A GROUND STATION FOR THE AMATEUR SATELLITE SERVICE

by

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(ABSTRACT)

This report presents the design of a ground station for performing satellite communications using amateur radio satellites. The resulting design integrates commercially available hardware and software to provide effective communications using all current amateur satellite analog and digital operating modes. The station is capable of growth to support message forwarding, gateway, and satellite monitoring and control functions. The acquisition plan spreads the station's acquisition over several years to keep costs within an individual's budget, and maintains flexibility to adapt to changes in satellites and communications modes available over the station's life. The station's major design drivers are sufficient link budget for reliable communications, the station's life cycle cost, ensuring radio frequency energy fields are at safe levels, placement of antennas and supports to comply with local architectural restrictions, and selection of a 435 MHz transceiver for the station.

This project illustrates the ability of individuals or small groups to economically acquire effective satellite communications capability by integrating largely off-the-shelf hardware and software. In conjunction with small, relatively low-cost satellites, this ability places space communications and related research within reach of groups otherwise excluded from participating in satellite programs.

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To my wife, Ellen, for her understanding and support for the past three years - I'm sure she didn't expect to play the role of "single mom" when I started this degree program. And to my son, Marcus, for having far more patience than anyone should expect of a two-year-old for allowing "Daddy to do his homework." Thanks to both of you - your encouragement and support helped make this moment possible.

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To my managers and co-workers at Dynamics Research Corporation - thanks for your support, encouragement, and for letting me tie up the office laser printer.

Special thanks to Andy MacAllister, WA5ZIB, and Presley Smith, N5VGC, for their encouragement and for sharing with me their first-hand experience on what works and what doesn't! 73 guys, and I'll "see" you on the 'birds!

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LIST OF ACRONYMS

AFC	Automatic Frequency Control
AFSK	Audio Frequency Shift Keying
AGC	Automatic gain Control
AMSAT	Radio Amateur Satellite Corporation
AMSAT, NA	Radio Amateur Satellite Corporation of North America
AOS	Acquisition of Signal
ARB	Architectural Review Board
ARRL	American Radio Relay League
BER	Bit Error Rate
bps	bits per second
BPSK	Bi-Phase Shift Keying
CBBS	Computer Bulletin Board Systems
CSDP	Command Station Development Program
CW	Continuous Wave
DSP	Digital Signal Processing
EIRP	Effective Isotropic Radiated Power
FCC	Federal Communications Commission
FM	Frequency Modulation
FSK	Frequency Shift Keying
HF	High Frequency
HH HOA	Hastings Hunt Homeowners Association
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LHCP	Left Hand Circular Polarization

OSCAR	Orbiting Satellite Carrying Amateur Radio
Ps	Received Signal Power
RF	Radio Frequency
RHCP	Right Hand Circular Polarization
RS	Radio Sport
SAREX	Shuttle Amateur Radio Experiment
SNR	Signal to Noise Ratio
SSB	Single Side Band
SWR	Standing Wave Ratio
TNC	Terminal Node Controller
VITA	Volunteers In Technical Assistance

1. INTRODUCTION

1.1 Introduction

Inexpensive microcomputers and VHF/UHF radios now enable small organizations, researchers, and individuals to acquire and operate affordable satellite ground stations. These ground stations integrate off-the-shelf and modified equipment to provide effective communications using a variety of satellites and operating modes.

Much of this equipment was developed by the Amateur Satellite Service. The Amateur Satellite Service consists of spacecraft and ground stations developed and operated by amateur radio operators to experiment with satellite communications, demonstrate new technology, and provide communications services that take advantage of global access provided by satellite systems. Figure 1-1 illustrates a typical amateur satellite system consisting of ground station, satellite, and other satellite users. Figure 1-2 illustrates the elements of a typical amateur satellite ground station.

Amateur satellite ground stations are typically assembled and operated by individuals or small groups. Some stations are sponsored by academic and research institutions. These stations usually operate a mix of commercial equipment (sometimes with small modifications performed by the owner) and equipment built by the owner from kits, published plans, and occasionally from scratch. This mix of commercial and customized equipment provides reliable, cost-effective access to the amateur satellites.

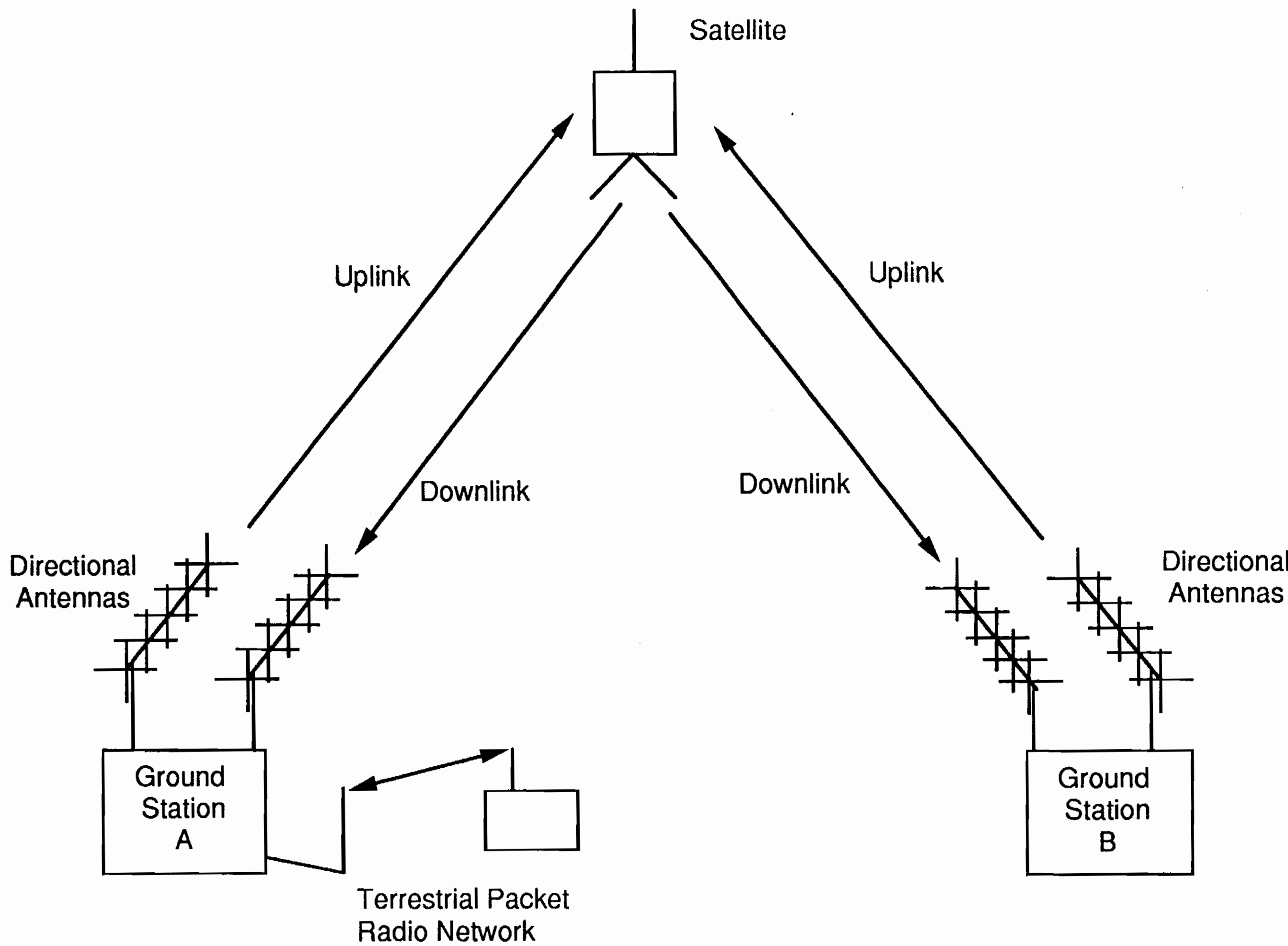

Figure 1-1 Amateur Satellite System

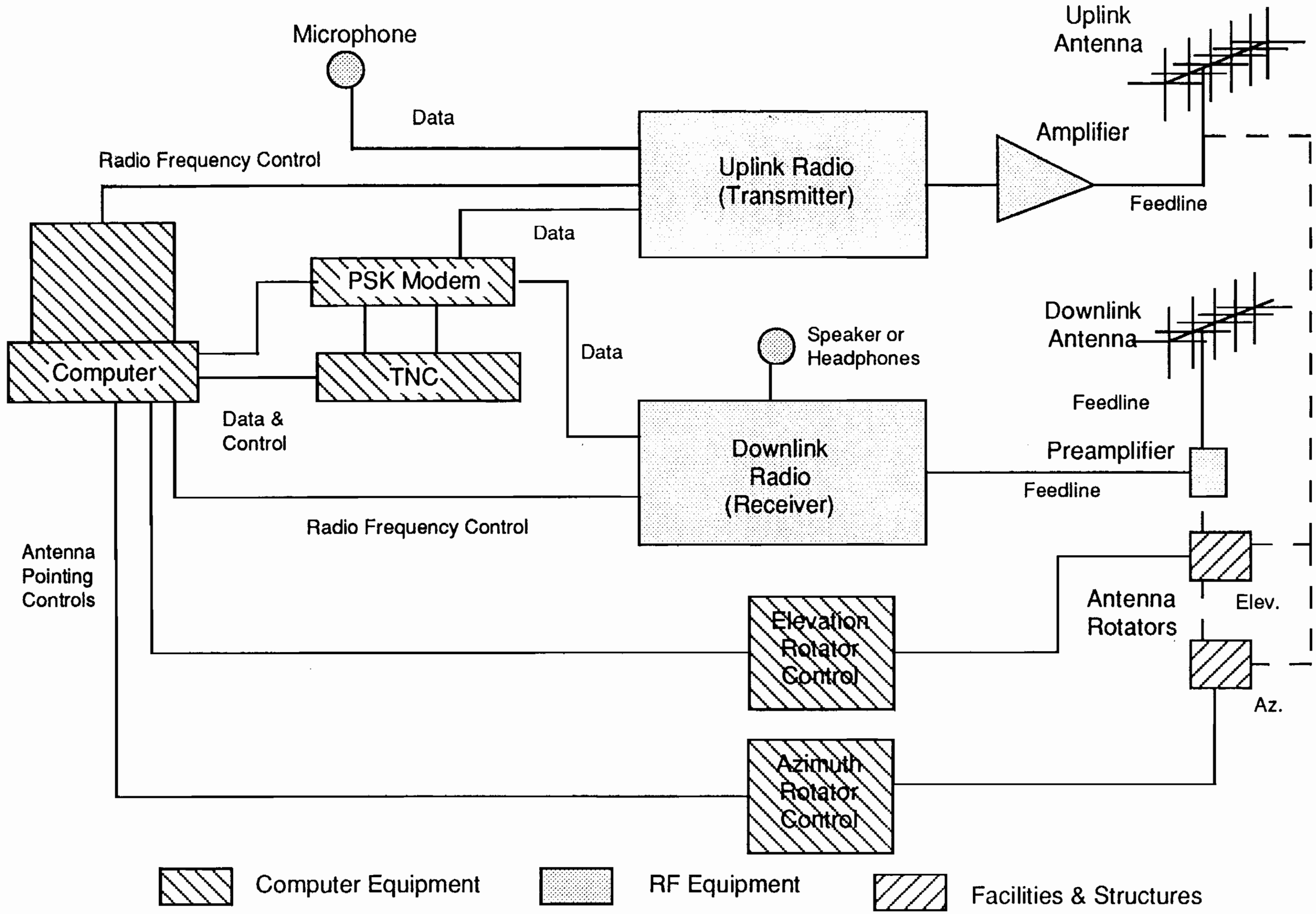

Figure 1-2 Amateur Satellite Ground Station Elements

1.2. The Amateur Satellite Service

The Amateur Satellite Service was born in 1961 with the launch of Orbiting Satellite Carrying Amateur Radio (OSCAR) 1. OSCAR 1 carried a simple battery powered beacon transmitting the characters "HI" in International Morse Code. Subsequent satellites have carried analog and digital transponders and a variety of communications and scientific experiments. Many national and international organizations have developed amateur satellites, including the United States, several European nations, the Soviet Union, and Japan. The Radio Amateur Satellite Corporation (AMSAT) and AMSAT North America (AMSAT, NA), the U.S. member of AMSAT, have sponsored many of these satellites.

These satellites support a mix of analog and digital communications. Table 1-1 summarizes the "modes" (uplink and downlink frequencies and modulation) used by amateur satellites.[1] Voice communications use real-time relay through satellites in Low Earth Orbit (LEO) and in highly elliptical Molniya orbits. Digital communications employ real-time relay and store-and-forward modes using satellites in LEO.

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[1]Satellite "modes" refer to the frequency bands used for uplink and downlink, versus the usual non-satellite use of "mode" to the type of modulation used (e.g. SSB, FM, etc.). Satellite modes were named in sequence of their first use, after the country of origin, or to follow commercial radio engineering practice.

Table 1-1 Amateur Radio Satellites Operating Modes

Mode	Uplink (MHz)	Downlink (MHz)	Modulation	Satellites Using
A	145	29	Analog (CW, Voice)	RS-10/11,RS-12/13
B	435	145	Analog (CW, Voice)	AO-10,AO-13,AO-21
JA	145	435	Analog (CW, Voice)	AO-13,FO-20
JD	145	435	Digital	UO-14,AO-16,WO-18,LU-19, FO-20,UO-22,KITSAT
L	1269	435	Analog (CW, Voice)	AO-13
S	435	2400	Analog (CW, Voice)	AO-13
NA	145	145	Digital, Voice	Mir, SAREX
NA	NA	145	Digital, Digitized Voice	DO-17

Most amateur satellites provide communications relay services (real time or store-and-forward). Real-time communications use Modes A, B, J, L, and S.[2] Store-and-forward communications satellites use Mode JD.[3] Several satellites broadcast sensor and experiment data in addition to communications services. WO-18 and UO-22, for example, broadcast digitized images taken by their on-board cameras. Table 1-2 lists the amateur satellites in use in early 1992 and their communications capabilities.

The equipment to use these satellites is readily available and is inexpensive compared to commercial satellite ground stations. Additional requirements for using the amateur satellites are an amateur radio license authorizing use of the frequency band covering the satellite uplink and the proper communications equipment. Communications must comply with the regulations prohibiting commercial traffic from amateur radio stations.

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[2]Mode J is sometimes identified as Mode JA, where the "A" designates analog, to differentiate it from the digital Mode JD.
[3]These satellites are known generically as "Pacsats" or "Microsats".

Table 1-2 Amateur Radio Satellites In Service

Satellite	Sponsor	Launched	Orbit	Payload(s)
AO-10 (Phase 3B)	AMSAT	June 1983	Molniya	Analog transponders
AO-13 (Phase 3C)	AMSAT	June, 1988	Molniya	Analog transponders
UO-14 (UoSat 3)	Univ. of Surrey, UK	January, 1990	LEO	Digital transponder (High speed)
AO-16 (Pacsat)	AMSAT, NA	January, 1990	LEO	Digital transponder
DO-17 (Dove)	AMSAT Brazil	January, 1990	LEO	Digitized Voice
WO-18 (Webersat)	Weber State Univ.	January, 1990	LEO	CCD Camera
LU-19 (Lusat)	AMSAT Argentina	January, 1990	LEO	Digital transponder
FO-20 (Fuji-Oscar	Japan	February, 1990	LEO	Analog and Digital transponders
AO-21 (RS-14)	U.S.S.R.	Late 1990	LEO	Analog transponders
UO-22 (UoSat 5)	Univ. of Surrey, UK	Summer,1991	LEO	Digital transponder (High speed), CCD Camera
KITSAT	Univ. of Surrey, UK KAIST, ROK	Summer, 1992 (Planned)	LEO	Digital transponder (High speed), CCD Camera
RS-10/11	U.S.S.R.	June, 1987	LEO	Analog transponders
RS-12/13	U.S.S.R.	Late 1990	LEO	Analog transponders
Mir	U.S.S.R.	Since 1988	LEO	FM Voice and digital
SAREX	NASA, AMSAT, NA	Selected Shuttle Missions	LEO	FM Voice and digital

1.3 Why This Topic

The goal of this project is to perform systems engineering, tradeoffs, and analyses to design a satellite ground station for the amateur satellites. The design will be based on commercially available VHF/UHF radio equipment and computers, along with modified and custom equipment where cost-effective. This ground station will support communications using current and anticipated satellites in the Amateur Satellite Service. The ground station's design will allow expansion or enhancements to support new satellites or modes, and participation in international message relaying, gateway operations, telemetry capture, and satellite control.

Designing the ground station requires a systematic systems engineering approach. Selection of operating modes and satellites determine the operating frequency and type of radio equipment required. Tradeoffs, some specific to the individual station, must be made to optimize equipment performance versus money spent. This project requires development and definition of a mission and development of quantitative and qualitative criteria for system performance. Design analysis and tradeoffs are based on real equipment and operating locations.

The author intends to design this ground station to support his own participation in Amateur Satellite communications.[4] The author will conduct design tradeoffs against his specific requirements, rather than designing for a generalized situation. He must therefore develop realistic schedules and cost estimates/budgets for this project. This project enables the author to pursue professional and avocational interests while accomplishing the goals of the MS Systems Engineering program.

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[4]Design decisions will reflect the conditions at the author's home address and the author's intent to install the design resulting from this effort.

2. REVIEW OF LITERATURE

The amateur satellite program is over thirty years old - almost as old as the entire space program. Considerable information has been published covering the theory and practice of satellite ground station design and operation for using the amateur satellites. This material includes handbooks on amateur satellite operations, feature articles and monthly columns in several amateur radio periodicals, and professional papers and conference presentations.

Davidoff provides an in-depth presentation of the history, theory, and practice of amateur satellite operations.[5] Several chapters address in detail the ground station requirements and operations for the major amateur satellites in service in 1990-1991. The theory and recommendations presented are a primary basis for this project.

Berglund presents a "how to" approach to using the OSCAR-13 satellite.[6] His practical advice complements Davidoff. While Berglund is directly applicable only to OSCAR-13, his approach is applicable to other satellites.

Crisler and Smith discuss using the digital store-and-forward satellites.[7,8] Crisler focuses on the computer hardware, software, and operating techniques required to use these satellites. Smith describes capture and analysis of telemetry from amateur satellites. His information is especially useful for receiving the "Pacsat" downlinks.

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[5] Davidoff, Martin, PhD, K2UBC, The Satellite Experimenter's Handbook, American Radio Relay League, Newington, CT, 1990.
[6] Berglund, Keith A., WB5ZDP, A Beginner's Guide To Oscar-13, The Radio Amateur Satellite Corporation (AMSAT, NA), Washington, DC, 1989.
[7] Crisler, Mike, N4IFD, The Pacsat Beginner's Guide, The Radio Amateur Satellite Corporation (AMSAT, NA), Washington, DC, 1991.
[8] Smith, G. Gould, WA4SXM, Decoding Telemetry from the Amateur Satellites, The Radio Amateur Satellite Corporation (AMSAT, NA), Washington, DC, 1991.

The American Radio Relay League (ARRL) publishes handbooks on theory and practical equipment for satellite stations. The ARRL's UHF/Microwave Experimenter's Handbook provides detailed discussion and analysis of UHF and SHF theory and practice, including several bands used by amateur satellites.[9] The ARRL Handbook contains information on every facet of amateur radio, including satellites, and covers aspects of station construction not addressed in the UHF Handbook.[10]

Use of amateur satellites requires accurate prediction of visible passes and knowledge of the satellite's location with sufficient accuracy to point hi-gain, directional antennas. Davidoff and Berglund cover this subject, Davidoff in considerable detail. Antonio describes the operation of one of the current leading satellite tracking programs.[11]

These sources provide a consensus on the broad requirements for an amateur satellite ground station capable of using the major satellites and operating modes:

- Ability to receive analog (e.g. Continuous Wave (CW) and Single Side Band (SSB)) and digital (audio frequency shift keying (AFSK), bi-phase shift keying (BPSK), and frequency shift keying (FSK)) signals on the 29 MHz, 145 MHz, and 435 MHz bands.[12] Good weak signal reception on all bands is essential.

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[9] The ARRL UHF/Microwave Experimenter's Manual, American Radio Relay League, Newington, CT, 1990.

[10] Hale, Bruce S., KB1MW, ed., The ARRL Handbook for the Radio Amateur, American Radio Relay League, Newington, CT, 1989.

[11] Antonio, Franklin, InstantTrack V1.00 User's Manual, 1989.

[12] These are the downlink bands for Modes A, B, JA, JD, and L.

- Ability to transmit analog and digital signals on the 145 MHz and 435 MHz bands.[13] Transmitter output power should be 25-100 W, depending on antenna gain and distance to the satellite.

- Personal computers are extremely useful for obtaining satellite tracking data and predicting passes; their use is deemed essential by serious operators. Computers are required to use any of the digital operating modes and to automate antenna pointing.

- High gain, directional antennas using circular polarization are required for satellites in highly elliptical Molniya orbits (AO-10, AO-13, Phase 3D). Tracking and antenna pointing is required, however manual antenna pointing is practical.

- Low gain, linearly polarized, omnidirectional antennas are usually effective for LEO satellites, although directional antennas greatly enhance performance. Computer-controlled antenna pointing is necessary when using directional antennas to limit the station operator's workload.

- Satellite communications circuits are affected by doppler shift, requiring retuning of receivers and transmitters during a pass. Retuning can be performed manually by an operator, or be automated to reduce operator workload. Automatic frequency control (AFC) of receivers is desirable for reliable reception of satellite downlinks when using digital modes.

[13] These are the uplink bands for Modes A, B, JA, and JD.

- A complete station for the primary analog and digital modes can be purchased from commercial vendors serving the amateur radio community. The operator must assemble and integrate the station. Some equipment may require slight modification or adjustment to work on some modes. Construction of station elements is possible, however the complexity and capability of commercial gear makes this less practical for transmitters and receivers. Older equipment can often be adapted to satellite use, realizing substantial savings over new equipment at the price of more difficult maintenance. Antennas, interface equipment, and operator aids are more suitable for home construction.

- Fully assembled commercial equipment is less available for Modes L and S. There are commercial sources for transmit and receive converters and antennas, but more assembly and integration of equipment by the station owner is required than for equipment for lower frequencies.

The above consensus forms the basis for the station design presented here. Numerous articles in several amateur radio periodicals and discussions with current satellite users support this consensus and provide details on specific points of assembling or operating a station. These articles and conversations are referenced wherever they were used in this project.

3. MATERIALS AND METHODS

3.1 Systems Engineering Process

The design of the satellite ground station follows standard systems engineering practice.[14] Systems engineering analysis, design, and assessment follow the steps listed below:

- Mission: Describe and prioritize the mission, goals, objectives, and constraints for the ground station.

- Operations and Support Concept: Describe how the station will be operated and supported during normal use.

- System Requirements: Flow-down the station's mission, goals, objectives, and constraints and the operations and support concept into top-level qualitative and quantitative requirements for the major station elements. Identify target or threshold values for all requirements.

- Functional Breakdown and Allocation: Describe the station in terms of the operating and support functions necessary to meet the top-level system requirements, and allocate functions and requirements among the station elements.

- System Design and Tradeoffs: Develop a system design for all the major station elements, performing design tradeoffs among the elements individually and collectively to optimize the station's performance.

[14] Blanchard, Benjamin S. and Wolter J. Fabrycky, Systems Engineering And Analysis, Prentice-Hall, 2nd Edition, 1990, Chapter 9.

- Test Plan: Develop a plan to test and verify each element of the station and the station as a whole meets performance requirements.

- Acquisition Plan: Develop a plan for acquiring the station, including partitioning the acquisition into distinct phases.

- Recommended Design: Based on the baseline design and tradeoffs, synthesize a design that accounts for all quantitative and qualitative requirements.

Activities taken for each step in this process are detailed in Section 5.

3.2 Link Analysis

Analysis of the communications link between ground station and satellite is a critical part of the design process. The factors affecting the quality of the signals received at each end of the link include:

- Distance between satellite and ground station (slant range), determined by satellite altitude, ground station antenna elevation angle, and distance from ground station to the sub satellite point.[15]

- Operating frequency for uplink and downlink.

- Amount of satellite transponder power allocated to the communications channel.

[15] The sub satellite point is the point on the Earth's surface where the satellite is directly overhead.

- Ground station transmitter power and losses between transmitter and uplink antennas.

- Gain and polarization of satellite and ground station uplink and downlink antennas.

- Noise figure, gain, and losses in ground station and satellite receive systems, including preamplifiers, feedlines, connectors, and receivers.

- Noise temperature of region where antennas are pointing - sky temperature for the ground station, and the Earth's noise temperature for the satellite, and strength of local man-made noise sources.

- Bandwidth of communications channel, or of ground station and satellite receive systems.

The literature referenced in Section 2 discusses calculation of communications links in detail.[16,17] The link analysis in this project and report uses the method presented by Davidoff.[18] This method determines the signal strength and signal-to-noise ratio (SNR) at the receiving end of the link. It accounts for signal gains, losses, and noise sources between the transmitter and the receiver. Noise sources controllable within the station design include feedlines, connectors, antennas, and preamplifiers. Calculations for losses and noise factors (noise temperature) from feedlines and connectors are based on material in the ARRL UHF Experimenter's Handbook.[19]

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[16] Davidoff, Chapters 9 and 13.
[17] UHF Experimenters Handbook, Chapters 5 and 7.
[18] Davidoff, Chapters 9 and 13.
[19] UHF Experimenters Handbook, Chapter 5.

Local man-made noise sources are generally uncontrollable and are ignored in the basic link analysis. Signal losses in the ionosphere and atmosphere are also uncontrollable and are ignored. Additional signal margin in the link can partly compensate for these losses. Signal losses from polarization mismatch are addressed by selecting antennas with the proper polarization (circular or linear) for each satellite. The ability to switch circular antenna polarization from right-hand to left-hand can compensate for Faraday rotation-induced fading of the satellite's circularly polarized downlink signals.

The downlink from the satellite to the ground station is usually more critical than the uplink. The amount of transponder power available to a single downlink channel is 10 to 20 dB less than the power available for the uplink. The downlink therefore becomes the main performance factor affecting selection of ground station antennas, and with the receiver system determines the station's overall performance.

Appendix A describes in detail the method used to analyze ground station-to-satellite links. Analysis of the links is presented in Section 5.5.1.

3.3 Life Cycle Cost Analysis

Life cycle cost (LCC) analysis includes all costs associated with the development, acquisition, operations and support, and disposal of a system. LCC analysis for the amateur satellite ground station must deal with the unique aspects of amateur radio station construction and operations.

Amateur radio operators receive no monetary compensation. Systems engineering and planning activities for the ground station therefore have little-to-no monetary cost. The principle investment is the time to learn about satellite communications and investigate practical station assembly. This investment is itself considered a benefit of the hobby.

Equipment acquisition accounts for a major portion of the ground station's cost. As detailed in the station acquisition plan, equipment selection and phasing is designed to maximize the delivered performance while minimizing cumulative acquisition costs. An alternative that may be the least costly for a single phase should not be selected if it leads to higher acquisition or operating costs later for a more capable station.

Precise operating and support costs are difficult to quantify. Amateur radio stations operate on irregular schedules, making estimates of equipment usage difficult. Most stations are located at the operator's residence, eliminating many facility-related costs. The primary operating cost is electrical power, which is equivalent to the cost of running a few light bulbs. The station owner performs routine maintenance and repairs of simpler station equipment. Commercial equipment is very reliable. When something does fail, repairs are often performed by a factory-operated depot. The primary support costs are therefore parts, supplies, and a few factory repairs, while the operator's time is free. Operating and support costs are roughly equal for new commercial equipment from the various vendors. Used equipment, while cheaper to purchase, is usually more expensive to maintain, due to age, less available parts, and less factory support.

Disposal costs for amateur radio equipment are usually minimal. Much equipment can be sold. The remainder is broken up for parts or simply scrapped. The station owner's time is again free.

LCC analysis therefore requires several assumptions to enable any estimates to be made. Table 3-1 lists these assumptions and their supporting rationale. These assumptions are used to estimate station operating and support costs when required for equipment tradeoffs, and to estimate the life cycle costs presented in Section 5.8. The assumptions are based on the author's personal experience with amateur radio equipment and operating patterns.

3.4 Acquisition Planning

Although the cost of an amateur satellite ground station is small compared to commercial systems, it remains significant for individuals. Dividing station acquisition into phases spreads out the total acquisition cost over a longer time period. The station owner can adapt to changes in available satellites and ground station equipment, rather than committing too early to a particular configuration or performance level.

The station acquisition plan is organized around the satellite operating modes introduced in Table 1-1. Each mode provides a distinct capability, useful in and of itself. Each acquisition phase adds a new mode to the station's capabilities. For example, a reliable Mode A capability could be the first phase. Mode B or Mode JD could follow. In this approach, each phase builds on the capabilities already installed to add a new mode to the station. From a cost perspective, the goal is to smooth out equipment expenditures, minimizing the incremental cost for each phase within the constraints of minimizing total acquisition and life cycle costs.

The ground station acquisition plan is presented in Section 5.7. This plan can change as needed to accommodate changes in available satellites and evolution of the station owner's goals and interests.

Table 3-1 Life Cycle Cost Assumptions

Item	Assumption	Rationale
Radios	One major failure with factory repair every 5 years; 3 shop hours @ $75, $100 for parts	Low failure rates for equipment, but major failures are possible
Antennas	Replace small hardware parts after ten years @ $100	Weathering
Rotators	Dissasemble and clean major parts after ten years @ $100	Weathering
Cables & Connectors	Complete replacement every five years	Weathering
TNCs, Modems	No failures	12 VDC supply isolates equipment from supply line voltage spikes
Preamplifiers	Complete replacement of one preamp every five years	Failure mode is accidental transmission into unprotected unit
Power Amplifiers	Replace output transistors every five years @ $100	Failure mode is accidental transmission with no load connected
Other Electronics	No failures	Random failures possible, no data to predict
Computer Hardware	Replace motherboard or disk drive	See discussion in Section 5.5.2.2
Software	Complete upgrade after five years	Maintain current versions
Power	No cost to station	Included in household operating costs
HVAC	No cost to station	Included in household operating costs
Disposal Costs	None	All equipment can be sold used or scrapped at no cost

4. RESULTS

The analyses and tradeoffs described in Section 5 result in a satellite ground station design capable of supporting all analog and digital modes currently in use. The proposed station design achieves acceptable communications performance for Modes A, B, J, JD, and L.

Figure 4-1 depicts the primary satellite ground station equipment: radios, antennas, amplifiers and preamplifiers, feedlines, computer, modem and TNC, antenna rotator, and controllers. The Mode B station configuration is depicted. The TNC and satellite modems (PSK-1 and EM NB-96) used with Mode JD are shown for completeness - they are not used for Mode B. Omnidirectional antennas, transverters and power amplifiers, and preamplifiers used for Modes A, J, and L are not shown, but would be arranged similarly to the Mode B configuration.

Figure 4-2 summarizes the ground station's life cycle cost. It covers equipment acquisition and five years of operating and support costs. Equipment is acquired in turn for each operating mode according to the acquisition schedule. Operating and support costs are then incurred for the equipment beginning at the time of acquisition, based on the assumptions presented in Table 3-1..

The station's performance on AO-13's Mode S is marginal. This may not be a significant problem, however. The Phase 3D satellite, a replacement for AO-13, is expected to be in service by the time the Mode S station is acquired. Phase 3D's higher transponder power and antenna gain should provide Mode S performance several dB better than AO-13's, enabling effective communications with simpler equipment.

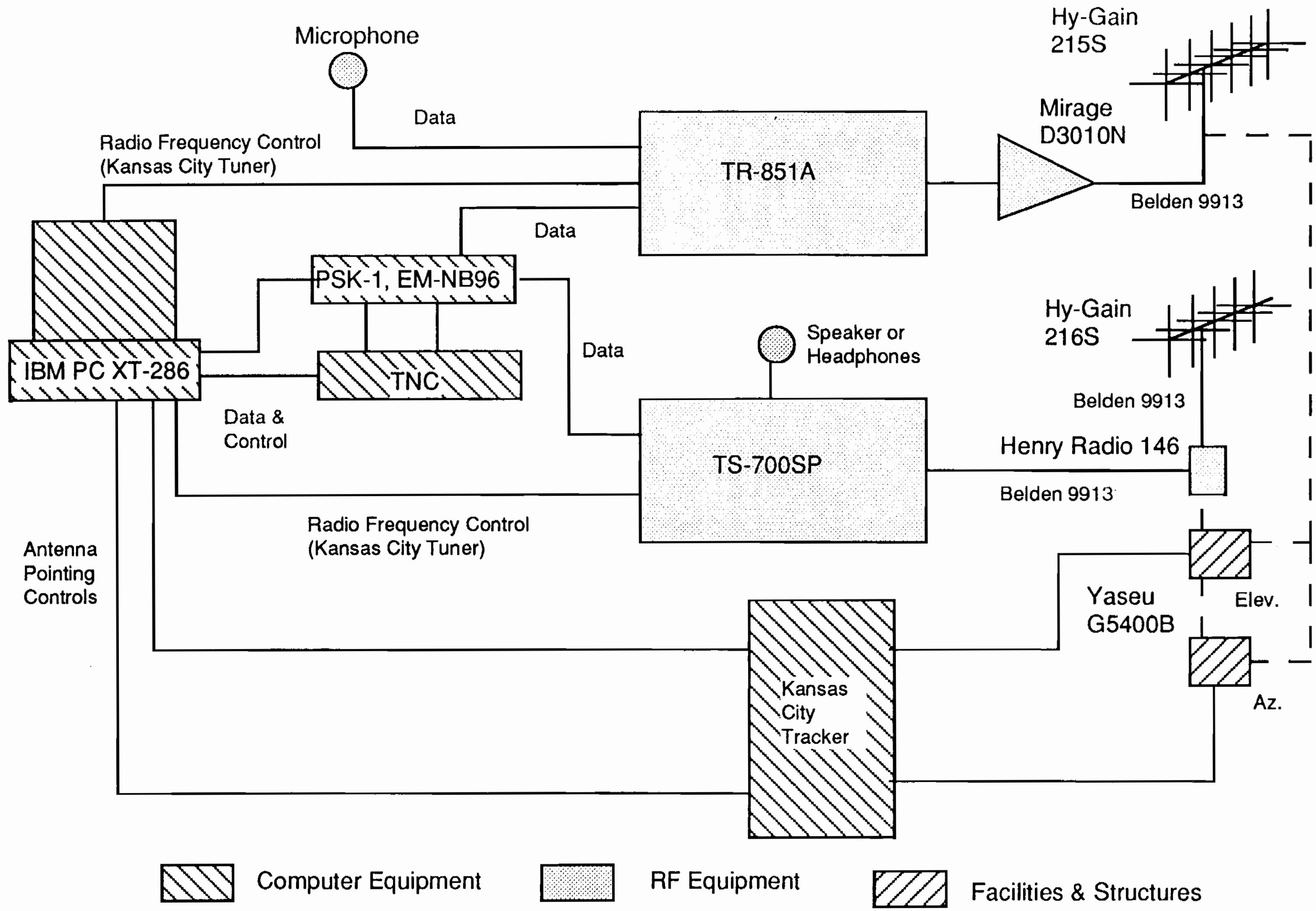

Figure 4-1 Satellite Ground Station Design

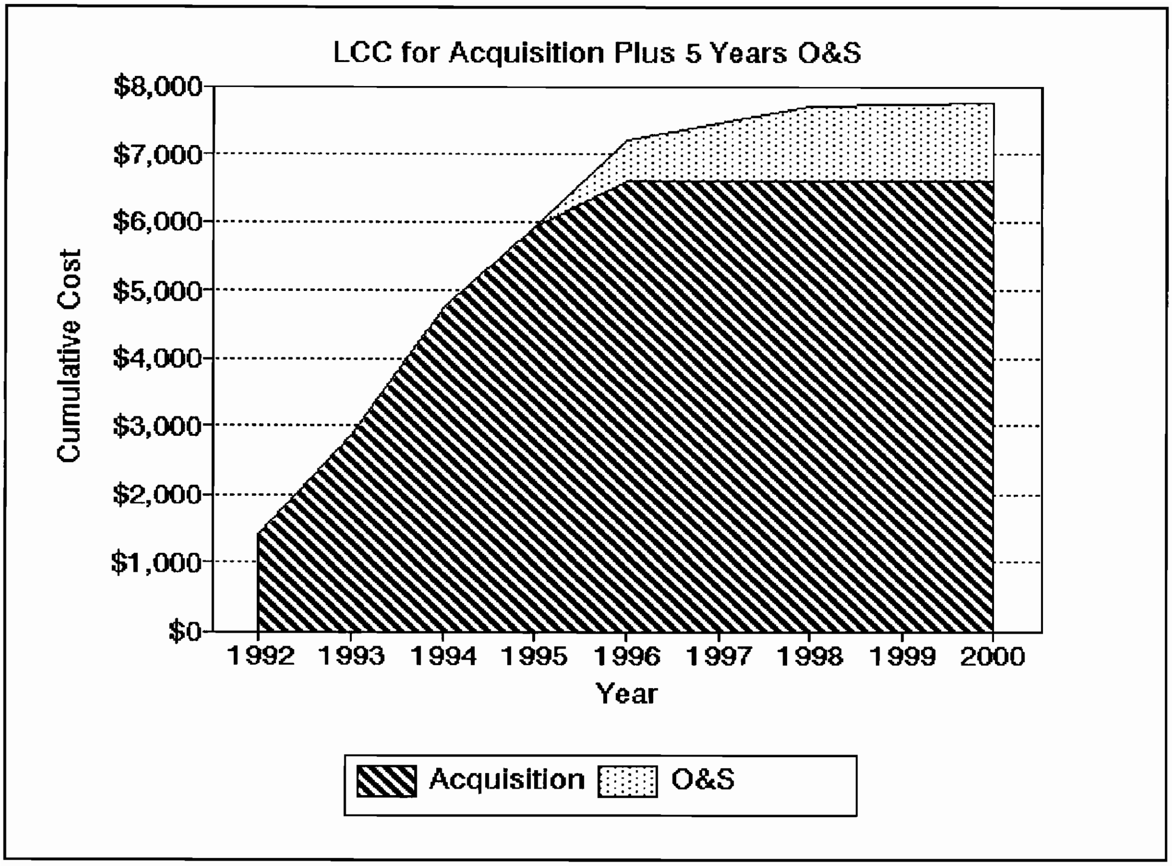

Figure 4-2 Satellite Ground Station Life Cycle Cost

5. DISCUSSION

This section presents the detailed systems engineering design, analyses, and tradeoffs leading to the recommended station design. Major sections address each of the following topics:

- Mission, Goals, and Objectives
- Operations and Support Concept
- Top-Level System Requirements
- Functional Breakdown and Allocation of Functions and Requirements
- System Design and Tradeoffs (includes link analysis, equipment, cost, system growth and flexibility, and other considerations)
- Recommended Design
- Test Plan
- Acquisition Plan

5.1 Mission, Goals, and Constraints

Systems engineering begins with a clear understanding of the of the satellite ground station's mission, goals, and objectives. The mission statement, goals, and objectives define top-level requirements for the station. Subsequent functional analysis and allocation, specifications, and performance assessment and optimization must support these top-level requirements.

5.1.1 Mission Statement

Monitor satellite downlinks and telemetry and conduct two-way communications using analog (CW, SSB, or Frequency Modulated (FM) voice) and digital modulation using current and planned communications satellites operating under the Amateur Satellite Service. Types of communications will include:

a. Receive broadcast messages from satellites and monitor satellite downlinks and telemetry signals.

b. Conduct two-way communications with other stations in real-time and using store-and-forward messaging.

c. Receive and forward satellite-transmitted messages, bulletins, and telemetry, and accommodate future automation of these tasks.

d. Permit growth to perform satellite telemetry capture, monitoring, and control functions under AMSAT's Command Station Development Program (CSDP).[20]

e. Permit growth to provide gateway service to other fixed and mobile amateur radio stations (located within two-way VHF/UHF communications range).[21]

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[20] Smith, 1991, Appendix K

[21] "Gateways" enable stations without satellite equipment to use a satellite by repeating their uplink signals and the satellite downlink over separate frequencies. Gateways supporting voice communications work in real time; gateways supporting digital modes may be real-time or use store-and-forward messaging.

5.1.2 Top-Level Goals and Constraints

a. Comply with Federal Communications Commission (FCC) regulations governing operation of ground stations for the Amateur Satellite Service.

b. Provide reliable communications on all modes, emphasizing two-way voice and digital store-and-forward communications.

c. Provide easy growth path and flexibility to support new modes and operating frequencies.

d. Allow for incremental installation and upgrade of equipment, with each increment providing a meaningful/useful capability.

e. Minimize incremental and life cycle costs for acquisition, installation, and operations/maintenance.

f. Comply with regulations and recommended practices for operator comfort and safety.

g. Provide a meaningful education experience in satellite communications technology and ground station operation.

h. Comply with land use and construction ordinances in Fairfax County, VA, and with architectural covenants and guidelines for the Hastings Hunt subdivision in Herndon, VA.

5.2 Operation and Support Concepts

5.2.1 Operation Concept

By law and its inherent nature, most amateur radio communications are experimental, educational, or casual.[22] Commercial-level signal quality and reliability is not required for most amateur communications. Communication occurs at indefinite intervals at the whim of the stations' operators.

The typical operating scenario for communicating during a satellite pass will be as follows:

- Obtain current keplerian element sets and operating schedules for amateur satellites and store in a format usable by the tracking software. Element sets are distributed as text files via several amateur satellites, the terrestrial amateur packet radio network, USENET newsgroups accessible via the Internet, and from several computer bulletin board systems (CBBS). Packet radio and the Internet will be the primary sources for element sets, with CBBS sources as back-ups. Element sets are usually distributed biweekly. For most amateur satellites, element sets even a month old have sufficient accuracy for prediction and tracking. The station operator must remove extraneous information not readable by the tracking software from the element set files. Operating schedules are distributed over the same channels as element sets.

[22] Emergency communications are the exception, but there has been little use to date of satellites in emergency or disaster communications. Satellites have been used in special situations, notably UO-11 to support the SkiTrek polar expedition and UO-14 for the Volunteers In Technical Assistance (VITA) and SatLife organizations.

- Predict upcoming usable passes. The tracking software data base is updated if necessary with the latest element set data. The software is then run to predict upcoming passes and display predicted antenna azimuth and elevation angles. Based on the satellite's schedule, time of the pass, and antenna pointing angles, the operator will plan usable passes for communications.

- Communicate during a pass. Before the pass starts, the operator will tune the station receiver and transmitter to desired frequencies and output power and point antennas in the direction predicted for Acquisition of Signal (AOS). Operation of station equipment will be verified to the extent practical, allowing for correction of minor discrepancies before the pass starts. During the pass, the operator will attempt to call and contact other amateur stations on a random basis (Mode A, B, JA, L, and S satellites) or upload and download messages and files (Mode JD satellites). Alternatively, the operator may capture telemetry broadcast by the satellite. If using Modes A, B, JA, L, or S, the operator may run the tracking software in real-time to provide antenna pointing and doppler correction information. If Mode JD is used, the station computer must run communications software, and precalculated antenna angles will be used for antenna pointing.[23] Operator aids (mechanical or automated) will be used to maintain correct relationship between uplink and downlink frequencies during the pass.

- Perform post-pass processing. The operator will close any data capture files opened during the pass, complete the station log, and reconfigure the station

[23]If automated antenna pointing is installed, the tracking software can run in the "background" during the pass.

equipment for the next satellite pass of interest. Equipment anomalies noticed during the pass will be investigated and corrected.

Initial operations of the satellite ground station will be ad-hoc, with no definite schedule except as dictated by visible passes of satellites of interest. As the operator builds experience with different satellites and modes, operations will begin to follow regular patterns. If operating activities move into message handling, satellite monitoring and control, or gateway service, regular operations will be required to provide what will have become an expected communications service or function.

5.2.2 Support Concept

During initial operations, reliability must be sufficient to support station testing and casual operations. Because there is no time-urgency for most communications, the station can tolerate short-term failures and malfunctions that can be corrected in time for a subsequent satellite pass.

As operations become more regular and frequent, station reliability must improve. While urgency remains low, failures and malfunctions have a greater effect on station utilization, simply because the station is in greater use.

The highest level of reliability is required for message handling, satellite monitoring and control, and gateway operations. While commercial levels of system availability are not required, users will generally expect as close as possible to 100% availability of the service whenever the desired satellite is accessible. Requirements are likely to be greatest for satellite monitoring and control.

Historically, amateur radio operators maintain their own equipment. Many amateur radio operators perform substantial maintenance of their stations themselves and with assistance from more technically-qualified acquaintances. Antennas, feedlines, cables, and accessories are usually operator maintainable with readily available and inexpensive test equipment and tools. Modern, highly integrated transceivers are not as easily maintained by the operator. Special test equipment and tools are often needed that are beyond many individuals' ability or budget.

Major domestic and foreign equipment manufacturers (Alinco, Drake, Icom, Kenwood, Ten-Tec, and Yaesu) operate repair facilities located in the U.S. They can make minor to major repairs to current and most of their older, out-of-production models, and stock replacement parts for their equipment. Even with overnight shipment, repairs may take several weeks to turn around. This service is not inexpensive - even simple repairs can cost \$50 - \$100 for labor alone. Parts and shipping are additional expenses.

Many amateur radio stores and individuals operate repair services, especially for older equipment no longer supported by a manufacturer. Their costs for repairs are comparable to the manufacturer's operations, but with longer turn around time.

Table 5-1 summarizes the qualitative reliability, maintainability, and availability goals and the maintenance strategy for each type of station operation. Initial maintenance is performed by the station operator, with ad-hoc assistance from other amateur radio operators. Manufacturer or independent repair facilities will perform "depot" maintenance or repairs that are beyond the operator's ability or confidence. Because the station will evolve from initial ad-hoc, casual operation to more regular and critical uses, higher levels of reliability, maintainability, and availability (and the associated investment in support capability) will not be needed until considerable experience has been achieved in satellite ground station operation.

Table 5-1 Reliability, Availability, and Maintainability Goals and Strategy

Type of Operation	Relaib./Avail./Maint. Strategy
Casual, ad-hoc	Moderate/Moderate/Owner + Depot
Regular	High/High/Owner + Depot
Message handling (attended)	High/High/Owner + Depot [Note 1]
Message Gateway	V High/V High/Owner + Depot [Note 1]
Real-Time Gateway	V High/V High/Owner + Depot [Note 1]
Satellite Monitoring/Control	E High/E High/Owner + Depot [Note 1]

Notes:

1. More, better test equipment, spare parts, backup equipment
2. More capable test equipment, spare parts, redundancy for critical items that cannot be repaired by operator; express shipment, expidited service for factory repairs

Candidate items for operator maintenance and support include antennas, antenna supports, feedlines, cables, power supplies, and some station accessories. Except for simple repairs and initial testing and fault isolation, depot service will be necessary for most radio frequency (RF) generating and receiving equipment (transmitters, receivers, preamplifiers, and power amplifiers).

Redundancy, where implemented, will be at the item level (e.g. transmitter, receiver, preamplifier, power amplifier, antenna). Degraded operation during an equipment failure will be possible as the station adds satellite operating modes. Examples include using different antennas than the primary antennas for accessing a particular satellite, and operating without preamplifiers or power amplifiers. Reconfiguration to use redundant equipment or degraded modes will be by operator reconfiguration, reconnection, and activation of equipment. There will be no automatic switching into service of redundant or backup equipment.

Station down-time will be dictated by the nature of a failure and the extent amount of repairs or reconfiguration required. Down-time can range from seconds (preamplifier and amplifier power up/down) to minutes (switch radio, antenna, or Terminal Node Controller (TNC)/modem connections) to hours or even days (repair of major station items). Since LEO satellite passes last only 10-20 minutes, downtime longer than a minute results in loss of the pass. Satellites in Molniya orbits are visible for many hours per pass, so longer downtime does not lose the entire pass.

Based on the operator's personal experience with radio equipment and the characteristics of satellite operation, the following practices should minimize station down-time and thereby maximize station availability:

- Operate all station equipment regularly, preferably daily (failures increase when equipment sits idle).

- Activate equipment needed for a pass well-enough in advance to be able to correct minor malfunctions before the pass begins.

- Install protective devices on preamplifiers and other equipment to limit or prevent damage from static charges, power-line spikes, and lightning (including closing station and disconnecting equipment during electrical storms).

- Keep supplies and test and repair equipment on-hand to perform basic repairs (e.g. fuses, feedline, cable, and connector failures) in time to catch the next pass of a LEO satellite (estimate 30 minute time to repair).

- Plan equipment acquisitions to obtain back-ups for major station items (transmitters and receivers) as early as possible.

- Use overnight express shipment and expedited repair service to minimize downtime during depot repairs of major items. (This step may become necessary if the station evolves into message gateway service.)

5.3 Top-Level System Requirements

The station's goals and objectives, along with how it will be operated and supported, lead to specific requirements for the station equipment and design. These top-level requirements are divided into requirements for the RF equipment, computer equipment, other equipment, and facilities and structures.

5.3.1 Radio Frequency Equipment

5.3.1.1 Downlink Requirements

- Receive satellite downlink signals on the 29 MHz, 145 MHz, 435 MHz, and 2.4 GHz amateur satellite downlink bands.

- Receive analog (CW, SSB) signals on all bands.

- Receive digital (AFSK, BPSK, and FSK) signals on the 145 and 435 MHz bands, at data rates of up to 1200 bits per second (bps) on 145 MHz and 1200 and 9600 bps on 435 MHz.

- Target SNR of 20 dB for analog signals under reasonable conditions.[24]

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[24]Define "reasonable conditions" as combination of slant range and off-pointing ("squint angle") of satellite antennas likely to be encountered during normal operations.

- Provide sufficient SNR for a Bit Error Rate (BER) of 10^{-5} or better for digital signals under reasonable conditions.

- Support doppler shift compensating AFC commands to receiver during reception of digital *(optional: analog)* satellite signals.

- *Optional:* Support "slaving" of receiver and transmitter operating frequency during a pass to account for doppler shift and frequency translation by the satellite's transponder.

5.3.1.2 Uplink Requirements

- Generate satellite uplink signals on the 145 MHz, 435 MHz, and 1269 MHz amateur satellite downlink bands.

- Generate analog signals on all bands.

- Generate digital signals on the 145 MHz band at data rates of 1200 and 9600 bps.

- Generate a level of Effective Isotropic Radiated Power (EIRP) comparable to AMSAT or other published guidelines for accessing each satellite of interest, with following target values:

  Received Signal Power (P_S), estimated at the satellite, of -110 dBm or better (analog signals) under reasonable conditions.

  Provide sufficient SNR (as estimated at the satellite's receiver input) for a BER of 10^{-5} or better for digital signals under reasonable conditions.

- Provide means for adjusting uplink power to keep station's downlink no louder than satellite beacon (analog signals).

- Minimize transmitter power required to maintain communications under reasonable conditions.

5.3.2 Computer Equipment

- TNCs and modems that support sending and receiving digital signals at current data rates (1200, 9600 bps) and modulation (AFSK, BPSK, and FSK); receive telemetry signals at current data rates (400, 1200, 9600 bps) and modulation (AFSK, BPSK, and FSK).

- TNCs and modems that support connection to the terrestrial packet radio network (1200 bps, AFSK modulation).

- Modems and access to dial-up telephone lines to enable connection to terrestrial data networks (2400 bps or greater).

- Operate satellite tracking software during satellite passes, predict visible passes. and generate tracking data prior to a pass.

- Operate digital communications software, including software supporting packet satellite protocols, during satellite passes.

- Operate software for processing messages and files downloaded from packet satellites following a pass.

- Operate software for processing satellite telemetry data during a pass and/or following a pass, including preparing telemetry for forwarding to telemetry collection and archive sites.

- Allow collection of satellite tracking data in machine-readable format (e.g. Keplerian element files) and update tracking program data base.

- Permit simultaneous control of antenna rotators (optional: radio frequencies) during a pass and operation of another program. **Minimum Requirement:** Simultaneous control of rotators and operation of packet satellite communications software.

- Support use of word processing, spreadsheet, data base, and other comparable applications software to automate station operations, record-keeping and other related functions.

5.3.3 Other Equipment and Requirements

5.3.3.1 Facilities And Structures

- All station equipment must fit in locations designated for radio operations within the station owner's residence; equipment not required for real-time support of a satellite pass may be located in different rooms than the primary radio and support equipment.

- Operate from commercial power (nominal 115 VAC) available at the station owner's residence.

- Provide correct operating voltages and currents required for all station equipment, permitting simultaneous use radio equipment required for any given satellite pass and computer equipment necessary to support that pass, plus a safety margin.

- No requirements for special heating, cooling, or ventilation of operating areas beyond that already installed.

- Minimize length of antenna feedlines from station equipment to antennas; **Maximum Value:** All antenna feedlines under fifty feet; *Target Value:* All antenna feedlines under thirty feet.

5.3.3.2 Safety

- Achieve recommend safe levels of RF energy fields around uplink antennas.

- Comply with recommended practices for system grounding for protecting people, equipment, and structure from lightning and electrical storms.

- Limit/prevent possibility of unauthorized persons (including children) contacting antennas while station is transmitting and limit/prevent unauthorized access of station equipment when station owner or authorized operator is not present.

- Comply with applicable state and local building codes affecting safety of antennas, support structures, and station power, heating, ventilation, and cooling.

5.3.3.3 Regulatory

- Comply with all FCC regulations governing operation of an amateur radio station for the operator's license class.

- Comply with applicable Federal, Commonwealth of Virginia, and Fairfax County land-use laws, regulations, and zoning ordinances.

- Comply with applicable covenants and architectural regulations of the Hastings Hunt Homeowners Association (HH HOA).[25]

5.3.3.4 Electromagnetic Compatibility and Interference

- Ensure compatibility of electronic and electrical equipment intended for interfacing (e.g. transmitters, receivers, TNCs, satellite uplinks and downlinks).

- Prevent/limit interference or incompatibility between equipment required to operate simultaneously to support a satellite pass.

- Minimize incompatibility or interference to satellite communications from equipment not required for a pass but likely to be operating during that pass.

- Comply with FCC regulations governing purity of RF emissions, especially with respect to potential for interfering with nearby electronics devices (e.g. radios, stereos, television systems, and telephone equipment).

- Minimize/eliminate interference to station equipment from other nearby electrical and electromagnetic equipment not associated with the station.

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[25] Architectural and Environmental Regulations, Hastings Hunt Community Association, December 1991, 8-9.

5.3.4 Prioritization of Requirements

The following priorities will be used when making trade-offs between competing goals, requirements, and constraints:

- Comply with minimum/maximum constraints on design or performance. Examples include antenna size, feedline lengths, power consumption, and RF field levels.

Within the limits these constraints establish on the design, the priorities, in descending importance, are as follows:

- Received signal level (P_S, SNR)
- Life cycle cost
- Acquisition cost (considering effects over acquisition of the complete station)
- Reliability and elimination of or safeguards against failure modes
- Flexibility to support different satellite modes or changes in satellite usage
- Operator convenience and reducing operator workload

5.4 Functional Baseline and Allocated Requirements

The next step in the satellite ground station's design are functional analysis and allocation of functions and requirements. Functions necessary to perform the ground station's mission are developed. A candidate list of the hardware and software elements comprising the station is prepared. The functions and requirements are then allocated to the hardware and software elements.

5.4.1 Functional Analysis and Baseline

Figures 5-1, 5-2, 5-3, and 5-4 present the functional breakdown and interconnections for the satellite ground station at the top level, for tracking, for communications, and for data processing, respectively. Table 5-2 describes each of these functions.

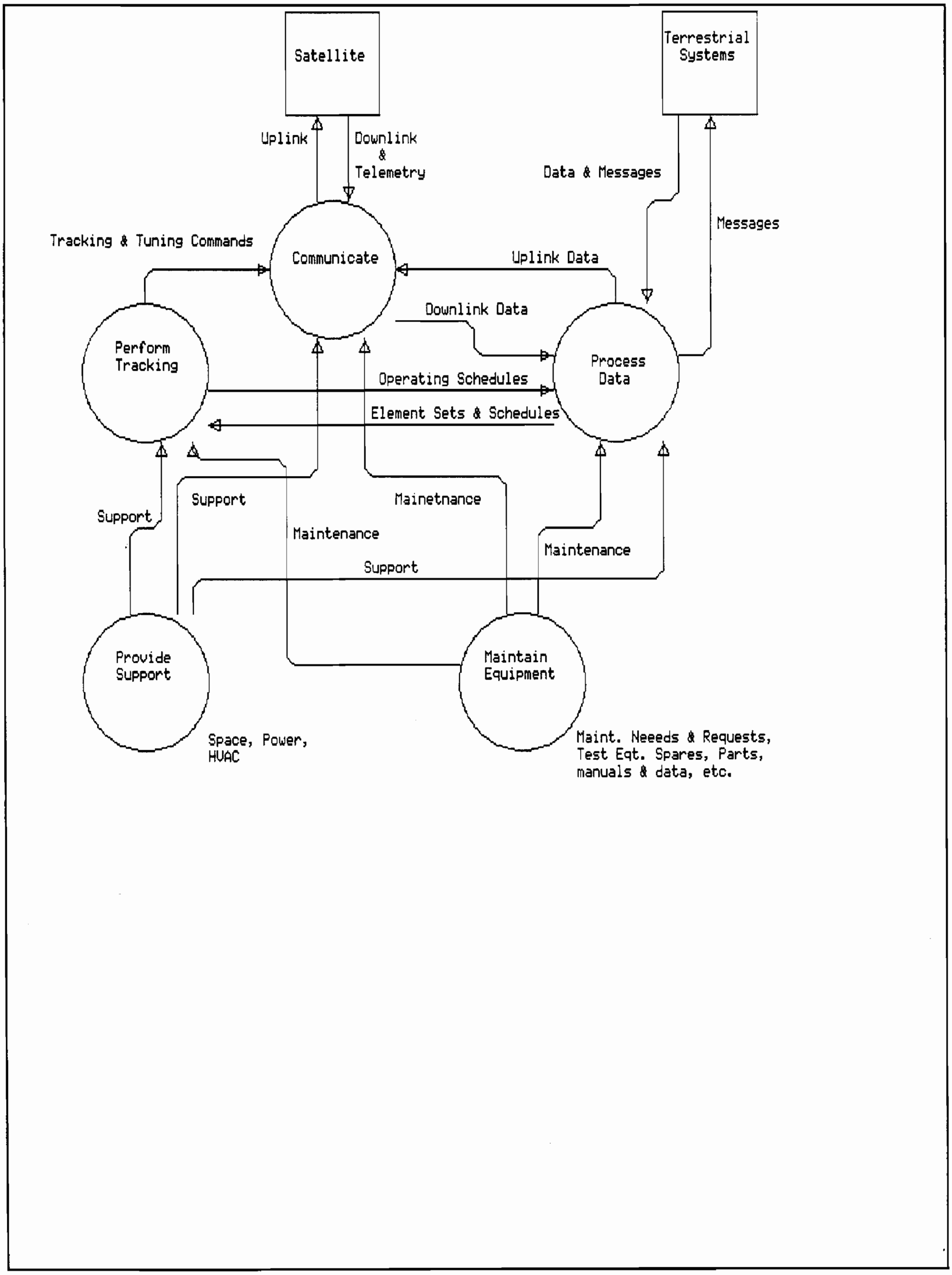

Figure 5-1 Top-Level Ground Station Functions

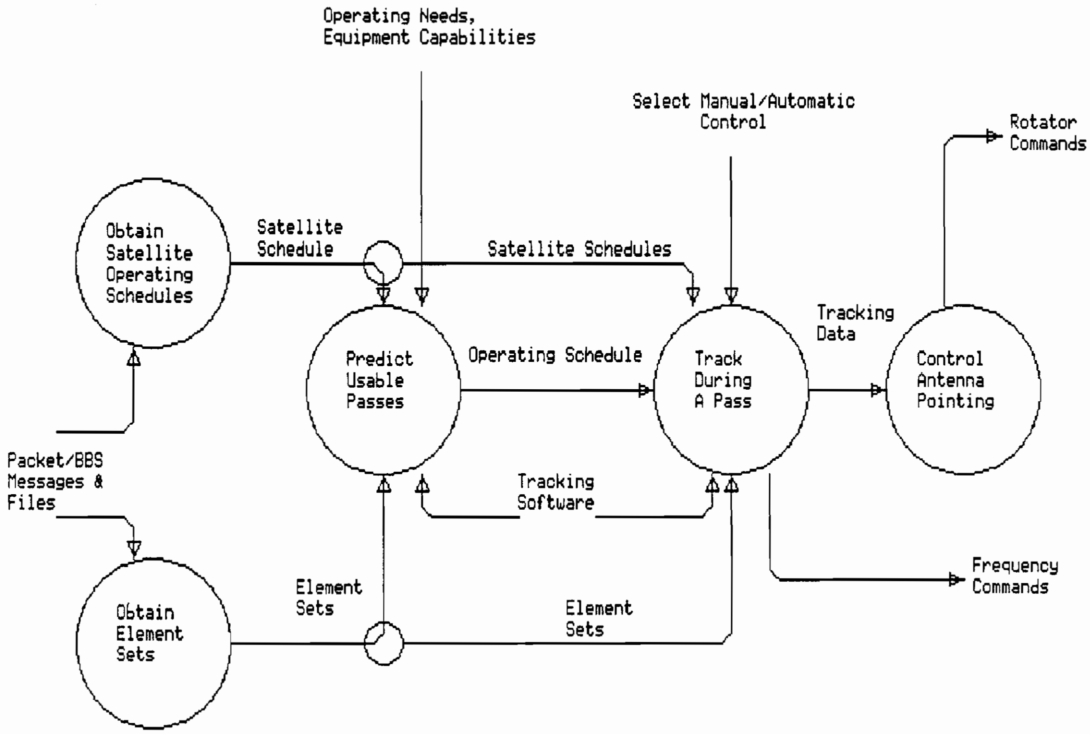

Figure 5-2 Tracking Functions

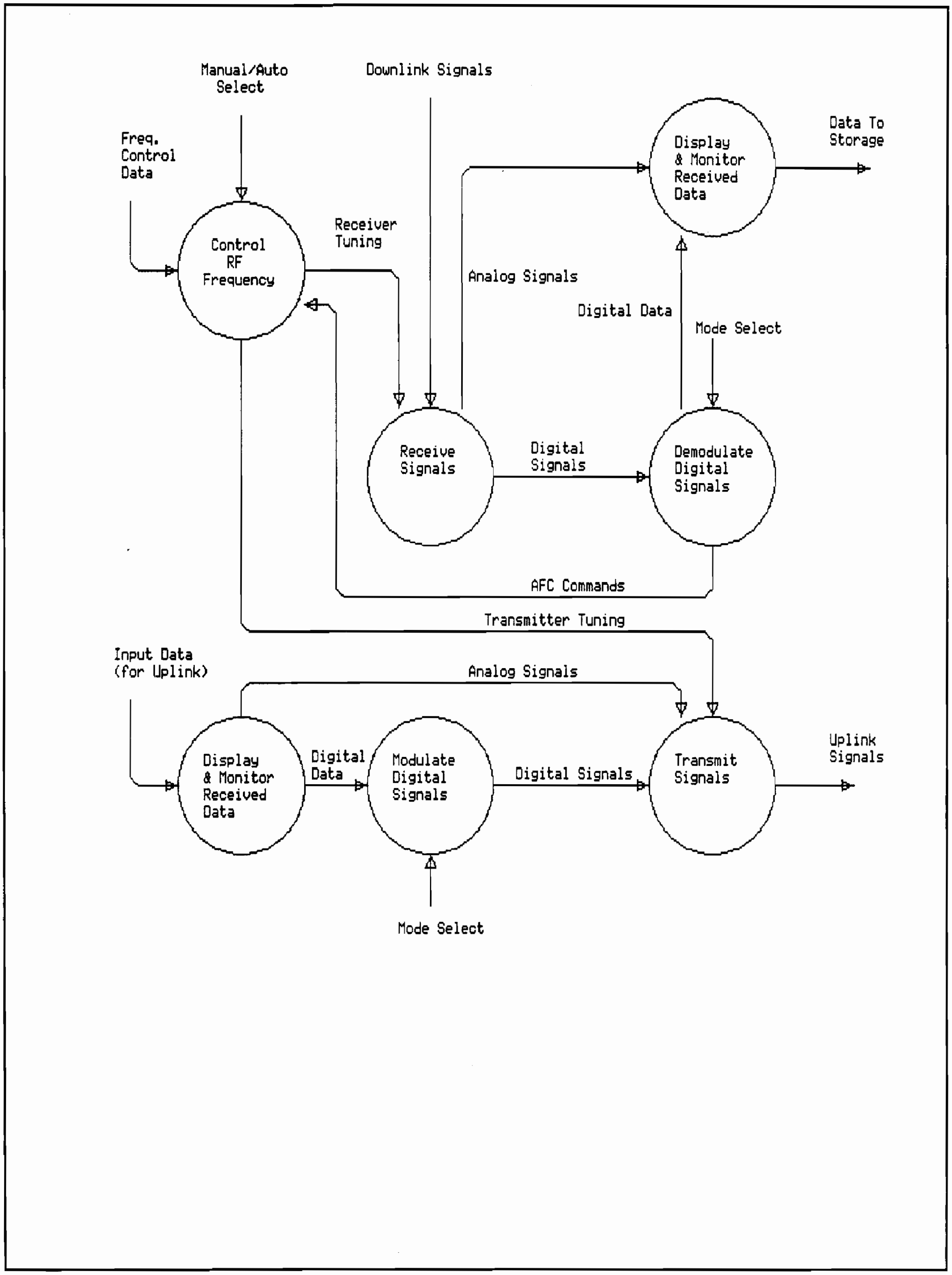

Figure 5-3 Communications Functions

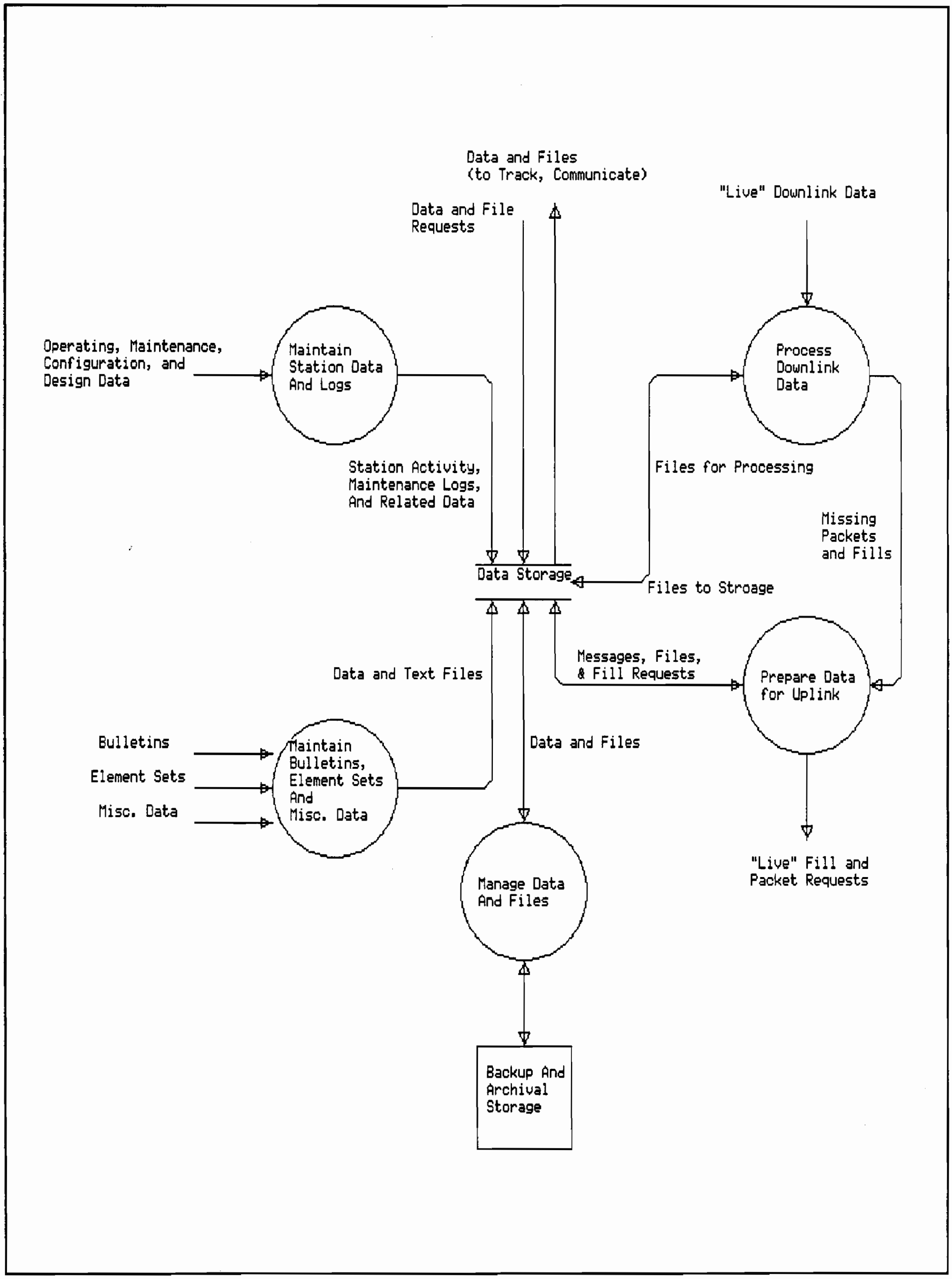

Figure 5-4 Data Processing and Control Functions

Table 5-2 Description of Ground Station Functions

Function	Description
Perform Tracking	
Obtain Satellite Operating Schedules	Get times, dates for operating modes, special situations
Obtain Element Sets	Get current keplerian element sets for tracking program
Predict Usable Passes	Predict days, times when satellite available for use
Track During A Pass	Predict satellite azimuth, elevation, and doppler during pass
Control Antenna Pointing	Point directional antennas at satellite during pass
Communicate	
Control RF Frequency	Adjust uplink and downlink frequencies for doppler and passband
Receive Signals	Recieve satellite downlink signals
Demodulate Digital Signals	Demodulate digital audio to data
Display/Monitor Data (Rcv)	Display/store downlink data
Display/Monitor Data (Xmit)	Display data being sent to satellite
Modulate Digital Signals	Convert uplink data to digital audio for transmitter
Transmit Signals	Transmit uplink signal to satellite
Process Data	
Maintain Station Data and Logs	Maintain files on station configuration and use
Maintain Bullettin, Element, and Misc. Dat	Maintain files on satellite status, messages, and tracking data
Process Downlink Data	Process telemetry and messages received from satellites
Prepare Uplink Data	prepare messages for sending to satellite
Manage Files and Data	Management and control of operating and data files, software
Store Data	On-line and backup/archival storage of program and data files
Provide Support	
Provide Space	Provide operating and storage space for station equipment
Provide Power	Provide adequate AC and DC power for equipment
Provide HVAC	Provide heating, ventalation, and cooling of station and equipment
Provide Support Structures	Provide locations and structures for antennas
Provide Spare and Replacement Parts	Provide spare and replacement parts for equipment
Provide Miscellaneous Equipment	Provide operating aids and accessories
Maintain Equipment	
Maintain RF Equipment	Keep RF equipment in proper condition
Maintain Computer Equipment	Keep computer equipment in proper condition
Maintain Other Electronics	Keep other electronics equipment in proper condition
Maintain Other Equipment	Keep non-electronic equipment in proper condition
Supply and Maintain Test Equipment	Provide test equipment and keep in proper condition

5.4.2 Requirements Allocation

Table 5-3 lists the main elements of the satellite ground station. These elements were selected based on a "typical" station configuration (see Figure 1-2), published information, and conversations with active satellite operators.[26,27] The station

[26]Davidoff, 9-21.

elements are organized into five categories: RF Equipment, Data Processing and Control Equipment, Power Equipment, Facilities Equipment, and Support Equipment.

Table 5-4 shows the allocation of the station functions developed in Section 5.4.1 to the station elements. Table 5-5 shows the allocation of the top-level requirements developed in Section 5.3 to the station elements.

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[27] Electronic mail communications, Internet rec.radio.amateur.misc Newsgroup, March 1992.

Table 5-3 Satellite Ground Station Equipment - Major Elements

Abbreviation	Name	Description
Satellite Ground Station Equipment		
RF Equipment	Radio Frequency Equipment	
Xmtr Eqt.	Transmitter Equipment	Generates uplink signal on frequencies/modulation of interest
Rcvr Eqt.	Receiver Equipment	Receives downlink signal on frequency/modulation of interest
Power Amp.	Power Amplifier	Amplifies uplink signal to required power level
Rcv. Preamp	Receiver Preamplifier	Amplifies downlink signal to usable level
Xmtr Ant.	Transmitter Antenna	Direct uplink signal to satellite
Rcvr Ant.	Receiver Antenna	Capture downlink signal from satellite
Aux. Radio	Auxiliary Radio	Radio equipment for terrestrial communications supporting satellite operation
Aux Ant.	Auxiliary Antenna	Antenna for terrestrial communications supporting satellite operation
Ant. Rotator	Antenna Rotator	Points satellite antennas in azimuth and elevation towards satellite
Ant. Feedline	Antenna Feedline	Carries signals between radios and antennas
Control Cable	Control Cable	Carries power and control signals between station equipment
Ant. Suppt.	Antenna Support	Supports antennas above the ground or structure.
Data Proc. & Control Eqt.		
TNC	Terminal Node Controller	Interfaces radios and computers for digital communications
RF Modem	Radio Frequency Modem	Modulates/demodulates satellite digital signals (used with TNC)
Phone Modem	Telephone Modem	Connects computer equipment with telephone lines for data transfer
Computer	Computer	Performs all data processing-related functions and communications terminal
Monitor	Monitor	Dispaly of data processed by computer
Printer	Printer	Prepares permanent copies of data in computer
Rotator Interfc.	Rotator Control Interface	Interfaces computer with rotators for automatic control
Radio Interfc.	Radio Control Interface	Interfaces radios with computer for automated control
Software	Computer Software	Software for performing all functions involving data processing and control eqt.
Power Equipment		
Power 110V	Power - 110VAC	Nominal 110-115V AC power for radios and other station equipment
Power DC	Power - Direct Current	Low and high-current supply of DC power for radios and other station eqt.
Facilities Equipment		
HVAC	Heating, Ventilation, & AC	Heat, ventilate, and cool station and equipment
Space	Space	Enclosed space for station and rquipment
Support Equipment		
Test & Spt. Eqt.	Test and Support Equipment	Equipment for testing, checkout, and maintenance of station equipment
Spares & Parts	Spares and Repair Parts	Components, assemblies, etc. for repair of station equipment
Tech Data	Technical Data	Manuals, instructions, data sheets, and maint. records

Table 5-4 Allocation of Functions To Station Elements

Function	Xmtr Eqt.	Rcvr Eqt.	Power Amp.	Rcv Preamp	Xmtr Ant.	Rcvr Ant.	Aux. Radio	Aux. Ant.	Ant. Rotator	Ant. Feedline	Control Cable	Ant. Suppt.	TNC	RF Modem
Perform Tracking														
Obtain Satellite Operating Schedules							x	x					x	x
Obtain Element Sets							x	x					x	x
Predict Usable Passes														
Track During A Pass									x		x	x		
Control Antenna Pointing														
Communicate														
Control RF Frequency	x	x									x		x	
Receive Signals		x		x		x				x		x		
Demodulate Digital Signals													x	x
Display/Monitor Data (Rcv)		x												
Display/Monitor Data (Xmit)														
Modulate Digital Signals													x	x
Transmit Signals	x		x		x					x		x		
Process Data														
Maintain Station Data and Logs														
Maintain Bullettin, Element, and Misc. Data														
Process Downlink Data														
Prepare Uplink Data														
Manage Files and Data														
Store Data														
Provide Support														
Provide Space														
Provide Power														
Provide HVAC														
Provide Support Structures												x		
Provide Spare and Replacement Parts														
Provide Miscellaneous Equipment														
Maintain Equipment														
Maintain RF Equipment														
Maintain Computer Equipment														
Maintain Other Electronics														
Maintain Other Equipment														
Supply and Maintain Test Equipment														

Table 5-4 Allocation of Functions To Station Elements (continued)

Function	Phone Modem	Comput	Monitor	Printer	Rotator Interfc.	Radio Interfc.	Software	Power 110V	Power DC	HVAC	Space	Test & Spt Eqt.	Spares Parts	Tech Data
Perform Tracking														
Obtain Satellite Operating Schedules	x	x		x			x							
Obtain Element Sets	x	x					x							
Predict Usable Passes		x	x	x			x							
Track During A Pass		x	x	x	x		x							
Control Antenna Pointing		x		x			x	x						
Communicate														
Control RF Frequency		x				x	x	x	x					
Receive Signals								x	x					
Demodulate Digital Signals								x	x					
Display/Monitor Data (Rcv)		x	x	x			x	x	x					
Display/Monitor Data (Xmit)		x	x	x			x	x	x					
Modulate Digital Signals								x	x					
Transmit Signals								x	x					
Process Data														
Maintain Station Data and Logs		x	x	x			x	x						
Maintain Bullettin, Element, and Misc. Data		x	x	x			x	x						
Process Downlink Data		x	x	x			x	x						
Prepare Uplink Data		x	x				x	x						
Manage Files and Data		x	x	x			x	x						
Store Data		x					x	x						
Provide Support														
Provide Space											x			
Provide Power								x	x					
Provide HVAC										x				
Provide Support Structures														
Provide Spare and Replacement Parts													x	
Provide Miscellaneous Equipment												x		
Maintain Equipment														
Maintain RF Equipment								x	x			x		x
Maintain Computer Equipment							x	x				x		x
Maintain Other Electronics								x	x			x		x
Maintain Other Equipment								x				x		x
Supply and Maintain Test Equipment								x	x			x		x

Table 5-5 Allocation of Requirements To Station Elements

Requirement	Xmtr Eqt.	Rcvr Eqt.	Power Amp.	Rcv Preamp	Xmtr Ant.	Rcvr Ant.	Aux. Radio	Aux. Ant.	Ant. Rotator	Ant. Feedlin
Radio Frequency Equipment:										
Downlink:										
Receive Analog Signals		x							x	
Receive Digital Signals @1200-9600 bps		x								
20 dB (target) Signal-to-Noise Ratio		x		x		x				x
BER of 10^-5 or less		x		x		x				x
Support AFC Control		x								
"Slave" Receiver - Transmitter Tuning (optional)	x	x								
Uplink:										
Generate Analog Uplink Signals	x									
Generate Digital Signals @ 1200-9600 bps	x									
Generate Required EIRP (Goal: -110 dBM or 10^-5 BER	x		x		x					x
Adjust Uplink Power	x		x							
Minimize Required Transmitter Power	x				x				x	x
Computer Equipment:										
Operate Tracking Software										
Operate Digital Communications Software										
Operate Telemetry Software										
Collect Tracking Data & Update Tracking Program										
Control Rotators, Freq., and Comm. Sftwr.	x	x							x	
Support Office Automation Software										
Other Equipment:										
TNCs & Modems Support Signaling Rates										
Support Terrestrial Packet Connections							x	x		
Enable Connections to Terrestrial Phone System										
Supply Required Power										
Facilities and Structures:										
Fit In Available Space	x	x	x	x	x	x				
Operate from Commercial Power	x	x	x	x					x	
No Special HVAC Requirements	x	x	x	x						
Feedlines 50' or Less					x	x				x
Safety:										
RF Fields Near Uplink Antennas					x	x				
Lightning & Electrical Storm Protection	x	x	x	x	x	x				x
Limit Access to Antennas and Station Equipment	x	x	x	x	x	x				
Comply With Buidling Codes					x	x				x
Regulatory:										
Comply with FCC Regulations	x		x							
Comply With Land-Use & Zonning					x	x				
Covenants and Architectural Guidelines					x	x				
Electromagnetic Compatibility & Interference:										
Compatibility of Interfacing Equipment	x	x	x	x	x	x			x	x
Limit/Prevent Incompatibility	x	x	x	x	x	x				x
Minimize Interference from Non-Required Equipment		x		x	x	x				x
Prevent Interference to Non-Station Equipment	x		x							x
Minimize Interference To Station Equipment		x		x					x	x

Table 5-5 Allocation of Requirements To Station Elements (continued)

Requirement	Control Cable	Ant. Suppt.	TNC	RF Modem	Phone Modem	Compu	Monitor	Printer	Rotator Interfc.
Radio Frequency Equipment:									
Downlink:									
Receive Analog Signals									
Receive Digital Signals @1200-9600 bps			x	x		x	x	x	
20 dB (target) Signal-to-Noise Ratio									
BER of 10^-5 or less									
Support AFC Control									
"Slave" Receiver - Transmitter Tuning (optional)						x	x	x	
Uplink:									
Generate Analog Uplink Signals									
Generate Digital Signals @ 1200-9600 bps			x	x		x	x	x	
Generate Required EIRP (Goal: -110 dBM or 10^-5 BER									
Adjust Uplink Power									
Minimize Required Transmitter Power									x
Computer Equipment:									
Operate Tracking Software						x	x	x	
Operate Digital Communications Software			x	x		x	x	x	
Operate Telemetry Software			x	x		x	x	x	
Collect Tracking Data & Update Tracking Program			x	x	x	x	x	x	
Control Rotators, Freq., and Comm. Sftwr.	x					x	x	x	x
Support Office Automation Software						x	x	x	
Other Equipment:									
TNCs & Modems Support Signaling Rates			x	x					
Support Terrestrial Packet Connections			x	x		x	x	x	
Enable Connections to Terrestrial Phone System					x	x	x	x	
Supply Required Power									
Facilities and Structures:									
Fit In Available Space		x	x	x	x	x	x	x	x
Operate from Commercial Power			x	x	x	x	x	x	x
No Special HVAC Requirements			x	x	x	x	x	x	x
Feedlines 50' or Less		x							
Safety:									
RF Fields Near Uplink Antennas									
Lightning & Electrical Storm Protection	x	x	x	x					x
Limit Access to Antennas and Station Equipment		x							
Comply With Buidling Codes		x							x
Regulatory:									
Comply with FCC Regulations									
Comply With Land-Use & Zonning		x							
Covenants and Architectural Guidelines		x							
Electromagnetic Compatibility & Interference:									
Compatibility of Interfacing Equipment	x		x	x	x	x	x	x	x
Limit/Prevent Incompatibility	x		x	x		x	x	x	x
Minimize Interference from Non-Required Equipment	x		x	x	x	x	x	x	x
Prevent Interference to Non-Station Equipment	x		x	x		x	x	x	x
Minimize Interference To Station Equipment	x		x	x		x	x	x	x

Table 5-5 Allocation of Requirements To Station Elements (concluded)

Requirement	Radio Interfc.	Softwar	Power 110V	Power DC	HVAC	Space	Test & Spt Eqt	Spares Parts	Tech Data
Radio Frequency Equipment:									
Downlink:									
Receive Analog Signals							x	x	x
Receive Digital Signals @1200-9600 bps							x	x	x
20 dB (target) Signal-to-Noise Ratio									
BER of 10^-5 or less									
Support AFC Control							x	x	x
"Slave" Receiver - Transmitter Tuning (optional)	x								
Uplink:									
Generate Analog Uplink Signals							x	x	x
Generate Digital Signals @ 1200-9600 bps							x	x	x
Generate Required EIRP (Goal: -110 dBM or 10^-5 BER							x	x	x
Adjust Uplink Power							x	x	x
Minimize Required Transmitter Power									
Computer Equipment:									
Operate Tracking Software		x							
Operate Digital Communications Software		x							
Operate Telemetry Software		x							
Collect Tracking Data & Update Tracking Program		x							
Control Rotators, Freq., and Comm. Sftwr.	x	x							
Support Office Automation Software		x							
Other Equipment:									
TNCs & Modems Support Signaling Rates									
Support Terrestrial Packet Connections		x							
Enable Connections to Terrestrial Phone System		x							
Supply Required Power			x	x			x	x	x
Facilities and Structures:									
Fit In Available Space	x		x	x		x	x	x	x
Operate from Commercial Power	x		x	x			x	x	x
No Special HVAC Requirements	x		x	x	x	x	x	x	x
Feedlines 50' or Less						x			
Safety:									
RF Fields Near Uplink Antennas									
Lightning & Electrical Storm Protection	x		x	x					
Limit Access to Antennas and Station Equipment						x			
Comply With Buidling Codes	x		x	x		x			
Regulatory:									
Comply with FCC Regulations							x		x
Comply With Land-Use & Zonning						x			
Covenants and Architectural Guidelines						x			
Electromagnetic Compatibility & Interference:									
Compatibility of Interfacing Equipment	x	x					x	x	x
Limit/Prevent Incompatibility	x						x	x	x
Minimize Interference from Non-Required Equipment	x						x	x	x
Prevent Interference to Non-Station Equipment	x					x	x	x	x
Minimize Interference To Station Equipment	x					x	x	x	x

5.5 System Design and Tradeoffs

This section addresses the detailed design and tradeoff analyses resulting in the recommended design for the satellite ground station.

The analysis of the communications links in Section 5.5.1 provides the parameters for selecting station antennas, transmitters, amplifiers, and receive preamplifiers. Section 5.5.2 describes the selection of suitable items for the station's RF and computer equipment, facilities, and structures. Safety issues affecting station design are also addressed. The station's test plan appears in Section 5.6. Section 5.7 presents the acquisition plan and schedule. The recommended design is summarized in Section 5.8.

5.5.1 Link Analysis

The communications link between the ground station and the satellite controls the performance requirements for the station's major RF equipment. Appendix A presents the methods used to evaluate satellite communications links. This section analyzes these links for the amateur radio satellites in service in April 1992.

The analysis of the satellite communications links assumes the satellite is at an elevation angle of 10°, as adjacent buildings obstruct the path at lower angles. The satellite is assumed to be at apogee. These assumptions place the satellite at the maximum possible slant range, the worst case situation for free-space path losses.

The signal's share of the satellite's transponder power output depends on the type of transponder. For linear transponders (AO-10, AO-13, FO-20 Mode JA, Radio Sport (RS) series, and AO-21), the transponder output is assumed to be divided equally among the number of 3000 Hz SSB signals its pass band can accommodate at 70%

occupancy. For digital transponders (all satellites using Mode JD, Mir, and Shuttle Amateur Radio Experiment (SAREX), the single downlink channel uses all the transponder's output power. When the satellite uses a gain antenna for downlink (AO-13), gain values assume the link is at the antenna's half-power (-3 dB) beamwidth. This assumption accounts for off-optimal satellite orientation. Information on satellite transponders and antennas is from Davidoff.[28]

Performance of ground station antennas, preamplifiers, feedlines, and connectors represent typical values for equipment available in the retail amateur radio market that could be used for each particular downlink. Circular polarization is assumed for antennas for accessing AO-10 and AO-13, and linear polarization for antennas used with all other satellites. Specific antennas (primarily for AO-13) are discussed in Section 5.5.2. Sky noise temperatures are average maximum values for the downlink frequency.[29] Again, this is a worst-case assumption for the link analysis.[30] Signal bandwidth for linear transponders is assumed to be 3000 Hz (typical SSB signal). Signal bandwidth for digital transponders is the nominal bandwidth for the entire channel.

This analysis does not directly consider uncontrollable signal losses from ionospheric and atmospheric attenuation, polarization mismatches from Faraday rotation, or man-made noise sources near the ground station. Additional margin in the communications link can partly compensate for reductions in SNR from these factors.

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[28] Davidoff, 1990, Appendix B.
[29] Ibid, Table 9-1, p 9-1.
[30] The 145 MHz "sky temperature" displayed by the InstantTrack program suggests real-life values will often be much less, improving the link SNR by several dB.

Satellite uplinks are analyzed in a similar manner to the downlinks. Transmitter power for the uplinks uses recommended EIRP values from AMSAT or the satellite's operator, as provided by Davidoff.[31] Uplink ground station antennas use typical gain values. Circular polarization is assumed for AO-10 and AO-13, and linear polarization for all other satellites. When the satellite uses gain antennas to receive uplinks, the gain at the half-power (-3 dB) beamwidth is used to account for off-pointing.

Table 5-6 presents the analysis of the satellite downlinks. Table 5-7 presents the analysis of the satellite uplinks.

[31] Davidoff, 1990, Appendix B.

Table 5-6 Analysis of Satellite Downlinks

Satellite	AO-10	AO-13			FO-20		UO-14	AO-16	DO-17	WO-18	LU-19	UO-22	RS-10/1	RS-12/1	AO-21	Mir
Mode	B	B	JL	S	JA	JD	JD	JD	JD	JD	JD	JD	A	A	B	FM
Downlink Freq. (MHz)	145.9	145.9	435.86	2400.73	435.85	435.91	435.07	435.051	145.825	437.102	437.153	435.12	29.4	29.45	145.9	145.55
Apogee (km)	35,500	36,265	36,265	36,265	1,745	1,745	800	800	800	800	800	800	1,003	1,003	1,003	400
Max Slant Range (km) [Note 1]	41,271	42,044	42,044	42,044	4,916	4,916	3,180	3,180	3,180	3,180	3,180	3,180	3,602	3,602	3,602	2,183
Transponder Power (W)	50	50	50	1.25	2	1	5.4	5.4	2.92	5.4	5.4	5.4	5	8	12	5
Transponder Bandwidth (kHz)	150	150	290	36	100	NA	20	6	6	6	6	20	40	40	80	6
# Users (70% loading) [Note 2]	35.0	35.0	67.7	8.4	23.3	NA	NA	NA	NA	NA	NA	NA	9.3	9.3	18.7	NA
Power/User (PEP W) [Note 2]	1.43	1.43	0.74	0.15	0.09	1	5.4	5.4	2.92	5.4	5.4	5.4	0.54	0.86	0.64	5
Received Signal Power (Ps):																
Power per User (dBm)	31.5	31.5	28.7	21.7	19.3	30.0	37.3	37.3	34.7	37.3	37.3	37.3	27.3	29.3	28.1	37.0
Downlink Antenna Gain (dBi)	3.0	3.0	6.5	11.2	9.5	2.1	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.1	2.1	0.0
Path Loss (dBi)	168.0	168.2	177.7	192.5	159.0	159.0	155.2	155.2	145.7	155.3	155.3	155.2	132.9	132.9	146.8	142.4
Receiver Antenna Gain (dBi)	11.0	11.0	13.0	24.0	13.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	13.0	13.0	2.1	2.1
Received Signal Power (dBm)	-122.4	-122.6	-129.5	-135.6	-117.2	-124.7	-117.9	-117.9	-111.1	-117.9	-117.9	-117.9	-90.5	-88.5	-114.5	-103.3
Received Noise Power (Pn):																
Sky Temperature (K)	600	600	108	43	108	108	108	108	108	108	108	108	44000	44000	600	600
Rcvr. System Noise Figure (dB)	1.4	1.4	1.5	4.1	1.5	1.5	1.5	1.5	1.4	1.5	1.5	1.5	1.7	1.7	1.4	1.4
Rcvr. System Tempreature (K)	108	108	122	449	122	122	122	122	108	122	122	122	134	134	108	113
Effective System Temp. (K)	708	708	230	492	230	230	230	230	216	230	230	230	44134	44134	708	713
Rcvd. Noise Pwr (dBm) [Note 3]	-135.3	-135.3	-140.2	-136.9	-140.2	-140.2	-132.0	-137.2	-137.5	-137.2	-137.2	-132.0	-117.4	-117.4	-135.3	-135.3
Signal-To-Noise Ratio (SNR):																
Received Signal Power (dBm)	-122.4	-122.6	-129.5	-135.6	-117.2	-124.7	-117.9	-117.9	-111.1	-117.9	-117.9	-117.9	-90.5	-88.5	-114.5	-103.3
Received Noise Power (dBm)	-135.3	-135.3	-140.2	-136.9	-140.2	-140.2	-132.0	-137.2	-137.5	-137.2	-137.2	-132.0	-117.4	-117.4	-135.3	-135.3
SNR (dB)	12.9	12.7	10.7	1.4	23.0	15.5	14.1	19.3	26.4	19.3	19.3	14.1	26.9	28.9	20.9	32.0

Notes:

1. Slant range calculated at apogee for 10 degree elevation angle
2. Transponder # users and power/user assumes 3000 kHz SSB signals (Modes A,B, JA, JL, S) or one signal per transponder (Mode JD)
3. Assumed bandwidth for receiver noise is 3000 kHz; Mode JD signals use transponder bandwidth

Table 5-7 Analysis of Satellite Uplinks

Satellite		AO-13		FO-20		PACSATS	RS Series	AO-21	Mir
Mode	B, S	J	L	JA	JD	JD	A	B	FM
Modulation	SSB	SSB	SSB	SSB	NBFM	NBFM	SSB	SSB	NBFM
Bandwidth (Hz)	3000	3000	3000	3000	6000	6000	3000	3000	6000
Uplink Freq. (MHz)	435	144	1269	144	144	145	144	435	145.55
Apogee (km)	36,265	36,265	36,265	1,745	1,745	800	1,003	1,003	400
Max Slant Range (km) [Note 1]	42,044	42,044	42,044	4,916	4,916	3,180	3,602	3,602	2,183
Received Signal Power (Ps):									
Transmitter Power Output (W)	5.0	10.0	20.0	60.0	60.0	60.0	10.0	25.0	10.0
Transmitter Power Output (dBW)	7.0	10.0	13.0	17.8	17.8	17.8	10.0	14.0	10.0
Feedline Loss (dB) [Note 2]	0.87	0.51	0.1749	0.51	0.51	0.51	0.51	0.87	0.51
Connector Loss (dB) [Note 3]	0.06	0.01	0.5	0.01	0.01	0.01	0.01	0.06	0.01
Uplink Antenna Gain (dBi)	16.1	13.6	24.0	3.0	3.0	3.0	3.0	3.0	3.0
EIRP (dBW)	22.2	23.1	36.3	20.3	20.3	20.3	12.5	16.0	12.5
EIRP (W)	166	205	4301	106	106	106	18	40	18
Recommended EIRP (dBW)	27	29	36	20	20	NA	NA	NA	NA
Margin (dBW)	-4.8	-5.9	0.3	0.3	0.3	NA	NA	NA	NA
EIRP (dBm)	52.2	53.1	66.3	50.3	50.3	50.3	42.5	46.0	42.5
Path Loss (dBi)	177.6	168.0	186.9	149.4	149.4	145.7	146.7	156.3	142.4
Receiver Antenna Gain (dBi)	6.5	3.0	9.2	2.1	2.1	0.0	2.1	2.1	0.0
Received Signal Power (dBm)	-118.9	-111.9	-111.4	-97.0	-97.0	-95.4	-102.1	-108.1	-100.0
Received Noise Power (Pn):									
Earth Temperature (K)	290	290	290	290	290	290	290	290	290
Rcvr. System Noise Figure (dB) [Note 4]	1.0	1.0	1.0	1.0	1.0	1.0	2.0	1.0	3.0
Rcvr. System Tempreature (K)	75	75	75	75	75	75	170	75	289
Effective System Temp. (K)	365	365	365	365	365	365	460	365	579
Rcvd. Noise Pwr (dBm) [Note 5]	-138.2	-138.2	-138.2	-138.2	-135.2	-135.2	-137.2	-138.2	-133.2
Signal-To-Noise Ratio (SNR):									
Received Signal Power (dBm)	-118.9	-111.9	-111.4	-97.0	-97.0	-95.4	-102.1	-108.1	-100.0
Received Noise Power (dBm)	-138.2	-138.2	-138.2	-138.2	-135.2	-135.2	-137.2	-138.2	-133.2
SNR (dB)	19.3	26.3	26.8	41.2	38.2	39.8	35.1	30.1	33.2

Notes:
1. Slant range calculated at apogee for 10 degree elevation angle
2. Based on loss in dB/100 ft, 30' feedline
3. Based on loss of 0.5 dB per pair of N-connectors at 1269 MHz, adjusted per formula in ARRL UHF Handbook, Chpt 7
4. Assumed
5. Assumed bandwidth for receiver noise is 3 kHz (SSB); Mode JD signals use 6KHz (NBFM)

5.5.2 Station Design

Communications and computer equipment already available forms the starting point for the satellite ground station. Table 5-8 lists this equipment.

Table 5-8 Current Station Communications and Computer Equipment

Equipment Catagory	Item	Description
Communications	Drake R-4B	3.5-30 MHz Receiver
	Drake T-4XB	3.5-30 MHz Transmitter
	Inverted V Antenna	3.5-30 MHz Antenna
	Kenwood TS-700SP	144-148 MHz CW/SSB/FM Transceiver, 10 W Output
	Cushcraft "Ringo Ranger" Antenna	144-148 MHz omnidirectional antenna, optimized for terrestrial use
Computer	IBM PC XT-286	MS-DOS computer, with monitor and software
	Seikosha SP-100 Printer	Dot matrix printer
	MFJ-1270 TNC	AX.25 TNC, upgraded to support "KISS" mode
	NEC PC-8500	CP/M laptop computer

This equipment provides modest SSB voice and CW capability on the high frequency (HF) amateur bands (1.8-30 MHz), and local FM voice and packet radio on the 2 meter (144-148 MHz) band. The station is capable in theory of communicating with the Mir space station, the SAREX payload, and satellites in LEO using Mode A.[32]

5.5.2.1 Radio Frequency Equipment

This section examines the design tradeoffs for RF portion of the station. The RF equipment includes all items that generate, process, or carry RF energy: antennas, feedlines, transmitters, receivers, amplifiers, and preamplifiers.

[32]The RS-10/11 and SAREX downlinks have been monitored. The uplink has been heard by Mir's automated station, although a complete contact was unsuccessful.

This section is organized by satellite mode. As described in Section 1, each mode represents a pair of uplink and downlink frequency bands. The different characteristics of these bands and the satellites that use them dictate specific design requirements and tradeoffs.

5.5.2.1.1 Mode A

Mode A uses a 145 MHz uplink and a downlink at 29 MHz, and is supported by the Russian RS-10/11 and RS-12/13 satellites. Each spacecraft consists of a pair of 50 kHz bandwidth linear transponders carried aboard a larger satellite platform orbiting at 1000 km altitude. Table 5-9 lists the equipment for Mode A.

Table 5-9 Mode A Equipment

144 MHz CW/SSB Transmitter
144 MHz Power Amplifier (optional)
144 MHz Antenna and Feedline
29 MHz Antenna and Feedline
29 MHz Receive Preamplifier
29 MHz Receiver

The link analysis in Section 5.2.1 shows that the RS satellites' downlink signals are strong and easily received with modest receiving equipment. A simple linearly polarized dipole antenna (2.1 dBi gain) is sufficient. Low feedline losses at 29 MHz allow use of inexpensive RG-8x feedline. Because sky noise dominates the receive system noise figure, a medium-performance preamplifier can be located with the main receiver, rather than at the antenna, without sacrificing performance. This placement reduces problems suppling power and protecting the preamplifier from weather and static discharges. The preamplifier does not have to pass a signal from a transmitter to the antenna, simplifying the design. The current station HF receiver is used to receive the Mode A downlink.

The uplink analysis suggests a 10 W, 145 MHz signal to the station's current low-gain omnidirectional antenna should be adequate. This antenna's radiation pattern emphasizes low elevation angles for terrestrial service. This antenna will be used for initial tests of Mode A. Regular Mode A operations will likely require an antenna optimized for satellite service. Quarter and 5/8-wave verticals, vertical dipoles, J-poles, and turnstile arrays are all feasible candidates. The verticals are easiest to build and should have sufficient performance. No amplifier is planned for the Mode A uplink, although using one would make communications more reliable. If an amplifier is acquired, it will be sized for Mode J and JD uplinks, which are more likely to require an amplifier.

The primary goal for Mode A is to demonstrate the ability to perform satellite communications. Operator aids for timing passes and adjusting to doppler shift can be tested without a major investment in equipment. Mode A is intended for casual operations and to build experience in satellite communications.

5.5.2.1.2 Modes B and J

This section presents the design and equipment selection for using Modes B and J on AO-13 and the planned Phase 3D satellite. Mode B is a primary mode on AO-13. Mode B uses 435 MHz uplinks and 145 MHz downlinks, while Mode J reverses this usage. AO-13 Mode B has a 150 kHz bandwidth linear transponder. The Phase 3 satellites (AO-10, 13, and Phase 3-D) are in highly elliptical Molniya orbits. These orbits provide passes 8-10 hours long, with little change in satellite azimuth, elevation, or signal doppler shift for much of the pass. The great distances (36,000 to 42,000 km slant range) covered by the signals requires high-performance, low-noise receiving systems for effective communications.[33] Table 5-10 lists the equipment required for Modes B and J.

Table 5-10 Mode B and J Equipment

435 MHz CW/SSB Transceiver
435 MHz Power Amplifier (Mode B, optional)
435 MHz Antenna and Feedline
435 MHz Receive Preamplifier (Mode J)
144 MHz CW/SSB Transceiver
144 MHz Power Amplifier (Mode J, optional)
144 MHz Antenna and Feedline
144 MHz Receive Preamplifier (Mode B)
Antenna Rotator (optional)

Receiving the AO-13 Mode B and J downlinks requires high-gain antennas, low noise preamplifiers, and low loss feedline. Table 5-11 compares the characteristics of commercially available antennas for Modes B and J on AO-13. These antennas all use circular polarization to minimize losses from signal cross-polarization. The Hy-Gain, KLM, and M^2 antennas include a remote-control switch to reverse the antenna's polarization. This feature is available at additional cost for the Cushcraft antennas. When used with a low noise mast-mounted preamplifier and low loss feedline, these antennas provide SNRs from 14 to almost 17 dB on Mode B and 12 to 15 on Mode J. Note that this assessment assumes -3 dB gain loss on the satellite's antenna to account for off-optimum pointing ("squint") angle.

[33] Path losses on Mode B are over 30 dB greater than on Mode A.

Table 5-11 Downlink Performance of Antennas for AO-13

Mode	Mode B							Mode JL					Mode S
Antenna													
Vendor	Cushcraft	Cushcraft	KLM	KLM	Hy-Gain	M2	M2	Cushcraft	KLM	KLM	Hy-Gain	M2	DEM
Model	A144-10T	A144-20T	2M-14C	2M-22C	216-S	2MCP14	2MCP22	416TB	435-18C	435-40CX	217-S	436-30CP	1345LYK
Gain (dBic)	12.6	14.3	13.1	15.1	13.6	12.4	14.6	14.6	14.1	17.3	16.1	16.6	24.0
Boom Length (FT)	5.8	10.8	12.75	19	14.2	10.5	18.5	6.7	7.3	14.6	10.2	9.75	21
Price ($)	NA	$86	$179	$234	$140	$149	$225	$76	$235	$255	$120	$229	79
Satellite													
Downlink Freq. (MHz)	145.9	145.9	145.9	145.9	145.9	145.9	145.9	435.86	435.86	435.86	435.86	435.86	2400.73
Apogee (km)	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265	36,265
Max Slant Range (km) [Note 1]	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044	42,044
Transponder Power (W)	50	50	50	50	50	50	50	50	50	50	50	50	1.25
Transponder Bandwidth (kHz)	150	150	150	150	150	150	150	290	290	290	290	290	36
# Users (70% loading) [Note 2]	35.0	35.0	35.0	35.0	35.0	35.0	35.0	67.7	67.7	67.7	67.7	67.7	4.0
Power/User (PEP W) [Note 2]	1.43	1.43	1.43	1.43	1.43	1.43	1.43	0.74	0.74	0.74	0.74	0.74	0.31
Received Signal Power (Ps):													
Power per User (dBm)	31.5	31.5	31.5	31.5	31.5	31.5	31.5	28.7	28.7	28.7	28.7	28.7	24.9
Downlink Antenna Gain (dBi) [Note 3]	3.0	3.0	3.0	3.0	3.0	3.0	3.0	6.5	6.5	6.5	6.5	6.5	11.2
Path Loss (dBi)	168.2	168.2	168.2	168.2	168.2	168.2	168.2	177.7	177.7	177.7	177.7	177.7	192.5
Receiver Antenna Gain (dBic)	12.6	14.3	13.1	15.1	13.6	12.4	14.6	14.6	14.1	17.3	16.1	16.6	24.0
Received Signal Power (dBm)	-121.0	-119.3	-120.5	-118.5	-120.0	-121.2	-119.0	-127.8	-128.3	-125.1	-126.3	-125.8	-132.3
Received Noise Power (Pn):													
Sky Temperature (K)	600	600	600	600	600	600	600	108	108	108	108	108	43
Rcvr. System Noise Figure (dB)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	4.1
Rcvr. System Tempreature (K)	108	108	108	108	108	108	108	122	122	122	122	122	449
Effective System Temp. (K)	708	708	708	708	708	708	708	230	230	230	230	230	492
Rcvd. Noise Pwr (dBm) [Note 3]	-135.3	-135.3	-135.3	-135.3	-135.3	-135.3	-135.3	-140.2	-140.2	-140.2	-140.2	-140.2	-136.9
Signal-To-Noise Ratio (SNR):													
Received Signal Power (dBm)	-121.0	-119.3	-120.5	-118.5	-120.0	-121.2	-119.0	-127.8	-128.3	-125.1	-126.3	-125.8	-132.3
Received Noise Power (dBm)	-135.3	-135.3	-135.3	-135.3	-135.3	-135.3	-135.3	-140.2	-140.2	-140.2	-140.2	-140.2	-136.9
SNR (dB)	14.4	16.1	14.9	16.9	15.4	14.2	16.4	12.4	11.9	15.1	13.9	14.4	4.6

Notes:
1. Slant range calculated at apogee for 10 degree elevation angle
2. Transponder # users and power/user assumes 3000 kHz SSB signals
3. Lost gain from "squint" angle -3dB (1/2 power beamwidth)
4. Assumed bandwidth for receiver noise is 3000 kHz
5. Circular polarization for Modes B, J, and L; linear polarization for Mode S

Several active satellite users did not recommend the Cushcraft antennas. Although they perform well on paper and are lowest in cost, several individuals reported they perform poorly in normal use.[34] Local restrictions limit antenna size to fifteen feet or less, making the KLM 2M-22C and M^2 2MCP22 too large for the station location.[35] Based on performance and price, the Hy-Gain 216-S is the best antenna. The M^2 2MCP14 is the second choice. It is approximately the same price as the Hy-Gain, is only about 1 dB lower in performance, and is much smaller.

For the Mode J downlink, the KLM 435-40CX, M^2 436-30CP, and the Hy-Gain 217-S are within 2 dB in performance. The KLM antenna has a solid reputation, but is the largest and most expensive. The Hy-Gain antenna is significantly less expensive, making it the first choice. The M^2 antenna is again second choice based on its combination of performance and size.

Preamplifiers for Modes B and J should be mounted at the antenna mast, have a low noise figure, and a nominal gain around 20 dB. The ability to handle up to 100 W of power eliminates the chance of destroying the preamplifier by accidentally connecting it to a transmitter. Table 5-12 lists the characteristics of units from Advanced Receiver Research, Henry Radio, Mirage, and SSB Electronics useable for Mode B or Mode J. (Preamplifiers selected for Modes A, JD, and S are also listed.) The preamplifiers sold by Henry Radio offer the best combination of price and performance, and will be used for the station. The preamplifiers will be protected from static discharges (including lightning) to prevent destroying their GAsFET active devices.

[34] Electronic mail communications, Internet rec.radio.amateur.misc Newsgroup, March 1992.
[35] Architectural and Environmental Regulations, Hastings Hunt Community Association, 9.

Table 5-12 Preamplifier Characteristics

Vendor	Model	Freq. [MHz]	Gain [dB]	Noise Fig. [dB]	Power Hdlg. [W]	Price [$]	Comments
ARR	P28VD	28-30	15	1.1	0	30	Selected for Mode A
	SP432VDG	420-450	16	0.56	25	110	Selected for Mode JD
DownEast Microwave	13LNA	2400	NA	0.7	0	130	Selected for Mode S
ARR	MML144VDG	144-148	22	0.55	160	210	Mode B Candidate
	MML432VDG	420-450	16	0.6	160	210	Mode J Candidate
Henry Radio	145	144-148	19	0.7	150	161	Mode B Candidate
	432	430-450	18	1.1	150	161	Mode J Candidate
Mirage	KP-2/2M	144-148	15-25	0.6	165	165	Mode B Candidate
	KP-2/70cm	430-450	15-25	0.6	165	165	Mode J Candidate
SSB Electronics	SP-2	144-148	20	0.8	200	200	Mode B Candidate
	SP-70	430-450	20	0.9	100	200	Mode J Candidate

Several multi-mode (CW, SSB, and FM) 435 MHz transceivers will satisfy Mode B and J requirements when used with the station's existing equipment. Selection of a specific transceiver is driven by acquisition cost, as described in Section 5.7.5.

Low loss feedlines are essential for Mode B and J reception. Belden 9913 offers suitable performance at a reasonable cost. Feedline similar in performance to 9913, but more rugged and easier to handle, is available locally and will be used for the station. Type N connectors will be used for all feedline connections to reduce losses at Mode B and J frequencies.

The Russian AO-21 satellite also uses Mode B. AO-21 is a set of linear transponders carried aboard a large satellite in LEO. Accessing AO-21 requires the ability to track the satellite with the ground station antennas during passes of 10-15 minutes, or use of low gain omnidirectional antennas. AO-21 will be most useful to verify system operation before the AO-13 system is fully operational. Communications using AO-21 can use the Mode JD antennas described in the next section.

5.5.2.1.3 Mode JA

Mode JA is a linear transponder using a 145 MHz uplink and a 435 MHz downlink. Mode JA specifically refers to FO-20's analog transponder. FO-20 also supports a digital Mode JD transponder. RF equipment requirements are the same for FO-20's Mode JA and JD and the other Mode JD satellites.

5.5.2.1.4 Mode JD

Mode JD uses digital-modulated signals on a few channels, rather than the wide bandwidth linear transponder used on AO-13's Mode J and FO-20's Mode JA. All Mode JD satellites are in LEO. Gain antennas must therefore be steerable during a pass lasting 10-15 minutes. Alternatively, omnidirectional antennas may be used with reasonable results. The link analysis in Section 5.2.1 showed SNRs of 14 to over 19 dB are feasible with omnidirectional antennas. Table 5-13 lists the equipment required for Mode JD.

Table 5-13 Mode JD Equipment

144 MHz CW/SSB Transceiver
144 MHz Power Amplifier (optional)
144 MHz Antenna and Feedline
435 MHz CW/SSB Receiver (with AFC)
435 MHz Antenna and Feedline
435 MHz Receive Preamplifier
Antenna Rotator (optional)
PSK Modem
Packet Satellite Communications Software

Omnidirectional antennas used for Mode A are also feasible for Mode JD. Vertical dipoles are recommended for Mode JD because they have a suitable radiation pattern and are simple to build. The J-pole, an end-fed vertical dipole, is a favorite because uplink and downlink antennas can be combined into a single structure.[36] Figure 5-5 depicts a stacked pair of J-poles for Mode JD.[37] Some Mode JD users report better results receiving the Mode JD downlink from UO-14 using broad beamwidth, moderate gain antennas, such as a short helix.[38] Gain antennas for Mode JD will be used only if performance with the J-poles is inadequate.

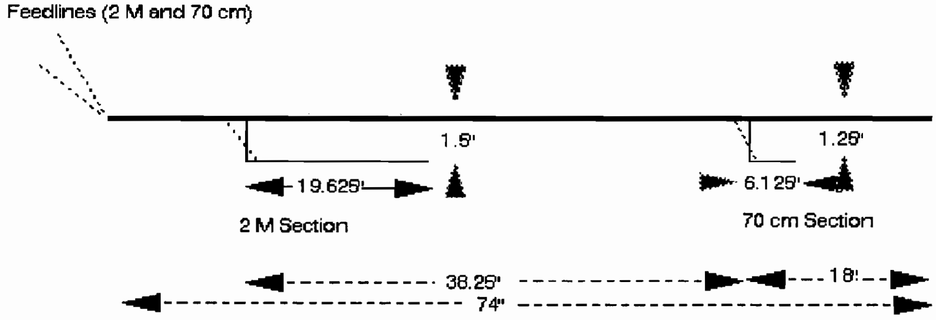

Figure 5-5 Stacked J-Pole Antennas for Mode JD

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[36] Jansson, Dick, WD4FAB, "Antennas for Microsat Ground Stations", *The AMSAT Journal*, March 1990, 11 - 14.

[37] Private correspondence, Presley Smith, N5VGC, March-April 1992.

[38] Branegan, John, GM4IHJ, "Low Budget UoSAT-OSCAR 14 9600 Baud Reception", *The AMSAT Journal*, September 1990, 8 - 11.

A mast-mounted preamplifier will be used to ensure good reception of the Mode JD downlink. This preamplifier does not have to pass high-power signals - a rating of 25 W is sufficient, and only if the Mode JD antennas are also used for AO-21 Mode B. The Advanced Receiver Research SP432VDG offers good performance at a reasonable price. The preamplifier requires protection from static discharges which can destroy it's GAsFET active devices. Low-loss Belden 9913 or equivalent feedline will be used for Mode JD.

A radio with 435 MHz receive capability, such as the 435 MHz transceiver used for Mode B uplink and Mode JA downlink, will be used for Mode JD reception. This radio must be able to accept AFC commands from the PSK modem. While the link analysis suggests as little as 10 W uplink power is sufficient, AMSAT and the experience of current users suggest 50-60 W is often needed when using omnidirectional antennas. The amplifier selected will provide this output level with 10 W of drive, and will be able to handle higher drive levels if needed.

5.5.2.1.5 Mode L

Mode L uses a 1269 MHz uplink and a 435 MHz downlink. Mode L is currently supported by AO-13, and will be a primary mode on the planned Phase 3D satellite. The most significant feature of the Mode L transponder is its considerably wider bandwidth versus Mode B. Table 5-14 lists the equipment required for Mode L.

Table 5-14 Mode L Equipment

1269 MHz CW/SSB Transceiver
1269 MHz Power Amplifier
1269 MHz Antenna and Feedline
435 MHz CW/SSB Receiver (same as Mode J)
435 MHz Antenna and Feedline (same as Mode J)
435 MHz Receive Preamplifier (same as Mode J)
Antenna Rotator (optional)

AMSAT recommends an EIRP of 34 to 37 dBW for Mode L. A 35 W (15.4 dBW) signal fed to a 20 dBi antenna will produce a 35 dBW uplink signal. Commercially available 1269 MHz transceivers and transverters usually produce about 10 W. An amplifier is therefore necessary for Mode L.

Feedline losses are over 8 times as great at 1269 MHz as at 435 MHz. To minimize signal losses and the cost of expensive low-loss feedline, the 1269 MHz amplifier and a 1269 MHz signal source (depending on the transmitter used) will be located in a weather-proof equipment box at the antenna mast.[39,40] The short run of feedline from the amplifier to the mast will minimize feedline losses.

Based on the transmitting scheme selected (see discussion in Section 5.8), a 144-to-1269 MHz transverter may be used to convert the signal from the station's 144 MHz transceiver to 1269 MHz. The transverter will be placed at the antenna to minimize feedline losses. The transverter's output is amplified to 35 W to drive the Mode L uplink antenna.

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[39] Herzler, Ralph E., "Mode L, My Way", *73 Amateur Radio*, May 1989, 50-51.

[40] Mascaro, Dave, WA3JUF, "A High-Performance UHF and Microwave System Primer", *QST*, May 1991, 30 - 33

The 1269 MHz antenna is a pair of home-made helical antennas fed in phase.[41] Suitable commercial antennas are not available, and this design is easy to build and adjust. It provides a theoretical gain of 20 dBi. With 35 W (15.4 dBW) of drive, the uplink signal should be about 35 dBW EIRP, the level recommended by AMSAT for Mode L.

5.5.2.1.5 Mode S

AO-13 is the only satellite with an analog Mode S transponder. AO-13's Mode S transponder is actually a hybrid Mode B/Mode S unit, using a 435 MHz uplink and a 2.4 GHz (S Band) downlink. Future Mode S transponders, such as Phase 3D's, may use 1269 MHz for uplinks to take advantage of the greater bandwidth available at the higher frequency. The Phase 3D Mode S transponder will also use higher power and higher gain antennas, improving the downlink signal several dB vs. AO-13's. AO-16, DO-17, WO-18, and LU-19 have a digital Mode S transponder downlink used for experiments. Table 5-15 lists the equipment for Mode S.

Table 5-15 Mode S Equipment

435 MHz CW/SSB Transceiver (same as Mode B)
435 MHz Power Amplifier (same as Mode B)
435 MHz Antenna and Feedline (same as Mode B)
2400-144 MHz Receive Converter
2400 MHz Antenna and Feedline
2400 MHz Receive Preamplifier (same as Mode J)
2400-144 MHz Receive Converter
Antenna Rotator

[41] Herzler, Ralph E., "1269 MHz Helix Array", *73 Amateur Radio*, May 1989, 71-72.

Mode S requires very high gain antennas. Parabolic dishes are most effective but present structural problems. Most are homemade. Loop yagis are available commercially from DownEast Microwave and are easier to construct and support. Loop yagis do not offer the gain of a dish, but are easier for beginners to Mode S.[42] Antennas for Mode S have narrow beamwidths, requiring use of antenna rotators to keep the antenna pointing directly at the satellite throughout the pass.

Signal losses in feedlines are considerable at 2.4 GHz. Preamplification of the Mode S downlink signal must be performed as close as possible to the antenna feedpoint.[43] Commercially available and kit-built equipment is available from two sources, DownEast Microwave and SSB Electronics USA.

The receiving system uses a 13 cm GAsFET preamplifier mounted at the antenna feedpoint. With weatherproofing, the 13 cm - 2 m receiving converter can be located at the antenna. By converting the signal to 144 MHz at the antenna, feedline losses are reduced and receive system performance improved. This improvement may be critical, given the marginal SNR predicted for Mode S. Another loop yagi can be added to further improve Mode S performance. A second antenna will be added only if absolutely necessary to obtain usable performance.

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[42] Krome, Ed, KA9LNV, "Mode S: Plug and Play!", *The AMSAT Journal*, January, 1991, 21 - 25.
[43] Ibid.

5.5.2.2 Computing Equipment

Computing equipment is integral to the satellite ground station's operations before, during, and following a satellite pass. This section describes the computer equipment, control and interface hardware, and software required for the station.

5.5.2.2.1 Computer Hardware

Computer hardware already on hand consists of an IBM PC XT-286, using the MS-DOS operating system, and an NEC PC-8500 laptop, using the CP/M operating system. The PC-8500 is used as a communications terminal for terrestrial packet radio. The XT-286 is used for general office automation tasks.

The XT-286 has sufficient performance to run satellite tracking software to predict passes and control antenna pointing during a pass. The XT-286 can run the communications software required for using the Mode JD satellites, software for processing files received via Mode JD, and analysis software for telemetry captured from the satellites.

The XT-286 has poor long-term reliability for this project. It is one of six systems surplused by the author's employer after over five years of use. These six systems have suffered catastrophic motherboard, monitor, and hard disk failures. Based on this small sample, a hard disk or system motherboard failure is likely within a few years. A failed disk can be replaced with a new, higher performing unit. A motherboard failure is more serious, since the board is obsolete and out of production. New motherboards with memory are available for about $500, but compatibility may force replacement of most other system components as well. A complete replacement system using new components can be purchased for $1,000-$1,500. For twice the cost of a partial repair, a new, higher-performing system is obtained. For this reason, a replacement system unit (Intel 80386SX CPU or better) is included in the station acquisition budget, rather than a motherboard replacement.

The PC-8500, using its built-in communications software, is adequate for obtaining current satellite orbital elements and bulletins distributed via the terrestrial packet radio network. The PC-8500 can communicate with Mir and SAREX payloads, but cannot run the software required to use the Mode JD satellites. Data stored on PC-8500 disk's must be converted by the XT-286 into MS-DOS format before it can be used for satellite tracking. The packet station hardware will be connected to the XT-286 to eliminate these interoperability issues. The PC-8500 will be surplused to free up resources for acquiring other station equipment.

5.5.2.2.2 Control and Interface Hardware

Several items of hardware are required to interface the station computers with the communications equipment, and to enable computer control of some station functions. TNCs, satellite modems, and telephone modems interface the computers with satellite and terrestrial radios and with the telephone network. A rotator control interface enables automated antenna pointing.

The station's MFJ-1270 TNC interfaces the XT-286 with the TS-700SP transceiver for terrestrial packet radio communications. The TNC's internal modem uses AFSK modulation, while the Mode JD satellites and the AO-13 telemetry beacon require BPSK or FSK modulation. A separate satellite modem is required. Table 5-16 compares several satellite modems that can support Mode JD.

Table 5-16 Comparison of Satellite Modems

Vendor and Model	Price	Modes Supported	Comments
L.L. Grace, DSP-12	$794	All satellite and terrestrial modes	True all-mode modem and TNC
AEA DSP2232	$999	All satellite and terrestrial modes	Marginal perfomance reported on satellite modes
PacComm PSK-1	$230	1200 bps satellites (AO-16,WO-18, LU-19,FO-20)	Adapts TNC to satellites and telemetry recepetion, retains terrestrial packet modes
PacComm EM-NB96	$160	9600 bps satellites (UO-14,UO-22,KITSAT)	Works with TNC and PSK-1T
PacComm TNC NB96	$300	9600 bps satellites (UO-14,UO-22,KITSAT) and terrestrial modes	TNC with buil-in 1200/9600 bps modem

The L.L. Grace and AEA modems use digital signal processing (DSP), while the PacComm modems are hardware-based designs. Both DSP modems claim to support all current satellite data rates and modulation schemes. The DSP modems are more expensive but are easier to adapt to changes in Pacsat operation than the PacComm modems. Because a high speed Mode JD capability is not needed immediately, a DSP modem can be acquired after the price-performance tradeoff versus conventional hardware-based modems improves.

The station will use the PacComm PSK-1 satellite modem for 1200 bps Mode JD. The PSK-1 supports the 1200 bps BPSK signals used by AO-16, WO-18, LU-19, and FO-20, and comes completely assembled.[44] Connection to the station's TNC requires the addition of a socket to the TNC to permit connection of the PSK-1 modem. This modification will be performed by the station owner/operator. A switch on the PSK-1 allows use of TNC's built-in modem for terrestrial packet communications.

[44]Goodman, Dick, WA3USG, "The PacComm PSK-1", *73 Amateur Radio Today*, December, 1990, 32 - 33.

The PSK-1 does not support the 9600 bps FSK signals used by UO-14, UO-22, and KITSAT. The PacComm EM NB-96 will be used for these satellites. The EM NB-96 interfaces with the TNC and PSK-1. The three units together support all digital modes required for the satellite station: 1200 bps Mode JD (BPSK), 9600 bps Mode JD (FSK), and 1200 bps AFSK packet for accessing the terrestrial packet radio network.

L.L. Grace's Kansas City Tracker is a hardware interface providing open-loop computer control of the station's antenna rotators. This control is necessary when using high gain, directional antennas with satellites in LEO. Without automated antenna pointing, the workload during a LEO satellite pass is too much for a single operator. The Kansas City Tracker is an option for Mode JD capability, as many current users report adequate results using omnidirectional antennas on Mode JD. The Kansas City Tracker interface will be acquired if operational experience shows directional antennas are needed for reliable Mode JD operations.

L.L. Grace's Kansas City Tuner adds automated doppler correction frequency control to the Kansas City Tracker. Automated doppler correction is reported to be useful for using 9600 bps Mode JD.[45] The Kansas City Tuner must be purchased with the Kansas City Tracker. It is not available as an add-on.

The station computers and control hardware have the potential to cause RF interference to the station receivers. The increased noise level from this interference can make satellite communications impossible. The computer and control equipment can be tested to see if they interfere with the satellite downlinks. RF interference can be controlled by effective shielding; bypassing of leads, connectors, and cables; and

[45]Electronic mail communications, Internet rec.radio.amateur.misc Newsgroup, March 1992.

grounding. Placing antennas and preamplifiers away from the offending equipment can also control interference.

5.5.2.2.3 Software

Computer software currently on-hand supports terrestrial packet communications and satellite orbit prediction and tracking. These are the core capabilities required for satellite operations. Standard communications software is used with the station's TNC to connect to the packet radio network and obtain satellite orbital elements sets and operating schedules. This data is input to the InstantTrack satellite tracking software to predict and track satellite passes. This software runs on the station's XT-286 under the MS-DOS operating system.

Additional software is required to use Mode JD and interpret data files and telemetry from the amateur satellites. The PE and PB programs implement the communications protocol used with the Mode JD satellites. WEBERWARE converts image files taken by WO-18. TLMDC decodes Microsat telemetry, and WHATS-UP decodes DO-17 telemetry. The QuickTrack tracking program performs orbit prediction and supports the Kansas City Tracker/Tuner better than the InstantTrack software already on hand. While the station's communications software is adequate for satellite operations, the LAN-LINK program offers special features for satellite use.

PE and PB and WEBERSAT are available from AMSAT. TLMDC, WHATS-UP, and LAN-LINK are distributed directly by their authors and as shareware via amateur radio CBBSs. Acquisition costs for the software, including one upgrade within five years, are included in the life cycle cost analysis in Section 5.8.

Office automation software is on-hand to support logging of station use and maintenance, creation and storage of correspondence, and some basic analysis of station equipment. No acquisition of additional software is planned for these functions.

5.5.2.3 Facilities and Structures

5.5.2.3.1 Facilities

The current station operating location is a portion of the basement in the station owner's house. This location has sufficient space, power, ventilation, heating, and cooling to accommodate the additional equipment for the satellite station. A separate desk for holding the satellite equipment is already on hand. The equipment is located underneath the station's current roof-mounted HF and VHF antennas. Satellite antennas will be located with or near these antennas.

Antenna feedlines are presently run to the outside via an unused clothes dryer vent. The location of this vent relative to the station equipment and the likely location of the satellite antennas requires longer feedlines than desirable for satellite communications. To reduce feedline losses and save on expensive, low-loss coaxial cable, a new feedthrough will be installed directly underneath the current antennas. This feedthrough will also use dryer vent hardware, and will be sealed and insulated to maintain the basement's weather proofing.

A separate 110 VAC, 15 A circuit is available to provide power to the station equipment. As shown in Table 5-17, this circuit has ample capacity to power the station. Station grounding will be directly to the municipal water main, which is easily accessible. This is the same ground used by the house's power wiring.

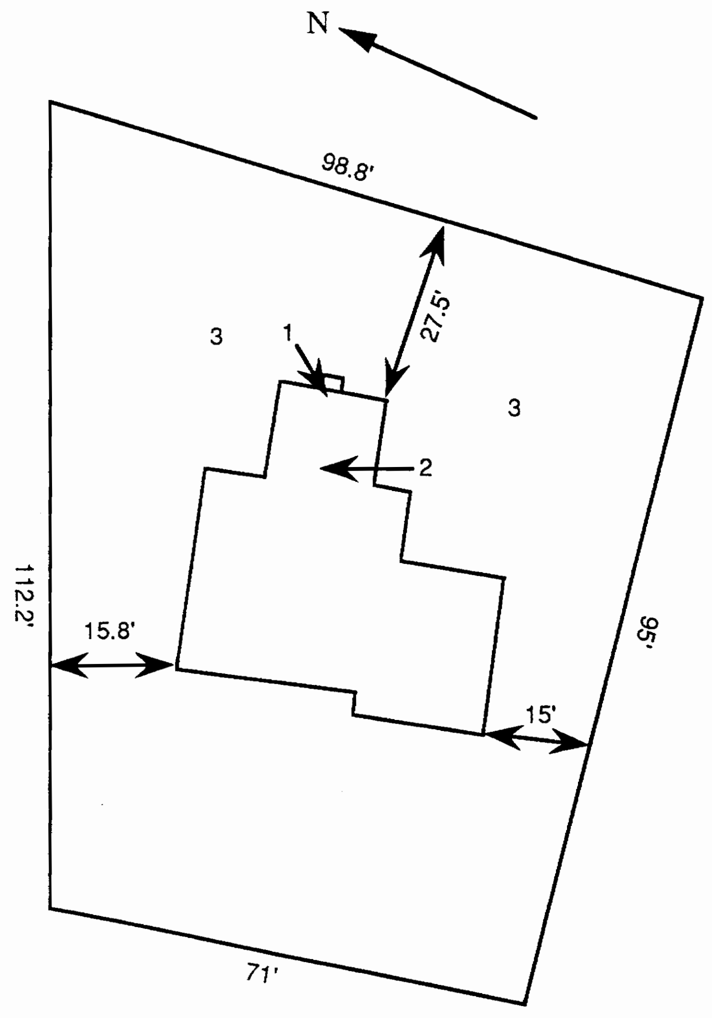
Table 5-17 Station Power Budget

Item	Maximum Power Consumption (VA)	Current (A) @ 13.8 VDC	Current (A) @ 115 VAC
2 m Transceiver	998		1.0
70 cm Transceiver	100	7.5	
Power Amplifier (1 operating, 1 off)	300	20.0	
Preamplifier (1 operating, 1 off)	2	0.2	
Az-El Rotator	70		0.6
TNC+PSK Modem	6	0.6	
Computer	150		1.0
Monitor	120		1.0
Room Lighting	200		1.7
TOTAL	948	28.3	4.3
Station Power Supply Requiremnts:			
Current @ Voltage		30	10
Margin		1.1 vs. supply ICS rating	1.53 vs. 15A circuit

5.5.2.3.2 Structures

External structures are required to support the station's antennas and rotators. A weather-proof equipment shelter is required to house Mode L uplink hardware, which is not designed for unprotected mounting outdoors. Rotators and preamplifiers are designed for outdoor use, and require no special protection.

Figure 5-6 depicts the station's site plan. Placement of the dwelling and property boundaries at the station location, and the locations for station antennas are shown. Feedlines from the station equipment to antennas at these locations are about thirty feet long, minimizing signal losses.



1	Preferred Location for Directional Antennas (Roof-top Mast)
2	Preferred Location for Omni-directional Antennas (Modes A, JD)
3	Alternate Location for Directional Antennas (Moveable Mast)

Figure 5-6 Station Site Plan

Architectural guidelines in the author's subdivision restrict outside antennas.[46] While the author believes the proposed antennas for the station are within these guidelines, this will likely be disputed by the homeowners association's Architectural Review Board (ARB). The methods for mounting antennas are designed to minimize the impact on the station's ability to operate should the ARB's opinion ultimately stand.

Omnidirectional antennas for accessing LEO satellites using Modes A, B, J, and JD are mounted on the dwelling chimney, replacing the current "Ringo Ranger" used for terrestrial communications on the 2 m band. This location places the antennas relatively clear of obstructions and provides a short cable run to the station equipment.[47] The roof adjacent to the chimney provides a convenient work area for adjusting antennas and preamplifiers. The roof area is reached directly from an upper floor window, eliminating the need for ladders to access the antennas.

Directional antennas for AO-13 may be mounted on a short mast near ground level or on/near the chimney used for the omnidirectional antennas. If the ground-mounted mast is moveable (e.g.; not a permanent structure), the ARB has no jurisdiction and cannot force its removal. Such a mast will therefore be used until the issues with the ARB are resolved. The moveable mast allows easy access to the antennas for manual pointing, adjustment, and servicing. The disadvantages of a moveable mast are inability to withstand extremely high winds, antenna blockage at low elevation angles, and potential safety hazards from RF energy and accessibility of the antennas themselves.

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[46] Architectural and Environmental Regulations, Hastings Hunt Community Association, 8-9.
[47] The house's main roof line may block low elevation satellite passes to the west of the station.

Figure 5-7 presents the analysis of ballasting requirements for a moveable mast. The analysis assumes a 2.4 m (8 ft) tall mast. Manufacturer's data provides the equivalent flat-plate area for the antennas and rotator. The cross-sectional area of the cross boom is added, resulting in the area affected by the wind at the top of the mast. The area of the mast itself is added at a point equal to one-half the mast height. A 1.1 m (3.5 ft) square base is assumed, simply supported (antenna, mast, and rotator hardware plus additional weight) at the ends. The weight of the antenna, mast, and ballast must exceed the force from the wind acting on the antennas and mast to prevent the mast from tipping.

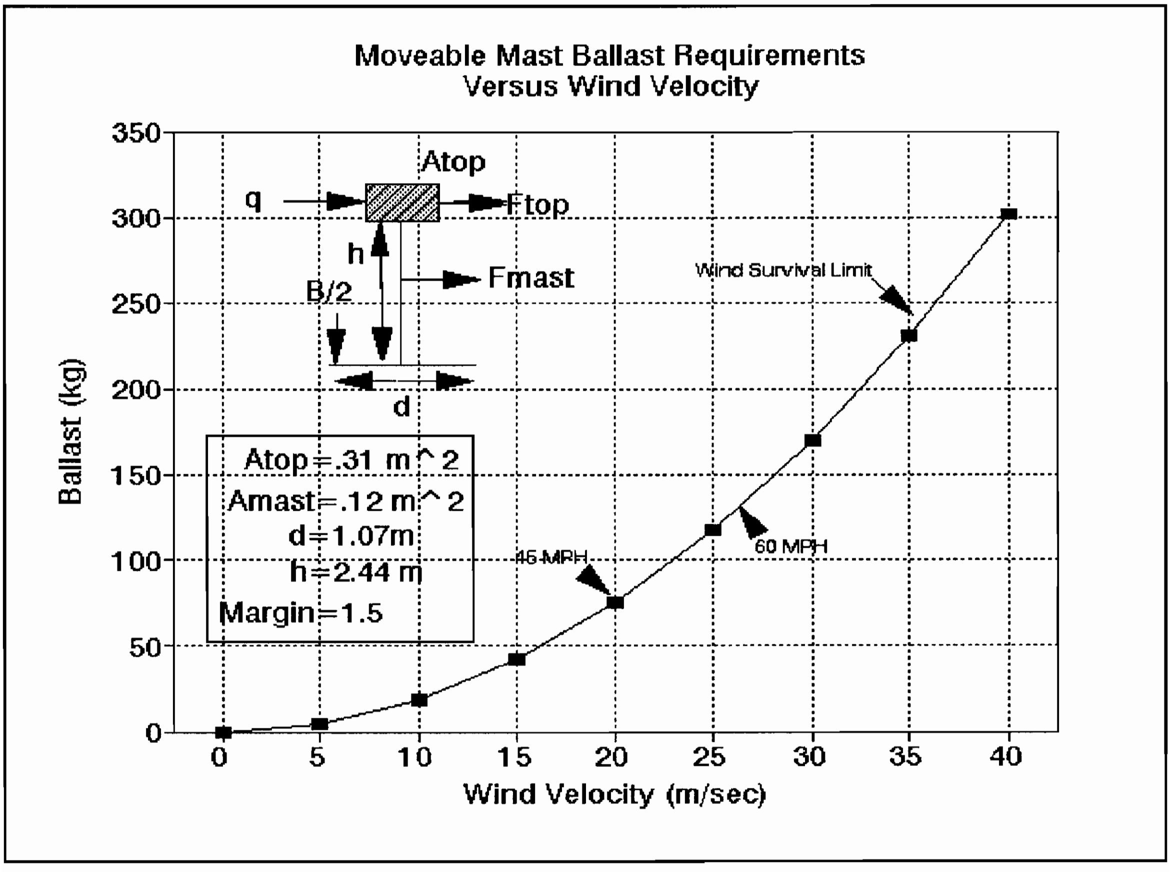

Figure 5-7 Moveable Mast Ballast Requirements

A heavy concrete base is necessary to make the mast self-supporting at the 80 MPH wind-survival limit quoted for the antennas. Such a base is impractical for a moveable mast. A base sufficient to withstand moderate winds (below 30 MPH) without guy lines is feasible. The mast will have to be guyed, secured, or brought inside when winds over 30 MPH are expected.

5.5.3 Safety Analysis

This section examines the safety issues affecting the satellite ground station. RF safety, dealt with in Section 5.5.3.1, addresses the exposure of people near the station's uplink antennas to RF power densities exceeding recommended levels. Other safety issues, including electrical, mechanical, and physical safety, are discussed in Section 5.5.3.2.

5.5.3.1 RF Safety

The ground station uplink must meet safety requirements for exposing people to high levels of RF energy. The American National Standards Institute (ANSI) published in 1982 the current guidelines for human exposure to RF energy. Table 5-18 summarizes the allowable power densities for the three uplink frequency bands of interest:[48]

[48] Davidoff, Figure 9-17, p 9-13, from "Radiation Protection Guide of the American National Standards Institute (ANSI)", 1982.

Table 5-18 Allowable RF Power Density for Satellite Uplink Bands

Mode	Frequency [MHz]	RF Density [mW/cm^2]
B	435	1.5
J	144	1.0
L	1269	4.2

Good safety practices requires the ground station uplink antennas be located and operated to prevent people from encountering RF power densities exceeding these guidelines. In the absence of field strength measurements, RF power densities should be evaluated at transmitter power levels 6 dB (i.e. 4 times) greater than expected.[49]

The equation for evaluating far-field energy density is:[50]

RF Energy Density $[W/m^2] = (P*G)/(4*\pi*R^2)$ [Equation 5.1]

where:
P average power at antenna input [W]
G antenna gain [decimal, not dB]
R distance from antenna [m]

To express power density in mW/cm^2 (the units used in the ANSI standard), use the conversion factors of 1000 mW/W and 100,000 cm^2/m^2. For this analysis, P is expressed in W EIRP (accounting for antenna gain) and G represents the 6 dB safety factor (G=4). The equation then becomes:

[49] Davidoff, Table 9-3, p 9-14.
[50] Ibid, Eq. 9.1, p 9-14.

$$\text{RF Energy Density [mW/cm}^2] = (1/10)*(P*G)/(4*\pi*R^2) \quad \text{[Equation 5.2]}$$

where:

P average effective isotropic radiated power [W]
G antenna gain [decimal, not dB]
R distance from antenna [m]

Table 5-19 shows the recommended minimum safe distance based on Equation 5.2, using the EIRP recommended by AMSAT for AO-13. Distances are shown for 100% and 10% of the ANSI levels for individuals in mainbeam of the antenna (e.g.; on boresight). Note that the EIRP levels used here are a worst-case situation - the recommended EIRP is at least 7 dB lower for LEO satellites. Furthermore, Phase 3D, the replacement satellite for AO-13, is expected to achieve higher uplink and downlink gains, enabling effective communications at lower uplink power.

Table 5-19 Minimum Safe Distance In Antenna Mainbeam

Mode	Frequency [MHz]	EIRP [W]	Gain Factor	ANSI Limit [mW/cm^2]	Distance [m]	10% of ANSI Limit [mW/cm^2]	Distance [m]
B	435	500	4	1.5	3.3	0.2	10.3
J	144	800	4	1.0	5.1	0.1	16.0
L	1269	4000	4	4.2	5.5	0.4	17.4

Although power densities are below the ANSI standards within the lot boundaries of the station's property, they remain at an appreciable level (10% of the standard) well into adjoining properties. Erring towards greater safety (there are several young children in the neighborhood, including the station owner's!), suggests keeping power densities well below the ANSI standard. Ten percent of the standard was arbitrarily chosen as the target level, in addition to the 6 dB safety margin already included. To operate at these levels, EIRP must be lowered by at least 3 to 6 dB from AMSAT's recommendations for reliable communications. Alternatively, the antennas must be placed further from the lot boundaries and out of reach from the ground.

Two installations are feasible at the proposed station location. A roof-mounted installation will place all antennas 6-8 meters above the ground. Even at low antenna elevation angles, individuals at ground level remain outside the uplink antenna main beam.

The other possibility is the ground-mounted moveable mast described in Section 5.5.2.3.2. This mast places the antennas 2.4 m (8 ft) above ground level. Obstruction by nearby dwellings make operations impractical for antenna elevation angles below 20-30 degrees above the horizon. The 1/2 power (-3 dB) beamwidth for the uplink antenna designs under consideration is 30 to 50 degrees. Elevation angles greater than 25 degrees therefore place individuals at ground level in the antenna's sidelobes, reducing the power levels they experience by at least 3 dB. Table 5-20 shows the results of calculations incorporating this 3 dB reduction in EIRP experienced at ground-level:

Table 5-20 Minimum Safe Distance in Antenna Sidelobes

Mode	Frequency [MHz]	EIRP [W] [Note 1]	Gain Factor	ANSI Limit [mW/cm^2]	Distance [m]	10% of ANSI Limit [mW/cm^2]	Distance [m]
B	435	250	4	1.5	2.3	0.15	7.3
J	144	400	4	1.0	3.6	0.10	11.3
L	1269	2000	4	4.2	3.9	0.42	12.3

Note 1: EIRP in antenna sidelobes (Recommended AO-13 uplink EIRP -3 dB)

For a full-power Mode B uplink, 10% of the ANSI standard level occurs within the station property lines. The full-power Mode J and Mode L uplinks remain unacceptable for a ground-mounted installation.

Operating practices can be further limit RF exposure. Using reduced power whenever possible will improve safety by 3 to 5 meters in allowable distance per 3 dB of EIRP. Antenna elevation angles for AO-13 will usually be well above 30 degrees, further reducing ground-level power density. Operating at night will reduce the likelihood of individuals, especially children, being near the uplink antenna beam.

In the final analysis, however, high-power VHF/UHF operation in a small lot with a ground-mounted antenna system is impractical. High power levels are currently necessary for the AO-13 Mode L uplink. Effective Mode L operation will likely force a rooftop antenna installation. Such an installation in turn requires resolving the antenna issue with the HH HOA's architectural review board (ARB).

Combining RF safety with local antenna restrictions suggests the following strategy for station acquisition:

- Operate Mode B at up to recommended EIRP with moveable ground-mounted antennas; no operation at elevation angles below 20-30 degrees.

- Operate Mode J below the AMSAT recommend EIRP; no operation at elevation angles below 20-30 degrees.

- Postpone full-power Mode L operation until installation of roof-top antennas, or until Phase 3D enters service, allowing communications at lower EIRP.

Regardless of placement, the antennas and attached equipment (such as GAsFET preamplifier) must be protected against lightning and electrical storms. Rooftop antennas will employ grounding straps. Ground-mounted antennas will use ground straps laid on the ground. Feedlines will use lightning arrestors to protect equipment from static charge buildup. All equipment will be shut down, with feedlines grounded and disconnected from transmitters and receivers during electrical storms and when the station will be unattended when such storms are possible.

5.5.3.2 Other Safety Issues

Other safety issues affecting the satellite ground station include physical safety and mechanical soundness of outside antennas, electrical safety of power and feedlines, and safety inside the operating room.

The AO-13 uplink and downlink antennas are designed to survive winds of up to 33-36 m/sec (75-80 MPH) without damage. By placing these antennas on a moveable, ground-mounted mast, they can be moved inside when severe conditions are expected. Inside storage will reduce weathering of antenna hardware and preamplifiers, at the cost of greater wear and maintenance of cables and connectors. Hardware will be made from treated steel and other materials capable of surviving exposure to the elements with minimal wear and maintenance. Hardware must enable easy movement and minimal disassembly of the antenna array to permit indoor storage when necessary.

People on the ground, especially children, must be protected from coming into accidental contact with the antenna to prevent injuries, including burns from RF energy. Placing the antennas on a mast helps keep them out of reach from accidental contact, even when high elevation angles place the antenna reflector and driven elements closer to the ground.[51] The mast installation will include a warning ring (nylon tape or similar markers) that can be placed about 3 m from the mast to mark a keep-out area.

Rooftop antennas are inherently out of reach from people on the ground. Omnidirectional antennas are easily mounted and pose little, if any, structural problems. The weight and wind loading of the AO-13 antenna array will likely require guying to insure stability in strong winds. Because the array is not easily moved into shelter, it must be capable of surviving winds at least as strong as the antenna itself. Hardware will be made from stainless steel or other materials capable of surviving exposure to the elements with minimal wear and maintenance.

Electrical safety requires use of good quality feedlines for RF and electrical power to the antennas. Low current DC power is required for mast-mounted preamplifiers. Antenna rotators use low current AC and DC lines. Cables designed for outdoor use will be used. All power lines will be fused. RF feedlines will use coaxial cables with non-contaminating jackets to prolong the life of the cable.

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[51] This requirement further limits antennas with boom lengths over 14-15 feet.

Electrical safety inside the operating room will be achieved by limiting the amount of power drawn from house circuits to the circuit's capacity. Power leads into and from main power supplies will be fused. Grounding will use the cold-water line. The main entry point for this line is accessible from the operating location, ensuring good DC and RF grounds.

Power leads, feedlines, and control cables will use polarized and/or color-coded plugs to limit chances for equipment to be connected incorrectly. Checklists and operating guides will be used to reduce the chance of transmitting into unprotected preamplifiers or without an antenna connected to the transmitter.

The existing household ventilation system provides sufficient fresh air to the operating room. The operating location will have a smoke/heat detector and a fire extinguisher rated for use on electrical equipment. Under normal circumstances, equipment will be shut off and disconnected from antennas and power when the station is not in use. When equipment must be left on, such as for unattended telemetry capture, only the equipment absolutely necessary will be left on or connected. Other members of the station owner's household will know how to disconnect the equipment's primary power if the need arises. The main power cutoff will be clearly marked.

5.6 Test Plan

The test plan for the station is intended to verify proper operation of station equipment to maximize the likelihood of satellite contacts. Equipment acquired during each phase of the station's acquisition must be demonstrated to provide the desired capabilities before further acquisitions are made.

For each acquisition, the basic test process will be as follows:

- If new antennas and feedlines are installed, verify proper antenna and feedline installation and matching for receive and transmit. Use Standing Wave Ratio (SWR) bridges, power, and field strength meters designed for the frequency in use. (Although good UHF test equipment is expensive, the author can borrow the basic equipment needed.)

- Verify receive performance using live satellite signals (RF system performance) and live and recorded downlink audio (digital system performance). Recordings of Mode JD signals are available from AMSAT for adjusting satellite modems.

- Verify transmit performance via on-the-air tests with nearby amateur stations.

- Demonstrate satellite station performance via contacts using the appropriate satellite and mode.

Portions of each acquisition can be tested separately for proper operation. For example, Mode A and Mode JD omnidirectional antennas can be tested using terrestrial stations as well as satellites. 144, 435, and 1269 MHz transmitters can also be tested through terrestrial contacts with local stations. Accuracy of rotators and antenna positioning can be checked by moving antennas to peak AO-13 downlink signal strength, then comparing the indicated antenna bearings versus the predicted bearings (after compensating for timing errors). A similar approach can be used to isolate problems with equipment following installation and initial use.

The test equipment already on hand is capable of verifying performance parameters of equipment up to 144-148 MHz. This includes power supply voltages and currents, continuity and resistance checks, estimates of transmitter and amplifier output power, and measurement of antenna and feedline impedance mismatches (e.g.; SWR). New equipment is required for checking transmitter and amplifier output and antenna system SWR at 435 and 1269 MHz and 2.4 GHz.

5.7 Acquisition Plan

The station acquisition plan divides the purchase and installation of the ground station equipment into discrete phases. Each phase adds a new satellite mode to the station. Phasing equipment acquisition this way spreads out the cost of the station over several years. It ensures that new equipment is not left idle because critical supporting items are not yet purchased.

5.7.1 Acquisition Plan and Schedule

The ground station equipment will be acquired one mode at a time over several years. The goal will be to acquire, install, and begin operating on Mode A and Mode JD during 1992. One of the remaining modes is added each year until the station is complete or the owner decides there is sufficient capability to meet his needs. Table 5-21 summarizes this acquisition schedule.

Table 5-21 Acquisition Schedule by Mode

Mode	Year Acquired
Mir, SAREX	1992
A	1992
JD (1200 bps)	1992
B, J	1993
L	1994 [Note 1]
JD (9600 bps)	1995
S	1996 [Note 1]

Notes:

1. If AO-13 fails or reenters, delay acquisition of this mode until Phase 3D becomes available

Equipment will be purchased from local amateur radio equipment dealers and by mail order. Some items, notably the Mode L and Mode S equipment, preamplifiers, and the satellite modems are available only by mail. The RF equipment for Modes B and J is available locally and via mail order. The decision to purchase from a specific dealer will be based on price, availability, and the amount of support expected to be needed after purchase. Equipment which may require post-sale support will be purchased locally, if possible.

5.7.2 Selection of 435 MHz Transceiver

Selection of the transceiver for use on the 435 MHz (70 cm) band is the key decision affecting acquisition of transmitting and receiving equipment. 435 MHz is the most important band for satellite use. It is used for Mode B and S uplinks and Mode J, JD, and L downlinks. The 435 MHz equipment decision dictates subsequent equipment choices for Modes B, JA, JD, and L. This decision therefore affects both system performance, operating flexibility, and acquisition and operating costs.

Researching available 435 MHz equipment identified five radios with 435 MHz transmit capability for further consideration:

- Ten-Tec 2510B: Combines a 10 W 435 MHz transmitter with a 2 m preamplifier and a 2 m - 10 m receive converter. Allows "slaved" tuning of uplink and downlink after adjustment for doppler shift. While out of production, limited quantities of new units are available at reduced price.

- Multi-mode (CW/SSB/FM) mobile transceivers from Kenwood (TR-851A) and Yaesu (FT290RII): These radios offer full transceive capability on 70 cm. Designed for mobile installations, they can be used as base stations if 13.8 VDC at 8-10 A is provided. Power output ranges from 3-5 W up to 25 W. The Yaesu unit can run off internal batteries at 3 W output, making it useful for non-satellite portable UHF operations.

- Multi-mode (CW/SSB/FM) base station transceivers from Icom (IC-475H) and Yaesu(FT-736R). Power output ranges from up to 25 W (Yaesu) to 75 W (Icom). These radios offer superb performance and are the UHF state-of-the art. The Yaesu unit can operate in a "satellite" mode simultaneously on 144, 435, and (optional) 1269 MHz. The Icom unit offers similar capabilities when used with companion 144 or 1269 MHz models and an interface unit.[52]

Table 5-22 summarizes the comparison of these five radios. The table covers only acquisition costs of equipment for each satellite mode required by each unit. Equipment common to all five (such as antennas and preamplifiers) is left out of the comparison. Operating and support costs are assumed roughly equivalent for all

[52]Multi-band radios from Icom and Kenwood similar to the FT-736R were not considered because of their higher price without additional features to justify the cost.

alternatives and are therefore also left out of the comparison. Because the FT-736R operates on 144 MHz as well as 435 MHz, a sixth alternative, trading-in or selling separately the stations' existing 144 MHz transceiver, was added to the comparison.

Table 5-22 Cost Comparison of 435 MHz Radios

		Multi-Mode Mobile		Base Station		Yaesu
Alternative	Ten-Tec	Yaesu	Kenwood	ICOM	Yaesu	(w. trade-in)
Mode B:						
Ten-Tec 2510B	$350					
Yaesu FT290RII		$600				
Kenwood TR-851A			$670			
ICOM IC-475H				$1,400		
Yaesu FT-736R					$1,500	$1,250
70 cm Power Amp	$310	$310	$310		$310	$310
12 VDC Supply	$190	$190	$190	$190	$190	$190
Mode B Total	$850	$1,100	$1,170	$1,590	$2,000	$1,750
Mode JA						
2 M Power Amp	$195					
70cm-10M Converter	$100					
Mode JA Total	$295	NA	NA	NA	NA	NA
Mode JA & JD:						
2 M Power Amp		$195	$195	$195	$195	$195
Mode JA & JD Total	NA	$195	$195	$195	$195	$195
Mode L:						
2M-23cm Transverter	$600	$600	$600	$600		
23cm Module					$500	$500
23cm 35W Power Amp	$325	$325	$325	$325	$325	$325
70cm-2M Converter	$100					
Mode L Total	$1,025	$925	$925	$925	$825	$825
Cumulative Cost by Mode:	2510B	FT290RII	TR-851A	IC-475H	FT-736R	FT-736R (ti)
B	$850	$1,100	$1,170	$1,590	$2,000	$1,750
JA	$1,145	NA	NA	NA	NA	NA
JA+JD	NA	$1,295	$1,365	$1,785	$2,195	$1,945
L	$2,170	$2,220	$2,290	$2,710	$3,020	$2,770

All six alternatives support Mode B operation. The IC-475H does not require a power amplifier, but does require a 12-13.8 VDC supply. The power supply chosen provides enough current to run all DC-powered equipment planned for the station. The FT-736R has an internal power supply, and may require the power amplifier under some conditions.

The Ten-Tec 2510B supports only Mode B. Mode J requires use of the existing 144 MHz transceiver and a power amplifier. A receiving converter is required to receive the analog downlink signals on 435 MHz, providing basic Mode JA capability. The current station equipment cannot be interfaced with Mode JD AFC circuitry, limiting its usefulness for Mode JD. The other 435 MHz radios all support Mode J and accept AFC tuning commands for Mode JD. They require a power amplifier to boost the existing 144 MHz transceiver's power output to the level needed for reliable Mode J operation.

Mode L requires converting and amplifying the signal from the station's 144 MHz transceiver to 1269 MHz. A transverter performs the frequency conversion. The FT-736R has an optional 1269 MHz module which is slightly less expensive than the transverter. All alternatives require the power amplifier. The Ten-Tec 2510B requires the receiving converter used for Mode J to receive the Mode L downlink.

Mode S requires reception of 2.4 GHz signals and a 435 MHz uplink. All alternatives require the 2.4 GHz receiving equipment and are capable of providing the uplink signal. Since equipment requirements are identical, Mode S does not affect the decision and is ignored.

All alternatives use new equipment and should have similar reliability. Expected operating costs are therefore comparable and do not affect the decision.

Analysis of capabilities and acquisition costs shows that while the Ten-Tec 2510B provides the least expensive Mode B capability, it makes no contribution to Modes J or L. The unit is out of production and will quickly become available only as used equipment. Effective Mode JD operation is essential for this station. This capability is not supported by the 2510B, eliminating it from consideration.

Either multi-mode mobile transceiver provides a solid base for operating Mode B, J and L. Their size and 13.8 VDC power requirements allow easy portable operation. They also cost substantially less than the larger base station radios. Of the two, the TR-851 appears to be the better radio for satellite use. The author knows of at least one station using the TR-851 on Mode JD, while he is unaware of anyone using the FT-790. The principle limitation of these radios is their simpler receiver systems when compared to the IC-475H or FT-736R.

The FT-736R is a better alternative than the IC-475H. While the FT-736R is more expensive, it is designed for satellite operation and is highly recommended in this use. Because the FT-736R operates on 144 MHz as well as 435 MHz, it offers the opportunity to trade-in the current 144 MHz radio or use it as a backup unit.[53] While the 475H provides superb 435 MHz performance and eliminates a power amplifier, it still requires a high-current DC power supply. To obtain the operating conveniences of the FT-736R, the companion 144 MHz model must be purchased, doubling the acquisition cost of the Icom alternative.

The FT-736R Mode B system acquisition cost is $650 more than the TR-851 alternative. This is a substantial difference - equivalent to the purchase of the Mode B

[53] For example, to back up a failure of the FT-736R's 144 MHz module or dedicate to terrestrial voice and packet use.

antennas plus a preamplifier or an elevation rotator. The TR-851A is therefore more cost-effective than the FT-736R. This decision could change in favor of the FT-736R from the following factors:

- Feedback from active satellite operators that the operating convenience of the FT-736R is a significant benefit, or that the difficulty of integrating the TR-851 with other radios is a significant deficiency.

- An new or good-condition used FT-736R can be purchased for substantially less than the price used in this analysis.

5.7.3 Acquisition Plan By Mode

5.7.3.1 Mode A Acquisition

This acquisition phase demonstrates basic satellite operating capability. The main equipment acquired are a 29 MHz preamplifier and construction of an uplink antenna for the 2 m band. This antenna uses the J-pole design described earlier and will also be used for Mode JD. Purchase of the Mode JD amplifier will be advanced to this phase only if an amplifier is required for the uplink. The amplifier and uplink antennas are the only items acquired in this phase that are usable in subsequent phases.

5.7.3.2 Mode JD Acquisition

This phase introduces 1200 bps digital satellite communications capability to the station. The major equipment acquisitions are a 435 MHz transceiver (downlink reception), 144 MHz amplifier, satellite modem, PE and PB software, and Mode JD antennas. The current station computer will be used to run the communications and tracking software. The RF equipment is usable for other acquisition phases. Note that the RF equipment supports AO-21 Mode B operation.

5.7.3.3 Mode B Acquisition

This phase adds CW and SSB communications via AO-13. Major items acquired are high gain directional antennas, the moveable antenna support, and a 145 MHz preamplifier. An amplifier for the uplink signal will be purchased if necessary. Azimuth and elevation rotators and computer control interface are optional at this point. They are not required for successful AO-13 Mode B use, so can be purchased as the station owner's budget allows.

5.7.3.4 Mode L Acquisition

This phase adds AO-13 Mode L capability to the station. Mode L capability adds a 1269 MHz transverter, amplifier, and antenna to the station. Azimuth and elevation rotators will be purchased as the station owner's budget allows.

This phase may be deferred if RF safety concerns and the issue of installing the AO-13 array on the roof cannot be resolved. In addition, AO-13 may have reentered or be close to reentry by the time the station is ready for Mode L. Mode L will then be postponed until the launch of the Phase 3D satellite provides a working Mode L satellite. Phase 3D is planned to have higher gain antennas and more transmitter power, so a simpler Mode L uplink may be possible than the one described in Section 5.5.

5.7.3.5 High Speed Mode JD Acquisition

This phase requires purchase of a 9600 bps satellite modem and modification of the Mode JD transmitter and receiver to accommodate a 9600 bps FSK signal. Other Mode JD equipment is used as is. The original station computer is replaced at this time.

5.7.3.6 Mode S Acquisition

This phase adds 2400 MHz receive capability to the station. It will likely be deferred until the Phase 3D satellite is operating. Mode S is currently an experimental mode available for a small percentage of each pass. It should come into regular use with Phase 3D. In addition, the current Mode S uses a 435 MHz uplink, while the Phase 3D Mode S will likely use 1269 MHz to take advantage of the wider uplink available at L-band.

Using equipment now available, the Mode S station is based on a single 2400 MHz antenna, a preamplifier, and a 2400-144 MHz receive converter. While analysis of the link budget suggests additional antenna gain is needed, Phase 3D is expected to have more powerful transponders and higher gain antennas. These features will improve the Mode S downlink and may make additional antenna gain for the ground station unnecessary.

5.8 Recommended Design

Figure 5-8 depicts the recommended station design. The station is shown configured for Mode B operation. Although not used for Mode B, the modems and TNCs used for digital modes are also shown. Equipment for other modes not shown in the illustration would be connected similarly to the Mode B equipment.

Table 5-23 summarizes the equipment acquired for each satellite operating Mode. Equipment is listed for the mod where it is first acquired or placed into a new role, e.g.; the TR-851A transceiver appears once as the Mode JD and Mode J downlink receiver and once again as the Mode B uplink transmitter. Table 5-24 shows the acquisition budget for the station equipment acquired for each mode.

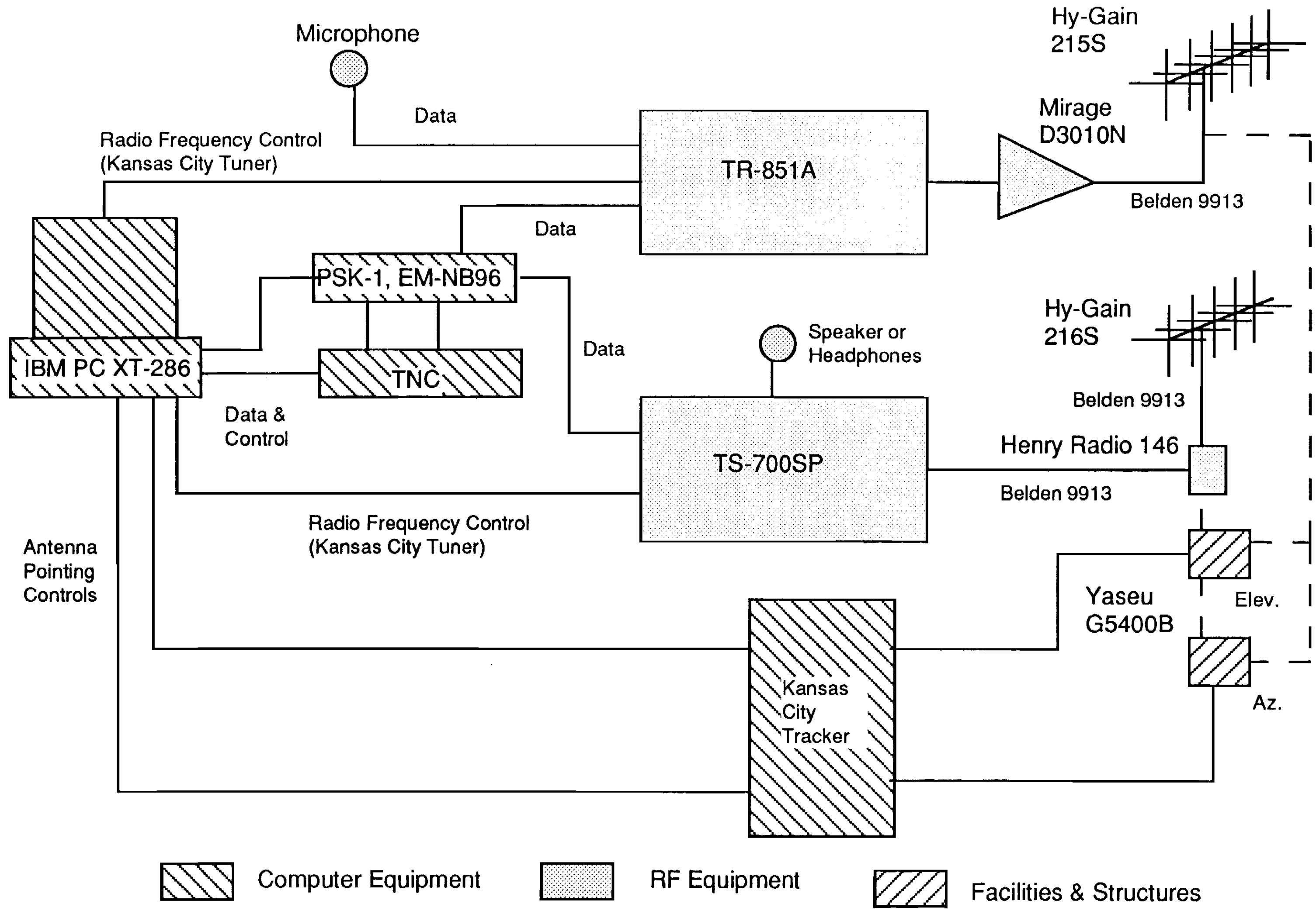

Figure 5-8 Recommended Satellite Ground Station Design

Table 5-23 Satellite Ground Station Equipment

Name	Initial Equipment	Operating Mode A	Operating Mode JD-1200	Operating Mode B
Satellite Ground Station Equipment [Notes 1, 2]				
RF Equipment				
Transmitter Equipment	TS-700SP		TS-700SP	TR-851A
Receiver Equipment	TR-4B		TR-851A	TS-700SP
Power Amplifier			Mirage B108G	Mirage D3010N
Receiver Preamplifier		ARR P28VD	ARR SP432VDG	HR 145
Transmitter Antenna		J-Pole (2M)		HG 215S
Receiver Antenna		H.Dipole (10M)	J-Pole (70cm)	HG 216S
Auxiliary Radio	TS-700SP			
Auxiliary Antenna	Ringo Ranger			
Antenna Rotator				manual
Antenna Feedline	RG-8x	9913	9913	9913
Control Cable				
Antenna Support		chimney-mount	chimney-mount	ground-mast
Data Processing & Control Equipment				
Terminal Node Controller	MFJ-1270		modify TNC	
Radio Frequency Modem			PSK-1	
Telephone Modem	2400 bps			
Computer	IBM PC XT-286			
Monitor	EGA			
Printer	SP-100			
Rotator Control Interface				
Radio Control Interface				
Computer Software	InstantTrack Procomm	LAN-LINK	PE,PB,TLMDC WHATSUP,WEB	
Power Equipment				
Power - 110VAC	x			
Power - Direct Current		Daiwa RS3080		
Facilities Equipment				
Heating, Ventilation, & Air Conditioning	x			
Space	x			
Support Equipment				
Test and Support Equipment	x			for 435 MHz
Spares and Repair Parts	x		x	x
Technical Data	Mfg. manuals	Mfg. manuals	Mfg. manuals	Mfg. manuals

Notes:

1. Only new equipment/new use of on-ha nd equipment listed
2. Abbreviations: ARR - Advanced Receiver Research; DEM - Down East Microwave; HG - Telex/Hy-Gain; HR - H enry Radio; SSB - SSB Electronics

Table 5-23 Satellite Ground Station Equipment (continued)

Name	J	JD-9600	L	S
Satellite Ground Station Equipment [Notes 1, 2]				
RF Equipment				
Transmitter Equipment			SSB LT24S	
Receiver Equipment		TR-851A (mod.)		SSB UEK-13 P3
Power Amplifier			DEM 2335PA	
Receiver Preamplifier	HR 432			DEM 13LNA
Transmitter Antenna	HG 216S		2 x 20 turn Helix	DEM 1345LYK
Receiver Antenna	HG 215S			
Auxiliary Radio				
Auxiliary Antenna				
Antenna Rotator	manual		Yaseu G5400B	
Antenna Feedline	9913	9913	9913	9913
Control Cable			8-conductor	
Antenna Support	ground-mast	chimney-mount	ground mast	
Data Processing & Control Equipment				
Terminal Node Controller				
Radio Frequency Modem		EM-NB96		
Telephone Modem				
Computer		386 PC		
Monitor				
Printer				
Rotator Control Interface		KC-Tracker		
Radio Control Interface		KC-Tuner		
Computer Software		QuickTrack		
Power Equipment				
Power - 110VAC				
Power - Direct Current				
Facilities Equipment				
Heating, Ventilation, & Air Conditionin				
Space				
Support Equipment				
Test and Support Equipment		tuning indicator	for 1269 MHz	for 2.4 GHz
Spares and Repair Parts	x	x	x	x
Technical Data	Mfg. manuals	Mfg. manuals	Mfg. manuals	Mfg. manuals

Table 5-24 Satellite Ground Station Equipment Acquisition Budget

Name	Operating Mode			
	A	JD-1200	B	J
Satellite Ground Station Equipment				
RF Equipment				
Transmitter Equipment				
Receiver Equipment		$670		
Power Amplifier		$195	$310	
Receiver Preamplifier	$30	$110	$161	$161
Transmitter Antenna	$25		$120	
Receiver Antenna	$10	$25	$140	
Auxiliary Radio				
Auxiliary Antenna				
Antenna Rotator			$0	
Antenna Feedline	$28	$56	$56	
Control Cable				
Antenna Support	$10		$50	
Data Processing & Control Equipment				
Terminal Node Controller				
Radio Frequency Modem		$230		
Telephone Modem				
Computer				
Monitor				
Printer				
Rotator Control Interface				
Radio Control Interface				
Computer Software		$10		
		$10		
Power Equipment				
Power - 110VAC				
Power - Direct Current	$190			
Facilities Equipment				
Heating, Ventilation, & Air Conditioning				
Space				
Support Equipment				
Test and Support Equipment			$273	
Spares and Repair Parts				
Technical Data	$0			
TOTAL	$293	$1,306	$1,110	$161

Table 5-24 Satellite Ground Station Equipment Acquisition Budget (continued)

Name	Operating Mode			TOTAL COST
	JD-9600	L	S	
Satellite Ground Station Equipment				
RF Equipment				
Transmitter Equipment		$600		$600
Receiver Equipment			$255	$925
Power Amplifier		$325		$830
Receiver Preamplifier			$130	$592
Transmitter Antenna		$50	$79	$274
Receiver Antenna				$175
Auxiliary Radio				$0
Auxiliary Antenna				$0
Antenna Rotator		$461		$461
Antenna Feedline		$28	$28	$196
Control Cable		$19		$19
Antenna Support				$60
Data Processing & Control Equipment				
Terminal Node Controller				$0
Radio Frequency Modem	$160			$390
Telephone Modem				$0
Computer	$1,000			$1,000
Monitor				$0
Printer				$0
Rotator Control Interface		$229		$229
Radio Control Interface		$90		$90
Computer Software	$25			$35
Power Equipment				
Power - 110VAC				$0
Power - Direct Current				$190
Facilities Equipment				
Heating, Ventilation, & Air Conditioning				$0
Space				$0
Support Equipment				
Test and Support Equipment		$58	$200	$531
Spares and Repair Parts				$0
Technical Data				$0
TOTAL	$1,185	$1,860	$692	$6,597

Figure 5-9 shows the ground station's estimated life cycle cost by year for station acquisition plus an additional five years of operations and support. The estimate combines acquisition costs from Table 5-24 with estimates of operating and support costs using the assumptions from Section 3.3.

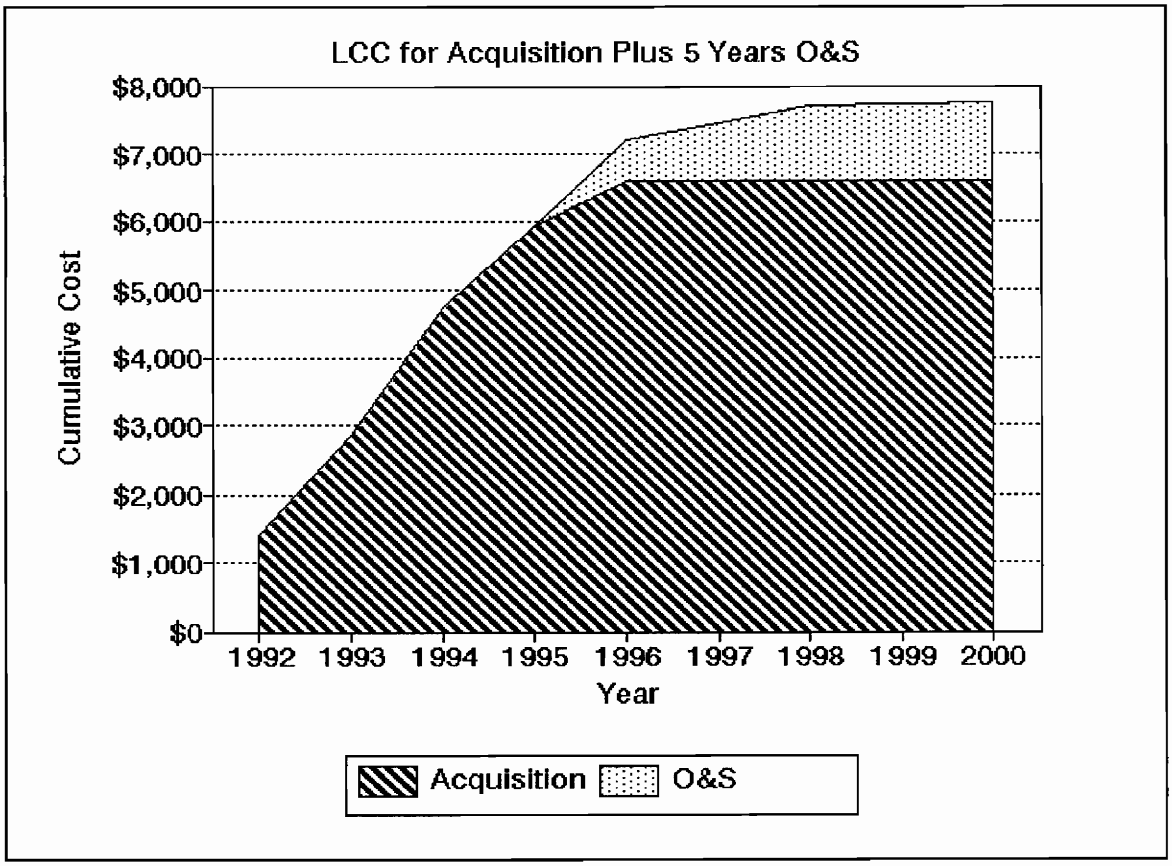

Figure 5-9 Estimated Ground Station Life Cycle Costs

6. CONCLUSIONS

6.1 Conclusions

An effective ground station for the amateur radio satellites can be assembled from mostly commercial equipment readily available from amateur radio dealers. The station operator must perform final assembly of some items (connecting cables, antennas) and integrate and check-out the completed station.

New satellite operators can approach the various amateur radio satellite operating modes in a step-by-step fashion. By starting with the simplest modes (monitoring downlinks, using Mode A, Mir) the beginner builds confidence and operating experience before tackling modes requiring more complex and expensive equipment.

Phasing the satellite station's acquisition by mode spreads the acquisition cost over several years, minimizing the amount of money the station owner must spend at one time. Planning the overall station enables the owner to optimize each phase while preserving his ability to use each phase as the foundation for the next one. Because of continuing advances in radio and computer technologies, and the changing availability of different satellite modes, such flexibility ensures the station is kept reasonably current without risking obsolescence of major station elements.

Computers are now as important as the RF equipment to an effective satellite station. Computers are essential to using any of the digital satellite modes and to capture and analyze satellite telemetry. Computers eliminate most of the time-consuming tasks of predicting satellite passes and determining where to point antennas. The ability of computers to automate antenna pointing and frequency tuning is of great benefit to reducing operator workload. For tracking LEO satellites, these automation aids are almost a necessity.

6.2 Implications for Using Future Amateur Satellites

The ground station developed in this project is based on the capabilities of the current amateur satellites. AO-13 is the basis for the Mode B, L, and S designs, while the Pacsats are the basis for the Mode JD station.

The trend in amateur satellites is towards more capable satellites and simpler ground stations. The Phase 3D satellite, which will replace AO-13 in the mid-1990s, will offer much better communications links than AO-13. Phase 3D will have higher gain antennas, higher transponder power and the ability to apply automatic gain control (AGC) on individual uplink signals, and 3-axis stabilization to keep the antennas always pointing at the Earth. These features will greatly reduce the amount of power required for uplinks and simplify downlink requirements.

The station designed in this project has more capability than is expected necessary to use Phase 3D. However, Modes L and S, the most demanding modes, are last in the acquisition strategy. In several years, more information will be available on Phase 3D's expected capabilities. Mode L and Mode S equipment will likely be more available and higher performing than now. The Mode L and S designs can therefore be modified to take advantage of these changes. There is no need to commit to a major expenditure today for equipment that will not be needed for several years.

The trend in Pacsat satellites is towards more message and file capacity aboard the satellite, more uplink and downlink channels, and faster data rates. The popularity of the 9600 bps satellites has led to several modifications to enable current radios and modems to operate at these speeds. The major effect of high speed Mode JD satellites may be to promote radios and modems that are more flexible and can easily support new modulation schemes and data rates.

6.3 Implications for Other Users of Satellite Communications

This project demonstrates that an individual can assemble from mostly off-the-shelf sources a state-of-the-art satellite ground station capable of voice and data communications for an acquisition and five year operations and support cost under $10,000. A station for only one operating mode will be simpler and less expensive. This has important implications for educational, research, and commercial enterprises requiring satellite communications.

An organization can have their own dedicated satellite communications station at a cost comparable to other equipment, research, and operating expenditures. Non-profit groups, such as SatLife, VITA, and the SKITREK polar expedition have proven the usefulness of simple ground stations and low-cost satellites. Educational institutions, such as Weber State University and the University of Surrey, have shown how to integrate satellite design, construction, and operation into undergraduate and graduate education and research. Finally, the advent in the near future of several LEO satellite systems will place easily accessed satellite communications within reach of the general population.

The technologies and equipment described in this project can support research, non-profit, and commercial activities. By showing how satellite communications is affordable even to individuals on a hobby basis, this project shows it is affordable to almost any organization that needs satellite communications.

6.4 Future Work

The next step in this project is to assemble, test, and operate the station. As presented in the acquisition plan, equipment to use Mode A and Mode JD will be the first acquired. Test and evaluation of actual performance will identify any additional requirements to use these two modes effectively. As operating experience increases, a decision can then be made to add AO-13's Mode B to the station's capabilities.

Long-range goals are to make satellite operations routine, and then to pursue active participation in the amateur satellite programs. Three choices are: real-time and store-and-forward message gateway using the Mode JD satellites, participation in AMSAT's CSDP effort, and becoming part of the Phase 3D satellite development program. Designing, assembling, and operating a ground station is valuable preparation for any of these activities.

7. SUMMARY

7.1 Summary

This report presents the design and acquisition plan for a ground station for the Amateur Satellite Service. The complete station is capable of using all modes currently available for amateur satellite communications.

The station design and acquisition plan is inherently flexible to adapt to changes in satellite operations and usage and advances in satellite station equipment. Flexibility is an essential feature of the design, because of the extended acquisition schedule and uncertainty about use and availability of the various amateur satellites over several years.

The station design supports analog Modes A, B, J, L, and S; and digital Mode JD (1200 and 9600 bps). The design has sufficient link performance to provide quality communications for Modes A, B, J, JD, and L. The time span before Mode S capability is acquired makes the current predicted poor Mode S performance tolerable. The improved link capabilities expected from the Phase 3D satellite should make Mode S performance acceptable when it is acquired.

The station design provides a firm foundation for regular satellite operations and for providing communications services to the amateur radio community. The Mode JD station is capable of joining the international network of station relaying message traffic using the Pacsats. The station is also capable of participating in AMSAT's CSDP effort, especially to capture and analyze satellite telemetry.

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APPENDIX A. SATELLITE COMMUNICATIONS LINK ANALYSIS

This appendix presents the method used in this project and report to analyze the communications links between the ground station and the various amateur radio satellites.

Analysis of satellite communications links accounts for the signal received by the receiving system and the amount of noise received with the signal. The SNR measures the difference between the received signal and the noise level. SNR indicates the quality of the signal - signals with high SNR are high quality, allowing easy extraction of information. Low SNR signals, on the other hand, are difficult to receive accurately, and inhibit accurate communications.

A.1 Received Signal Power

The equation for received signal power is:[54]

$$P_s = P_t + G_t + G_r - L \qquad \text{[Equation A.1]}$$

where:

P_s	received signal power [dBm]
P_t	transmitted signal power [dBm]
G_t	transmitter antenna gain [dBi]
G_r	receiver antenna gain [dBi]
L	free-space path loss [dB]

For uplink signals and single channel downlinks (e.g.; beacons and Mode JD satellites) transmitted signal power is the output power of the transmitter (measured at the

[54] Davidoff, 13-12.

transmitter antenna terminals). For analog transponders, transmitted signal power is the communication channel's share of the transponder's total output power.

Transmitter and receiver antenna gain are expressed as gain over an isotropic radiator (e.g.; a point source). Values for antenna gain are provided by satellite developers, antenna manufacturers, or from tests. Gain value is usually specified for the antenna's main lobe (e.g.; directly on boresight). Other parts of the antenna's radiation pattern, such as the half-power beamwidth (-3 dB vs. the maximum antenna gain) can be evaluated to assess off-optimum performance.

Free-space path loss is determined by the following formula:[55]

$$L = 32.4 + 20 \log f + 20 \log \textit{'rho'} \qquad \text{[Equation A.2]}$$

where:
L free-space path loss [dB]
f frequency [MHz]
'rho' slant range [km]

Free-space path loss excludes signal losses caused by Faraday rotation-induced signal polarization shifts, and signal losses in the ionosphere and atmosphere. The ability to switch antenna polarization (e.g.: from right-hand circular to left-hand circular) can partially eliminate polarization losses. The other losses are not controllable, and require a link margin adequate to compensate for the lost signal.

Slant range is calculated in two steps. First, the distance between the ground station and the subsatellite point (SSP), the point on the surface of the earth directly below the satellite, is calculated. This distance is a function of the satellite's altitude and the

[55]Ibid.

elevation angle of the ground station's antenna. With a value for the distance to the SSP, slant range can be calculated.

The formula relating ground station antenna elevation angle, satellite altitude, and distance to the SSP is:[56]

$\tan(\epsilon) = [(R + h)\cos(s/R) - R]/[(R + h)\sin(s/R)]$ [Equation A.3]

where:
ϵ ground station antenna elevation angle [radians]
R spherical Earth's diameter = 6371 km
h satellite's altitude (height) above Earth's surface [km]
s distance from ground station to SSP [km]

Given the satellite's height and a minimum antenna elevation angle, say 10°, Equation A.3 can be solved for s. Using the satellite's height at apogee provides a worst-case situation for the link analysis.

[56] Davidoff, 12-11.

Slant range is calculated by the following equation:[57]

$$\text{'}rho\text{'} = [(R + h)^2 + R^2 - 2R(R + h)\cos(s/R)]^{1/2} \qquad \text{[Equation A.4]}$$

where:
'*rho*' slant range [km]
R spherical Earth's diameter = 6371 km
h satellite's altitude (height) above Earth's surface [km]
s distance from ground station to SSP [km]

A.2 Received Noise Power

The received noise power for the satellite link accounts for all sources of noise entering the receiver system. Principal noise sources are background noise (sky noise for ground station's and the Earth for satellites) entering the receive system antenna, and noise introduced by the receive system itself. Other man-made noise sources may cause problems at a particular station location. The latter sources are generally not controllable, and require an adequate link margin to compensate.

Received noise power is calculated by the following formula:[58]

$$P_n = 10 \log k + 10 \log T_e + 10 \log B \qquad \text{[Equation A.5]}$$

where:
P_n received noise power [dBm]
k Boltzman's constant = 1.38×10^{-20} [mW/HzK]
T_e receive system effective temperature [K]
B Receiver system bandwidth [Hz]

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[57] Ibid.
[58] Davidoff, 13-13.

The receive system's effective temperature, T_e, is the sum of the noise received by the antenna and the noise generated in the receiver:[59]

$$T_e = T_R + T_S \quad \text{[Equation A.6]}$$

where:
T_e receive system effective temperature [K]
T_R receive system temperature [K]
T_S sky temperature [K] for ground station, or
Earth's temperature = 290K for satellite[60]

The receive system temperature, T_R, is in turn determined by the receive system's noise figure:[61]

$$T_R = 290(10^{(FT/10)} - 1) \quad \text{[Equation A.7]}$$

where:
T_R receive system temperature [K]
F_T receive system noise figure [dB]

The system noise figure combines the various noise sources in the receive system, including feedlines, connectors, relays or switches, and preamplifiers. For this project, the noise figure calculation ends at the input terminals of the station receiver. Emphasis is on items the station designer can control: feedline length and selection, connector selection, and selection and placement of preamplifiers.

[59]Ibid.
[60]Davidoff, Figure 9-1, p 9-1, provides average minimum and maximum sky noise temperatures at various frequencies.
[61]Davidoff, 13-12.

The equations for system noise figure are:[62]

$F_T = 10 \log(f_T)$ [Equation A.8a]

$f_T = f_1 + (f_2 - 1)/G_1 + (f_3 - 1)/(G_1 * G_2) + \ldots$ [Equation A.8b]

where:
F_T receive system noise figure [dB]
f_T receive system noise factor [decimal ratio]
F_i noise figure of stage i, $= 10 \log(f_i)$
f_i noise factor of stage i, $= 10^{(Fi/10)}$
G_i Gain of stage i, [decimal ratio]

Values for F_i, f_i, and G_i are quoted in manufacturers' literature, or can be estimated from other published data. For feedlines and connectors, available data may be for a different frequency than the one of interest. The data can be converted to the required frequency by the following equation:[63]

$\alpha_H/\alpha_L = \sqrt{(f_H/f_L)}$ [Equation A.9]

where:
α_H, α_L insertion loss of connector [dB] or feedline [db/100 ft] at the higher and lower, respectively, of the two frequencies
f_H, f_L the higher and lower of the two frequencies [MHz] of interest

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A.3 Signal To Noise Ratio

Signal to noise ratio (SNR) measures the strength of the received signal relative to the amount of background noise received. It is a measure of signal quality: the higher the

[62]Davidoff, 9-2.
[63]UHF Experimenters Handbook, Equation 33, p 5-16.

SNR, the stronger the signal and the easier it is to comprehend or process by the receive system.

The equation for SNR is:[64]

$$SNR = P_s - P_n \qquad \text{[Equation A.10]}$$

where:
SNR signal to noise ratio [dB]
P_s received signal power [dBm]
P_n received noise power [dBm]

Amateur radio communications usually do not require the degree of signal quality expected of commercial circuits. An SNR around 20 dB is considered a very good quality signal for a nominal 3000 Hz bandwidth voice circuit.[65] Manufacturers' data sheets for receivers usually specify a minimum signal (in μV at the antenna input) for a 10 dB SNR, suggesting 10 dB is the minimum SNR for practical voice communications.

The relationship between SNR and bit error rate (BER) determines signal quality for data communications. For the BPSK Mode JD downlinks, an SNR of 9.4 is sufficient for a 10^{-4} BER.[66] An SNR of approximately 10 to 13 dB will provide a 10^{-5} BER.[67]

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[64] Davidoff, 13-13.
[65] Ibid.
[66] Mulally, Daniel J., and Lefevre, Don. K., "A Comparison of Digital Modulation Methods for Small Satellite Data Links", 7th Annual Computer Networking Conference (location and date unknown), Table 1, p 2.
[67] Horton, David E., "SOESAT Low Cost Telemetry Ground Station", 5th Annual AIAA/Utah State University Conference on Small Satellites, 1991, Figure 13, p 25.

A.4 Other Factors Affecting SNR

Several other factors causing signal losses, and therefore reducing SNR, have been mentioned in this discussion. They include polarization mismatches, Faraday rotation, ionospheric and atmospheric attenuation, and local man-made noise sources.

AO-10 and AO-13 are designed to produce a right-hand circular polarization (RHCP) signal at a ground station. Satellite orientation with respect to the ground station and ionospheric effects may occasionally shift the signal's sense to left-hand circular polarization (LHCP). Several dB of signal will be lost, unless the antenna's polarization sense can be shifted during the period of fading. Use of linearly polarized antennas on the ground for the AO-10 and AO-13 downlinks will also result in signal loss from polarization mismatch. The Mode JD satellites are designed to allow use of linear polarized antennas on the ground. Even here, circular polarized antennas can reduce fading caused by temporary polarization shifts versus linear polarized antennas.[68] Spin-modulation may occur on AO-10 and AO-13 downlinks, is also minimized by using circular polarized antennas.[69]

Faraday rotation is the rotation of a linear polarized signal about its line of travel. The signal passes through different amounts of ionosphere during a pass, causing the amount of rotation to change over the entire pass. The effect is greatest at 29 MHz (Mode A downlink), and lessens dramatically at 146 MHz (Mode B downlink) and 435 MHz (Modes J and L downlinks). Circular polarized antennas at the ground station minimize the amount of fading caused by Faraday rotation.[70]

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[68] Davidoff, 7-7.
[69] Davidoff, 13-8.
[70] Davidoff, 13-7.

Signals are attenuated as they pass through the ionosphere and atmosphere. Both these losses are uncontrollable, causing temporary signal fades during a pass. High F-layer activity can completely block Mode A downlinks. Attenuation of as much as 12 dB has been observed in some cases.[71] Atmospheric attenuation is generally negligible at current downlink frequencies. The Phase 3D satellite, however, will include a 10 GHz transponder. Signal loss due to water vapor, rain, fog, and clouds in the atmosphere may become noticeable at these frequencies.[72]

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[71] Davidoff, 13-8.
[72] UHF Experimenters Handbook, Chapter 3.

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Staff Engineer, Specialty Engineering Group. Provide systems engineering and acquisition support to Department of Defense and NASA programs.

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American Institute of Aeronautics and Astronautics (AIAA):

- Member, MIT Student Branch, 1974-1977

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- Member of Systems Engineering Working Group, Space Launch Systems (SLS) Committee on Standards (COS), 1991-present.

Toastmasters International:
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- Area Governor, 1985-86, Secretary, 1986-87, District 31

International Society of Parametric Analysts (ISPA):
- Member, 1984-1988

Amateur Radio:
- Novice License (WN2OWC) 1971, upgraded to General Class (WB2OWC) 1973, to Advanced Class (WB2OWC, later KA1LM) 1975
- Member, American Radio Relay League (ARRL), 1971-present
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I became interested in amateur satellites during the AO-6 program in the early 1970s. My active interest in amateur satellites resumed in 1990 with the launch of the Microsat payloads. I decided in 1991 to assemble a home satellite station and to use this as the topic of my Project and Report for my M.S. Systems Engineering degree.

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