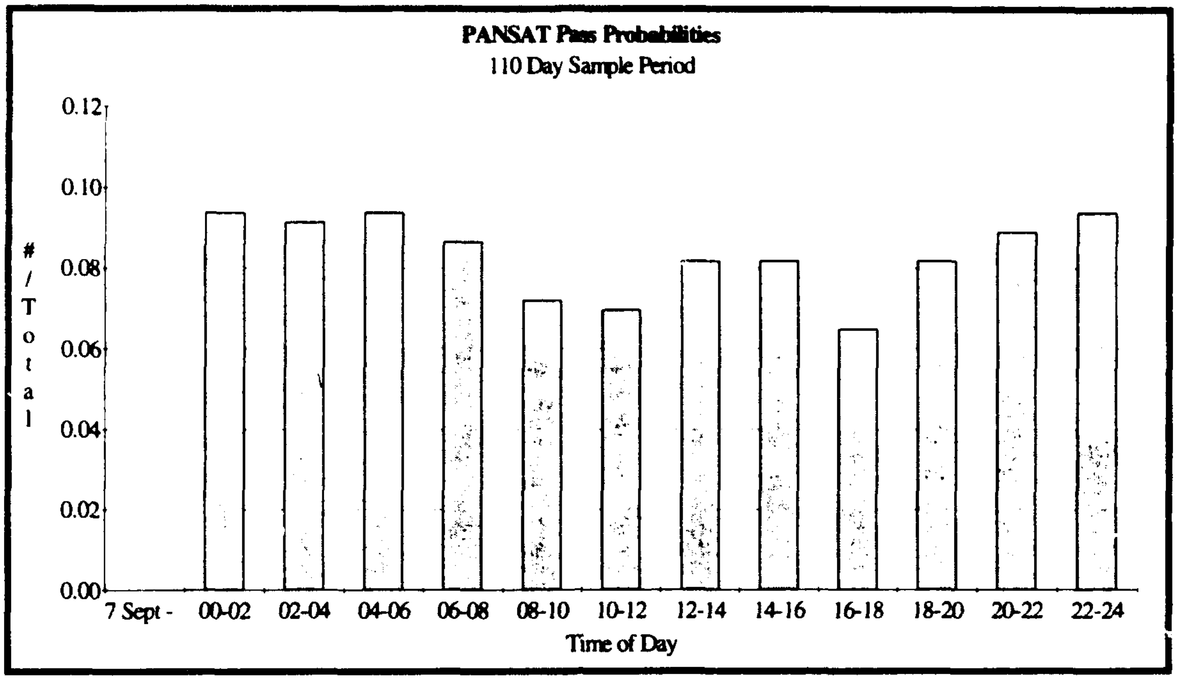

Figure 25: Probabilities for 110 Day Sample

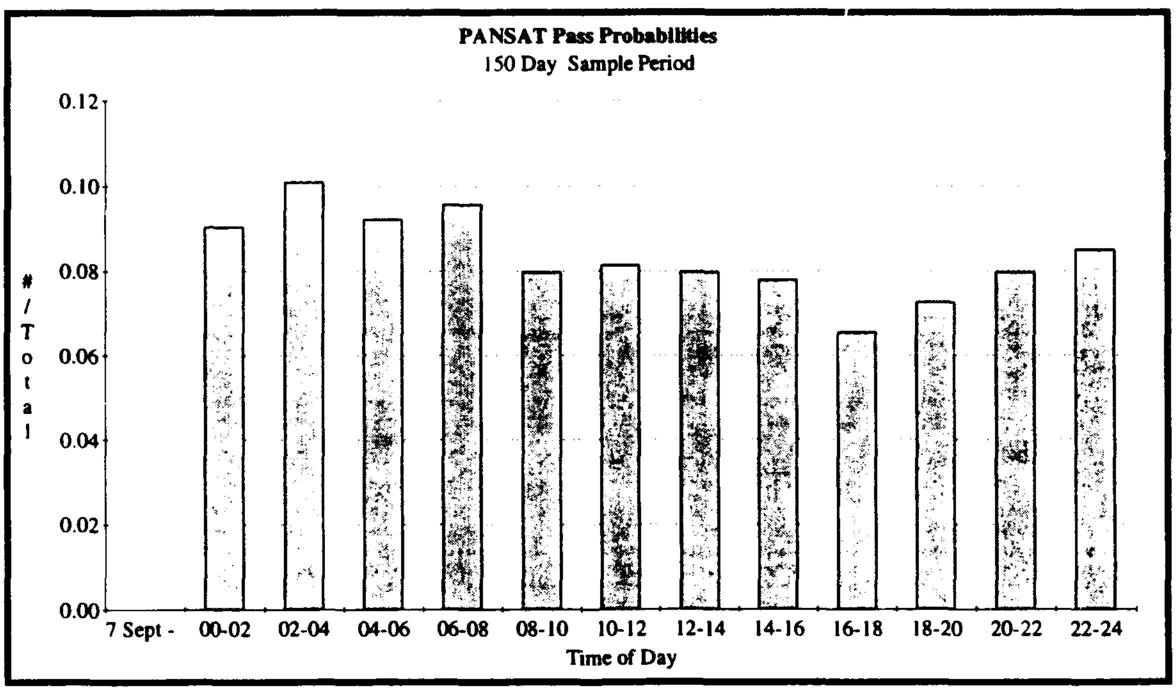

Figure 26: Probabilities for 150 Day Sample

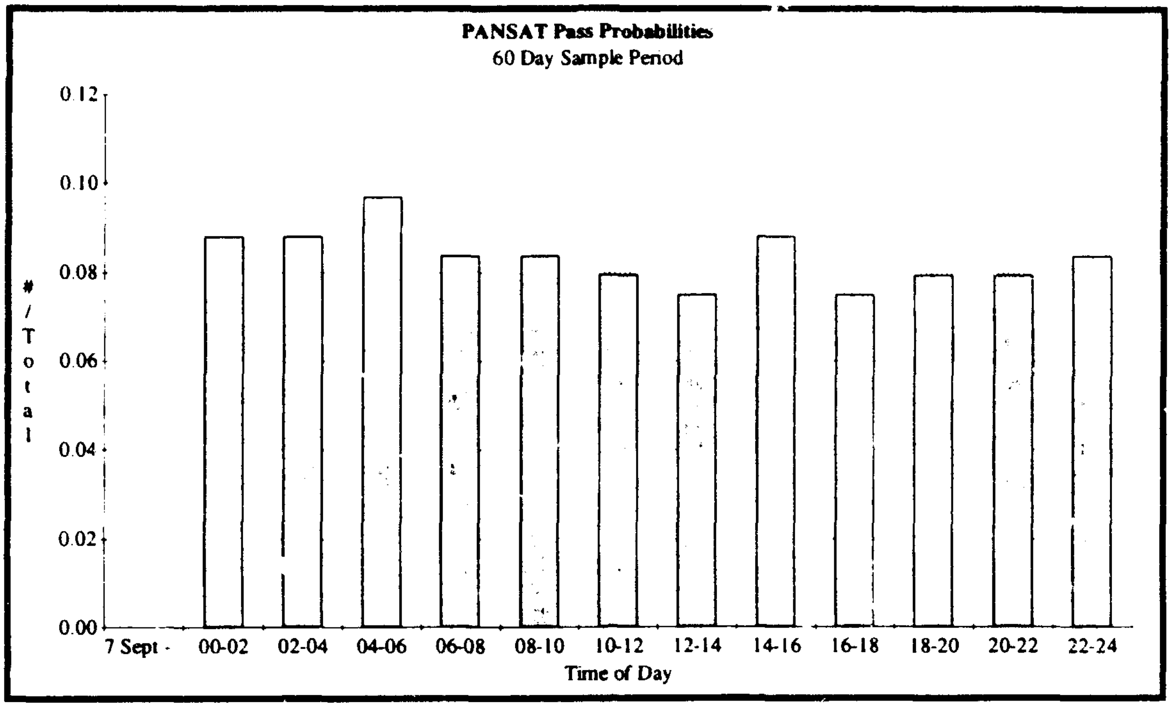

Figure 27: Probabilities for 60 Day Sample

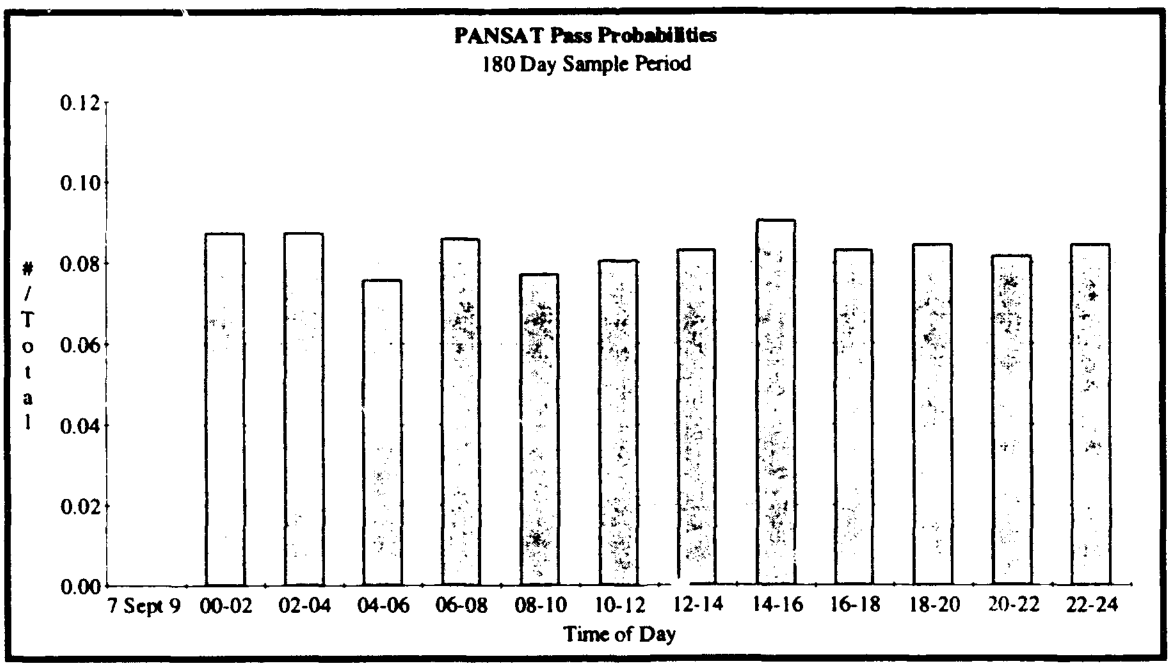

Figure 28: Probabilities for 180 Day Sample

LIST OF REFERENCES

1. Panholzer, R. and Sakoda, D. J., "Proposal for PANSAT (Petite Amateur Navy SATellite," proposal to Amateur Satellite (AMSAT) Corporation, 5 April 1989.

2. Naval Research and Development Command, Subject: PANSAT Program Review and Recommendations, 6 April 1993.

3. Department of Defense Military Standard MIL-STD-499B, *Systems Engineering Management Guide (Working Draft),* May 1992.

4. Weiding, D., Vendrasco, R., Finnegan, M., Hunt, L., Mihal, J., Miller, J., Turner, M., Zoppa, R., "PANSAT Systems Review," report of group project for AA-4831 (Spacecraft Systems II) to Prof. I. M. Ross, 10 June 1994.

5. Space Systems Academic Group Engineering Staff, "PANSAT Engineering Design Review," report of findings for technical program review, March 1994.

6. Brown, A. O., *Direct Sequence Spread Spectrum Binary Phase-Shift-Keyed (BPSK) Communication Subsystem for PANSAT,* Master's Thesis Naval Postgraduate School, September 1993.

7. Ellrick, D. A., *An Antenna Design for PANSAT Using NEC,* Master's Thesis, Naval Postgraduate School, June 1991.

8. Space Systems Academic Group, "PANSAT Functional Requirements," working document (SSD-S-SY000) for the PANSAT project, November 1993.

9. Horning, J., "PANSAT Digital Control System Hardware Design Description," working document (SAG-D-PA:002) for the PANSAT project, March 1994.

10. Ross, I. M., Course notes for AA-4831, Spacecraft Systems II, April 1994.

11. Rich, M., George, G., Shaw, J., Grindle, C., Kirschbaum, A., Lamb, J., Marshall, L., Vincent, G., "PANSAT Test Plan," report of group project for AA-4831 (Spacecraft Systems II) to Prof. I. M. Ross, 10 June 1994.

12. Department of Defense Military Standard MIL-STD-1540B, *Test Requirements for Spacecraft,* 1982.

13. NASA Goddard Space Flight Center, Specification for Small Shuttle Payloads Project, *Customer Accomodations and Requirements Specifications,"* October 1993.

14. Sakoda, D. J. *Structural Design, Analysis, and Modal Testing of the Petite Amateur Navy Satellite (PANSAT),* Master's Thesis Naval Postgraduate School, September 1992.

15. U. S. Federal Communications Comissions, *Code of Federal Regulations, Part 80 to End,* Section 97.313., U. S. Government Printing Office, Washington DC, 1992.

16. Department of Defense Military Standard MIL-STD-1541B, *Electromagnetic Compatibility Requirements for Space Systems,* 1989.

17. Defense Systems Management College, *Test and Evaluation Management Guide,* Fort Belvoir Virginia, March 1988.

18. Memorandum of Agreement Between the USAF Space and Missile Test Center, Small Vehicle Programs Office and The Naval Postgraduate School for the Integration, Launch, and Spaceflight of NPS-901 Petite Amateur Navy Satellite (PANSAT), April 1994.

19. Cuff D., *Petite Amateur Navy Satellite (PANSAT) Lifetime and Reentry Prediction,* Master's Thesis Naval Postgraduate School, June 1994.

20. Traufler, P. E., *TRAKSAT Version 3.0 Instruction Manual,* 1993.

21. Chobotov, V. A., *Orbital Mechanics,* American Institute of Aeronautics and Astronautics, 1991.

22. Naval Research Laboratory, Naval Center for Space Technology document # SSD-D-061, *Procedure for the Preperation of Program Plans,* March 1989.

23. Naval Research Laboratory, Naval Center for Space Technology document # SSD-D-033, *General Work Breakdown Structure, Code 8100,* October 1987.

BIBLIOGRAPHY

1. Agrawal, Brij N., *Design of Geosynchronous Spacecraft,* Prentice-Hall, Inc., 1986.

2. Bate, Roger R, Mueller, Donald D., White, Jerry E., *Fundamentals of Astrodynamics,* Dover Publications, Inc., 1971.

3. Devore, Jay L., *Probability and Statistics for Engineers*, Brooks/Cole Publishing Company, 1991.

4. Freeman, Roger L. Telecommunication Transmission Handbook, Third Edition, John Wiley and Sons, Inc., 1991.

5. Larson, Wiley J., Wertz, James R., *Space Mission Analysis and Design,* Microcosm Inc. and Kluwer Academic Publishers, 1992.

6. Schweber, William, *Electronic Communication Systems,* Prentice-Hall, Inc., 1991.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 052 Naval Postgraduate School Monterey, California 93943-5101	2
3.	Dr. Rudolph Panholzer Chairman, Space Systems Academic Group Code SP Naval Postgraduate School Monterey, California 93943-5002	1
4.	Commander, Naval Space Command ATTN: N112 5280 4th Street Dahlgren, Virginia 22448-5300	1
5.	Dr. I. Michael Ross Code AA/RO Naval Postgraduate School Monterey, California 93943-5002	5
6.	Captain Michael A. Cervi Code CC/CE Naval Postgraduate School Monterey, California 93943-5002	1
7.	Mr. Mark Powell Code 8101.1 Naval Research Laboratory Washington DC 20375-5320	1
8.	LCDR Markham K. Rich Fighter Squadron 102 NAS Oceana Virginia Beach, Virginia 23460	4