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by

Gerald M. Kowalski

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SATELLITE DATA COMMUNICATIONS LINK REQUIREMENTS FOR A PROPOSED FLIGHT SIMULATION SYSTEM

by

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. Lance Erickson, Department of Aeronautical Science, and has been approved by the members of his thesis committee. It was submitted to the Office of Graduate Programs and was accepted in partial fulfillment of the requirements for the degree of Master of Aeronautical Science.

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ABSTRACT

Author: Gerald M. Kowalski

Title: Satellite Data Communications Link Requirements
for a Proposed Flight Simulation System

Institution: Embry-Riddle Aeronautical University

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The purpose of this study was to investigate the requirements necessary for data and voice communication via satellite, linking Embry-Riddle Aeronautical University (ERAU) and other flight training facilities. The proposed research was conducted following a descriptive method of collecting information, generating and analyzing data, and listing the results for the proposed link requirements. The current fiber-optic communications link at ERAU in Daytona Beach was presented to establish a general foundation of communications. Research was done into methods used by satellite common carriers for realistic data and calculations. A proposed data link to connect flight simulators at the ERAU Prescott campus with the air traffic control simulation facilities at the ERAU Daytona Beach campus was developed. Data link requirements based on this scenario were gathered and the final assessment was presented. A suggested method of implementing this proposal, including carrier service and equipment selection, was developed and further research into expanding this proposal into a network was suggested.

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INTRODUCTION

Embry-Riddle Aeronautical University (ERAU) is currently expanding its research faculty and capabilities. A keystone research facility, the Airway Science Simulation Laboratory, has received over $2 million in federal funding. At the lab, several research programs are being drawn together into a single flight simulation system program. In this program, air traffic control and flight simulation combined with artificial intelligence programs and real-time weather data are being coordinated to simulate the dynamics of the national airspace environment. This will provide the university with a unique ability to educate students in the most realistic training environment available. The Air Traffic Control Simulation System (ATCSS) gives Embry-Riddle the opportunity to expand itself as a resource to other universities that offer flight training programs.

STATEMENT OF THE PROBLEM

The purpose of this study was to investigate the requirements necessary for data and voice communication via satellite, linking Embry-Riddle Aeronautical University and other flight training facilities. This will allow access in real-time to users of the ATCSS.

REVIEW OF RELATED LITERATURE

Space communication has been defined as the transmission of any form of intelligence through the space environment (Krassner & Michaels, 1964). Since it was first demonstrated in October, 1957 with the launch of Sputnik, man-made satellites and space communications have become a way-of-life for many on Earth. Space telecommunications have been in use since the early 1960s by the early 1960s by telecommunication companies such as Western Union and American Telephone and Telegraph, and by branches of the military for classified communications. Space telecommunications has also been used for many years by television networks broadcasting live news events and cross-continent entertainment shows.

The role of satellite communication in education has not been as prominent as commercial broadcasting, although telemetry has been in use in education for years. In 1974, the National Air and Space Administration (NASA), the Department of Health, Education, and Welfare, and the Corporation for Public Broadcasting were jointly involved in a technology program to demonstrate the usefulness of satellite television distribution of health education. When this program was completed in 1975, the satellite used was orbited at a longitude and latitude centered above India. There, the satellite was used to broadcast education programs to a large number of remote villages (Janky & Potter, 1976).

Some universities use telemetry to conduct classes at sites that are distant from the main campus. The Illinois Institute of Technology has been conducting remote courses via a ground microwave communication link between its main campus and facilities throughout Chicago (IIT Bulletin Graduate Programs 1985-87, 1985). Other universities are also conducting remote courses by ground link. However, few operate over satellite since the distances to the classrooms from the campus do not require such technology.

One method of conducting distant classes that was implemented in Canada utilized satellite communication for the one-way transmission of audio and video signals of a professor's lectures to remote parts of the country (D. Carl, personal communication, September 12, 1989). Ground telephone communication provides the two-way audio link that enables students to ask questions in real-time. The satellite link is provided via a leased transponder over a frequency range of six gigahertz (GHz) or six billion cycles per second for the uplink and four GHz for the down-link, commonly written 6/4 in the C-band (Feher, 1983). A transponder is the electronic circuit onboard a satellite which acts as a receiver and a transmitter for each channel.

The Royal Thai Air Force and Unisys (formerly Sperry) used satellite data communication for training purposes when Unisys was contracted to supply that country with command, control, and communication hardware and software for their air defense system. In this unique application, radar information from local sites throughout Thailand was brought together at a main long haul communications center. This information was data linked via satellite to training facilities in California. Aircraft radar data from Thailand appeared in real-time to the controllers in California. This allowed the Royal Thai Air Force to fly practice missions in their country, and the air defense staff had the opportunity to get training on the new equipment while still controlling traffic in the skies over Thailand (Aviation Week & Space Technology, April 4, 1988).

The rapid increase in air traffic since passage of the Airline Deregulation Act of 1978 and the air traffic controller's strike of 1981 has increased the complexity of the National Airspace System (NAS) in the form of crowded skies and overburdened and inexperienced air traffic controllers and pilots. This has created the need for more effective training programs for both flight crews and air traffic controllers (Blanchard, Cieplak, Gibb, Schneider, & Smith, 1989). Work is currently in progress at ERAU's Daytona Beach campus on an ATCSS that will coordinate the activities of pilots in training simulators with student air traffic controllers at air traffic control (ATC) stations. This system will provide a training environment that is more realistic than current methods, by simulating various portions of the National Airspace System (Blanchard, 1987). ERAU would be in an opportune position by providing this type of training facility to students at the University, and to promote these facilities to other schools that offer flight training with simulators.

A current proposal has been approved by the university which calls for a fiber optic data link between the flight simulators located near the school's flight line and the Airway Science Simulation Laboratory's AWS building, approximately one mile away. The AWS will house ATC simulator stations, additional pilot ground-trainers, and the weather facilities that supply data to the total simulation. Communication parameters that will be passed through the fiber optic system are similar to those used in satellite telemetry communication systems.

STATEMENT OF THE HYPOTHESIS

The need for well trained flight crews and air traffic controllers coincides with research being conducted with the ATCSS at Embry-Riddle Aeronautical University. Enhanced development of this research would provide real-time satellite data links with other flight training facilities. Related information suggests that a data link of the air traffic control simulators at the ERAU Daytona campus to other flight training schools would be beneficial to users at both ends. Therefore, it is hypothesized that a satellite data link could be established between the ERAU Daytona Beach campus and the ERAU Prescott campus, and the link could provide real-time data and voice information transfer between the two facilities. An investigation of the data link requirements would support or deny this hypothesis.

METHOD

INSTRUMENT

Several instruments are used in this research. Many of the instruments are the books, journals, manufacturer's operating manuals, satellite directories, and electronics magazines containing related and necessary information. The data analysis had been completed on a Hewlett Packard 41 CX programmable calculator. All relevant information has been compiled on Macintosh computers. The data collected represents a trade study showing system assessments and practical recommendations.

DESIGN

The design approach to this study is a variation of descriptive research. Descriptive research is defined as the collecting of data in order to test the hypothesis. A body of knowledge concerning satellite communications, specific equipment, and mathematical analyses is developed and from this body of knowledge, potential system descriptions and their requirements are presented. The requirements of these systems and the performance of the equipment are assessed using mathematical analysis, trade study comparisons, and economical logic to prove or disprove the hypothesis.

PROCEDURE

A library search of materials relevant to satellite communications was performed. Books, electronic and data communication journals, and magazine articles have been reviewed and relevant information was compiled as a reference source. This resource contains the review of related literature section of the thesis. Electronic hardware manufacturers and users were contacted for information on any equipment that could be used if the proposal were implemented. This information and data from satellite directories formed the basis of the equipment comparative analysis to optimize system design. From all materials and data collected, engineering calculations were performed to determine the data link requirements.

THEORY

I. CURRENT FIBEROPTIC COMMUNICATIONS LINK

It was previously noted that the communication parameters between the AWS and the ERAU flight line will be the same as the information transferred between the two Embry-Riddle facilities linked via satellite. Therefore, it is necessary to understand this system and define these parameters.

The system currently designed for the AWS/flight line link is intended to allow at least ten aircraft simulators at the flight line to communicate with at least eight air traffic control stations at the AWS. This communication consists of the computer data generated by each of the aircraft flight simulator's computers (basically a personal computer), voice communications between the pilot and various air traffic controllers (such as ground control, local control, departure control, etc.), and computer information from the voice communication remote station. Appendix A contains an overview to communications and greater detail to key terms.

As a pilot is operating or "flying," a Frasca® flight simulator, the simulator's computer is transmitting information concerning the craft's identity, altitude, attitude (in terms of pitch, roll, and yaw), and position (latitude and longitude). This information is received at the AWS building by the SUN® workstation computer, where it is manipulated and computer generated aircraft are added to the scenario (see Figure 1). Additionally, weather information, either current or historical, is added to the simulation by importing data to the SUN from the ERAU weather lab computer. This information is then sent to the Silicon Graphics® ATC stations where it is displayed to air traffic control students as ATC screens. The air traffic control students then make appropriate decisions for guiding the aircraft.

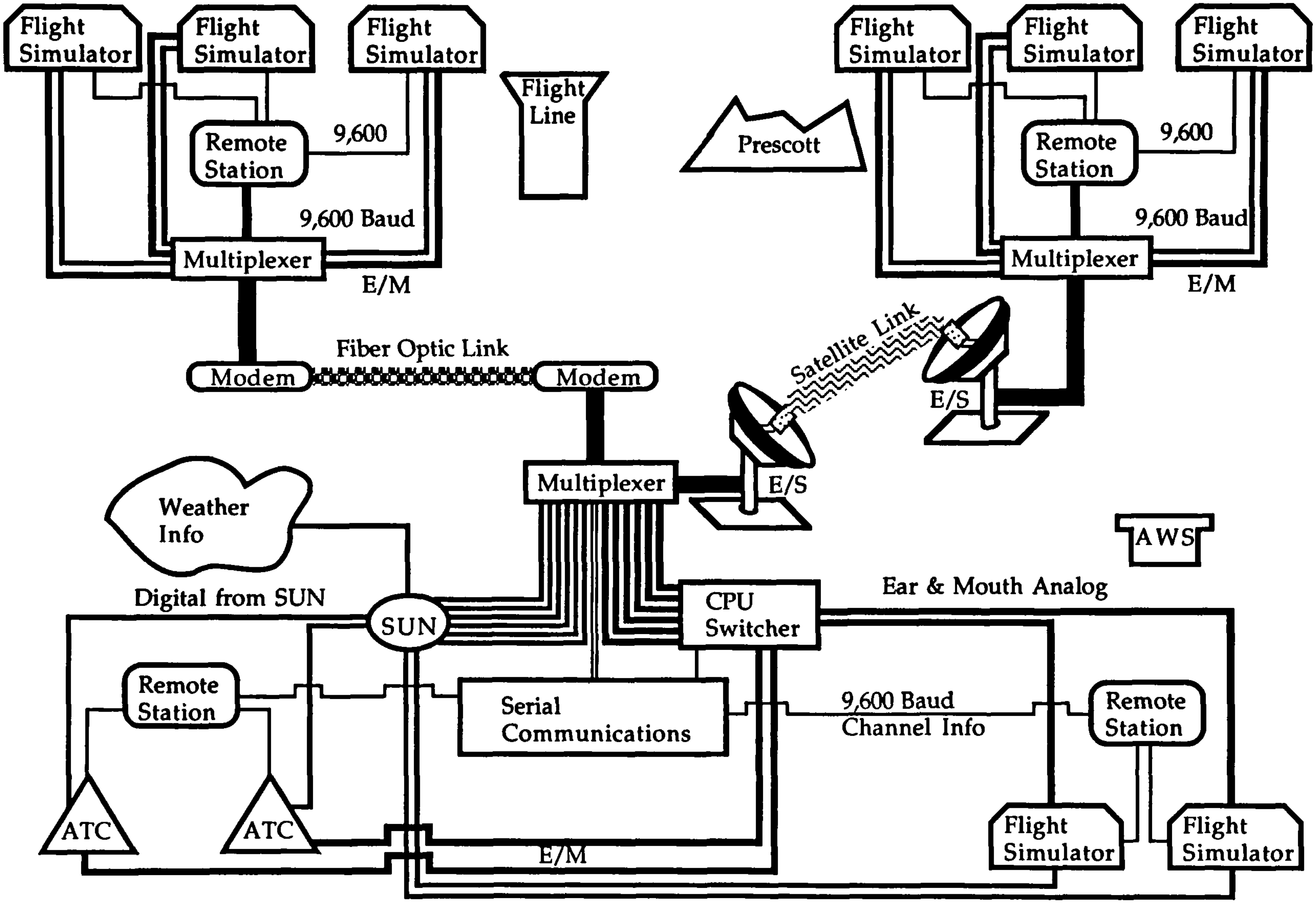


Figure 1. Diagram of Microworld Simulation Communications.

Controllers at the ATC stations are in two-way, or full-duplex, voice communication with the pilot. The pilot has the option of dialing which controller (i.e., ground, departure, etc.) he/she wishes to communicate with. The voice communication system is the only full-duplex communication between the AWS and the flight line since the aircraft simulator's computer needs only to send one-way, or simplex, information concerning the aircraft flight parameters.

Referring to Figure 1 will help in understanding the architecture of the system. Digital data from the ten or similar number of operating flight simulators are combined at the multiplexer and sent to the fiber optic transmitter/receiver (modem). A multiplexer is a device capable of interleaving the events of two or more activities or capable of distributing the events of an interleaved sequence to the respective activities (Datapro Communications Reports, 1991). More simply stated, it is a device which combines signals from several sources to transmit them simultaneously over a single medium. It can also retrieve the several separate signals from the single medium. The interleaving is accomplished by either frequency or time allocation of the signal. In frequency multiplexing, each signal is preassigned a frequency by the multiplexer for transmission over a single carrier signal. The summation of all incoming signals at their respective frequencies becomes the output signal. This signal operates within the frequency spectrum limitations set by the constraints of the carrier signal. Time multiplexing allocates the individual signals to transmit a certain amount of information at repeated and specified time increments. Frequency multiplexing is preferred when the incoming data is analog, while time multiplexing is used for digital data. The methods of multiple access to satellites are done in similar fashion and will be covered in a later section.

Several methods for transmitting a signal exist, and are reviewed in Appendix A. A modem (modulator/demodulator) is a device for converting the digital message signal of a computer or multiplexer onto a signal of more suitable analog transmission. This is done by modulating a carrier wave proportional to the incoming signal. Modulation is the process of varying the characteristics of a carrier wave in accordance with the input message signal. The resulting signal then occupies a specific frequency spectrum centered about the particular carrier frequency. Demodulation is restoring of the signal back into its original form. This process of modulating and demodulating is done because it has been determined that certain frequencies are ideal for transmitting signals through different mediums, depending on the distance and data rate by which the message has to be sent (Kennedy, 1985). In this proposed system, the signals are actually modulated and demodulated several times during the transmission.

An example of how these devices operate can be illustrated in the way an average telephone conversation is transmitted. The human ear can sense a limited spectrum of sound, from 20 to 20,000 cycles per second (Hertz or Hz) at best. Adequate perception of speech occurs in the 300 to 3,400 Hz range (Rey, 1987). The first form of modulation occurs when the voice frequency from the speaker's larynx (acoustic signal) converts a direct current electrical signal (carrier signal) at 0 Hz to a speech signal of varying amplitude and frequency at the telephone handset. This works fine with local systems, where only two persons are communicating at one time. However, due to signal fade (attenuation), crosstalk interference, and more efficient use of bandwidth, this single voiceband channel, or *baseband channel*, is not a practical frequency to transmit information (Kennedy, 1985). Therefore, the signal is modulated to a higher frequency spectrum of 60 to 108 kilohertz (kHz). This information can then be multiplexed with other signals and transmitted over fiber optic, coaxial, or twisted pair cable for several miles before the signal attenuates to a level where it can no longer be properly received. Satellite communications is often used to cover the great intercontinental distances of the United States. To be able to travel this medium, the signal is modulated to a microwave frequency of 6 GHz for transmission by C-band uplink to the satellite, a distance traveled of approximately 22,300 miles.

In a like manner, the message from the fiber optic modem at the flight line is transmitted via the fiber optic cable to a second modem in the AWS building. This signal is demodulated and passed through the multiplexer, where up to ten individual signals are then fed to the SUN workstation. The SUN interprets this as if the ten flight simulators were connected directly into it. Local flight simulators at the AWS can be entered into the simulation by direct connection to the SUN. At the SUN, the flight data is processed to appear as recognizable information to the air traffic controller. This information is in the form of aircraft identification, position, and assigned altitude if the simulator is indicating an ascending or descending condition. An additional input to the SUN is information coming from the Kavorus® computer located in the ERAU weather lab. All this information is displayed on the Silicon Graphics® terminal, which generates the ATC display. Having the SUN in the network allows the Silicon Graphics to dedicate more memory and processing time to generating the ATC display, thus allowing real time interpretation of data.

II. VOICE DATA TRANSFER

This chapter will present a general system description of the proposed voice communication link to establish an operating baseline system. The multiplexer will be described in detail since its operation is key to the entire communication link. It is assumed that any voice link system with equivalent communication specifications will require no greater amount of bandwidth for operation, and can be used in substitution. It will also be applicable for use over a satellite link.

The voice communications system between students in the flight simulators at the flight line and the ATC stations in the AWS will be on a unique system initially proposed by ERAU student Bryan Jasper. Each pilot has the capability of dialing up to 64 different channels on his/her communication radio. This adds authenticity to the scenario by simulating the variety of a real aircraft radio band. The student can dial the actual communication frequency (indicated on the radio display) rather than just selecting a channel designated by arbitrary numbers. As an example, a pilot might dial 125.35 on the communication radio to contact departure control when departing the Daytona Beach Regional Airport. This is the actual radio frequency of the airport's departure control, and would be well known to Daytona based ERAU flight students. Another benefit of this radio concept is that it allows flight simulator students to communicate with each other while on the same frequency, adding to its realism.

Although the actual radio communication frequency spectrum allows for a possible 720 different channels in the megahertz band, the 64 channel capability of the AWS system will allow enough flexibility for realism. Initially, eight channels are planned for use since only eight air traffic control stations will be active in the AWS building. This means that 56 channels will be unoccupied, waiting further expansion of the system.

The radio in the instrument panel of the flight simulator will house the communication frequency channel selector and audio amplifier. The face-plate will have the communication frequency display, a frequency selector, a volume control, and a jack for a headset. The simulator manufacturer's radio may be used, or units may be fabricated at the school. The radio will modulate the student's voice into a radio frequency (RF) suitable for transmission, while demodulating the received signal of a controller's voice to an audible frequency. The radio would also provide the power and amplification of this signal to the pilot's headset. Since these radios are to be used in a network situation, a modification to the current simulator units will be necessary to establish proper pilot/controller link, allow pilot cross-communication, and provide the flexibility of multiple channel selection.

Three devices will expand the use of the aircraft simulator standard radios to the network capability needed for this simulation. The Voice Communications Remote Station assigns each specific radio output, a digital code which identifies the simulator with the selected communication frequency. This is necessary since each simulator radio may transmit an output at the same frequency. A modification to the radio would provide this link between the radio frequency selector (and display) and the remote station. It is important to reiterate that the communication frequency is strictly provided as a human factors cue to the simulation. It would have no significance to the operation of the system. The remote station also acts as the communication frequency interface between the simulator radio and the serial communications device. The serial communications device is where the radio channel/communication frequency assignments would be input into the system and stored. The serial communications device would also be the circuit which interprets the digital radio location code from the remote station and commands the CPU Switcher (third device) where to direct the voice signal. If the voice signal is directed to the ATC controller, it would be transmitted to a radio at the ATC station which would be similar to the radio in the aircraft simulator.

An example of system operation may aid in its understanding. The exercise would begin with the simulation facilitator, or lab director, adding communication frequency assignments into the serial communications circuit. Each of the 64 channels would have a frequency assignment. As a student pilot is instructed to dial a specific frequency, i.e. 125.35 MHz on the radio display, the microprocessor in the remote station is polling for an input from the radios. When an input is found, the microprocessor tags the simulator's voice channel (as active) and the code for the communication frequency selected. This information is sent to the multiplexer where it is combined with the digital data from the simulators and the voice channel. The multiplexed signal is modulated and sent to the AWS building where it is demodulated, demultiplexed, and subsequently sent to the SUN, CPU switcher, and serial communications circuit (physically located within the CPU switcher). The serial communications circuit identifies the code for the communication frequency selected, and signals the CPU switcher where to direct the voice channel, i.e. 125.35 MHz may be air traffic controller #2. The flexibility of this system allows voice channels to be directed to other simulators or several ATC controllers simultaneously.

Although the operating logic has not been identified, white noise (static) could be generated over the headset when a student (either pilot or air traffic controller) would select a frequency that has no channel assignments. Alternately, blank sound may be heard when a student selects a communication frequency that has a channel assignment but no connection.

The digital communication parameters between the radio communication frequency selector, remote station, serial communication circuit, and the CPU switcher will be at 9,600 baud (Appendices A & B). The operating standards for the voice circuit will be defined by the multiplexer. The current multiplexer selected for flight line/AWS link, the Canoga Perkins® 3140, would be of identical use in the satellite system. At this multiplexer, analog voice input is modulated and converted to digital format using a pulse code modulation (PCM) technique. Pulse code modulation is covered in Appendix A. With the voice now in digital format, this signal can be multiplexed with the digital data from the remote poller and from the ten flight simulator computers.

Specifications of the multiplexer allows for an output of either 4 wire, twisted pair or fiber optic transmission media at data rates of either 1.544 or 2.048 Mbps (million bits per second). In its present configuration, the communication will operate at 1.544 Mbps, the standard T1 configuration, or fractions of T1 (FT1). T1 is a medium operating standard set by Bell and the International Telegraph and Telephone Consultative Committee (CCITT) in the early sixties (Appendix A). The data requirements will need to be defined to determine whether a full T1 line or a fractional (FT1) line will be necessary. The multiplexer's FT1 capability is designed to support AT&T's Accunet Spectrum of Digital Services (ASDS) if AT&T were used as a satellite carrier. However, other communication service packages can be used, regardless of the bandwidth configuration.

The voice modulation is done through the E&M (ear & mouth) circuit using PCM. It can deliver a frequency response of 300 to 3,000 Hz. The design of the multiplexer allows for low speed asynchronous data transfer at rates up to 38.4 kbps per port, with each port being one transmission line. It would take two ports for full-duplex communication. However, this is four times our requirements of 9.6 Kbps for data transfer. The multiplexing is time division interleaved of both the data and digital voice. This system could supply a maximum combination of 150 synchronous and 30 voice channels, or any combination of less than the T1 data rate.

An additional advantage of this system is its ability to employ segregated or composite communication lines. Twisted pair and fiber optic lines can be used separately or together, as with our needs of a local network and a national network operating simultaneously.

The output of the multiplexer carries the interleaved digital signals of the simulator data and student voice channels. This signal is directed to the modem, which modulates the signal to light frequencies and transmits the signal back and fourth between the flight line and a modem at the AWS building. At the AWS, the signal is demodulated, and sent to the multiplexer, to be split into the separate voice and digital data signals. These are sent to the respective computers and ATC students.

III. DATA TRANSFER

In this chapter, the systems parameters just presented shall be summarized, with the product being the data requirements for both the flight line/AWS link and the Prescott/Daytona link. A broad definition of data transfer terms can be found in Appendix B to aid in the understanding of these requirements.

In order to set the system requirements, some assumptions will be made of the system size. Therefore, it will be assumed that ten flight simulators will be operating at the flight line, and eight ATC stations will be operating at the AWS building. Although any number of simulators could be chosen, in reality the system's size would only be constrained by available funding. These assumptions are made to optimize the type and amount of data which will be transferred. A trade study is presented at the end of this chapter to better understand the need to tailor the system design between projected needs and available funds.

Recalling the system architecture of Figure 1, digital information would be coming from the ten flight simulator computers and the remote station. The computer data is delivered at a standard rate of 9,600 bits per second (baud). The data delivered are 68 characters long, composed of 8 bytes, each without a parity bit. It is a requirement of the Canoga Perkins multiplexer that the data be supplied in an asynchronous data character frame, which this fulfills (see Appendix B). With the ten computers and the remote station, the total bandwidth requirement for this data transmission would be

$$11 \times 9.6 \text{ kbps} = 105.6 \text{ kbps}$$

Ten flight simulators would require ten voice, analog to digital (PCM) channels, commonly referred to as E & M. The Canoga Perkins codes the incoming 4 kHz bandwidth analog signal of each simulator into a 64 kbps digital signal.

It then digitally multiplexes (MUX) the ten signals together with the eleven digital signals from the computers, for a total requirement of:

$$\begin{array}{r} 10 \times 64\text{ kbps} = 640\text{ kbps} \\ \underline{+\ \ 105.6\text{ kbps}} \\ 745.6\text{ kbps} \end{array}$$

An additional 8 kbps is added for establishing and maintaining synchronization. The total bandwidth requirements for ten flight simulators and eight ATC simulators under the present system architecture would then be 753.6 kbps. If operating under T1 conditions of 1.544 Mbps, this leaves 790.4 kbps open for system expansion. This expansion would allow an additional ten flight simulators at the flight line needing a 745.6 kbps transmission bandwidth.

The previous pages described how the Canoga Perkins operated T1 for fiber optic transmission under a variety of data and voice configurations. Also presented was the fractional T1 or FT1 option of the multiplexer. In the case of the flight line/AWS link, FT1 is not necessary since the fiber optic link has already been established. However, as one can imagine, the cost of operating a satellite data link is proportional to the quantity of data transmitted. FT1 service offered by satellite common carriers presents one option. Tailoring system designs to the needs of presently available equipment may offer more cost effective alternatives.

The overall system design presented was devised to maintain the CPU switcher at the AWS lab, where codes could be input at a common location and only one piece of this type of equipment would be required. The drawback to this design is the increased bandwidth required for increased numbers of flight simulators. For situations where the number of ATC stations will be less than the number of flight simulators, it may be more advantageous to build three CPU switchers. One could be located at each grouping of flight simulators (e.g. flight line, Prescott, and AWS). With the CPU switcher at each location, the E&M channels are switched and directed to the respective ATC controller before going to the multiplexer (see Figure 13 in Appendix C). Using the example of twenty flight simulators at Prescott and eight ATC stations at the AWS building, this alternate design would only require a 625.6 kbps bandwidth. Additionally, the ability to input communication codes could remain at the AWS lab if the serial communications controller is separated from the CPU switcher.

The choice of the system design is an academic one, dependent upon potential funding and curricular objectives. If classes in ATC would be offered at the Daytona campus using this equipment, it is assumed that a much greater number of ATC stations would be in use (over the number of flight simulators). This would make the initial design a better choice. In either case, the cost of satellite T1 or FT1 will be the paramount consideration for this system.

IV. SATELLITE DATA LINK MEDIUM

Since the early days of the telegraph, the primary medium for long line (long distance) communication has been copper wires with amplifiers located every few miles to boost the signal. Although still in use, copper wires are being replaced by satellites and fiber optic cable to support the greater demands of increased capacity for long distance requirements. Both terrestrial methods and satellites offer the transmission of video broadcasts, thousands of telephone conversations, and millions of bits per second of digital data. However, only satellites can provide this service as point-to-point, point-to-multi-point, or points-to-points transmission, and this can be accomplished from a single satellite.

Modern satellite communications (satcom) offer widespread use for network and aviation applications. The once large earth station requirements meant that only major telecommunication companies could afford the benefits of satellite communications. The advent of very small aperture terminals (VSAT) in the 1980s made satcom practical for smaller operations for which it is ideally suited. VSATs provide rapid, cost effective transmission for private, interactive data, voice, and video communications. Retail corporations such as K-mart use VSAT networks for inventory control, point-of-sale and credit verification. First Union Corporation recently signed a $7 million agreement with satellite carrier GTE Spacenet to extend its satellite-based telecommunications network to include operations to Maryland, Virginia, and Washington, DC (Aviation Week, 1993). The small rectangular dish antennas visible on First Union Bank roof tops are part of the VSAT link, providing automatic teller machine verification and data transfer between remote sites and the First Union central data processing location.

In addition to navigation applications, satellites offer a new role as a direct digital contact between pilots and air traffic controllers. In June 1993, the Federal Communications Commission (FCC) gave the first Type Acceptance approval to Honeywell for a commercial satcom system with aviation applications (Aviation Week, 1993). Honeywell has sold the satcom system to more than 20 airline customers flying Boeing 747s, McDonnell Douglas MD-11s, and Airbus A310s. In addition to aircraft control, satcoms offer an excellent replacement for the VHF mobile communications package passengers now use. The 200 mile radial limit on current VHF systems (especially evident on transoceanic flights) will be replaced by the latest GTE Airfone digital satcom system. This technology can be seen on the ground with personal communications via digital satcom networks, such as Motorola's MAGNAPhone (SKY, 1993). The most ambitious satcom project (surpassing the Defense Department's Global Positioning System navigation network) is Motorola's Iridium system. Motorola intends to maintain a galaxy of 77 satellites in Low Earth Orbit (LEO), providing two-way radiotelephone voice communications (Datapro Communications Reports, 1991).

A satellite communication involves three basic elements: the space element, the signal element, and the ground element. The space element comprises the mechanics of the satellite's orbit, the means of launching it into orbit, and the design of the satellite itself. The signal element comprises the frequency spectrum used for communicating by satellite, the effects of distance on communications, the sources of interference, and the modulation schemes and protocols used to insure proper transmission and reception. The ground segment includes the placement and construction of earth stations, the types of antennas used for different applications, and multiplexing and multiple access schemes that allow fair and efficient access to satellite channels.

THE SPACE ELEMENT Satellite design, launching and orbit are considered out of scope for this thesis, and will be covered only where the information is applicable to the end user. The basic function of a satellite is to act as a stationary (yet active) repeater in the sky, neither creating or terminating a signal. To the earth station, the satellite appears stationary in the sky because it is moving in synchronization with the Earth's rotation. A satellite within a few degrees of the Earth's equator having the same 24-hour period is in the *geosynchronous* orbit. The more effective use is for a satellite to be maintained within a few tenths of a degree of the equator, in the *geostationary* orbit.

The geostationary orbit is approximately 22,280 statute miles (35,800 kilometers) above the surface of the Earth. This is the cause of one major problem in satcom systems, dealing with real-time data exchange. The radio signals transmitted across a satellite system travel at the speed of light (300,000 kilometers per second or 186,000 mi/sec). This results in a minimum one-way propagation delay of 250 milliseconds, but averaging slightly higher when compounded with other delays. This inherent delay is several times the propagation delay for a signal transmitted over any terrestrial link, and can be a source of irritating signal echo. Telecommunications companies use methods of echo suppression to counter this effect, however the inherent delay can still cause a delay in real-time communications.

The most densely occupied orbital arc covers an area of the Western Hemisphere from approximately 67° west longitude to approximately 143° west longitude. This arc is affectionately known as the Big MAC for the Mexican-American-Canadian constellation of satellites it contains. Table 1 shows current and near future satellites occupying this orbit. FCC regulations mandate a minimum separation distance of 2° between satellites in this arc to avoid signal interference of neighboring satellites. This puts an upper limit on the number of satellites (and transponders) which can operate in this orbit at any one time (Jansky, 1976). Consequently, although improved technology has caused the cost of satellite transmission to decrease, an increase in their demand has kept the cost of "transponder time" high. As an example, the cost of renting a transponder on Satcom C1 for a few hours per day for one month could cost $10,000 (S. Boyce, personal communication, April 15, 1990).

Table 1.

<u>Late 1994 projected domestic satellite belt</u> (Melton, 1992).

SATELLITE	OWNER	FREQUENCY	ORBITAL POSITION
Spacenet IIR	GTE Spacenet	C/Ku	69°W
Satcom F2R	GE	C	72
Galaxy 2R	Hughes	C	74
Satcom H1	GE	C/Ku	79
Satcom K2	GE	Ku	81
Satcom F4	GE	C	82
Satcom K1	GE	Ku	85
Telestar 302	AT&T Skynet	C	86
Spacenet IIIR	GTE Spacenet	C/Ku	87
Telestar 402	AT&T Skynet	C/Ku	89
Galaxy 7	Hughes	C/Ku	91
SBS 4	Hughes	C	91
Gstar III	GTE Spacenet	Ku	93
Galaxy 3R	Hughes	C	93.5
SBS 3	Hughes	Ku	95
Telestar 401	AT&T Skynet	C/Ku	97
SBS 2	Hughes	Ku	97
Galaxy 4H	Hughes	C/Ku	99
SBS 6	Hughes	Ku	99
Spacenet IV	GTE Spacenet	Ku	101
Spacenet 1R	GTE Spacenet	Ku	103
ANIK D1	Canada	C	104.5
Gstar II	GTE Spacenet	Ku	105
ANIK E2	Canada	C/Ku	107.3
ANIK D2	Canada	C/Ku	110.75
ANIK E1	Canada	C/Ku	111.1
Morelos 1	Mexico	C	113.5
ANIK C3	Canada	C/Ku	114.9
Morelos 2	Mexico	C	116.8
Spacenet I	GTE Spacenet	C	120
SBS 5	Hughes	Ku	123
Telestar 303	AT&T Skynet	C	123
Galaxy 5W	Hughes	C	125
Gstar 4	GTE Spacenet	Ku	125
Galaxy B	Hughes	C	131
Satcom C3	GE	C	131
Galaxy 1R	Hughes	C	133
Satcom C4	GE	C	135
Satcom C1	GE	C	137
Aurora 2	GE	C	139

Currently, or planned for the near future, 39 satellites occupy 70° of the Big MAC from 69° west to 139° west. These are made of C and Ku-band satellites which are operated by one of six companies or organizations. Other satellites exists in the orbital arc, but are not used for public communications. Comstar D1 is one such satellite. Owned by Comsat, this old satellite's life span was extended using the pioneering "Comsat Maneuver." This maneuver conserves satellite station-keeping fuel by allowing a maximum allowable in-orbit drift. Commands from ground control stations maintain contact to command the satellite to continually repoint the onboard antennas to maintain constant downlink power levels (Long, 1991).

The Anik satellites E1, E2 are Telesat Canada, Canadian owned and the most powerful and largest communications satellites built to date for domestic communications. Anik D1 is no longer used for public communications. Morelos satellites are owned by Telecomunicaciones de Mexico, the Mexican satellite operator, for telecommunications and entertainment. The remainder of the Big MAC satellites are American owned, with the majority owned by the Hughes Communications Group. Hughes owns the Galaxy, SBS, and former Westar satellites. Hughes bought Westar's operating company, Western Union, and changed the names of the satellites in the process.

With the average life span of a satellite at eight to ten years, some satellites have continued in service beyond this time. As others age, their signal power fades to an unacceptable level, or more often, they run out of onboard station-keeping fuel. New, and usually more powerful, satellites are launched into position to take-over the duty of the previous occupant. As Hughes has been replacing older satellites in its control with more powerful, longer life-span, hybrid (both C and Ku-band) satellites. Satellites which are replacements are designated with an "R" in the name.

GE American Communications operates a variety of Satcom and Aurora satellites. Satcom H satellites are hybrid, and C, F and Aurora satellites are C-band. Table 1 shows Satcom C5 as its more common name of Aurora 2. The old Anik D2 (now called Satcom F4R) was purchased by GE to replace the failing Satcom F4. American Telephone and Telegraph, AT&T, satellite division, which operates the Skynet Services, controls the Telestar satellites. The older Telestar 3 series C-band satellites are being replaced with newer, more powerful 4 series hybrid satellites. Telestar 401, a 7,000 pound satellite launched in December of 1993, is the latest technology satellite in the AT&T line, and one of the finest in the American constellation with an expected life span of twelve years (Howes, 1994).

GTE Spacenet merged with Contel ASC in 1991, making it the second largest communications carrier operating nine satellites. ASC satellites were renamed Spacenet and added to the fleet of GStar satellites. GTE plans to replace older GStar satellites with hybrid Spacenet models. Spacenet 1R will replace GStar at 103° west and 2R will replace Spacenet 2 at 69° west.

As previously mentioned, the satellite can be considered a stationary repeater in the sky. The transponder is the onboard unit which receives frequency translates, amplifies, and transmits a given signal. Greater description will be given in the signal element section. Fixed Service Satellites, the FCC assigned frequencies for satcom, are primarily broken down into two major categories. C-band at 6/4 GHz and Ku-band at 14/12 GHz are the two frequency bands which dominate the Big MAC constellation. The frequencies are expressed 6/4 or transmit/receive, where the earth station transmit frequency is always the higher frequency. As seen in Table 1, satellites are assigned as C or Ku-band, with several operating as hybrid satellites which have both C and Ku-band transponders onboard. Hybrid satellites offer the flexibility of "cross-strapping" or utilizing both frequency bands on a single satellite communication link (Melton, 1992). An example would have an operator transmit up to the satellite at 6 GHz in the C-band and the satellite would broadcast down at 12 GHz in the Ku-band.

The FSS satellites have more than one transponder onboard. C-band satellites usually have 24 transponders, each with a 36 MHz bandwidth, while a Ku-band satellite will only have six to sixteen at bandwidths up to 72 MHz each. A hybrid satellite, such as Spacenet II has six 72 MHz wide Ku-band channels, six 72 MHz wide C-band channels and twelve 36 MHz wide C-band channels. These channels are broadcast to Earth at very low power. The Spacenet II Ku-band amplifier is rated at 16 watts, and the C-band amplifier is 8.5 watts for narrowband and 16 watts for wideband (Long, 1991).

Figure 2 shows the satellite footprint of the Spacenet II satellite. The footprint is the area on the Earth where the signal can be received by virtually an unlimited number of earth stations. Footprints are available from satellite manufacturers, operators, and various publishers in the satcom industry. On the footprint are a series of contour lines that show the points at which the intensity of the signal decreases from the beam's center to the beam edge. The beam edge is the furthest location in the footprint where adequate signal strength can be received. Each contour line represents a defined signal quantity or effective isotropic radiated power (EIRP) level. Mathematical representation of the EIRP as a performance parameter in the satellite link budget is developed in Chapter VI.. Earth station locations where the EIRP values are high represent strong signal reception and a high quality link.

For the ERAU proposal, a satellite can use either a spot beam (narrow) or global beam (wide beam), depending on the onboard antenna used. From Figure 2, it can be seen that Spacenet II's C-band spot beam cover's several thousand square miles. A spot beam can be as narrow as a few hundred square miles covering only a particular city, or the continental United States (CONUS), as in this case. A global satellite covers the entire surface of the Earth as seen from the satellite. The spot beam's benefit is that it concentrates the transponder's relatively weak signal to a particular geographic location, yielding proportionally higher signal strength. This way the satellite user does not waste signal on areas such as oceans or foreign territories. As a final generalization to footprints, Ku-band satellites tend to have more narrow footprints than C-band satellites, yielding higher signal strengths and requiring smaller earth station antennas.

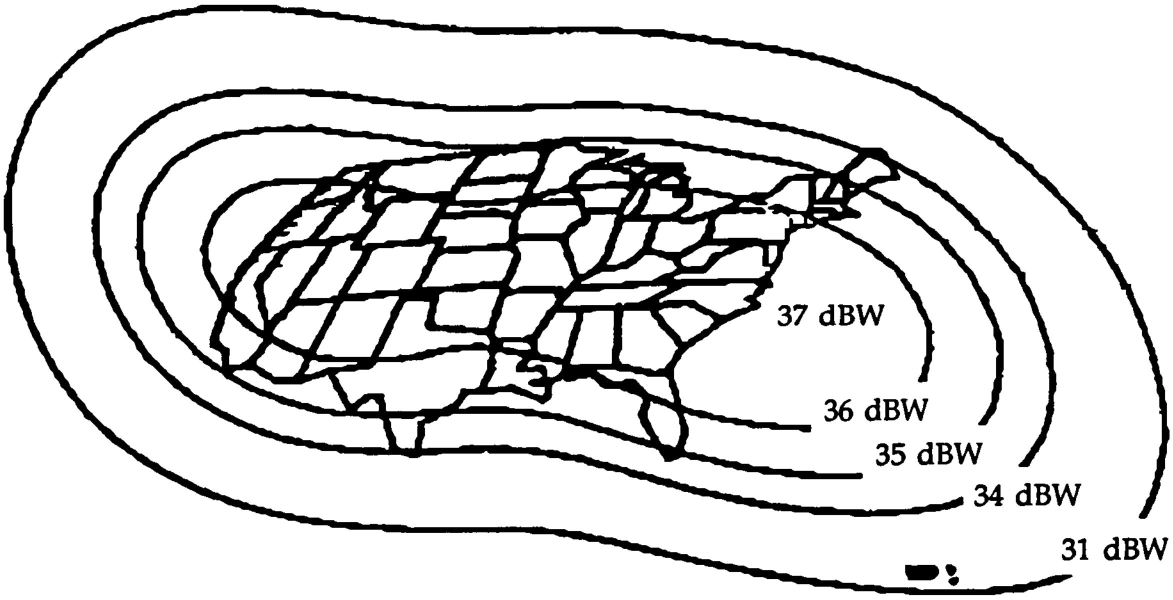


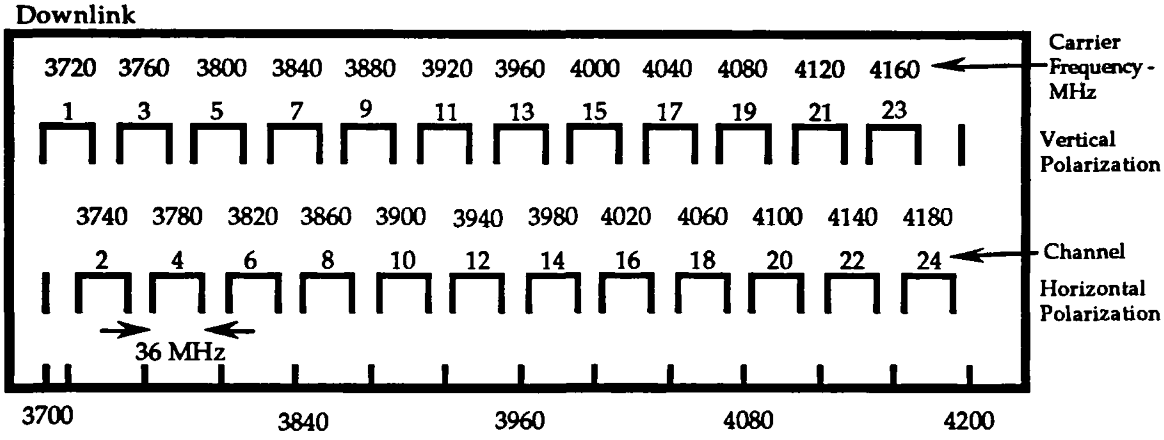
Figure 2. C-band EIRP values for Spacenet II (Long, 1991).

In addition to onboard power, launch, navigation, and station keeping systems, the very role of a satellite is dictated by its transponders. These are the hardware which process the incoming signal and transmit it back to Earth. The main amplifying component of the transponder is the vacuum tube traveling wave tube amplifier (TWTA) or the solid state gallium arsenide (GaAs) amplifier. The TWTA is more powerful and has been favored for use with smaller earth stations. The GaAs amplifier is used when the channel bandwidth is densely packed. The transponder design is a function of the type of signal used and would be dictated by the primary owner/user of the satellite. This is one way in which the signal and space elements are closely related.

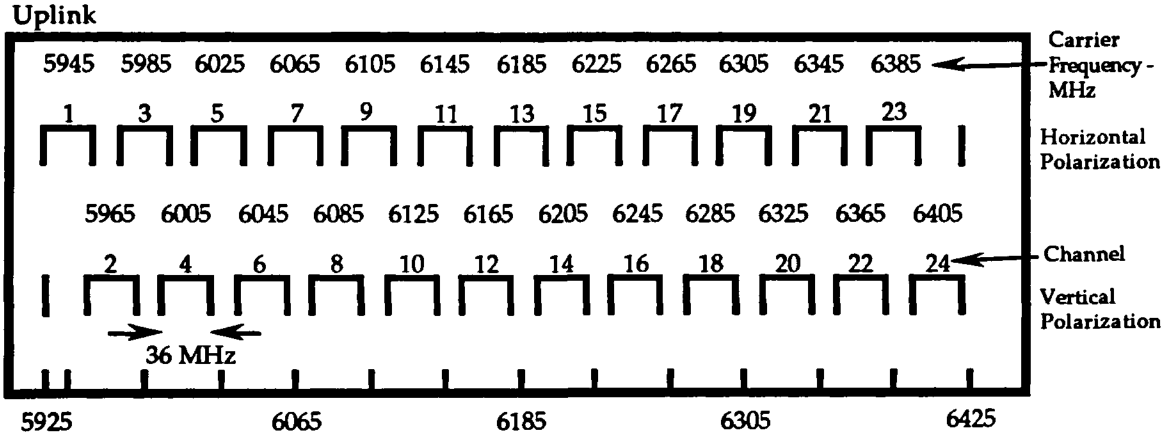
THE SIGNAL ELEMENT Much of the background information of the signal element was covered as communications in the preceding chapters. The first aspect of the signal element is the basic signal itself. The limitation in data transfer can be measured in the amount of bandwidth available. Using television as a driver for satellite requirements, the bandwidth of a single color channel is 6 MHz. Typical satcom transponders offer a frequency spectrum of 36 MHz. Although the color channel is only 6 MHz wide, this bandwidth is just the video baseband with modulation peaks averaging 18 MHz to 27 MHz. Consequently, each transponder is the equivalent of one television channel.

With the average C-band satellite carrying 12 or 24 transponders (16 transponders for Ku), a maximum usable satellite bandwidth of 432 MHz or 864 MHz, respectively, can be achieved (576 MHz for Ku). Adding a 4 MHz guard band between each channel and at the ends of the frequency spectrum yields a total transmitted signal of 1,000 MHz bandwidth. The guard band is to insure that neighboring frequencies do not interfere with channel transmission. Figure 3 graphically illustrates the channel bandwidth assignments of some C-band satellites.

The number of channels of a satellite can be doubled, and consequently increasing the information capacity of the satellite, by using a technique known as frequency reuse. In frequency reuse, the transponder is capable of transmitting/receiving two independent signals at similar frequencies, by either circular or linear polarization of the wave.



Frequency - MHz
(Polarization for: Satcom C & F and Telstar III satellites.)



Frequency - MHz
(Polarization for: Galaxy satellites.)

Figure 3. Typical C-band satellite frequency channelization (Gould, 1976, Long, 1991, Long & Keating, 1988, Melton, 1992).

Linear polarization is the transmission of a wave which is polarized so the maximum power is incident on the receiving antenna at a predominantly horizontal or vertical direction. Simultaneously, another wave of similar or overlapping frequency would be at maximum power 90° to the first signal. That is, the planes of the two signal's electric fields are separated by 90°, horizontal or vertical, preventing interference with each other. In practice however, the two planes are not exactly orthogonal and minor interference does occur.

In circular polarization, the waves are either right-hand (RHC) or left-hand (LHC) circularly polarized. The waves and matching incident antennas offer the same frequency reuse as linear polarization. This method is predominantly used by European and Middle Eastern satellite operators.

Beam polarization and frequency reuse can be seen in Figure 3 as satellite Telestar 302, transponder 1, transmits (downlink) a carrier signal for channel one. Channel one is vertically polarized and overlaps the carrier signal of channel two, which is horizontally polarized. This cascading scheme alternately adds 36 MHz-wide channels, where the carrier frequencies are centered every 20 MHz and 4 MHz guard bands separate neighboring channels.

Telestar 302 uses twenty-four 36 MHz bandwidth channels. With the addition of the guard bands, Telestar 302 has the potential for occupying 1,000 MHz bandwidth. However, through frequency reuse Telestar 302 only occupies 500 MHz. On C-band uplink transmission, this covers the 5.925 to 6.425 GHz band, while the downlink uses the 3.7 to 4.2 GHz band (see Figure 4, page 32). For a signal relayed through a satellite, the downlink carriers always offset the uplink carriers by 2.225 GHz (Hollis, chap. 1-2, 1982).

The frequency bands shown in Figure 4 are some of the frequencies set by the FCC as the Fixed Satellite Services (FSS) frequency bands. Most of the domestic systems operate in either the C-band or the Ku-band ranges, with C-band preferred because of its superior propagation characteristics (Cook, Springer, & Vespoli, 1990). Table 2 lists some of the major differences between the C and Ku-bands.

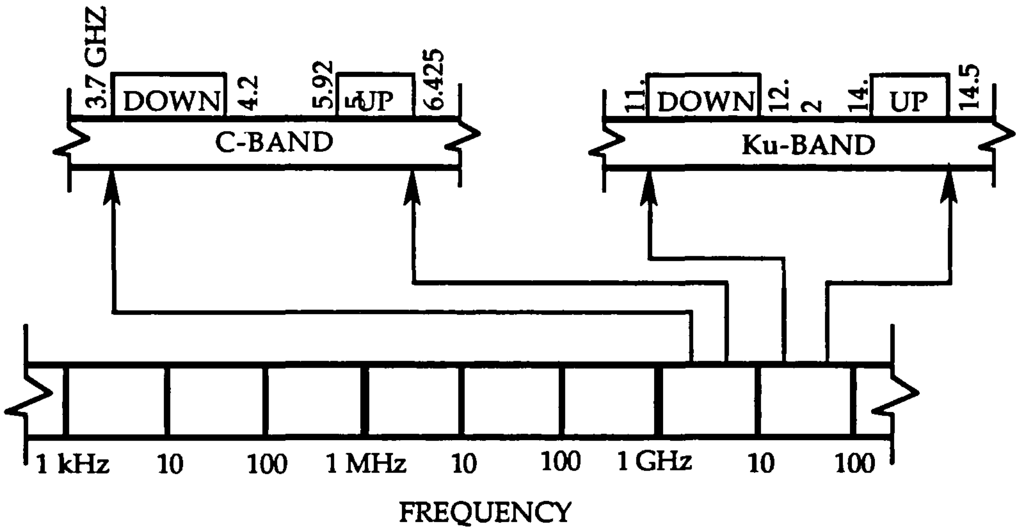


Figure 4. Frequencies in the microwave range of communications satellites (Cook, 1990).

Table 2 is meant to be a general reference for differences between frequency bands. Unexplained terms will be developed in the following pages. Although Table 2 may show the Ku-band to be the better choice, the decision may not be an easy one. C-band equipment is competitively priced and dominates older and possibly more affordable and available systems. However, the current availability for direct site-to-site link via a satellite operator is through their scheme using frequency division multiple access (FDMA) at prescribed times. The major common carriers, GTE Spacenet and AT&T Skynet, offer this option only at Ku frequencies. Therefore, this thesis will study communications in both frequency bands.

Some key characteristics of Ku-band signals are directly related to the higher operating frequencies.

Table 2.
Merits of C & Ku-bands for satellite communications (Cook et al, 1990).

C-Band Advantages

1. Less susceptible to rain outages
2. Established manufacturing infrastructure
3. Antenna surface tolerance can be achieved by various techniques that lend themselves to low cost manufacturing

C-Band Disadvantages

1. Frequency band is congested because it is shared with terrestrial microwave, making frequency coordination (orbiting-terrestrial) a requirement
2. Requires relative large antennas because of low satellite EIRP levels and necessity of narrow half-power beamwidth to allow two degree spaced satellites
3. Avoiding terrestrial interference makes site selection a difficult process, sometimes requiring artificial shielding
4. Faraday rotation of polarization can affect system performance
5. Satellite dispersal signal is required to prevent harmful interference to terrestrial stations, resulting in more stringent receiver needs

Ku-Band Advantages

1. Frequency band is only used for satellite communications
2. Smaller antennas may be used because of higher gain and higher satellite EIRP
3. Easier site selection because of smaller size of antenna and lack of terrestrial interference
4. Narrower antenna beamwidth is desirable in reduced orbital spacing
5. Lower reception equipment cost
6. Flexibility in channelization plan
7. Not affected by Faraday rotation
8. No satellite dispersal signal disadvantages

Ku-Band Disadvantages

1. Affected by rain attenuation and depolarization
2. Narrow beamwidths of antennas may require more rigid mounts
3. Reflector surface tolerance increase manufacturing cost
4. Waveguide and coaxial transmission line losses are quite high
5. Noise temperature of low noise amplifiers may cause the use of large antennas to achieve desired G/T

The higher propagation losses characteristic of these frequencies require higher spacecraft power (EIRP) to achieve the transmission performance as C-band, usually derived from higher spacecraft antenna gains. Since the Ku-band frequencies are not shared with terrestrial systems, the power flux density (PFD) limitation is less stringent and there is no FCC requirement for coordination with terrestrial microwave systems. The higher EIRP allows the use of very small earth station antennas, usually at a substantial savings to the user. However, the higher EIRP is often needed just to offset the attenuation caused by rain.

SATELLITE TRANSMISSION FORMATS Modulation methods were covered previously in Chapter II and Appendix A. The audio tone modulation technique used by terrestrial modems mentioned earlier cannot be applied to satcom since the transmission rates used are too low. Instead, frequency and phase shifting of the transponder's RF carrier signal have the capability of reaching transmission speeds into the tens of millions of bits per second. Nearly all commercial analog satellite signals use frequency modulation (FM) because of its simplicity and low cost of receivers and demodulators. In digital satellite systems, the most common modulation technique is phase shift keying (PSK). The two most common forms of PSK are quarternary phase shift keying (QPSK) and binary phase shift keying (BPSK) (Cook et al, 1990, Datapro Communications Reports, 1991). However, QPSK and BPSK are different from the PSK described in Appendix A. The changes in phase are measured in degrees, varied from the data signal's amplitude. As with PSK, BPSK represents a zero value bit as a positive phase change of 90^o, and one bit value with a negative 90^o phase change. In QPSK, four possible values are represented by some multiple of 45^o. The most common scheme is for the binary value of 10 to be represented by a positive phase change of 45°, 11 by positive 135°, 01 by negative 45°, and 00 by negative 135°. BPSK carries one bit per cycle, while QPSK carries two, making QPSK the more efficient method, and the more popular. However, BPSK is more resistive to noise, requiring less signal strength for transmission. Both BPSK and QPSK are superior to PSK because phase modulation techniques use the least energy for a given bit-error rate.

Digital communication protocols are another handicap of satcom over terrestrial communication links. As discussed in Appendix B, the protocol is the initial 'hand-shake' which establishes the data transmission's format and characteristics. Two factors in satcom which create this handicap are the satellite channel's inherent 250 millisecond propagation delay and the relatively high level of noise on satellite channels. The early protocols such as IBM's Binary Synchronous Communications line discipline required a receipt from the receiver after each transmission was sent before the next information block could be transmitted. With an average round trip delay of 500 milliseconds, this became an inoperable method with transmission rate efficiencies ranging from 78% down to 8% (Datapro Communications Reports, 1991). Understanding protocols and the effects of satellite transmission on the data signal is important to this thesis. Since the protocol will be established at the ERAU campus, and not dictated by the satellite common carrier, an appropriate protocol will have to be used to minimize any adverse affects caused by the satellite medium.

Protocols developed specifically for use with satcom have overcome the delay effects of earlier models. The 'sliding window' technique allows multiple data blocks to be transmitted without stopping the sender from transmitting in-wait for an acknowledgment. The best protocols for satellite transmission are the newer, bit-serial types such as CCITT's HDLC and IBM's

SDLC. With these techniques, a large frame of variable length requires an acknowledgment of its correct reception from the receiver. However, the transmitting station may continue sending frames up to a specified limit of each frame. This limit, set in the transmission of each frame, defines a frame window called a modulo. It represents the number of frames that a station can wait for acknowledgment from the receiver. The maximum number of such blocks is the window size minus one, with most forms of the sliding window protocol using a window size of eight. For a three-bit window (modulo 8), a station can transmit seven unacknowledged frames. If the time required to send this many blocks is less than twice the satellite delay of 0.48 second, the sender will be flow controlled and the effective data transfer will be reduced.

For satellite transmission, the most practical window is seven bits long or modulo 128. With this window, a station can transmit 127 frames before receiving an acknowledgment. As the modulo size increases, the amount of time that an actual transmission can occupy of the satellite channel increases in proportion to the constant propagation delay. In other words, the use of the channel grows more efficient as the frame window grows larger. The delay effects are compounded on higher level protocols, such as CCITT's X.25.

In addition to the acknowledgment of the protocol, a repeat request for damaged frames is also established in the protocol. The transmitting station stores each frame until it receives positive acknowledgment of that frame from the receiving station. If the transmitter does not receive an acknowledgment after a predetermined period, it will automatically retransmit the frame. Depending on the protocol, just the frame or the entire block may be retransmitted if no acknowledgment is received. The delay effects of satellite transmission may time-out some transmissions before the acknowledgment is received, causing unnecessary delays and inefficiencies. The 500 millisecond delay will have to be incorporated into the protocol to reduce the number of retransmissions.

Another format established in the protocol is data error detection and correction. The probability of error for each bit in a satellite transmission is independent of the probability of error for any other bit in the transmission. This allows error correction to be based on statistical methods. A technique called forward error correction (FEC) checks proper character encoding. FEC adds redundant information to the datastream during transmission. The receiver would is then able to reconstruct the datastream, even if the original pattern had been altered by noise. A technique known as noise averaging adds the redundant information using probabilities based on the datastream. With FEC, a probability of 1 in 10 million that a given bit will be received in error is possible. Techniques such as this have made satellite transmission one of the cleanest media for data transmission.

To clarify the satellite digital transmission system, digital data links are characterized by data interface, data rate, code rate, and modulation scheme. Data interface refers to the connector and signal levels. Typical data interfaces are DS1, RS-422, RS-232, and V.35. The data rate refers to the number of bits per second transmitted by the modem which converts digital data to analog for modulation to an intermediate frequency to uplink. This can be at speeds from fractions of T1 (56 kbps) to multiples of T1. The code rate refers to the FEC encoding scheme. The code rate configuration is referred to as 'm/n.' 'm' refers to the number of bits per block of original data, and 'n' is 'm' plus error-correction bits per block of transmitted bits. A code rate of 3/4 means that for every three data bits, four data bits are transmitted (i.e. a 1024 kbps modem operating with a code rate of 3/4 would transmit 1365 kbps over the satellite). The modulation scheme refers to the method of digital-to-analog modulation, most commonly as BPSK or QPSK.

Signals types described previously were input data and voice information of the sort which would be generated at the ERAU lab. This information would have to be converted to a signal format suitable for access to satcom. This is dependent of the type of system to be chosen and the format used by the selected satcom common carrier. Single channel per carrier (SCPC) is a satellite format that assigns a single FM-modulated radio frequency (RF) carrier to each audio or data SCPC signal. These SCPC signals are located at spaced intervals throughout the transponder's frequency range. When transmitting several RF signals to a single transponder, both forms of multiplexing, FDM and TDM formats, are used. Appendix A describes the two methods of multiplexing and their application to satellite communications.

Satellite multiple access transmission formats form the basis of the point-to-point and point-to-mutipoint characteristics of satellite communications. The four formats for multi-access to the same transponder are FDMA, TDMA, DAMA, and CDMA. Frequency division multiple access (FDMA) is a method similar to FDM in which several carriers (usually FDM/FM) simultaneously access different frequencies within the transponder's available bandwidth. As separate earth stations, each is assigned specific SCPC uplink and downlink frequencies to access the satellite, independent of time, location, and capacity of the other earth stations. A hazard to these neighboring frequencies could occur if the carrier assignments for the earth stations are too close and their power levels are not uniform. This could generate the inter modulating "crosstalk" distortion as described in the multiplexing section of Appendix A. As mentioned earlier, the common carriers, GTE Spacenet and AT&T Skynet, offer FDMA as their point to point(s) service where the earth station does not require a direct interface with the carrier's main earth station or control center. This autonomous control makes FDMA the most viable alternative for the ERAU proposal.

Time division multiple access (TDMA) is similar to TDM in that it allows different earth stations to share a common satellite transponder and utilize the entire available bandwidth within a specific time segment. Within the carrier's network of earth stations, access to the same transponder is synchronized by a master earth station which assigns precise time intervals to each participating earth station. Each earth station must wait for its assigned time slot before it can transmit. To complete the assignment, the earth station will buffer voice, data, and video signals and then, through a burst modem, transmit the entire bandwidth of the assigned transponder. Drawbacks to this technique include the dependence on the master earth station for time assignments to access the satellite, the need for a terrestrial link to the master earth station, and the need for ongoing coordination with the master earth station. By comparison, FDMA allows near autonomous control of satellite access with the exception of initial start-up and equipment maintenance by the satellite service carrier.

Demand assignment multiple access (DAMA) is used with single channel per carrier frequency modulation (SCPC/FM). In DAMA, a master earth station assigns the single channels, on demand, to a requesting earth station. The advantage of this technique is that it allows more economical use of the available capacity of the transponder. Within the Intelsat system, DAMA is used between countries that do not have enough traffic between them to justify full-time FDMA circuits.

Code division multiple access (CDMA) is usually used for transmitting low data rates to a large network on inexpensive, receive-only ground stations. CDMA superimposes the specific coded address waveform onto the data information. The combined signal is then modulated onto an RF carrier, producing signals that are spread across the bandwidth of the transponder. For this reason, CDMA is sometimes referred to as spread spectrum multiple access (SSMA). Spread spectrum technology was originally developed by the military as an encryption technique to prevent deciphering of satellite transmitted information. At the CDMA receiving station, the receiver is programmed to ignore all but the correctly coded signals. With each CDMA carrier having its own unique address waveform, multiple carriers can be simultaneously transmitted, overlapping other signals at the same frequency spectrum without interference. GTE has installed thousands of VSAT earth stations using CDMA across the United States.

A final characteristic to the signal element is the effects of signal attenuation and interference on data transmission. Several sources of signal attenuation have been covered in previous chapters and thoroughly in Appendix D. Signal attenuation for satcom is primarily a function of the affects of the signal medium on the transmission received at the earth stations and the satellite. Since the satellite power is fixed by the builder and user, the effects of signal attenuation can only be minimized at the ground station through more efficient antenna/receiver systems, greater uplink power, and unique operational methods. Similarly, effects on signal interference can be directly attributed to earth station conditions. Although the effects of rain (for Ku-band), atmospheric conditions and the semi-annual sun-transit outages can completely destroy data integrity, local interference can also have devastating consequences on signal integrity, local terrestrial microwave links, electrical power distribution systems, or out buildings and local vegetation can all interfere with signal transmission. Understanding the causes and effects of signal attenuation aids in system design and operation. Beginning with proper earth station planning for the ground segment can help to prevent these hazards to signal quality.

THE GROUND ELEMENT Several earth station designs exist which are representative of their functions and cost. These costs depend on system complexity and equipment necessary for network operation. In addition to the receive and/or transmit functions, earth stations provide all the processing operations for satcom. These operations include uplink techniques to the satellite and downlink to the earth station, multiplexing, modulation, amplification, signal processing and frequency conversion. A simple television receives only (TVRO) for home entertainment requires as little as $2,000 worth of equipment, including the dish antenna, frequency downconverters, and channel receiver. This is the least expensive type of earth station since the application is very specific and both the satellite and signal elements are designed to minimize earth station cost. In addition to TVRO, small earth stations can be designed to receive voice-only, data-only or a combination of the three mediums. In these networks, the signal is transmitted from a master earth station and is received by all sub-earth stations.

The next larger type of earth station network uses a single master earth station for central broadcasting and control, and independent VSAT earth stations for locations throughout the satellite's footprint. These VSAT networks can work with either a terrestrial link (to maintain transmission protocol) or a direct satellite link to the master earth station. Depending on system design, some VSAT networks require a double satellite hop throughout the master earth station for inter-VSAT communication, while terrestrial links to the master earth station give the control to other networks and allow direct inter-VSAT communication. These are generally networks offered by satellite common carriers and corporate networks for data transmission and digital voice and video. Represented in Figure 5, this is the most capable earth station for the ERAU proposal. The equipment of a VSAT earth station is similar to the TVRO station, compact and relatively light weight. In TVRO, the channel is typically a 36 MHz wide composite audio/video analog signal. The VSAT channel can vary from 56 Kbps to multiples of T1, usually of digital information and the receiver is commonly called the controller. Referring to Figure 5, the VSAT equipment is primarily broken down into two main groups. The antenna module contains the parabolic reflector dish antenna, the low noise amplifier (LNA), the high power amplifier (HPA), the upconverter, and downconverters. The second group, the controller module, contains the power supplies, terrestrial modem, satellite modem circuits, modulators, control circuits, processors, and status monitoring devices. The following chapter details the equipment used in a micro earth station.

An expensive corporate network provides video teleconferencing, electronic mail data and voice services through a system where all earth stations in the network have the same capability and can connect to any other station. The largest satellite earth station category is the type used by satcom common carriers. These are expensive systems which would have a "dish farm" located near the main earth station, each with a dedicated antenna per transponder per satellite. This allows the high capacity data transmission, large scale network capabilities, and where the carrier is also the satellite owner, orbit station keeping command control. In addition to these large and

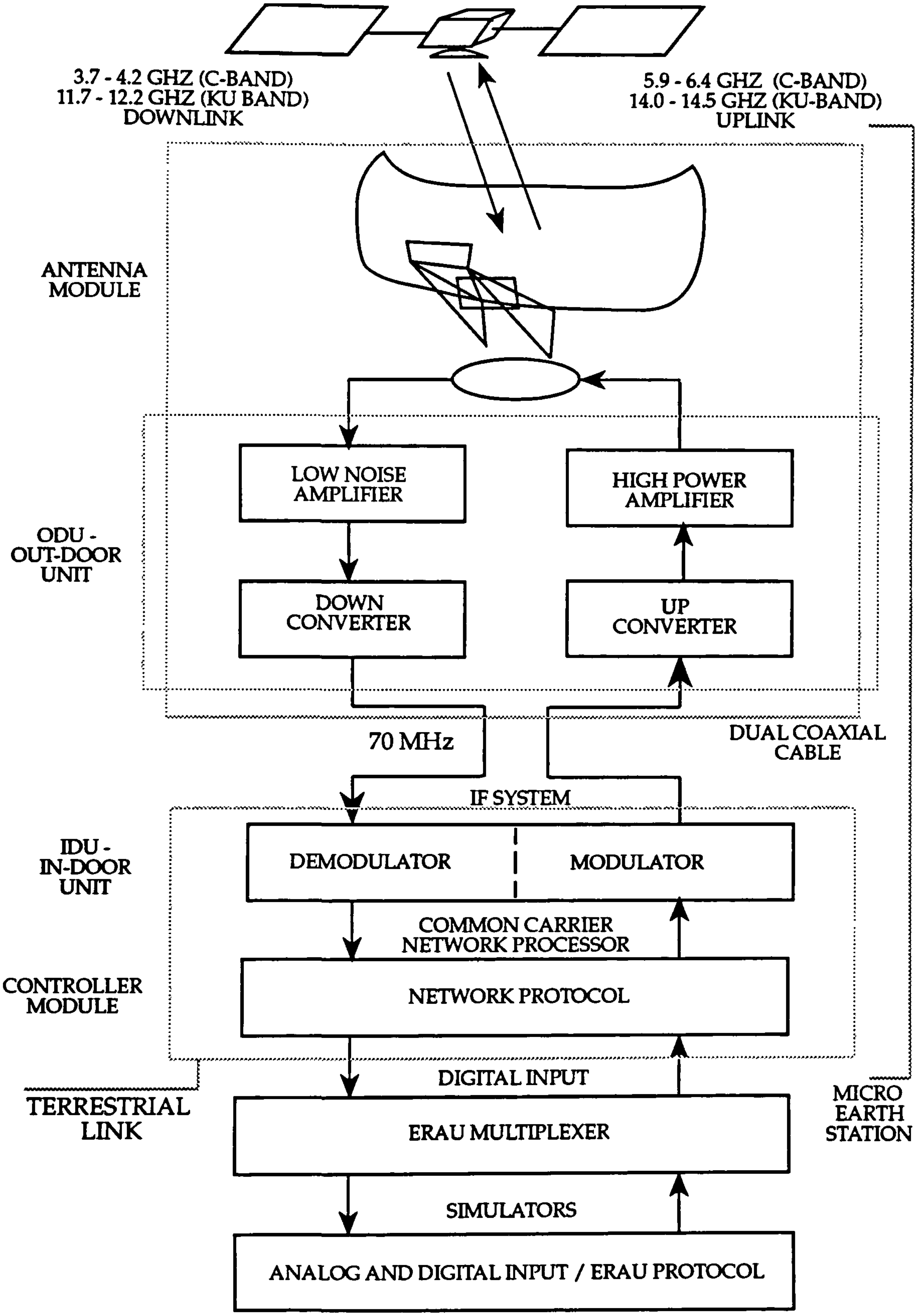


Figure 5. Block diagram of micro earth station (Hecker, 1988).

very complex systems, some common carriers will carry the responsibility for maintaining control of the satellite. A constant data link is required between the command control centers on earth and the satellite. This way engineers are able to monitor the satellite's station-keeping status. If this duty is not maintained with the common carrier/owner, then it is the responsibility of the satellite manufacturer.

Relating to the previous section on the satellite signal element, the operation method of C or Ku-band frequencies will have an impact on the earth station design. In addition to the obvious frequency up-conversion equipment differences, the antenna size, needs for specific local interference blocking (see Appendix D) and antenna mounting quality control will also be characteristics to address. Also, the geographic location often adds considerations to earth station planning. The heavy Florida rainfalls can influence the choice of C-band over Ku for the Daytona Beach earth station (Appendix D). In the case of Ku-band, the rain caused attenuation is of more interest since the carrier-to-noise ratio is estimated to be much smaller than the carrier-to-interference ratio resulting from rain depolarization (McKimmey, 1982).

V. SATELLITE DATA LINK COMPONENTS & OPERATION

An earth station can be broken down into four major subsystems, the antenna, the transmitter, the receiver, and the monitor and control subsystems. These subsystems are represented in an illustration of an earth station for the ERAU proposal in Figure 6. Each of these major subsystems consists of many component parts, each of which will be covered in detail.

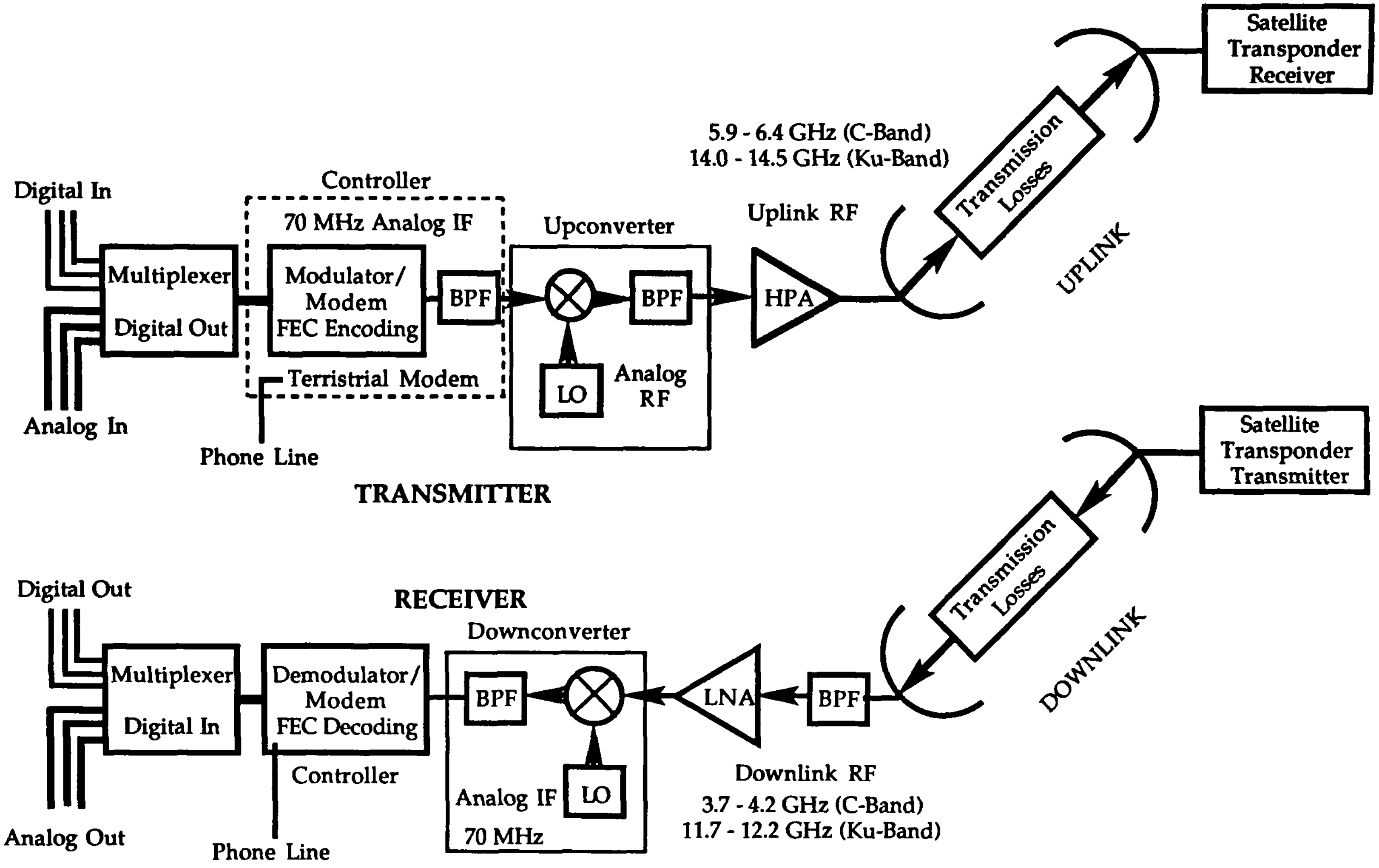


Figure 6. Block diagram of a satellite system.

Some major hardware subsystems of the earth station include:

Antenna and Feed
Low Noise Amplifier (LNA)
High Power Amplifier (HPA)
Up/Downconverters
Monitoring and control equipment
Interface equipment
Ground communication equipment

ANTENNA The antenna is one of the more important components since it provides the means of transmitting signals to the satellite and collecting the signals transmitted by the satellite. The antenna must not only provide the gain necessary to allow proper transmission and reception but also have radiation characteristics which discriminate against unwanted signals and minimize interference to other satellites or terrestrial systems. The antenna also provides the means of polarization discrimination of unwanted signals. The individual communication system's operational parameters dictate to the antenna designer the necessary electromagnetic, structural, and environmental specifications necessary for the antenna.

Antenna requirements can be grouped into several major categories. Electrical or RF (radio frequency), control systems, pointing and tracking accuracy's, environmental, and miscellaneous requirements such as radiation hazard, primary power distribution, etc. Since antenna design is a study all to its own, the following paragraphs will summarize some of the more important aspects of this topic. Table 3 lists some of the important parameters of antenna design (Cook et al, 1982).

The most basic element in satellite antenna design is the size or diameter of the dish. The antenna size is directly proportional to its gain, an important parameter in link performance. Gain, expressed in decibels, is a ratio showing an increase in signal power from one stage to another in a amplifying system, as discussed in Appendix E. Table 4 in Chapter VI lists calculated gain values for standard and high efficiency microwave dish antennas. It shows that increasing frequency and size increases the gain of the antenna. Also increased with antenna size is the focus of a transmitted beam. This is important since the orbital spacing of satellites has been reduced to 2°, a wide beam might illuminate more than the desired satellite, causing headaches not only to satellite operators, but also the FCC. For downlink transmission, a higher gain antenna provides greater signal clarity in an analog voice or video transmission and a lower error rate for data transmission.

Table 3.
Considerations for earth station antenna design (Cook et al, 1990).

Electrical Performance	Frequency (Bandwidth)
	Gain
	Noise Temperature
	Radiation Pattern
	Polarization
	Axial Ratio
	Power Handling Capability
	Port-to-port Isolation
	Out-of-band Emissions
Mechanical Performance	Angular Travel
	Drive Speed and Acceleration
	Pointing and Tracking Accuracy's
	Compatibility with Environmental Conditions
	Reflector Surface Accuracy
	Physical Dimensions
	Weight
	Structural Integrity to Wind Loads
System Considerations	Operational Functions
	Local and/or Remote Operation
	Availability and Maintainability
	Design Lifetime
	Interface Conditions with Other Subsystems

The primary electrical specifications of an earth station antenna are gain, noise temperature, power rating, receive/transmit group delay, radiation pattern, polarization, axial ratio, isolation and G/T (to be discussed in Chapter VI). Of all these parameters, only radiation pattern is not set by the system requirements. It is limited by the requirements set by the FCC. Earth stations operating in the regulated environment of the United States must meet the requirements set under FCC Regulations, Part 25, paragraph 25.209, pertaining to earth station antennas, the antenna aperture diameter, sidelobes, and radiated power density (transmit). Appendix F summarizes FCC requirements for earth station ownership and operation.

The desired radiation properties to satisfy the communication system design dictate the choice of type of antenna to be employed at the earth station. The three most important radiation properties are gain, sidelobe performance, and noise temperature. Most earth station antennas are designed to maximize gain and minimize noise, thereby maximizing G/T. These two criteria have led to the predominance of reflector type antennas for earth station applications although other types of antennas such as arrays have been used. The sidelobe is a parameter describing an antenna's ability to detect off-axis signals, with larger sidelobes detecting greater noise and interference (Cook, 1982).

The sidelobes and consequently beamwidth determine what the antenna will actually receive. Empirically derived plots of the sidelobes and beamwidth establish a "fingerprint" of the dish, characteristic of that design. The beamwidth is a measure of the dish's ability to target a narrow region of space and is defined as the width of the main lobe (Baylin & Gale, 1991). The beamwidth also indicates how well a dish will detect off-axis radiation.

Most of the different types of earth station antennas in use domestically can be broken down into two categories; single-beam and multi-beam antennas. A single beam antenna is one which generates a single electromagnetic beam directed toward a satellite by means of a positioning system. A multiple beam antenna generates multiple electromagnetic beams by illuminating a single reflector with a number of microwave feeds. The individual beam from a particular feed is directed to a satellite by positioning the feed without moving the reflector. An example of this type is the COMSAT antenna in the Kennedy Space Center Rocket Park at Cape Canaveral, FL. A more common example can be found on dual frequency home entertainment TVRO antennas. Multiple beam antennas are designed for large earth stations which require multiple and simultaneous satellite access. This is beyond the needs for the ERAU system and will not be covered.

The majority of earth station antennas in use today, and the type which would be used in the ERAU proposal, are single beam antennas. Many types of single beam antennas are in use with earth stations, each having its own unique characteristics and advantages. Paraboloidal reflector with focal point feeds (prime focus antennas) are most often used in the TVRO industry and for micro earth stations; dual reflector antennas such as the Cassegrain and Gregorian antennas are mostly used with larger diameter antennas for common carrier master earth stations; horn reflectors rarely see used in modern systems, and offset-fed Paraboloidal antennas are most often use in Ku-band VSAT networks. A paraboloidal reflector with a focal point feed or offset-feed would be the most likely used antenna for the ERAU proposal.

The focal point fed antenna is also known as the prime-focus-fed Paraboloidal (PFFP) antenna. This type of antenna can have excellent sidelobe performance in all the angular regions except the spillover region around the edge of the reflector, but even in this region the FCC requirements can be met. This antenna type offers good compromise choice between gain and sidelobes. Its basic limitations are in its location of the feed for transmit applications and for aperture sizes less than approximately 30 wavelengths, the blockage of the feed and the feed support structure raises the sidelobes with respect to the main beam such that it becomes increasingly difficult to meet the FCC requirements. The PFFP antenna is used for many receive only earth stations or for transmit/receive earth stations when only one transmit polarization is required, such as with the ERAU proposal.

The offset front-fed reflector antenna consists of a paraboloidal dish with a feed and support structure mounted to one side of the dish. The offset mount eliminates direct aperture blockage and also minimizes microwave diffraction scattering by removing the feed and feed support structure from direct illumination of the aperture. The offset-fed single reflector antennas generally lack in polarization performance, but the sidelobe patterns do meet FCC requirements.

FEED The electromagnetic microwave signal is reflected off the paraboloidal dish onto a waveguide surrounding the feedhorn. This channels the signals into the center of the feedhorn where it is directed down the waveguide to the receive port. The receive port contains the element which converts the satellite broadcast microwave RF signal to an electrical microwave RF signal for transmission through a cable to the downconverter. Several feed configurations are used in earth station antennas. These are typically classified by the frequency bands used and number of transmit and receive ports available in the feedhorn. A two-port feed may have two orthogonally polarized receive ports or a single transmit and single receive port, with the ports being either co-polarized or cross-polarized with respect to each other. An alternate to this is used on home entertainment TVRO antennas by having separate C and Ku-band receive ports with a servo-actuated polar rotor to rotate the element for frequency reuse. The three-port feed has two receive ports and a single transmit, with the receive ports being orthogonally polarized. The four-port feed allows dual polarization for both transmit and receive. The dual-band feed provides for simultaneous reception of C-band and Ku-band signals from a hybrid satellite.

LNA The element used in the receive port is attached to the low noise amplifier (LNA). Traditional C and Ku-band broadcast applications have used an LNA bolted to the feedhorn, and run a length of half-inch RG-6 foam insulated coaxial to the downconverter, which is mounted either to the pole or inside the building. The LNA amplifies the weak microwave signal from the satellite, and basically converts the waveguide signal input to a coaxial line output. The LNA does not change the frequency of the signal, only its method of transmission.

DOWNCONVERTER The downconverter (sometimes called the block downconverter or BDC) changes the C or Ku-band RF input signal to an intermediate frequency (IF) prior to demodulation. This intermediate frequency, typically 70 MHz, is generated at the local oscillator (LO) as shown in Figure 6. The downconverter inputs a signal range of 3.7 GHz to 4.2 GHz for C-band or 11.7 GHz to 12.2 GHz for Ku-band. Internal to the downconverter is the IF-filter. The IF signal is filtered through a bandpass filter which only allows specific frequencies to pass (70 MHz) and attenuates all others which would only result in noise at the demodulator. For downconverters mounted to the pole, a length of RG-59 or RG-58 (standard television-style coaxial cable) carries the IF signal into the building, to the controller containing the demodulator/decoder.

Used in later model TVRO systems and some micro earth stations, are downlink units where the LNA and BDC are combined as one unit. Mounted to the feedhorn or in a unit behind the antenna reflector, this low noise block downconverter (LNB and/or LNC) converts, filters, and amplifies the RF signal directly to the IF signal. The output of an LNB for either C or Ku-band is either 950 MHz to 1450 MHz (standard L-band for TVRO) or 70 MHz. This is more efficient transmission for longer coaxial cable runs, and offers less electromagnetic interference from fractured cables. A serious problem of local interference to terrestrial microwave links and earth stations occurs when a grounding failure of an uplink cable allows electromagnetic signals to radiate from an RF cable on the pole. The system for the ERAU proposal could use the LNA-70 MHz downconversion method since it remains an industry standard for C-band common carrier earth stations.

DEMODULATOR/CONTROLLER For an analog system, the filtered, amplified IF signal would then be input to the demodulator for FM demodulation. The output would be a baseband signal ready for processing into video and/or audio signals. For a digital system, the data is extracted from the IF carrier by the demodulator section of the modem. The data stream is then processed by the FEC-decoder removing the error-correction bits, correcting detected errors and output the received data and clock signals. The modem and decoder are part of the stand-alone controller, which is about the size of a personal computer. The controller sends the original transmitted digital data to the multiplexer via a standard RS-232 or RS-422 cable. This utilizes a common serial ASCII-protocol based interface. The RS-232 is used when the interface distance will be fifteen feet or less, while the RS-422 can run lengths up to 1,500 yards. The protocols for satcom are not standard, and most common carriers use their own version. Therefore, most earth station controllers offer a variety of serial equipment interfaces.

The satcom controller has an internal monitor and control system which monitors the equipment for failures and provides manual and automatic control of the components. The monitor and control circuit is linked via modem and terrestrial telephone line to the master earth station or wherever the local technical station for the common carrier may be located. This requires a dedicated telephone line so the technical staff can call in at any time to monitor the status of the equipment or even diagnose and repair a failure without going to the site.

UPLINK The transmit electronics utilize some of the same equipment as the receive hardware, but have different internal circuits. These electronics include baseband processors and modulators for analog signals, modems for digital inputs, upconverters and high power RF amplifiers. The controller adds FEC coding to the composite digital signal from the multiplexer and modulates the aggregate digital data via BPSK to a 70 MHz IF signal. The 70 MHz IF signal is transmitted via a RG-58 or RG-59 coaxial cable (part of the same dual line cable utilized in the downlink system) to the upconverter. An upconverter mounted to the pole is similar to, but separate from the downconverter. The upconverter's local oscillator converts the IF signal to an uplink RF frequency of 5.9 GHz to 6.4 GHz (C-band) or 14.0 GHz to 14.5 GHz (Ku-band) and passes the signal through a bandpass filter to the high powered amplifier via an RG-6 coaxial cable separate from the downlink's cable. The exact frequency for both uplink and downlink will depend on the allotment frequency from the common carrier, and will be maintained by the controller.

HIGH POWER AMPLIFIER The high power amplifier (HPA) amplifies the RF output signal from the upconverter to the required power level for transmission to the satellite. For micro earth stations, the amplifier is similar to the LNA by bolting directly to the feedhorn and containing an element for transmitting the electrical RF signal as a broadcast RF microwave. For these low power applications, the transmit power is usually 8 to 20 watts, based on the signal bandwidth. These types of amplifiers are usually referred to as PAs (power amplifiers) (K. Stevens, personal communication, February 23, 1994). PAs are widely available in solid state configurations. Amplifiers for satellite video application are typically sized in the range from 100 watts to 3 kilowatts (kW). These amplifiers typically use traveling wave tube (TWT) amplifiers for configurations up to approximately 750 watts, and klystron tube amplifiers above 750 watts. The HPA on larger systems often contains a bandpass filter to reject harmonics and power sampling circuits for monitoring the output transmit power and the reflected power from the antenna. If the reflected power exceeds a regulated level, the HPA will automatically shut-off. These HPAs are usually found at the network master station and are inside the central control building as several racks of equipment.

Uplink power is closely monitored to not only maintain FCC regulations but to adhere to proper transmission procedures. The downlink power has a direct relationship to the uplink power. Therefore, when the uplink power is boosted, the downlink power will in turn increase, usually at the expense of neighboring communication channels (K. Stevens, personal communication, February 23, 1994). This will remain in effect until the satellite operator identifies the anomaly and rectifies it.

MECHANICAL PERFORMANCE The mechanical design of an earth station antenna must provide the structural integrity to accurately point the antenna beam towards the desired satellite and to maintain the pointing accuracy within regulation. Additionally, to ensure maximum efficiency of an antenna, the reflecting surface must be designed and manufactured within specific tolerances. Slight distortions in the surface and oversized gaps in mesh antennas will cause unwanted reflections, interference, and propagation of waves through the surface. The antenna mount should provide a means to steer for variable pointing and tracking systems. This proposal is designed for a single satellite and would not require a variable positioning system. Finally, the structural integrity of the antenna mount must be capable of safely supporting the weight of the antenna and attached equipment, the expected ice and snow, windloads (in Florida, up to hurricane force), and earthquake loads (Cook et al, 1990). The University would require an approved site survey and design from a credited civil engineer showing the planned installation design and calculations for loads and margins of safety. Normally this service is performed by the satellite common carrier as part of the installation process.

VI. SYSTEM PARAMETERS AND DEFINITIONS

The data parameters and system description presented in previous sections have laid the foundation of the data transmission medium to be used. This section will build upon that knowledge by presenting the mathematical parameters associated with the system and deriving a link equation for one communication channel (carrier). Calculations made using these equations, known as link budgets, are used by communications engineers for feasibility studies and equipment estimates. This presentation of definitions is only intended to be introductory, as the references provide a detailed study. Also, since several authors vary their use of symbology, the nomenclature used by Feher (1983) shall be followed.

GAIN The key term in any communications link is the amount of gain transferred through the system. The gain is a ratio of the output power to the input power. From this, it can be seen that the gain is highly dependent on the input level, which would expect the power amplifiers to be operated near saturation (full-power). However, certain characteristics of these devices degrade the gain at full saturation; requiring trade-offs of power in the link budget.

An isotropic antenna is an ideal lossless antenna which radiates power equally well in all directions. This antenna exists only in theory, as a reference for comparison with actual antennas. An isotropic antenna has gain = 1; where the radiation in any direction is constant given by

$$\text{radiation intensity of isotropic antenna} = \frac{P}{4\pi}$$

with P = input power.

By focusing the antenna, the relative increase in power achieved is defined as the *gain of the antenna, G.* This is defined as

$$G = \frac{\text{maximum radiation intensity}}{\text{radiation intensity of isotropic antenna}}$$

assuming the same power at input. Substituting;

$$G = \frac{4\pi(\text{maximum radiation intensity})}{P}$$

By approximation, a common expression for the gain of a parabolic antenna is

$$G = \eta\left(\frac{\pi d}{\lambda}\right)^2 = \eta\frac{4\pi\upsilon^2 A_t}{c^2}$$

where

λ = wavelength

d = antenna diameter (meters)

η = antenna efficiency (55% to 70%)

$\upsilon = c/\lambda$ (carrier frequency in gigahertz)

$c = 2.99 \times 10^8$ m/s (the velocity of light)

$A_t = d^2\pi/4$ = aperture area of transmitting antenna

The average antenna efficiency can vary between 55% and 70% for standard (std) and high efficiency (he) antennas respectively. Approximate values for antenna gains can be determined by substituting the values for antenna efficiency, yielding

$$G_{std} = 60.7\,\upsilon^2 d^2 \qquad \text{or} \qquad G_{he} = 77.3\,\upsilon^2 d^2$$

The above equations show that the gain is defined by the antenna size and the frequency used. As a sample calculation of the down link, an earth station standard gain 15 foot (4.57 meter) antenna with an operating frequency of 3.72 GHz would be:

$$G = 10\log[60.7\,(3.72)^2(4.57)^2] = \underline{43.1\text{ dBi}}$$

A corresponding high efficiency antenna could increase the gain by 1 dBi. Table 4 lists gain values for C and Ku-bands antennas for both efficiency ratings. Based on standard industry applications, the antennas to be used for this proposal would be (L. Maynard personal communication, July 27, 1991, K. Stevens, personal communication, January 20, 1994):

3.7 meter for C-band @ 70% efficiency = 42.0 dBi

2.4 meter for Ku-band @ 70% efficiency = 48.1 dBi

Table 4.
Earth station antenna gain chart for C and Ku-bands.

		C-band (3.7-4.2 GHz)		Ku-band (11.7-12.2 GHz)	
Dish Efficiency		55%	70%	55%	70%
Diameter					
Feet	Meters	dBi	dBi	dBi	dBi
1	.30	19.4	20.5	29.0	3.1
2	.61	25.4	26.5	35.1	36.1
3	.91	29.0	30.0	38.6	39.6
4	1.22	31.5	32.5	40.7	42.1
5	1.52	33.4	34.4	43.0	44.1
6	1.82	35.0	36.0	44.6	45.6
7	2.13	36.3	37.4	45.9	47.0
8	2.43	37.5	38.5	47.1	48.1
9	2.74	38.5	39.5	48.1	49.2
10	3.05	39.4	40.5	49.0	50.1
11	3.35	40.2	41.3	49.9	50.9
12	3.65	41.0	42.0	50.6	51.7
13	3.96	41.7	42.7	51.3	52.4
15	4.57	43.1	44.1	52.6	53.7
16	4.87	43.5	44.5	53.1	54.1
20	6.09	45.4	46.5	55.1	56.1
25	7.62	47.4	48.4	57.0	58.0
33	10.05	49.8	50.8	59.4	60.4

The effective isotropic radiated power (EIRP) is the product of an earth station transmitter HPA power output or a satellite transponder TWTA power output and the antenna gain. For a transponder, the EIRP is graphically represented in the footprint of a given satellite's coverage of the Earth. Figure 2 in chapter V is the footprint of Spacenet II.

The EIRP is expressed as

$$\text{EIRP} = \text{PW}$$

$$\text{EIRP (in dB)} = \text{P (in dBW)} + \text{G (in dB)}$$

where

P = transmit power of the earth station HPA or transponder TWTA
G = antenna gain

The modulated output power of an HPA, P_u, is expressed in watts or in dBW (decibels above 1 W). For this application, the power requirement is considered low enough that this device is referred to as a power amplifier, with the term HPA reserved for large earth stations. The uplink power required for both C and Ku-band power amplifiers, based on similar system designs, is 15 W (Stevens, personal communication, February 23, 1994):

$$P_u = 10 \log 15\ \text{W} = \underline{11.8\ \text{dBW}}$$

Combining with the values for antenna gain, earth station EIRP values would be:

$$\text{C-band EIRP}_{es} = P_u + G = 11.8 + 42.0 = \underline{53.8\ \text{dBW}}$$

$$\text{Ku-band EIRP}_{es} = 11.8 + 48.1 = \underline{59.9\ \text{dBW}}$$

These are approximate values which would include earth station backoff and coupling losses. Backoff losses are reductions in output power to prevent the amplifiers from operating near saturation. Operating at or near saturation overdrives the amplifiers, adding excessive noise (covered in a following section) to the transmission and leads to early equipment failure. Typical backoff values for this type of system would be approximately 2 to 3 dBW.

The modulated power output of the traveling wave tube amplifier is expressed as P_d. Interpolating the footprint of Figure 2 shows the EIRP contour line of 36.0 dBW is approximately over the Daytona Beach area, and just below the Prescott area. Table 5 lists EIRP values of several satellites for Daytona Beach and Prescott in the C and Ku-bands. These values were obtained using the same interpolation method as above.

Table 5.
EIRP values for several satellites with orbit locations (Long, 1991).

Satellite	Daytona Beach (dBW)		Prescott (dBW)		°WEST
	C-band	Ku-band	C-band	Ku-band	
SPACENET II	36.0	40.1	36.1	43.6	69
SATCOM K2	—	46.5	—	46.8	81
TELSTAR 302	34.0	—	34.0	—	86
SPACENET III-R	37.7	44.2	37.2	48.5	87
GSTAR III	—	43.2	—	43.5	93
TELESTAR 401	37*	46*	37*	46*	97
GSTAR I	—	43.1	—	43.1	103
GSTAR II	—	43.1	—	43.1	105
SPACENET I	—	41.5	—	44.0	120
TELESTAR 303	34.4	—	36.0	—	123
GSTAR IV	—	42.8	—	43.4	125

* Proposed values of new satellite (Howes, 1994).

The American satellites that may be considered for this project also include any coupling and backoff losses that may be incurred within the satellite electronic system. Although this gives a more realistic prediction of the transmitted signal, it may only be a theoretical value with the actual value being slightly lower. Some satellite operators will do periodic signal strength assessments to determine the local values of EIRP and update the footprints. This is especially useful for older satellites which may be coming to the end of their service life.

In the downlink, several sources of gain contribute to signal propagation after passing the antenna. The LNA and amplifiers in the block downconverter are among the greatest contributors of gain to the received signal. High noise levels in the circuit is why several amplifiers are used where only one would be sufficient (K. Stevens, personal communication, January 20, 1994). Having several amplifiers operating well below saturation adequately boosts the weak satellite signal while adding minimal amounts of noise. For modern down conversion equipment (Baylin & Gale, 1991):

	LNA	BDC	LNB
C-band Gain (dB) =	37.5	27.5	65.0
Ku-band Gain (dB) =	30.0	25.0	55.0

LOSSES The transmitted signal PG is attenuated by the spreading factor, atmospheric losses, interference losses, and equipment losses. Understanding loss is as important as understanding gain since losses cause the principle degradation to signal propagation. Spreading factor, also called free space path loss, is the loss of radio wave power in space and is defined as the ratio of the power received to the power transmitted by isotropic antennas. It is expressed as

$$L_{fs} = \left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi \upsilon R}{c}\right)^2$$

where

υ = frequency of radio wave

λ = wavelength (= c/υ)

R = distance traveled in space or slant range

c = velocity of light ($c = 2.99 \text{ X } 10^8$ m/s)

The equation for earth station-to-satellite slant range (R) is:

$$R = [(h + r_e)^2 + r_e^2 - 2r_e(h + r_e) \cos \theta]^{1/2}$$

where θ is referred to as the central angle in a triangle formed by the satellite, the earth station, and the center of the Earth (Feher, 1983, Spilker, 1977). A more commonly used equation directly factors the latitude and longitude differences (Baylin & Gale, 1991, Cook et al, 1990, Hollis, chap. 1-2, 1982):

$$R = [r_e^2 + (r_e + h)^2 - 2r_e(r_e + h)\cos(LA_{es})\cos(L_{es}-L_{sat})]^{1/2}$$

where

LA_{es} = earth station latitude
L_{es} = earth station longitude
L_{sat} = satellite longitude

Values for the earth's radius and geosynchronous orbit vary between authors, none agreeing on universal numbers. This may be due in part to the 21 km bulge at the equator. In keeping with conformity, Feher's (1983) value of r_e = 6,378 km shall be used for an average over the United States, and the altitude of the geostationary orbit (h) = 35,930 km. Consequently, $r_e + h$ = 42,230 km. Locations for the two earth stations are (Rand McNally, 1972):

	LATITUDE	LONGITUDE
Daytona Beach, FL	29.2° N	81.1° W
Prescott, AZ	34.5° N	112.4° W

As previously noted, satellite choice will have an influence on the link budget. This is not strictly from the performance parameters of the particular satellite, but also of the satellite location. An ideal location for the satellite would be mid-way between the two earth station locations, a site at approximately 97° west longitude. Telestar 401 and SBS 2 are both at this location. However, since this is a realistic scenario utilizing a common carrier, the closest satellite operated by GTE that would be available to us is GStar III (93° west longitude). A prudent assumption would be to analyze a worst case scenario where the only available satellite is not located between the two earth stations, but at some location beyond the longitude of either site. A choice selection for this is the GTE satellite Spacenet II at 69° west longitude. Substituting the appropriate values for Daytona Beach into the equation from Baylin & Gale (1991) gives:

$$R_{DB} = [6{,}378^2 + (42{,}230)^2 - 2(6{,}378)(42{,}230)\cos(29.2^\circ)\cos(81.1^\circ - 69.0^\circ)]^{1/2}$$

$$R_{DB} = 36{,}936 \text{ km}$$

Similarly, for the Prescott earth station

$$R_P = [6{,}378^2 + (42{,}230)^2 - 2(6{,}378)(42{,}230)\cos(34.5^\circ)\cos(112.4^\circ - 69.0^\circ)]^{1/2}$$

$$R_P = 38{,}749 \text{ km}$$

The choice of satellite location has a small but important impact on the link budget. These effects are from total distance traveled and the earth station antenna elevation angle. Spilker (1977) presents a nomograph of earth station antenna azimuth and elevation look angles to geostationary satellites. This graph shows that as the relative difference (in longitudinal degrees) between satellite ground site and earth station increases, the earth station antenna elevation decreases. The decreasing elevation angles translates to increased slant ranges, varying from 35,930 km at a 90° elevation angle, E, to 37,930 km at 45° to 42,005 km at 0° (Spilker, 1977). By comparison to the total distance, a marginal increase seams insignificant. However, in looking at the loss factors below, an increase in distance relates to greater spreading losses. Additionally, a decrease in elevation angle results in an increased transit through the earth's atmosphere. This relates to lower frequency (4 to 6 GHz) attenuation caused by particles in the atmosphere. Finally, as the dish elevation angle decreases below approximately 30°, the antenna noise begins an asymtopic rise (Hollis, chap. 2A-2, 1982). These lower dish elevation angles allow greater susceptibility to terrestrial microwave interference and ground reflection of cosmic radiation. Baylin & Gale (1991) provide an equation for calculating the elevation and azimuth (primarily for pointing direction) angles:

$$Y = \cos^{-1}[\cos(LA_{es}) \cos(L_{es}-L_{sat})]$$

$$\text{Azimuth Angle} = \cos^{-1}[\tan(LA_{es})/\tan Y]$$

$$\text{Elevation Angle} = \tan^{-1}[(\cos Y-0.15116)/\sin Y]$$

where

LA_{es} = earth station latitude
L_{es} = earth station longitude
L_{sat} = satellite longitude

Substituting the variables for Daytona Beach

$$Y = \cos^{-1}[\cos(29.2) \cos(81.1-69.0)] = \underline{31.4}^{\circ}$$

$$\text{Azimuth Angle } (A_z) = \cos^{-1}[\tan(29.2)/\tan(31.4)] = \underline{23.7}^{\circ}$$

$$\text{Elevation Angle (E)} = \tan^{-1}[(\cos(31.4)-0.15116)/\sin(31.4)] = \underline{53.4}^{\circ}$$

By similar calculations, the values for Prescott are also determined.

Daytona Beach	$E = 53.4^{\circ}$	$A_z = 23.7^{\circ}$
Prescott	$E = 29.2^{\circ}$	$A_z = 59.1^{\circ}$

For an elevation angle of 90°, an approximation equation for L_{fs} is

$$L_{fs} \text{ (dB)} = 183.5 + 20 \log \upsilon$$

where υ is in gigahertz. Figure 7 shows the free space loss as a function of radio frequency. Also given in Figure 7 are the values for increases in L_{fs} (dB) with variations in the slant range elevation angle. Being on the order of less than 0.5%, these increases are minor in comparison with the values for L_{fs} (dB). Interpolating from the graph does give an adequate approximation for the value for L_{fs} (dB).

If more precise calculations are required, L_{fs} for Daytona Beach is:

$$L_{fs} = \left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi \upsilon R}{c}\right)^2$$

$$L_{fs\text{-}DB}\ (\text{dB}) = 20 \log (4\Pi R/c) + 20 \log \upsilon$$

$$L_{fs\text{-}DB}\ (\text{dB}) = 20 \log (4\Pi 36{,}936\text{x}10^3/2.99\text{x}10^8) + 20 \log \upsilon$$

$$L_{fs\text{-}DB}\ (\text{dB}) = 183.8 + 20 \log \upsilon$$

Similarly, for Prescott

$$L_{fs\text{-}P}\ (\text{dB}) = 20 \log (4\Pi 38{,}749\text{x}10^3/2.99\text{x}10^8) + 20 \log \upsilon$$

$$L_{fs\text{-}P}\ (\text{dB}) = 184.2 + 20 \log \upsilon$$

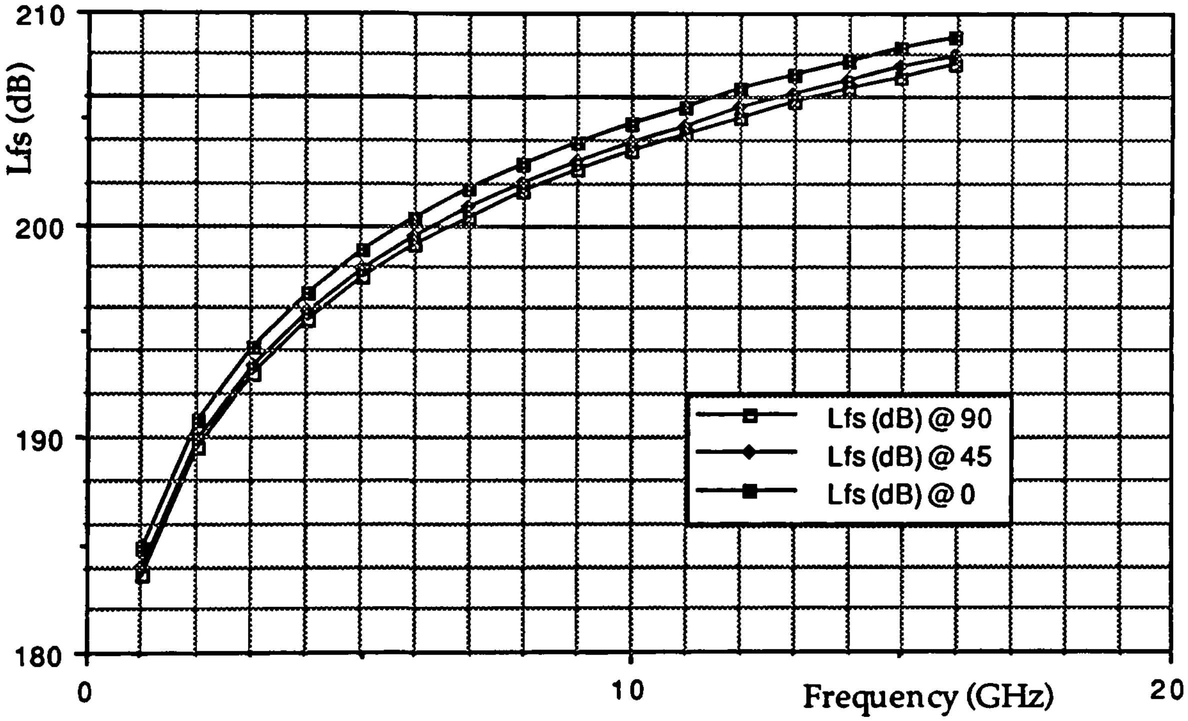


Figure 7. Free space path loss (Feher, 1983).

Since the exact uplink and downlink frequencies to be used are unknown (assigned values would be dictated by the satellite common carrier), their general values of 6/4 GHz for C-band and 14/12 GHz for Ku-band shall be used in calculating the free space path loss.

$$L_{fs\text{-}DB}\ (dB) = 183.8 + 20\ \mathrm{Log}\ 4 = 195.8\ dB$$

L_{fs}	UPLINK (dB)		DOWNLINK (dB)	
Daytona Beach, FL	199.4 C	206.7 Ku	195.8 C	205.4 Ku
Prescott, AZ	199.8 C	207.1 Ku	196.2 C	205.8 Ku

As a comparison of C to Ku, the uplink Ku-band has a 7.3 dB greater loss than the C-band and the downlink Ku transmission is attenuated by a 9.6 dB over the C-band. If a Ku-band antenna of equivalent gain to a larger C-band antenna were compared, the results would show these higher free space path losses require the higher operating power used on Ku-band transmissions.

Atmospheric losses are those not attributable to spreading losses, such as particles in the atmosphere, water vapor, oxygen, and rain. Although atmospheric losses are based on earth station elevation (Appendix D), mean values are (Feher, 1983):

	Uplink	Downlink
C-band	0.4 dB	0.2 dB
Ku-band	0.6 dB	0.4 dB

The second atmospheric loss, by rain, is much less predictable and can be critical for a Ku-band earth station in a high rain environment such as Daytona Beach. The higher the humidity or rainfall, the greater will be the reduction in power levels. A torrential downpour could cause a loss up to 10 dB and completely destroy the signal.

The amount of attenuation depends upon the rainfall intensity or rain rate and the path length in rain. Rainfall effects on signal propagation have been studied intensively since the 1960s. Rainfall data are available for most parts of the world, with charts defining quantities and average climate regions. This data describes the long term behavior of rain by cumulative probability distributions. For various rain climates, charts show the percentage of time that the rain rate exceeds a given value. Table 6 is an excerpt from Cook et al (1990) giving the rain rate distribution values vs percent of the year for the regions where Daytona Beach and Prescott are located.

The calculation of the rain attenuation is a two-step process. The first is to determine the point rate in mm/hr as a function of the cumulative probability of occurrence. This probability will be defined by the grade of service or availability of the link to be provided. The availability could also be interpreted as the reliability of the data link as it is based on the percentage of time that the reception is not disrupted during that type of heavy rainfall.

Table 6.
Point-rain-rate distribution values (mm/hr) versus percent of the year rain rate is exceeded (Cook et al, 1990).

% of Year	Availability %	Daytona	Prescott	Minutes/Year	Hours/Year
0.001	99.999	164.0	66.0	5.3	0.09
0.002	99.998	144.0	51.0	10.5	0.18
0.005	99.995	117.0	34.0	26.0	0.44
0.01	99.99	98.0	23.0	53.0	0.88
0.02	99.98	77.0	14.0	105.0	1.75
0.05	99.95	52.0	8.0	263.0	4.38
0.1	99.9	35.0	5.5	526.0	8.77
0.2	99.8	21.0	3.8	1,052.0	17.50
0.5	99.5	8.5	2.4	2,630.0	43.80
1.0	99	4.0	1.7	5,260.0	87.66
2.0	98	2.0	1.1	10,520.0	175.30

The second step determines the actual rain attenuation associated with the rain rate that was exceeded with such probability. Cook et al (1990) and Baylin & Gale (1991) show graphs of rain attenuation versus rain rate dependent on antenna elevation and frequency. Interpolating from these graphs gives the rain rate attenuation for Daytona Beach and Presc0tt in Table 7.

Table 7.
Rain attenuation (db) versus availability dependent on elevation angle E, where Prescott E = 29.2° and Daytona Beach E = 53.4°.

	14 GHz		12 GHz		6 GHz		4 GHz	
Availability	30°	50°	30°	50°	30°	50°	30°	50°
99.98	5.0	——	3.5	——	1.7	1.0	1.5	1.0
99.95	3.0	18.0	1.8	12.0	1.4	0.8	1.3	0.8
99.9	1.8	11.8	1.3	7.5	1.2	0.7	1.2	0.7
99.8	1.0	6.2	1.0	4.0	0.9	0.5	0.9	0.5
99.5	0.6	2.0	0.5	1.2	0.5	0.3	0.5	0.3
99	0.5	0.8	0.4	0.6	0.3	0.2	0.3	0.2
98	0.2	0.4	0.2	0.4	0.2	0.1	0.2	0.1

Tables 6 and 7 show how the availability of a satellite data link can be heavily dependent on the rain rate. Based on the data in Table 7, it can be seen that rain attenuation for Daytona Beach, even with a larger E, is much greater than for Prescott in the Ku-band. However, the C-band rain attenuation values are all larger for Prescott, where the signal has to travel through more of Earth's atmosphere. This also illustrates the low attenuation effects of rain on C-band transmission. For the example of this thesis, it will be assumed that the system will require a 99.8% availability when demanded, and use the attenuation factors at that level for the link budget.

The consideration of interference in a satellite data link is important, not only for being interfered with, but also in generating interference into existing systems. FCC regulations require proposed transmit systems to submit a coordination filing which includes an interference analysis (Appendix F). This analysis must show the impact of the proposed system on existing operational systems and must meet the allowable interference requirements. The interference analysis is based on the antenna characteristics, the spectral characteristics for the desired and interfering carriers, and must meet the FCC interference requirements for adjacent satellites spaced at the allowable 2^o minimum.

Although interference losses are important, their complexity and dependence on antenna design data and satellite common carrier data for calculation puts this analysis beyond the scope of the thesis. Also, Cook et al (1990) contributes interference losses in well planned and designed earth stations to be minimal in the overall link budget. This analysis is done by the common carrier prior to earth station installation.

Equipment losses are dependent on design and manufacturing quality. Losses in most equipment is negligible by comparison to the rest of the system losses in the link budget. Two key loss producers worth mentioning are signal attenuation through long runs of cable and losses caused by surface deformations in the surface of the antenna reflector dish. Losses in RG-59 cable average 10 db over 150 feet (K. Stevens, personal communication, February 23, 1994). This is a substantial loss which could degrade signal performance by the time it reaches the controller. However, since this loss could be countered with an in-line amplifier it will not be considered in the link budget.

Losses as a function of surface deformities are based on antenna design and operating wavelength (λ), where frequency = $\upsilon = c/\lambda$. For 14 GHz, $\lambda = 2.1$ cm, at 12 GHz, $\lambda = 2.5$ cm, at 6 GHz, $\lambda = 5.0$ cm, and at 4 GHz, $\lambda = 7.5$ cm. Antenna manufacturers rate surface irregularities using a value of the root mean square (RMS) deviation from a perfect shape. Antenna ratings in RMS are antenna specific and available from the manufacturer. Baylin & Gale (1991) illustrate signal loss in dB versus the depth of surface ripples as a function of the regularity at which they occur. For a minor deflection to occur in the C-band, ripples of at least 0.2 cm would have to be in the surface of the reflector. Ku-band is more sensitive to this with ripples of only 0.05 cm needed to cause microwave reflection. Therefore, this loss will be ignored for the C-band link budget, but an assumed high quality reflector will be assumed for Ku-band with a resulting surface deformity loss of 0.2 dB.

NOISE An understanding of electronic noise is critical in a study of satellite communications because the very low power signals transmitted are only slightly more powerful than the noise generated within the electronic equipment and from the surrounding environment (Baylin & Gale, 1991). By definition, noise is the random, unpredictable, and undesirable signals, or changes in signals, that mask, or interfere with, desired information content (Douglas-Young, 1981). Noise is broken-down into three types; galactic, atmospheric and receiver noise. Galactic and atmospheric noise have been previously discussed in the interference section. Receiver noise is caused by the random movements of electrons within the electronic materials in the equipment components. A second type of noise within the receiver is transistor noise. This noise occurs from variations in current flow between the emitter and collector. This noise make certain designs of equipment more desirable than others. The ultimate sensitivity of a receiver is set by the noise inherent to its input stage. In terrestrial microwave systems the power of noise generated in the equipment is specified in terms of the noise figure (NF) in dB. It is often required that earth station-satellite link budgets calculate and experimentally verify the accuracy of the noise budget within a fraction of a decibel. This is more necessary in a larger system having numerous earth stations since a 1-dB error in the link calculations could affect the system performance requiring unnecessary and expensive equipment. The low-noise sources of satellite communications often make the *equivalent noise temperature, Te,* a more practical parameter for link budgets since it is a measure of all the noise, both thermal and non-thermal.

Noise figure is defined as:

$$\text{Noise figure (NF)} = \frac{N_{\text{practical}}}{N_{\text{ideal}}} = \frac{N_{\text{practical}}}{AkT_oW'}$$

where

W' = double-sided noise bandwidth of the system being evaluated

A = gain of the system being evaluated

k = 1.380 X 10-23 Ws/K (Boltzmann constant)

= 10 log k = -198.6 dBm/K/Hz

= -228.6 dBW/K/Hz

T_o = temperature of the environment in which the measurement is performed (at room temperature $T_o = 290\ ^oK$)

Boltzmann's constant k relates temperature to the thermal energy of motion of matter. The random acceleration of electrons in any type of matter produces electrical noise power proportional to temperature (in Kelvins). Noise produced in this manner is sometimes referred to as thermal noise or white noise. The relation of a noise of power N and its equivalent noise temperature is expressed as

$$T_e = \frac{N}{kW'}$$

A practical expression for the noise power at the output of a receiver with a noise bandwidth W', gain A, and equivalent noise temperature T_e is

$$N_{\text{practical}} = AkT_oW' + AkT_eW' = Ak(T_o + T_e)W'$$

where

AkT_oW' = output noise power assuming an ideal noiseless receiver

and

AkT_eW' = output noise power due to the noise generated in the receiver at T_e

Substituting into the equation for noise figure;

$$NF = 1 + \frac{T_e}{T_o}$$

or

$$NF(dB) = 10\log_{10}\left[1 + \frac{T(K)}{290}\right]$$

An approximation for low-noise temperatures (below 100 ^oK) is

$$T_e(dB) \approx 70NF$$

also

$$T(K) = 290[\log^{-1}(NF/10)-1]$$

$$F_{12} = F_1+[(F_2-1)/G_1]$$

where

$T(K)$ = Noise temperature in ^oK, [$T(K) = {}^oC + 273$]

NF = Noise figure in dB

F_{12} = Overall noise figure

F_1 = Noise figure of first device (LNA)

F_2 = Noise figure of second device (BDC)

G_1 = Gain of first device (LNA Gain)

Although the noise temperature T_e is a hypothetical temperature, the performance of receive equipment is rated using this expression. By definition, all molecular motion stops at 0 ^oK. Hence, as T_e goes to zero, the noise figure goes to zero, and the higher performance receive equipment are those with the lowest T_e ratings.

The major sources of noise are associated with the receiving section of the communications link. The equipment onboard the satellite determines the uplink noise, and the receive section of the earth station determines the downlink noise. For the earth station, the antenna, LNA, BDC, waveguide, indoor unit, and cables all create noise and losses. Of all components, the antenna and LNA are the greatest contributors of noise to the total system.

Noise generated by the antenna primarily comes from the surrounding environment. This is based on the antenna size relative to the incident signal wavelength and its affect on the antenna beamwidth. A portion of this noise enters through the beam sidelobes, and a smaller amount of predominantly galactic noise enters through the main lobe. This noise is both man-made and natural sources, being any radiation in the microwave band (Cook, 1982).

Since the warm ground emits radiation, noise temperature increases as the antenna is pointed at lower elevation angles (below 30^o). Larger antennas detect less noise because they have smaller side lobes. Antennas which have deeper dish geometry's also detect less noise for the same reason. Noise is also created by off-axis signals and diffracted noise from the antenna's edge.

Based on the above description, antenna noise is based on the operating frequency, antenna size, antenna shape, and elevation angle. Antenna manufactures estimate and experimentally verify the noise values for their specific antennas. For this thesis application, exact values for earth station antenna noise were unavailable. Baylin & Gale (1991) provide the best estimates for similar antennas. Based on related literature, these values will probably be conservative, with actual values having lower noise levels (Cook et al, 1990). Interpolating from graphs (Baylin & Gale, 1991):

Values for antenna equivalent noise temperature, T_e

Daytona Beach, E = 53.4°

C-band antenna, diameter = 3.7 m, beamwidth = 0.45°, T_e = 28°K
Ku-band antenna, diameter = 2.4 m, beamwidth = 0.72°, T_e = 26°K

Prescott, E= =29.2°

C-band antenna, diameter = 3.7 m, beamwidth = 0.45°, T_e = 33°K
Ku-band antenna, diameter = 2.4 m, beamwidth = 0.72°, T_e= 28°K

Similarly, the LNA and BDC or LNB will also greatly contribute to the noise of the receive system. Values for this equipment are dependent on equipment design and experimentally verified. Average values for the LNA/LNB will be used based on current models (Satellite Retailer, 1993):

C-band LNA/LNB; T_e = 35°K
Ku-band LNA/LNB; T_e = 120°K

In addition to the antenna and LNA/LNB, other components in the system produce noise which add to the communication link. However, when taken as a sum of total system noise, T_s, the components prior to the LNA/LNB add the greatest contributions to T_s. The components following the LNA/LNB have negligible impact on T_s. Therefore;

Daytona Beach	C-band	$T_s = 35 + 28 = 63$°K
	Ku-band	$T_s = 120 + 26 = 146$°K
Prescott	C-band	$T_s = 35 + 33 = 68$°K
	Ku-band	$T_s = 120 + 28 = 148$°K

The importance of this parameter will be shown in the G/T section.

NOISE DENSITY, N_o, is the noise power that is present in a normalized 1 Hz of bandwidth. It is

$$N_o = \frac{N_{total}}{W'} = kT_e$$

where

N_{total} = total noise power measured in a system with a noise bandwidth W'

The following section will show the importance of this parameter in the total link budget.

CARRIER-TO-NOISE, C/N_o The basic integrity of a transmission system is based on the carrier-to-noise ratio. This ratio represents the equipment's ability to transmit or receive a signal while introducing the least amount of noise. Larger carrier-to-noise ratios represent higher carrier power at lower noise levels, a desirable effect. With the average wideband carrier power, C, and the noise density N_o, the ratio C/N_0 represents the average wideband carrier power-to-noise ratio. Substituting for N_o;

$$\frac{C}{N_o} = \frac{C}{kT_e}$$

FIGURE-OF-MERIT, G/T_e Satellite and earth station reception efficiency is sometimes referred to at the *figure of merit*, or the gain-to-equivalent noise temperature ratio:

$$\text{Figure of merit} = \frac{G}{T_e} \qquad (\text{dB/K or dBK}^{-1})$$

It will be shown in the link analysis that the one method an operator can use to control the signal quality is through the system G/T_e. The G/T_e is a function of the antenna gain, the LNA/LNB (noise temperature), and losses associated with the waveguide or cable run between the antenna and the LNA/LNB, and the noise temperature associated with antenna elevation angle. This ratio can be maximized by increasing the antenna gain through a larger sized antenna, increasing quality control of the LNA-waveguide interface, and decreasing the equivalent noise temperature of the LNA/LNB. Low noise C-band LNA/LNBs are rated in the 25° to 50° K range, while Ku-band LNA/LNBs are much higher, 80° to 120° K (Satellite Retailer, 1993). Hollis (chap. 2A-2, 1982) shows that the G/T remains constant throughout the receive section of the data link, from antenna to controller. However, the equipment parameters which have the greatest influence on G/T are the total system noise, T_S, and antenna gain. By comparison to other components in the system, the noise temperature of the receiver/controller is of little consequence since its value is masked by the LNA/LNB gain (Hollis, chap. 2A-2, 1982).

For C-band antenna gain = 42.0 dBi, and T_S for Daytona Beach = 63° K:

$$G/T = 42.0 - 10 \log 63 = 24.0 \text{ dB/K}$$

Similarly, G/T downlink values for both locations

Downlink G/T	C-Band	Ku-Band
Daytona Beach	24.0 dB/K	26.5 dB/K
Prescott	23.7 dB/K	26.4 dB/K

The above values compare closely to those listed for similar conditions in Cook et al (1990).

With the G/T being a parameter of the receiving equipment, the associated value for an uplink G/T is dependent on the satellite. As with values for the EIRP, satellite manufactures, operators, and common carriers publish footprints of satellite G/T values. For the Spacenet II satellite, G/T uplink values are (Cook et al, 1990, Long, 1991):

Uplink G/T	C-Band	Ku-Band
Daytona Beach	-2.1 dB/K	-0.9 dB/K
Prescott	-2.5 dB/K	0.9 dB/K

An addition to T_S is made by the antenna which is based on rain attenuation. In clear weather the antenna sees the cold background of space, but during rain it receives thermal radiation from the raindrops. Cook et al (1990) shows the contribution of rain to noise temperature on the normal clear sky in terms of G/T. The G/T degradation caused by rain attenuation also must be incorporated in the link budget with the rain attenuation losses. This is to insure a sufficient margin to compensate for the combined rain effects of signal attenuation and noise increase. Interpolating from a graph of G/T degradation versus rain attenuation at 99.8% availability (Cook et al, 1990):

G/T Degradation (dB)	Uplink	Downlink
Daytona Beach	1.8 C 3.8 Ku	1.8 C 3.4 Ku
Prescott	2.2 C 1.6 Ku	2.2 C 1.6 Ku

The allocations of rain fade margins in the uplink and downlink can be done independently, corresponding to specific availability requirements of the total link. Due to the localized nature of rain fades, the uplink fade and downlink fade can be considered as two statistically independent processes.

BIT ENERGY-TO-NOISE, E_b/N_o For digital systems, the *energy of bit-to-noise density* ratio is the measure for link performance, a digital equivalent to the C/N_o. This ratio allows a comparison between the various types of digital signals. Since our system will be transmitting a multiplexed wave of digitized voice and computer data, this will be a necessary parameter. The bit energy, E_b, is

$$E_b = CT_b$$

where C is the carrier power, and T_b is the bit duration. It can also be represented as

$$E_b = P_{osat}T_b$$

where P_{osat} is the saturated output power. Higher bit energy, E_b, yields stronger signals.

LINK EQUATIONS The link equations presented here are for a single RF carrier, or SCPC. This can be used since our system calls for a single point-to-point carrier by FDMA. Link calculations for multiple RF channels through a transponder are presented in Spilker (1977). For the uplink; the flux density, Ω_u, at the input of the satellite receive antenna is

$$\Omega_u = \frac{P_T G_T}{4\pi R_u^2} L_u \qquad (W/m^2)$$

where u denotes uplink, and d denotes downlink. The modulated carrier power at the satellite (receive uplink power) is

$$P_u = \Omega_u A_{su} = \frac{G_{su}\lambda_u^2}{4\pi} \qquad \text{(watts)}$$

where

A_{su} = effective area of the satellite antenna

G_{su} = satellite antenna gain

λ_s = wavelength of uplink carrier

The above values are given by the satellite chosen. Rain-induced noise, earth background noise, and thermal noise in the receiver make up most of the channel and system noise for the uplink. The carrier power-to-noise density ratio for the uplink is

$$\frac{C_u}{N_{ou}} = \frac{P_u}{N_{ou}} = \frac{P_u}{kT_e}$$

where

k = Atmospheric attenuation factor = -228.6 dBW/K/Hz

T_e = effective input noise temperature (K)

The above equations yields the *basic uplink equation:*

$$\left(\frac{C_u}{N_{ou}}\right) = \left\{\begin{matrix}\text{earth station}\\ \text{EIRP}\end{matrix}\right\} - \left\{\begin{matrix}\text{"free space}\\ \text{uplink loss"}\end{matrix}\right\} + \left\{\begin{matrix}\text{satellite}\\ \text{G/T}\end{matrix}\right\} + \left\{\begin{matrix}\text{additional}\\ \text{uplink losses}\end{matrix}\right\} - \left\{\begin{matrix}\text{Boltzmann}\\ \text{constant}\end{matrix}\right\}$$

$$\left(\frac{C_u}{N_{ou}}\right)_{dB} = 10\log P_T G_T - 20\log\frac{4\pi R_u}{\lambda_u} + 10\log\frac{G_{su}}{T_s} + 10\log L_u - 10\log k$$

Substituting C/T_e for kC/N_o:

$$\left(\frac{C_u}{T_{eu}}\right) = 10\log(P_T G_T) - 20\log\frac{4\pi R_u}{\lambda_u} + 10\log\frac{G_{su}}{T_s} + 10\log L_u$$

Using the same procedure yields the *basic downlink equations:*

$$\left(\frac{C_d}{N_{od}}\right) = \left\{\begin{matrix}\text{satellite}\\ \text{EIRP}\end{matrix}\right\} - \left\{\begin{matrix}\text{"free space}\\ \text{downlink}\\ \text{loss"}\end{matrix}\right\} + \left\{\begin{matrix}\text{earth station}\\ \text{G/T}\end{matrix}\right\} + \left\{\begin{matrix}\text{additional}\\ \text{downlink}\\ \text{losses}\end{matrix}\right\} - \left\{\begin{matrix}\text{Boltzmann}\\ \text{constant}\end{matrix}\right\}$$

$$\left(\frac{C_d}{N_{od}}\right)_{dB} = 10 \log P_S G_{Sd} - 20 \log \frac{4\pi R_d}{\lambda_d} + 10 \log \frac{G_d}{T_d} + 10 \log L_d - 10 \log k$$

and

$$\left(\frac{C_d}{T_{od}}\right) = 10 \log (P_s G_{sd}) - 20 \log \frac{4\pi R_d}{\lambda_d} + 10 \log \frac{G_d}{T_d} + 10 \log L_d$$

The attenuation caused by rain would be added to the additional link losses, but the G/T degradation due to rainfall would be factored into the G/T.

In classical frequency-translating satellite system, the overall (total) carrier power-to-noise density ratio $(C/N_O)T$ at the receive earth station is

$$\left(\frac{C}{N_o}\right)_T = \frac{1}{(N_{ou}/C_u) + (N_{od}/C_d)}$$

This equation indicates that the uplink and downlink noise will add up to result in an overall noise level. For digital communications systems the bit energy-to-noise density ratio is:

$$E_{bu} = C_u T_b$$

$$E_{bd} = C_d T_b$$

Where T_b is the inverse of the data rate.

Substituting into the equation for carrier-to-noise gives:

$$\left(\frac{E_b}{N_o}\right)_u = \left(\frac{C_u}{N_o}\right)_u T_b$$

$$\left(\frac{E_b}{N_o}\right)_d = \left(\frac{C_d}{N_o}\right)_d T_b$$

Substituting into the equation for total carrier power-to-noise ratio:

$$\left(\frac{E_b}{N_o}\right)_T = \frac{1}{(N_{ou}/E_{bu}) + (N_{od}/E_{bd})}$$

Note that the above quantities are ratios and not dB-s. The digital system probability of error will be a function of the total energy per bit-to-noise ratio $(E_b/N_o)_T$.

VII. SATELLITE LINK BUDGET ANALYSIS

The basic link equations were presented in the last section, with individual components developed throughout Chapter V. This chapter will present an example budget calculation for an uplink from Daytona Beach and a downlink to Prescott. Following the example will be a table listing budget values for clear sky and rain fade conditions. The table will also list C and Ku-band values together for comparison.

C-band uplink from Daytona Beach:

$$\left(\frac{C_u}{N_{ou}}\right) = \left\{\begin{matrix}\text{earth station}\\ \text{EIRP}\end{matrix}\right\} - \left\{\begin{matrix}\text{"free space}\\ \text{uplink loss"}\end{matrix}\right\} + \left\{\begin{matrix}\text{satellite}\\ \text{G/T}\end{matrix}\right\} + \left\{\begin{matrix}\text{additional}\\ \text{uplink losses}\end{matrix}\right\} - \left\{\begin{matrix}\text{Boltzmann}\\ \text{constant}\end{matrix}\right\}$$

$$= 53.8 \text{ dBW} - 199.4 \text{ dB} + (-2.1 \text{ dB/K}) + (-0.4 \text{ dB}) - (-228.6 \text{ dBW/K/Hz})$$

$$= 80.5 \text{ dBW/Hz}$$

C-band downlink to Prescott:

$$\left(\frac{C_d}{N_{od}}\right) = \begin{Bmatrix}\text{satellite}\\ \text{EIRP}\end{Bmatrix} - \begin{Bmatrix}\text{"free space}\\ \text{downlink}\\ \text{loss"}\end{Bmatrix} + \begin{Bmatrix}\text{earth station}\\ \text{G/T}\end{Bmatrix} + \begin{Bmatrix}\text{additional}\\ \text{downlink}\\ \text{losses}\end{Bmatrix} - \begin{Bmatrix}\text{Boltzmann}\\ \text{constant}\end{Bmatrix}$$

$$= 36.1\text{ dBW} - 196.2\text{ dB} + 23.7\text{ dB/K} + (-0.2\text{ dB}) - (-228.6\text{ dBW/K/Hz})$$

$$= 92.0\text{ dBW/Hz}$$

Substituting for total link carrier power-to-noise ratio:

$$\left(\frac{C}{N_o}\right)_T = \frac{1}{(N_{ou}/C_u) + (N_{od}/C_d)}$$

$$= \frac{1}{(1/80.5_u) + (1/92.0_d)}$$

$$= 42.9\text{ dBW/Hz}$$

Since our link is based on a carrier wave modulated by a digital input, the energy-to-bit noise must be calculated. With a total data rate of 753.6 kbps, approximated to 754 kbps:

$$\left(\frac{E_b}{N_o}\right)_u = \left(\frac{C_u}{N_o}\right)_u T_b$$

$$= 80.5\text{ dBW/Hz} + 10\log\left(\frac{1}{754 \times 10^3\text{bps}}\right)$$

$$= 21.7\text{ dB}$$

$$\left(\frac{E_b}{N_o}\right)_d = \left(\frac{C_d}{N_o}\right)_d T_b$$

$$= 92.0\text{ dBW/Hz} + 10\log\left(\frac{1}{754 \times 10^3\text{bps}}\right)$$

$$= 33.2\text{ dB}$$

Substituting into the equation for total carrier power-to-noise ratio:

$$\left(\frac{E_b}{N_o}\right)_T = \frac{1}{(N_{ou}/E_{bu}) + (N_{od}/E_{bd})}$$

$$= \frac{1}{(1/21.7\,\text{dB}) + (1/33.2\,\text{dB})}$$

$$= 13.1\,\text{dB}$$

The bit energy-to-noise density ratio, E_b/N_o, of 13.1 dB represents a quantifying measure of the digital channel quality. However, this must be put in a comparable form. The appendix in Schimm (1982) lists a conversion table of E_b/N_o to bit error rate (BER). The BER is a more commonly used parameter for measuring digital channel quality. A E_b/N_o value of 13.1 dB corresponds to a BER of at least 5.3×10^{-11}. Thus this system would expect to have an average of one error in every 5.3×10^{11} bits. Based on a realistic comparison, a GTE Spacenet digital data link operating at a data rate of 768 kbps requires (by GTE Spacenet Quality Control) a BER of no less than 10^{-7}. Therefore, with a BER of 10^{-11}, this system would more than sufficiently operate for the proposed Daytona Beach - Prescott satellite data link.

Tables 8 and 9 present the respective C and Ku-band Daytona Beach - Prescott link budgets. These budgets show Daytona Beach to Prescott and Prescott to Daytona links. They also show the effects of rain degradation on the link budget. The data of Table 8 shows that the total link budget in the C-band for both clear sky and rain fade conditions is acceptable, having BERs of less than 10^{-7}. However, the results in Table 9 show that rain fade conditions for the Daytona Beach to Prescott Ku-band link are unacceptable, having a BER of 1.0×10^{-4}.

Table 8.

C - BAND LINK BUDGET.

Satellite	Spacenet II	
Beam Type	CONUS	
Type of Service	SCPC - FDMA	
Transmit/Receive Carrier	6/4	GHz
Transmit/Receive Connectivity	3.7/3.7	meter (antenna)
Data Bit Rate	754	kbps
Occupied Bandwidth per Carrier	400	kHz
Transponder Bandwidth	36	MHz

Parameter	Values				
UPLINK	Daytona Beach		Prescott		
	Clear Sky	Uplink Fade	Clear Sky	Uplink Fade	Units
Earth Station EIRP	53.8	53.8	53.8	53.8	dBW
Path Loss	199.4	199.4	199.8	199.8	dB
Rain Attenuation	0	-0.5	0	-0.9	dB
Satellite G/T	-2.1	-2.1	-2.5	-2.5	dB/K
G/T Rain Attenuation	0	-1.8	0	-2.2	dB
Additional Losses	-0.4	-0.4	-0.4	-0.4	dB
Uplink Availability	N/A	99.8%	N/A	99.8%	
C/No	80.5	78.2	79.7	76.6	dBW/Hz
Eb/No at Transponder In	21.7	19.4	20.9	17.8	dB
DOWNLINK	Prescott		Daytona Beach		
	Clear Sky	Uplink Fade	Clear Sky	Uplink Fade	Units
Satellite EIRP	36.1	36.1	36.0	36.0	dBW
Path Loss	196.2	196.2	195.8	195.8	dB
Rain Attenuation	0	-0.9	0	-0.5	dB
Earth Station G/T	23.7	23.7	24.0	24.0	dB/K
G/T Rain Degradation	0	-2.2	0	-1.8	dB
Additional Losses	-0.2	-0.2	-0.2	-0.2	dB
Downlink Availability	N/A	99.8%	N/A	99.8%	
C/No	92.0	88.9	92.6	90.3	dBW/Hz
Eb/No at Receiver In	33.2	11.8	12.9	11.4	dB
TOTAL SYSTEM					
Eb/No	13.1	11.8	12.9	11.4	dB
BER	$6.8x10^{-11}$	$1.6x10^{-8}$	$1.8x10^{-10}$	$6.5x10^{-8}$	

Table 9.
Ku - BAND LINK BUDGET.

Satellite	Spacenet II	
Beam Type	CONUS	
Type of Service	SCPC - FDMA	
Transmit/Receive Carrier	14/12	GHz
Transmit/Receive Connectivity	2.4/2.4	meter (antenna)
Data Bit Rate	754	kbps
Occupied Bandwidth per Carrier	400	kHz
Transponder Bandwidth	72	MHz

Parameter	Values				
UPLINK	Daytona Beach		Prescott		
	Clear Sky	Uplink Fade	Clear Sky	Uplink Fade	Units
Earth Station EIRP	59.9	59.9	59.9	59.9	dBW
Antenna Surface Deformity	-0.2	-0.2	-0.2	-0.2	dB
Path Loss	206.7	206.7	207.1	207.1	dB
Rain Attenuation	0	-6.2	0	-1.0	dB
Satellite G/T	-0.9	-0.9	0.9	0.9	dB/K
G/T Rain Attenuation	0	-3.8	0	-1.6	dB
Additional Losses	-0.6	-0.6	-0.6	-0.6	dB
Uplink Availability	N/A	99.8%	N/A	99.8%	
C/No	80.1	70.1	81.5	78.9	dBW/Hz
Eb/No at Transponder In	21.3	11.3	22.7	20.1	dB
DOWNLINK	Prescott		Daytona Beach		
	Clear Sky	Uplink Fade	Clear Sky	Uplink Fade	Units
Satellite EIRP	43.6	43.6	40.1	40.1	dBW
Antenna Surface Deformity	-0.2	-0.2	-0.2	-0.2	dB
Path Loss	205.8	205.8	205.4	205.4	dB
Rain Attenuation	0	-1.0	0	-4.0	dB
Earth Station G/T	26.4	26.4	26.5	26.5	dB/K
G/T Rain Degradation	0	-1.6	0	-3.4	dB
Additional Losses	-0.4	-0.4	-0.4	-0.4	dB
Downlink Availability	N/A	99.8%	N/A	99.8%	
C/No	92.2	89.6	89.2	81.8	dBW/Hz
Eb/No at Receiver In	33.4	30.8	30.4	23.0	dB
TOTAL SYSTEM					
Eb/No	13.0	8.3	13.0	10.7	dB
BER	$8.7\text{x}10^{-11}$	$1.0\text{x}10^{-4}$	$8.7\text{x}10^{-11}$	$4.8\text{x}10^{-7}$	

Several methods could be employed to increase the Daytona Beach-to-Prescott link C/N_0 ratio to sufficient levels. Increasing earth station power amplification levels may be more detrimental than beneficial, possibly resulting in increased saturation levels and overdriving of the satellite receiver. A better alternative might be a combination of increasing the earth station antenna diameter to 3.7 m (resulting EIRP = 63.5 dB), decreasing the LNA/LNB effective temperature to 80° (resulting G/T = 31.4 dB/K) and reduce the availability requirements to 99.5% (resulting rain attenuation of -2.0 dB for uplink and -0.5 dB for the downlink). This would result in:

Cu/No = 77.9 dBW/Hz, Eb/No = 19.1 dB
Cd/No = 90.1 dBW/Hz, Eb/No = 31.3 dB
Total Eb/No = 11.9 dB
BER = 1.1×10^{-8}

Based on the parameters with an availability of 99.8%, the Ku-band would not be sufficient for this data link. This would make the C-band link the better choice for this proposal. Taking the above measures would ensure an adequate satellite link in the Ku-band for the data rate required in this proposal. This would make either band acceptable for this application. Although realistic parameters were employed where possible, a link budget performed by a common carrier would provide the best predictions for equipment requirements and band justifications.

VIII. APPLICATION

Chapters IV, V, VI, and VII developed satellite communication concepts and presented the requirements for a satellite data link between the ERAU campuses. To complete this assessment for a satellite data link of a proposed flight simulation system, a satellite link model is presented for a practical application of this proposal. An overview of common carrier services and costs is given in Appendix G. Based on the information supplied by GTE Spacenet, it is difficult to choose which service would be best suited for this application. Assuming the system will not be operational 24 hours per day, the part-time Switched Channel Services option would be selected. Two services are offered under this option, Metered Service and User Managed Service. The least expensive alternative would be the Metered Service with a public pool for satellite capacity. This would allow activation from either campus, guaranteed within 15 minutes of the request by GTE Spacenet. However, this alternative is only recommended for use up to 20 hours per month and would require an operator and security measures at both locations. Another drawback is GTE Spacenet only allows C-band operation on its Switched Channel Services private mode of satellite capacity. This would be a slightly more expensive option and would implicate the university to a fixed total satellite capacity allocated to the network link and a fixed monthly fee. However, the fixed monthly fee may appeal to the university with the services being more easily budgeted. Another drawback is the university would be charged whether the link was used or not. Hence, the choice of service type and operational needs may dictate the equipment requirements.

If the link would be in operation over 20 hours per month, GTE Spacenet's User Managed Service is recommended. This only allows activation control from one location, resulting in tighter control and better security. Also, using this option through C-band operation may be the most expensive alternative. Other common carriers are available, and should be contacted for the latest services, pricing, and availability information.

The block diagram of Figure 8 shows the specific equipment which could be used in this data link. This block diagram was developed from the equipment list for a GTE Spacenet earth station installation as developed in Appendix H. As with the common carriers, this list is one of several which could be used. If a Daytona Beach to Prescott link were implemented, the design in this block diagram would provide an adequate link.

The equipment shown in Figure 8 is used throughout the GTE Spacenet system for earth stations using Metered Service. If User Managed Service were chosen for the ERAU link, the NAT in Figure 8 would be replaced by the NCS 1000 controller for the control site, ERAU Daytona Beach. The remote node, ERAU Prescott, would have the NAT replaced by a direct cable from the Blackbox interface adapter to the Hayes Smartmodem^{TM}. The equipment illustrated in Figure 8 is a most complete list of the requirements for this proposal. This list could be used whether C or Ku-band were used. The primary difference of equipment would be the antenna, feed, and outdoor unit components. The indoor equipment would remain the same.

The equipment from the Canoga Perkins multiplexer to the satellite antenna would be supplied by the common carrier. The Hayes Smartmodem^{TM} and the IBM PS/2 are common pieces of hardware, and could be supplied by the university. The software used on the IBM, however, is proprietary, and would have to be obtained from the common carrier. Adequate storage and maintenance space would have to be allocated for the indoor equipment. The current location of the multiplexer in the AWS building would be sufficient. University engineers would have to install conduit from this location to the antenna base. Also, engineering would have to install 115 VAC electricity and a power outlet box at the antenna base for the outdoor electronics.

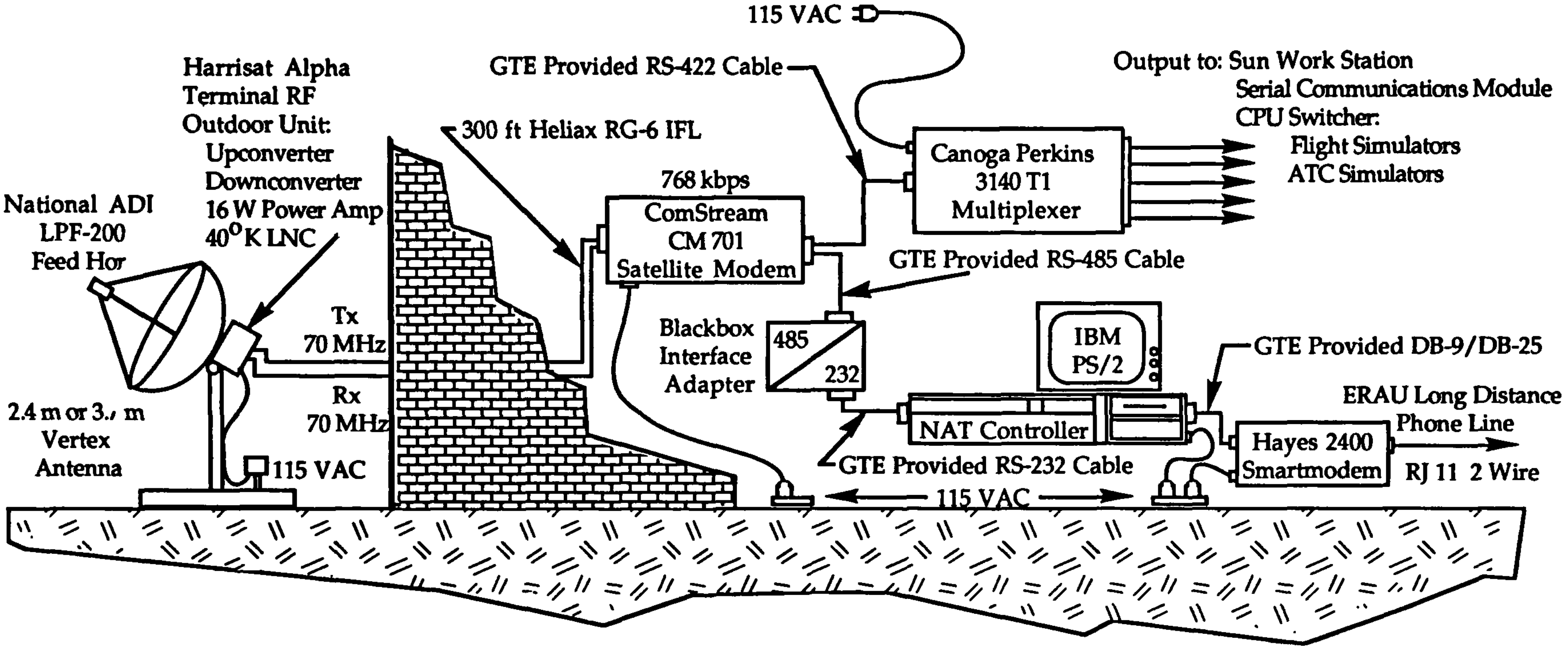


Figure 8. Equipment diagram for ERAU earth station installation using GTE Spacenet Metered Service.

FUTURE EXPANSION If the proposed simulation system was implemented and determined to be a cost effective and advantageous flight training method, the system may be developed into a larger flight training network. A propose microworld flight training network using point-to-multipoint satellite data links is shown in Figure 9. In this network, any multiple number of points, or nodes, could be incorporated into the network. Each additional node would require an additional satellite modem, multiplexer, and associated equipment at the master earth station control site in Daytona Beach.

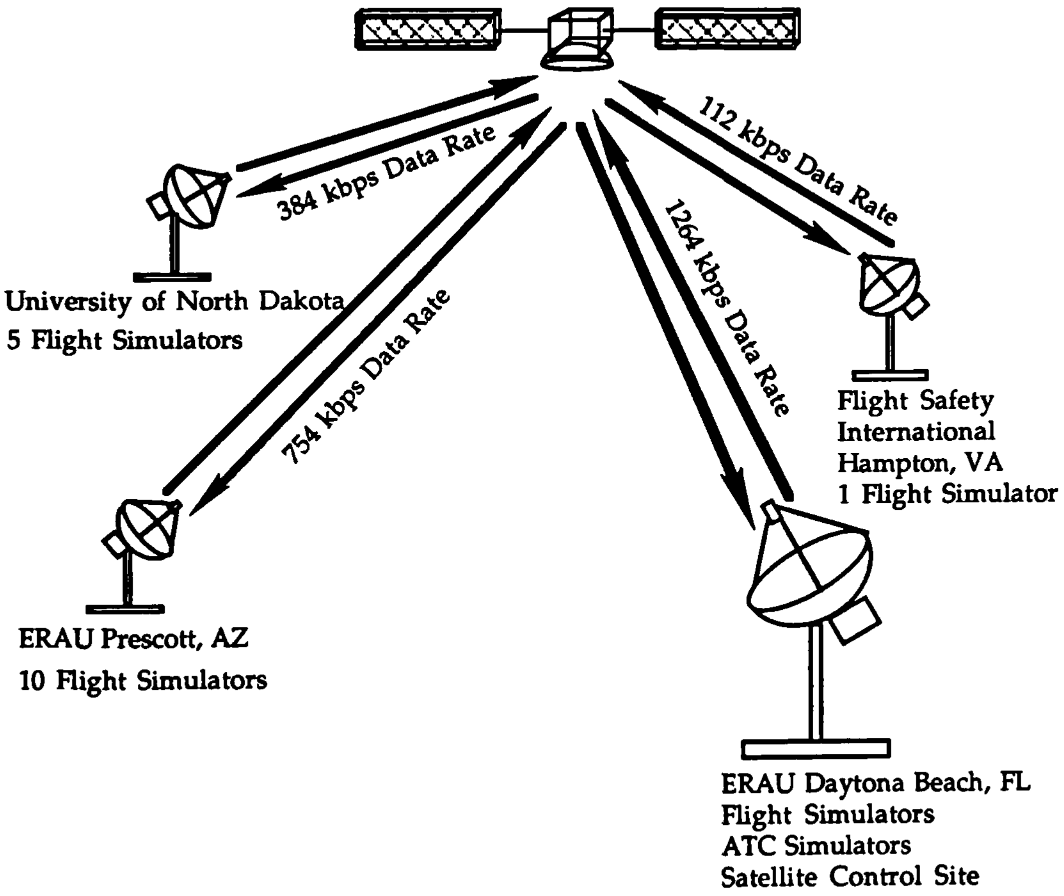


Figure 9. Large area network configuration for microworld simulation using GTE Spacenet User Managed point-to-point service.

The nodes would require all standard micro earth station equipment. The data link requirements would be an additional channel for each node at the prescribed bandwidth, with the composite signal to the master earth station. With increasing bandwidth comes a greater need for more uplink power and a larger earth station antenna to maintain the integrity of the uplink gain.

The configuration shown in Figure 9 is based on the GTE Spacenet User Managed point-to-multipoint service. In this scenario, flight training facilities in North Dakota with five flight simulators, and Virginia with one flight simulator are added to the ERAU Daytona Beach to Prescott link. The control site, at the ERAU Daytona Beach earth station, controls access to the network by all nodes. With each node as one channel, the aggregate signal of 1,264 kbps links from the satellite to Daytona Beach. Any nodes not participating still form a requirement for the Daytona Beach link to maintain the full 1,264 kbps bandwidth. Also, each node could act independently of each other, requesting activation and deactivation anytime during the simulation.

The earth station at the North Dakota site would have the same equipment as the Prescott site. The Hampton site could also use this same equipment, or it could use the ComStream satellite modem with an internal multiplexer module. A PCM modulator would still be required for the voice conversion, since this device is internal to the Canoga Perkins multiplexer. At the control site, a signal splitter between the up/downconverter and the satellite modems would divide the signal to separate modems, one for each channel. Further research could show how the independent satellite link signals would be multiplexed to the ATC simulation, and what type of equipment would be required.

Based on the information of Appendix G, the best alternative may also be the most expensive. A User Managed private mode service from GTE Spacenet would allow direct control from the ERAU Daytona Beach campus on either C or Ku-band. This would give the university control of allocating satellite link capacity among the various nodes in the network. It would also require the university to obligate to a fixed satellite capacity based on bandwidth and time allocations. However, this would guarantee that specific services would be provided when requested. This would also allow usage above 20 hours per month, a realistic assumption.

CONCLUSIONS

This study provides the feasible satellite data communications link requirements for a proposed flight simulation system. The proposed system is designed to link air traffic control (ATC) simulators at the Embry-Riddle Aeronautical University (ERAU) Daytona Beach campus with flight simulators at other flight training institutions. This microworld simulation is intended to provide the flight student with a realistic environment for enhanced flight training.

The enhanced flight training is provided through active interaction between the ATC students and the flight students. Data from the flight simulator computers is linked to the ATC simulator computers, displaying flight simulator parameters to the ATC student as a realistic ATC screen. The ATC student is in voice contact with the flight student and can direct flight control as necessary. This type of training, either local or via data link, emulates the procedural routines encountered in controlled air space, providing greater realism to the training environment.

A microworld simulation system based on the local fiberoptic network was presented to establish a baseline to define data requirements. The data requirements were used to define a satellite communications system for a larger scale simulation.

The fiberoptic link defined the basic operation of the system, specific equipment, and the data requirements. For purposes of this study, ten flight simulators, their respective voice circuits, and a computer controller, requiring 753.6 kbps data rate, were selected for the flight simulator requirement. These would link to eight ATC stations at the ERAU AWS building, where other parameters are added to the scenario.

To establish satellite parameters, a link was investigated between the ERAU campus in Daytona Beach, FL and the ERAU campus in Prescott, AZ. The 753.6 kbps data rate was rounded to 754 kbps and used in the determination of the satellite link budget. The link budget reviews power additions, gain, and losses, attenuation, to the data signal as it propagates through the link. Measured in decibels (dB), the various sources of gain and attenuation are added with the results showing the carrier-to-noise ratio of the signal. Converted to the more common bit error rate (BER), the resulting signal must meet a criteria set by the operating common carrier, usually $1X10^{-7}$ for 99.5% of the time the system is available or operational. The BERs for the two systems investigated, C and Ku-band operating frequencies, showed that these systems could successfully operate a satellite data link between the two campuses. Details of the proposed equipment appear in Appendix H.

FURTHER RESEARCH This study shows that the microworld simulation is capable of being conducted over a large distance. From a human factors perspective, the 0.5 second delay inherent in satellite communications would have to be investigated for possible adverse affects on the simulation. It is assumed that this will not be a problem since the related literature shows the FAA is allowing satellite communication between pilots of large commercial aircraft and air traffic controllers.

Additional research into a large network of the microworld simulation may show a unique development in flight training. Satellite common carriers offer point-to-point service as used in the Daytona Beach to Prescott link investigation. They also offer point-to-multipoint service which would allow any institution in the satellite's fooprint to join the link. The potential exists for ERAU Daytona Beach ATC simulation to emulate any ATC center, i.e. Chicago O'Hare, and offer that scenario to all flight students active in the simulation. Students in a multiple number of flight training institutes, would be able to log practice simulator landings at O'Hare. Initial investigation of this possibility shows this network would require the point-to-multipoint service, increased data rate to/from ERAU Daytona Beach, greater multiplexer capacity and an increased voice capacity at ERAU Daytona Beach. This link offers the potential to any institution with a satellite link capacity (for this network), a multiplexer, and a voice remote station to offer this type of unique and valuable training.

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APPENDIX A

BASIC COMMUNICATIONS

Basic Communications

The term communication, as used here, refers to the sending, receiving, and processing of information by electronic means. More specifically, with the sorting, processing, and storing of information before it is transmitted; processing and noise filtering during transmission; and decoding, storing, and further processing to a usable form after transmission. Key terms to this process are the *information* sent (as a message or signal), the *channel* sent on, *noise* or *distortion* in the system, *modulation* and *demodulatio*n of the carrier wave, and the *encoding* and *decoding* of the information (Kennedy, 1985).

The two most basic forms of information for transmission are analog and digital signals. In a common communications system, analog signals are continuous, varying electrical wave currents, reflecting variations in amplitude and/or frequency. Digital signals are discrete signals having explicit states, such as positive and negative voltage pulses over a local area network to indicate the 0s and 1s of binary code. In signal transmission of any significant length, analog signals will require amplifiers in the line, and digital signals will require repeaters. Amplifiers receive, boost, and re-transmit the signal, while also boosting the inherent noise level in the signal each time. With digital signals, the signal is repeated new each time, thus transmitting a clean, error-free signal. Because of the forgiving nature of analog signals, their interpretation can withstand greater levels of noise and interference over the amount of errors in a digital transmission. The transmission of digital signals must be of high quality and low error rate, which coincidentally yields a higher quality message.

The four cases of signal transmission are digital data on analog signals, digital data on digital signals, analog data on digital signals, and analog data on analog signals. In the first case, digital data can be encoded on an analog signal by modulating one the three characteristics of the carrier wave. *Amplitude-shift keying* (ASK), *frequency-shift keying* (FSK), *phase-shift keying* (FSK), or any combination of these modulation techniques are used for this. The ASK method represents the binary 0s and 1s as either a zero or a positive, constant amplitude respectively. Although the most basic modulation method, it is correspondingly inefficient and tends to limit the data transmission (baud) rate. The FSK method transmits the carrier wave on a center frequency, shifting down for 0s and up for 1s. The Bell System 108 series method for FSK centers the carrier wave on 1170 Hz, with a shift to 1270 Hz for each 1 and a corresponding shift to 1070 for each 0. This method has less interference than ASK and offers a higher baud rate. The two-phase PSK method represents a 0 with a signal burst of the same phase as the previous data bit. A 1 would result with a signal burst opposite in phase as the previous bit (whether 0 or 1). This is the most noise resistant method and offers baud rates up to 9,600 bps. It is common to find a combination of PSK and ASK where the phase shifts occur at one of two amplitudes. In their most familiar form, these analog signals are transmitted by a modem on standard phone line. As a final note to this case, fiber optic systems modulate a carrier light wave, usually to a digital message signal, by varying phase, amplitude, intensity, or a combination of these.

The method for transmitting digital data on digital signals is usually employed with local area networks (LANs) where system size may make it less expensive and provide better performance than using modems. Two coding techniques used are *non return-to-zero* (NRZ) and biphase. NRZ-L (NRZ-level) coding uses two different voltage levels, a constant negative voltage to represent 1 and a constant positive voltage to represent 0. A zero voltage is never used. This method is the easiest and is most often found for short distance connections, such as between a terminal and modem. However this method is inappropriate for networking since a common problem is the polarity reversal in the system, resulting in 0s and 1s being reversed in transmission. An alternative is the NRZI (NRZ, inverting on ones) where the voltage will invert from positive to negative at the presence of a 1 in a bit time (unit time taken to represent one bit). If there is no inversion during a bit time, a binary 0 is present. A drawback to NRZ coding is a large stream of 1s or 0s will generate a constant voltage over a long period of time, resulting in a loss of transmitter/receiver synchronization. Biphase coding is not subject to these problems and is commonly used in local networks. Manchester and Differential Manchester are two types of biphase codes similar in scheme to NRZ-L and NRZI respectively. The key difference is that a transition occurs at least once per bit time. In addition to overcoming the synchronization problems of NRZ, these methods also offer increased error detection if the expected transition does not occur. Digital signals can be transmitted over a variety of mediums, however most LAN systems use standard 4-wire conductors.

Representing analog data by digital signals is performed by a codec (coder/decoder). The most popular method for performing this is *pulse code modulation* (PCM). Based on the sampling theorem, PCM is defined by the following conditions (Rey, 1987, Stallings, 1990):

If a signal $f(t)$ is sampled at regular intervals of time, at a rate at least twice the highest significant baseband frequency, then the samples will contain all the information of the original signal. The function $f(t)$ can be reconstructed (demodulated) from the samples without distortion.

It is easiest to imagine this as a finite number of quantized samples taken from a sine wave representing the analog signal of a voice baseband, each relating to a specific amplitude at a specific time. Chapter I showed the voice channel baseband having a total bandwidth of 4000 Hz. Based on the above theorem, a sufficient sample for adequate characterization would be 8000 samples per second. Therefore, each of the 8000 samples would represent a value of the amplitude occupying a specific time increment. Smaller time increment corresponds to more representative samples. It has been shown (Rey, 1987, Stallings, 1990) that sufficient low noise representation can be achieved with 256 quantization levels. With n = bit samples required, and $2^n = 256$ levels, the signals use eight bit samples. A typical full-duplex voice 4 kHz baseband signal requires eight bits per sample x 8000 samples per second = 64 kbps to be transmitted digitally. A seven bit sample would require 56 kbps, a standard baseband size for many public satellite transmission carriers.

A problem with this form of PCM is that low amplitude signals would not get the proper representation if the 256 quantization steps were of equal size. Non-linear encoding is a technique which concentrates the steps at low amplitudes and lessens them at larger ones. This further reduces overall signal distortion.

If a modem were used to transmit the PCM digital signals over an analog carrier, it would require more bandwidth than the original analog signal. A corollary to the above theorem states that a baseband analog channel can be used to transmit a train of independent pulses at a maximum rate of twice the channel bandwidth (Rey, 1987). A 4 kHz analog voice baseband pulse code modulated to a 64 kbps digital pulse stream, would require 32 kHz bandwidth. Although this appears to be an inefficient use of analog bandwidth, the characteristics of PCM make it less susceptible to noise and other interference. This allows the transmission to occur over a lower quality voice baseband channel. Systems of this type are often used for short-haul twisted-pair wire and digital light wave fiber optic transmission.

The final case of transmission, analog data on analog signals was covered in Chapter II as the voice band example. Whenever any transmission is made, it is desirable to provide the most cost effective and efficient method available. Multiplexing offers such a means by carrying multiple signals simultaneously. From the description of Chapter I, frequency-division multiplexing (FDM) is the method of modulating several signals onto carrier waves where each is sufficiently separated so the bandwidths of each do not overlap. Each modulated signal is a channel separated by a guard band, a unused portion of the frequency spectrum designed to prevent cross-channel interference. Figure 10 shows how FSK is a simple form of FDM.

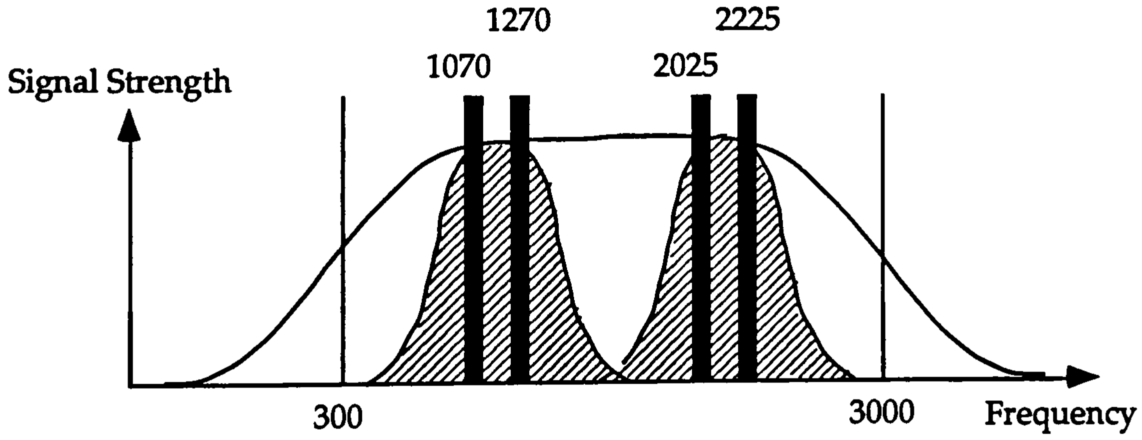

Figure 10. Full-Duplex FSK Transmission on a voice-grade line.

The example of Chapter I is a Bell Systems standard of adding a guard band to the 300 to 3400 Hz voice-band (4 kHz total), combining eleven additional signals, and modulating each to fit a 48 kHz wide bandwidth between 60 and 108 kHz. Figure 11 shows this in graphical form. The signals are modulated to a single sideband AM (SSB/AM) waveform. The twelve multiplexed signals form a composite baseband called a 'group.' In satellite telephony communications, several groups are multiplexed together to form a 'supergroup' that can contain from 12 to 3,600 separate voice channels. This super group would then be modulated onto a 70 MHz intermediate frequency (IF) carrier, which in turn would be modulated to microwave frequencies for uplinking to the satellite.

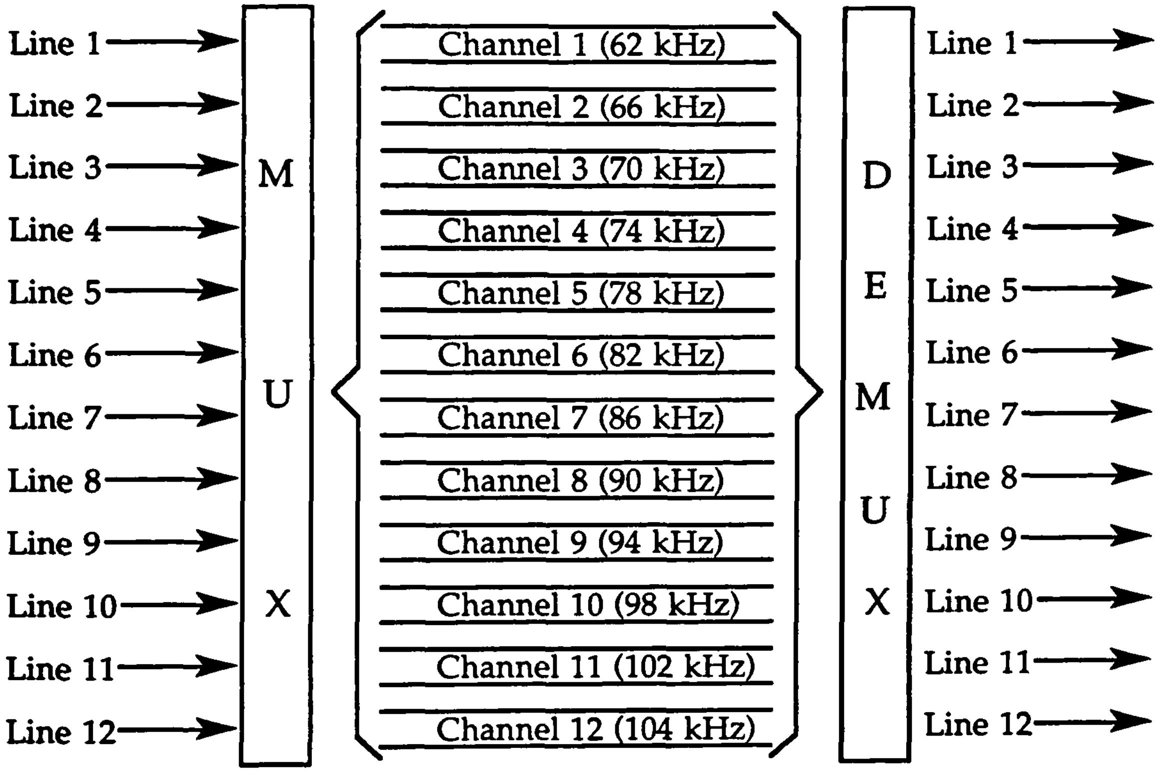

Figure 11. Illustration of Bell Systems standard 12 channel FDM scheme.

When transmitting either an analog or digital signal, a method needs to be established to classify the quality of the transmission. Voice and other audio signals are analog waveforms that exhibit great variance in intensity and frequency. Fidelity is achieved by attaining a high signal-to-noise (S/N) ratio for each audio signal received from the transmitter. Digital signals have only two sets of distinct states corresponding to the 0 and 1 information condition. An accurate digital signal reproduction is achieved by transmitting/receiving the digital bits of information with a low bit error rate (BER) (see BER in Appendix B).

Time-division multiplexing (TDM) uses the excess data rate capacity of the transmission medium to interleave several digital signals at either the bit level or in larger blocks. As with FDM, a single source into TDM is called a channel, and each bundle of channels per cycle is called a frame. While FDM signals are assigned to separate frequency segments within the composite baseband, each TDM transmission accesses the full channel bandwidth. This is graphically shown in Figure 12. When the frames are transmitted in preassigned time slots, they are called synchronous TDM. Asynchronous TDM dynamically assigns the slots as the channels become available. In the Bell T1 standard, data from each source is sampled 7 bits per cycle, with an eighth bit added for signaling. Twenty-four sources are combined, requiring 8 x 24 = 192 bits per frame. The addition of one more bit establishes and maintains synchronization; a total of 193 bits. With the sources being sampled 8000 times per second (PCM), 8000 x 193 = 1.544 Mbps is the total T1 data rate. Similar to FDM, the high bandwidths of today's mediums allow multiple TDM configurations. A grouping of twenty-four PCM channels is a Bell standard known as the DS1 level. Combinations of TDM and FDM can provide high quantity transmission systems, especially in the broad band LAN arena. Because TDM transmissions permit only one signal to occupy the available channel bandwidth at any one time, unwanted intermodulation distortion does not occur. This allows network operators to transmit at full power without concern of generating unwanted crosstalk between signals sharing the same frequency spectrum.

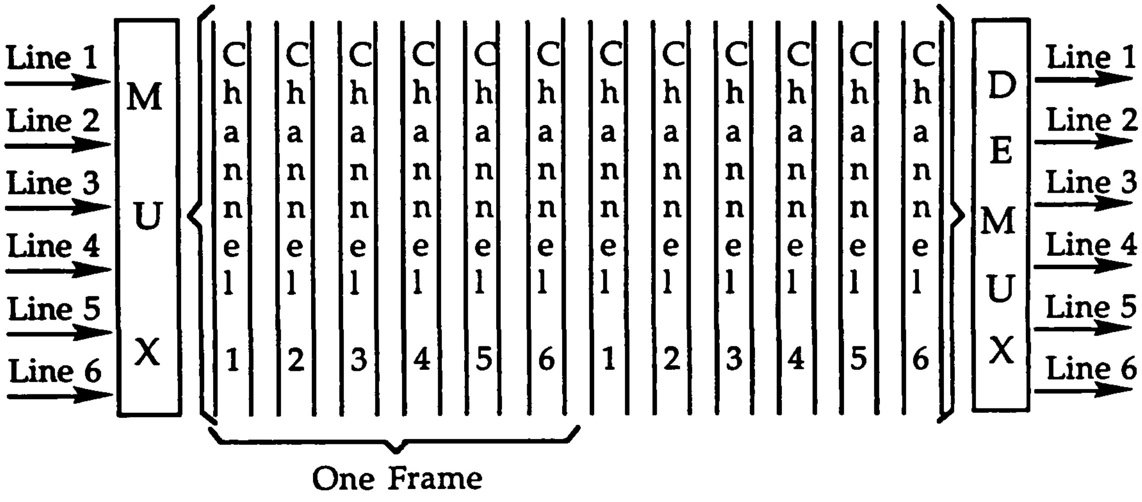

Figure 12. Illustration of TDM scheme.

APPENDIX B

GLOSSARY

Glossary

ACK - Acknowledgment; a communication control character transmitted by a receiver indicating that the message was received correctly.

A/D - Analog to digital; analog to digital converter.

Address - The coded representation of the destination of a message.

Amplitude - Magnitude or size of the transmission signal.

Analog - A special type of model, usually implying that the model is constructed using a different discipline than the real situation. A transmission that uses amplifiers to magnify the incoming signal, including any noise components.

Aperture - The clear diameter of the parabolic reflector of a microwave antenna.

ASCII - The American Standard Code for Information Interchange (ACSII) is an eight level code accepted as a communication standard in North America to achieve compatibility between data services. ASCII uses seven binary bits for information and the eighth bit for parity purposes.

Asynchronous Transmission - Transmission in which the time intervals between transmitted characters may be of unequal length. Transmission is controlled by start and stop bits at the beginning and end of each character.

Attenuation - A result of a distortion that alters the original form and causes a diminishing of a particular portion of the signal.

Bandwidth - The range of frequencies that can pass through a circuit. It is a measure of the rate that information can be passed through the circuit. The greater the bandwidth, the more information that can be sent through the circuit in a given amount of time.

Baud - A unit of signaling speed, typically equal to the bit rate.

BER - Bit Error Rate, digital signal characterization of the signal's reproduction qualities. BER is equal to the quotient of the number of errors divided by the number of bits transmitted.

Bit - A contraction of the term binary digit. A bit can be either 0 or 1 and is the smallest possible unit of information making up a character or word in digital code.

Bit Rate - The rate at which bits are transmitted over a communications path. Normally expressed in bits per second.

Bit Sense - Normal or inverted corresponding to assignment of a mark or space to a particular voltage level.

Bit Shift - The ability to inspect data characters formed with the first bit in different positions in the byte.

BOP - Bit-oriented protocol.

BPSK - Bi-phase shift keying; carrier modulation method in which the phase of the transmitted carrier is shifted +/- 180° with respect to a reference.

Broadband - Refers to circuits capable of transmitting 19.2 kbps or higher.

Burst - A sequence of signals counted as one unit in accordance with some specific criterion or measure.

Byte - A sequence of eight adjacent bits operated on as a unit or character.

Carrier - A high frequency radio signal which is modulated to carry information long distances through space or over wire.

CCITT - The International Telegraph and Telephone Consultative Committee, an international organization concerned with devising and proposing recommendations for international telecommunications.

Channel - A path along which signals can be sent.

C/I - Carrier-to-interference ratio; the power in the desired carrier divided by the power in the interfering signal or signals.

C/N - Carrier-to-noise ratio; ratio of carrier power to noise power in a defined frequency band.

C/N$_0$ - Carrier-to-noise-power density ratio.

Clock - A timing device used to indicate the passage of time or intervals of time. A clock circuit may be used in computers and data sets to synchronize and coordinate the manipulation and transmission of data.

Common Carrier Network - A network established and operated by a telecommunications company for the specific purpose of providing transmission services to the public.

Control Character - A character whose occurrence initiates a control function in the associated business machine or computer. Control characters are used for line control operations, formatting, terminal and device control or as information separators, like CR (carriage return), VT (vertical tab), and EOT (end of transmission).

Controller - A type of communication control unit that manages the details of line control and routing of data through a network.

CONUS - Contiguous (48) United States.

COP - Character oriented protocol; a protocol that uses control characters to perform the functions of data link control.

CRC - Cyclic redundancy check; a check method in which the numeric binary value of a block or frame of data is divided by a constant divisor. The remainder serves as the check sequence, a series of bits added to the end of a frame or block used to detect errors.

Crosstalk - Undesired energy appearing in one signal path as a result of coupling from other signal paths.

D/A - Digital to analog; digital to analog converter.

DCE - Data circuit terminating equipment; the equipment installed at the user's premises, which provides all functions required to establish, maintain, and terminate a connection. The signal conversion and coding equipment between the data terminal equipment and the common carrier's line is the data set or modem.

Data Code - A set of symbols and rules for use in representing information (i.e. ASCII code is an eight level system used for information interchange among data processing systems, communications systems, and associated equipment).

DATACOMM - The movement of encoded information by means of electrical transmission systems. Also, the transfer of data between points of origin and reception, including all manual and machine operations needed to transfer such data.

Decibel - (dB); a number denoting the ratio of the two amounts of power, being ten times the logarithm to the base 10 of this ratio.

Demodulation - The opposite of modulation, or the separation of coded separation of coded information from a carrier.

Demultiplex - DMUX; process of separating two or more messages which are interleaved in frequency or time for transmission on a single channel.

Digital - Non-continuous coded signaling; contrast with analog. Digital data is usually expressed in digits with binary digits implied.

Distortion - Any change from an original signal. Usually it refers to unpredictable changes which interfere with interpretation of the signal.

DCCMP - Digital data communication message protocol; a uniform discipline for the transmission of data between stations in a point-to-point or multipoint synchronous or asynchronous network.

Downlink - The circuit between a satellite and a receiving earth station including the satellite transmitter and antenna, the satellite-earth station path, and the earth station antenna and receiver.

DSE - Data switching exchange; the set of equipment installed at a single location to switch data traffic.

E_b/N_0 - Energy-per-bit-to-noise-power-density ratio; Signal-to-noise ratio normalized with respect to bit rate.

Echo - A signal which has been reflected at one or more points during transmission. Usually experienced as an attenuated reflection of a talker's voice, returned to him on the circuit on which he is talking and listening.

Echo Suppresser - Used to suppress echoes on long distance transmissions.

EIA - Electronic Industries Association; a consultative group of manufacturers recognized as the standards writing agency in the United States for electronic equipment (i.e. the EIA interface is a voltage-operated interface approved for use under the RS-232 standard).

EIRP - Effective isotropic radiated power; product of transmitted power times transmitting-antenna gain, usually expressed in dBW.

Emulate - Using one system to imitate another system.

Error Correction System - A system employing an error-correcting code and so arranged that some or all signals detected as being in error are automatically corrected at the receiving terminal before delivery to the data sink.

FCC - Federal Communication Commission.

FDM - Frequency division multiplexing; the technique of dividing up a single communications path into several data, using several carriers of different frequency, each supporting a different information stream.

FDMA - Frequency division multiple access (of a satellite transponder by different earth stations).

FDX - Full duplex; refers to a communications system or equipment capable of transmission simultaneously in two directions.

FEC - Forward error correction; A encoding technique for improving the BER in a data system. In a typical rate 3/4 FEC system, the BER may be improved by a factor of ten thousand.

Feed - That portion of an antenna which is coupled to the terminals and which functions to produce the aperture illumination on transmission or to couple energy concentrated at the focal point to the antenna terminals on receiving.

Flux Density - Power density; power per unit area normal to the direction of propagation of a propagating electromagnetic field.

Frame - In bit-oriented protocols, data is formatted in frames for transmission. Each frame consists of a start flag followed by an address field, control field, data field, frame check sequence, and a stop flag.

Front End Processor - A communications computer associated with a host computer. It may perform line control, message handling, code conversion, error control, and application functions, such as control and operation of special purpose terminals.

Four-Wire Channel - Two wire pairs (or logical equivalent) for simultaneous (full-duplex) two-way transmission.

Frequency - An expression of how frequently a periodic (repetitious) wave form or signal repeats itself. It is usually expressed it terms of Hertz (Hz), which is equivalent to the older expression cycles per second.

Frequency Reuse - A technique in which independent information is transmitted on orthogonal polarization's.

FSK - Frequency shift keying; a common form of modulation which uses two different frequencies to represent the two binary digits.

Gain - The ratio of the signal level received (or transmitted) by a unit to the signal level which would be received (or transmitted) by an isotropic unit at the same location and under same conditions.

G/T - Figure-of-merit of a receiving system, expressed in dB/K, the ratio of the receiving system gain, including the antenna gain, at a specified reference point in the receiving system (preceding the demodulator) to the receiving system noise temperature in Kelvins referred to the same point. Generally, the higher the G/T, the higher the sensitivity of the receiving system in detecting satellite signals.

HDX - Half duplex; sometimes referred to as two-wire channel, a circuit which provides non-simultaneous transmission.

Handshake - Exchange of predetermined signals occurring when the connection between two data sets is first established.

HDLC - High-level data link control; a link level bit-oriented protocol.

HPA - High power amplifier; in a transmitting earth station, this is the final RF amplifier between the modulator/exciter and the antenna.

Idle Character - A character that is sent when no information is to be sent.

Input-Output Channel - A functional unit, controlled by the central processing unit, that handles the transfer of data between main storage and peripheral equipment.

Intelligent Terminal - A terminal that contains a processing element.

Interface - A shared boundary. The connection point between business machines and the data set, modem, or communications channel.

Interrupt - To stop a process in such a way that it can be resumed.

ISO - International Standards Organization; The body which promotes the development of world wide standards.

K - Kelvin; temperature of a device in Kelvins, zero K = -273.15^{o}C.

Kilo (k) - Greek word meaning 1,000. Used as a prefix in the international system of measurements, i.e. kHz, kbps, etc.

Kilo (K) - 1024; Used in specifying memory size when denoted by capital "K," i.e. Kilobyte.

Leased Line - A telecommunications channel leased between two or more service points, usually in monthly rates for terrestrial lines.

Line - A communications channel, circuit, path, or link, including satellite or microwave channels.

Link - A transmission path between two stations, channels, or parts of communications systems.

Local Loop - The part of a communication circuit from the subscriber's equipment to the line terminating equipment in the central office.

LNA - Low noise amplifier; the preamplifier between the antenna and the earth station receiver.

LNC - Low noise converter; integrated LNA and downconverter.

LRC - Longitudinal redundancy check; a method of providing a level of confidence that data is being received correctly by performing a parity check across the data message.

LSB - Least significant bit.

Mark - An impulse on a data circuit used to signify a "one" binary condition.

Menu - Describes a method of configuring the setup of an instrument using prompts or choices directing the user down a decision tree.

Mesh Network - A communication system consisting of several nodes with point-to-point links to each other.

Message - A term identifying a complete transmission of data or text. It is sometimes used synonymously with block.

Modem - Contraction of the term modulator/demodulator. A modem is used to convert digital signal from a computer to an analog signal so that it may be transmitted over a network.

Modulation - The application of information onto a carrier signal by varying one or more of the signal's basic characteristics: frequency, amplitude, and phase.

MSB - Most significant bit.

MTBF - Mean time between failure; A statistical determination of the time in hours of use between failures.

Multiplex - MUX - To interleave or simultaneously transmit two or more messages on a single channel.

Multiplexer - Electronic device for combining several signals into a composite stream for economic transmission. Techniques employed are frequency division (FDM) and time division (TDM).

NAK - Negative acknowledgment; a communication control character transmitted by a receiver indicating it received some information incorrectly.

Network - A series of points interconnected by communications channels, often on a switched basis. Networks are either common to al users or privately leased by a customer for private use.

Network Management - Customer network management is the systematic approach to the planning, organizing, controlling, and evolving of a customer's communications network, while optimizing cost performance.

NF - Noise figure; A figure of merit of a device which compares the device with a perfect device.

Node - The node is that point in a transmission system where lines or trunks from many sources meet, or that location in a data network where switching is done.

Noise - Introduction of unplanned energy into a communications path, which can result in transmission errors.

Noise Temperature - A measure of the noise power referred to a given reference point of a matched receiving system, normalized to bandwidth.

Packet - Data grouped for transmission through a public data network such as an X.25 network.

Parallel Transmission - Simultaneous transmission of the bits making up a character or byte, in contrast with serial transmission; typically used between computers and their peripheral equipment.

Packet Switching - The transfer of data by means of addressed packets whereby a channel is only occupied for the duration of transmission of the packet. The channel is then available for the transfer of other packets.

Parity - Constant state or equal value. Parity checking is one of the oldest checking techniques. Character bit patterns are forced into parity (total number of one bits odd or even) by adding a one or zero bit as appropriate.

Parity Bit - A bit added to characters so that the total on "one" or "mark" bits in a character will always be either even (even parity) or odd (odd parity).

PBX - Private branch; telephone network service provided for a customer's use.

Point-to-Point - Two point (only) communications.

Point-to-Multipoint - More than two point communications.

Polarization - Wave polarization is described by the amplitude and direction of its electric field (normal to its direction).

Polling Selection - The process of "calling out" to remote stations from a central point on a sequential, systematic basis. The polling operation is to request or collect data. The selection operation is to distribute data.

Post-Processing - The ability of an instrument to perform analysis on data contained in a data capture buffer just as if the data were arriving real-time.

Power Gain - The ratio of the output power to the input power.

Propagation Delay - The time between when a signal is placed on a circuit and it is recognized and acknowledged at the other end, primarily used in satellite communications.

Protocols - The initial exchange of information at the start of a digital transmission to establish the format, operating parameters, and control of inputs and outputs between two communicating devices or processes.

Protocol Converter - A device for transmitting the data transmission code of one computer or peripheral to the data transmission code of another computer or peripheral, thus enabling equipment with different data formats to communicate with one another.

PSK - Phase shift keying.

Pulse - A signal described by a constant amplitude and the duration time.

Pulse Modulation - Transmission of information by varying the basic characteristics of a sequence of pulses; amplitude, duration, phase, and number.

QPSK - Quadriphase shift keying; a carrier modulation technique in which the phase of the carrier is shifted to any of 4 phases, whose separations are multiples of 90^{o}.

Real Time - Immediately, without delay.

Redundancy - Additional information or equipment, used in transmission error correction methods.

RS-232 - An industry standard for a physical interface with a 25 pin connector. Equivalent to V.24 in CCITT countries.

RS-422A - A balanced electrical implementation of RS-449 for high-speed data transmission.

RS-423A - An unbalanced electrical implementation of RS-449 for RS-232 compatibility.

RS-449 - A 37 pin physical connector specification.

RX - Receive or receiver.

SATCOM - Satellite communications; the movement of encoded information by means of Earth and satellite based electrical transmission systems.

SCPC - Single channel per carrier; A satellite transmission system that employs a separate carrier for each channel.

SDLC - Synchronous data link control; a subset of HDLC.

Side Band - The application of information on the constant frequency carrier signal (modulation), resulting in a symmetrical distribution of energy about the carrier. This is referred to as upper side band (higher frequencies that the carrier) and lower side band. Because of the symmetry, either the upper or lower side bands alone contain all the information. Single side band transmission suppresses the energy in the carrier and one side band, to concentrate it in the one side band being transmitted. The receiving station must supply its own carrier signal for retrieving information.

Signal - Information.

Signal-to-Noise Ratio - S/N; Relative power of signal to noise in a transmission. As the ratio decreases it becomes more difficult to distinguish between in formation and non-information (noise).

Simplex - One-way communication.

Slave - A remotely located instrument which can be controlled.

Space - A binary "zero." See mark.

Star Network - A communication system consisting of one central node with point-to-point links to several other nodes.

Synchronous Transmission - A data network in which the timing of all components of the network is controlled by a single timing source. No redundant information (such as start/stop bits in asynchronous transmission) to identify the beginning and end characters, also faster than asynchronous transmission.

Tie Line - A leased line for voice or data communications. It does not connect into a public telephone network exchange.

TDM - Time division multiplexing; sharing a single communications line among several data paths by dividing up the channel capacity into time segments.

TDMA - Time division multiple access (of a satellite transponder by different earth stations).

Transmission - The sending of data to one or more locations or recipients.

TX - Transmit or transmitter.

Uplink - The circuit between a transmitting earth station and a satellite, including the earth transmitter and antenna, the earth-satellite propagation path, and the satellite antenna and receiver.

V. - A series of voice grade CCITT interface and modem specifications.

V.24 - A CCITT V series recommendation that specifies the interchange circuits between data terminal equipment and data circuit terminating equipment similar to EIA RS-232.

V.35 - A high speed (56-64 kbps) modem standard and physical interface standard.

Voice Grade Channel - A channel with bandwidth equivalent to a telephone line obtained through the public telephone network, typically with a frequency response from 300 Hz to 3,000 Hz.

VRC - Vertical redundancy check. See parity.

Wideband Channel - A channel with greater bandwidth than a voice-grade channel, typically starting at 19.2 kbps and higher.

X. - A series of CCITT recommendations for transmission of data over public data networks.

X.21 - A CCITT recommendation specifying a general purpose interface between data terminal equipment and data circuit-terminating equipment for synchronous operation on a public data network.

X.25 - A CCITT recommendation specifying an interface between data t terminal equipment for terminals operating in the packet mode on public data networks.

X.75 - A CCITT recommendation which specifies the protocol used to communicate between packet switched networks.

APPENDIX C

DIAGRAM OF ALTERNATE MICROWORLD SIMULATION COMMUNICATIONS

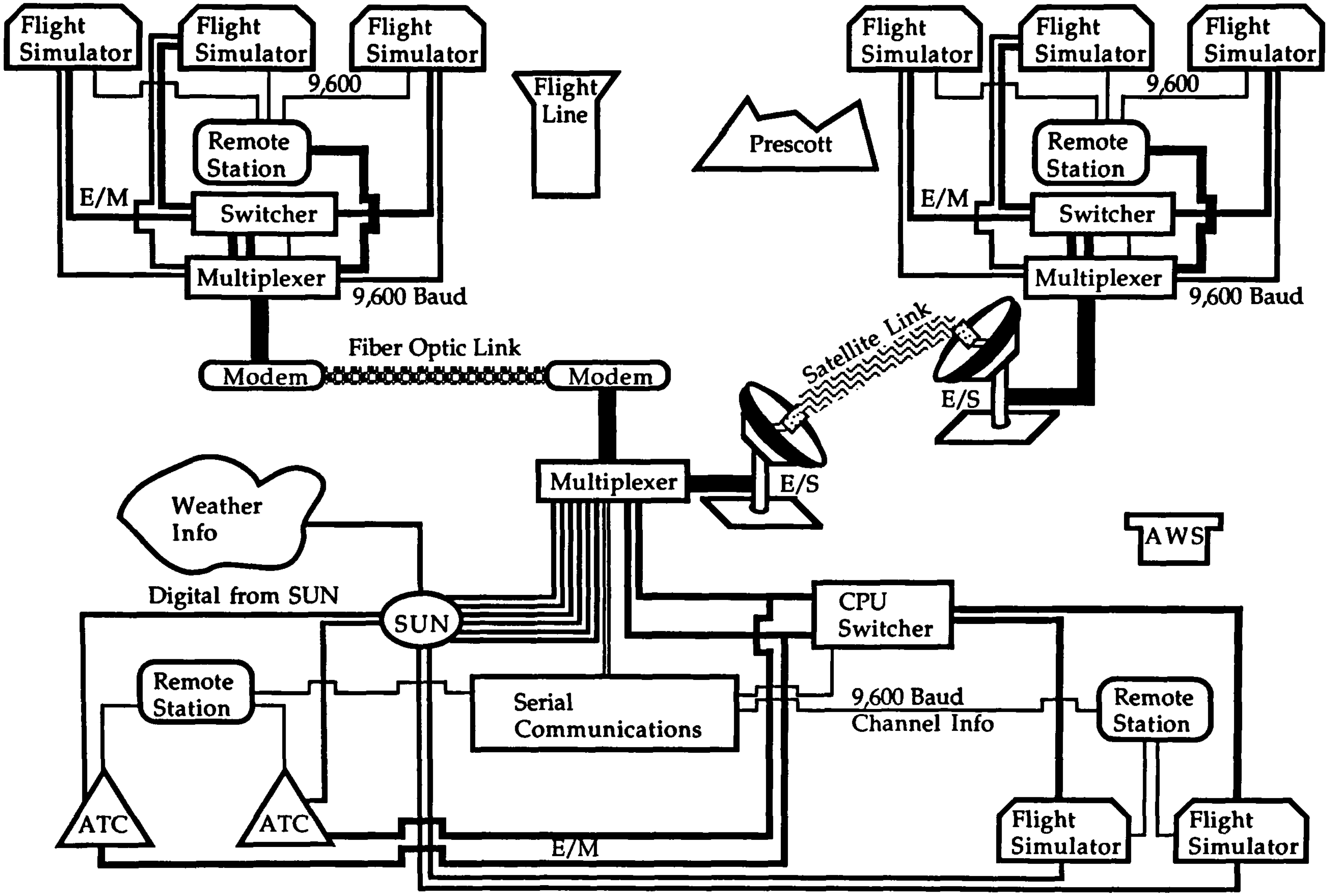

Figure 13. Diagram of alternate microworld simulation communications.

APPENDIX D

ATMOSPHERIC SIGNAL ATTENUATION

Atmospheric Signal Attenuation

Rain attenuation effects on microwave frequencies had been studied well before their use in satellite communications (McAvoy, 1976, Spliker, 1977, The Lenkurt Demodulator, October 1969). Path attenuation calculations for C and Ku-bands are identical and show up to a 6 dB (decibel) increase in signal attenuation of Ku over C-band. However, the gain of a Ku-band signal averages 6 dB higher than C-band for a given parabolic dish antenna, effectively equalizing their net gain. Standard design methods calculate path attenuation (also known as free space path loss) assuming them to be the same as in free space. This approximation is only effective up through the 6 GHz band. For frequencies above this, precipitation creates interference problems in the form of rain droplets scattering microwaves and absorbing the signals. The FCC considers rain scattering a significant problem since it creates local interference with terrestrial networks.

Precipitation attenuation is a function of droplet size and shape, air temperature, precipitation volume involved, signal frequency, and signal path (as a function of the elevation angle) through the affected area. In general, a Ku-band signal will increase in attenuation with an increase in rainfall and drop size. A signal path emanating from low elevation angle earth station antennas may encounter several convective rain cells, or it may traverse many miles of non-convective rain. At high angles, it is unlikely that the path will encounter more than one convective cell, with the distance through the cell being much less. However, it is not necessarily true that the exposure continues to diminish with increasing elevation angles since the worst exposure may be from directly above. In addition, it is not the annual rainfall rate that is of interest. It is the concentrated rainfall which causes signal degradation. Heavy rain can lead to serious attenuation problems.

Rain rate distribution along the signal path is dependent on the rain rate of the weather cells. This can be broken down into two types of precipitation: wide-spread precipitation at moderate levels, giving low values of attenuation and high-intensity, and localized precipitation at highly variable rates yielding high values of attenuation. Statistical charts showing rain rates throughout the continental United States are readily available from meteorological sources and technical handbooks.

In addition to energy absorption and signal scattering, satellite signals which use polarization for frequency reuse may be subject to cross-polarization interference due to rain. Known as cross-polarization discrimination, this affect is a function of the quality of polarization of a transmitted wave. Polarization quality deteriorates as the angle separating the two orthogonal signal planes decreases (or rotates) due to the rain. Polarization rotation leads to frequency cross-polarization between channels. Research has shown a worst case scenario develops from non-spherical rain droplets whose major axis is oriented 45° incident to the signal wave form (McAvoy, 1976). McAvoy also states that average drop tilt angles tend to be approximately 15°. Drops with positive and negative tilts cancel out, leaving only a small proportion of the rain drops to contribute to the cross-polarization. A completely random orientation would give zero polarization. As one might guess, overall research did not show polarization rotation to be a major concern throughout the industry. However, this unique condition may be one side effect of precipitation attenuation which may become a factor in a rainy climate such as Florida's.

One method of effectively reducing the large signal strength margins required to combat extreme rainfall rates occurring only a small percentages of the time is to provide space diversity on satellite paths. Since the most detrimental rainfall to satellite signals is heavy and localized, the space diversity scheme is to utilize two satellite antennas separated by a minimum of two miles. Heavy rain cells average three miles in diameter. For typical heavy rainfalls, space diversity will ensure a relatively clear path could be maintained from one antenna while the other was subject to the worst of the downburst.

Atmospheric attenuation is not strictly limited to rainfall. Attenuation by water vapor and oxygen also becomes effective for frequencies above 10 GHz. Although the peaks of this type of attenuation occur at 22.2 GHz, 60.0 GHz, and 183.3 GHz, it is important to note that for an elevation angle of 40^o, atmospheric attenuation varies between 0.11dB at 4 GHz to 0.2 dB at 12 GHz (Spliker, 1977, FCC, 1984). This type of attenuation is enough to cause headaches to operational managers of Ku-band links in areas such as San Francisco, where Bay area fog can stagnate for hours, degrading signal quality and causing errors in transmission (K. Stevens, personal communication, January 20, 1994). Feher (1983) believes this attenuation loss should be factored into the space path loss of the satellite link budget.

A final attenuation effect to review is the solar transit outage. This occurs when the earth station antenna's alignment (or boresight) to a satellite is nearly parallel to the pointing angle of the Sun's rays. The shadow of the sun falls near the center of the antenna, perceiving the sun as a disc of extreme thermal noise 0.48^o in diameter. The minimum noise temperature (see Chapter VI) of an average quiet sun could reach 25,000 ^oK. This is enough to overcome the satellite's incident signal at the earth station antenna. Fortunately, enough research has been done on this phenomena so that mathematical predictions can influence operational steps to counter these effects. In general, satellites centered in the Big MAC constellation will experience the outages for approximately three to six days; before and after the Spring and Fall equinoxes in mid-March and mid-September (Walle, 1990). This is when the Sun appears to be crossing the equator and the Big MAC constellation above it. The outages do not last long, only a minute or two on the first day and a maximum of nine minutes on the third or fourth day (Walle, 1990). These values, published annually, are approximations based on satellites centered in the Big MAC transmitting to earth station locations throughout the continental United States. The large size of the Big MAC makes these generalizations non-applicable for satellites at the extreme ends of the constellation. Also, the sun transit outages only affect down link signals, up links having no interference to the satellites. Sophisticated national networks are able to use earth station diversity arrangements, switching to earth stations in parts of the country not affected by the outages. The best resource for smaller networks and independent earth stations is simply to not utilize the system during the predicted outage periods.

APPENDIX E

THE DECIBEL AND BASE TEN MATHEMATICS

The Decibel and Base Ten Mathematics

The decibel (developed by Alexander Graham Bell) is used to express the ratio between two separate amounts, i.e. P1 and P2, according to the logarithmic formula:

$$dB = 10 \log (P1/P2)$$

This conversion allows a convenient manipulation of large numbers with fewer errors (Walle, 1994). By themselves, decibels have no true references since the decibel is a reference between two quantities (Stallings, 1990). In electronics, it usually defines the ratio of separate levels of power, gain, current, voltage, and loudness of sound.

Symbols following the decibel notation, such as dBW, dBm, dBi, etc. attach a reference to the decibel value. Gain is usually expressed in terms of dBi, indicating decibels relative to the gain of an isotropic radiator. Such terms represent dimensionless factors since they are a ratio. In dBW, W indicates 1 watt of power. Thus a value of 32 dBW is 32 dB greater than one watt, and 32 dBm is 32 dB greater than one milliwatt (0.001 watt). The difference between 32 dBW and 32 dBm is 30 dB (based on the 0.001 watt). These two quantities are often used in satellite link budgets.

Working with base ten mathematics substitutes addition for multiplication and subtraction for division while putting the quantity in logarithmic form. This method is illustrated in the following sample calculation. If two power values were measured along a transmission line where the initial value was 10 W and a second value further down the line is 5 W, then the loss would be:

$$\text{Loss} = 10 \log (5/10) = -3 \text{ dB}$$

Which is the same as

$$\text{Loss} = 10 \log 5 - 10 \log 10 = -3 \text{ dB}$$

Similarly, a loss from 1000 W to 500 W would also result in a 3 dB loss:

$$\text{Loss} = 10 \log (500/1000) = -3 \text{ dB}$$

This example illustrates the benefit of using decibels.

APPENDIX F

REGULATORY ISSUES

Regulatory Issues

Satellite communication systems are governed by the Federal Communications Commission (FCC) in the United States and by the International Telecommunications Union (ITU) internationally (Cook et al, 1990, FCC, 1989). The governing agencies assign frequency bands of operation, satellite performance characteristics and orbit location, and provide technical specifications of radiated power density and radiation gain patterns for the earth stations. The FCC is the licensing body for all transmit earth stations in the United States. FCC Rules and Regulations, Part 25, form the basis of the applicable documents which must be adhered to for the planning and implementation of any FSS band satellite communication system.

The FCC amends and interprets the rules as the technology and the requirements of satellite change. It is recommended that the FCC be contacted at the time of system planning to obtain the latest FCC rules and regulations. Some of the more important parts of the FCC regulations for earth station antennas are highlighted below. The FCC established criteria for the minimum aperture diameters and sidelobe gain envelopes for FSS band earth station antennas in the early 1970s to minimize interference between terrestrial systems and satellite systems and between systems. These criteria have been modified through the years as the use of satellite services has increased. In 1983, the FCC modified the section on sidelobes, reducing the close-in sidelobes to more stringent requirements based on the change to decrease satellite spacing to a two degree minimum. The ruling resulted in improved antenna radiation patterns in the close-in sidelobe region and have established maximum radiated power densities for antennas of less than 9 meters for C-band and 5 meters for Ku-band.

FCC License

The FCC requires licensing of transmitting earth stations and permits licensing of receive-only earth stations. The application requires the following information:

1. The nature of the proposed service.
2. A statement of public interest.
3. The name of the person to receive correspondence (usually head technician).
4. Statement of the applicant's technical qualifications.
5. A paragraph identifying that the application will have a minor environmental impact (i.e. antenna diameter of less than 30 feet, and the dish installation will not disrupt the surrounding aesthetics).
6. Description of the site as a plot plan and its availability.
7. A functional block diagram.
8. Description of the antenna mounting and range.
9. A statement of compliance with the requirements for antenna sidelobe performance.
10. A statement of FAA compliance if required.
11. The report of frequency coordination and interference analysis.
12. A technical summary showing that the antenna meets the performance criteria for a 3.7 meter antenna, if the antenna is less than 3.7 meters.
13. Completed FCC Forms 403 and 430.
14. A technical summary of the proposed station, including a description of the equipment to be used, major structures, the type of communication being received, frequencies and polarization's received, and satellites and transponders being used.
15. A statement that the applicant will only receive program material for which it has obtained rights.
16. The applicant's certification.
17. The technical certification, by a technically qualified person, that the engineering data is complete and accurate.
18. A statement of compliance with regulations for the protection of employees and the general public against excessive radiation.
19. A statement of compliance with FCC regulations regarding quiet zones.

APPENDIX G
COMMON CARRIER CHANNEL SERVICES

Common Carrier Channel Services

The following text was developed from several sources. Although the channel services information reviewed concentrates on services provided by GTE Spacenet, AT&T, Hughes Communications Inc, and several third-party carrier brokers offer similar services. GTE Spacenet offered the most comprehensive data package and assistance of all carriers. This appendix was developed with assistance from S. Dalrymple (GTE Spacenet) (personal communication, March 9, 1994, K. Stevens (GTE Spacenet) (personal communication, January 20, 1994, and S. Tillitson (AT&T Tridom) (personal communication, March 18, 1991).

SERVICES GTE Spacenet is an end-to-end service provider, performing network analysis, design, installation, operations, and maintenance tasks for satellite data links. This appendix details the services provided, including services specifically required for the ERAU satellite link.

Channels Services® is a package of full-time and switched, or occasional, satellites services that support wideband transmissions of digitally encoded information, data, video, image and voice in point-to-point or point-to-multipoint network configurations. The basic service provides "clear channel" telecommunications links between geographically dispersed locations. Clear channel means there is no change in the format of the signal or compensation for satellite delay as it passes through the channel.

The family of Channel Services is divided into Full-Time Channel Services, Switched Channel Services, and Customized Networks. Full-Time and Switched Channel Services can either be point-to-point, star, or mesh. Star is point-to-multipoint where all nodes, or sub micro earth stations, must pass through the master earth station. In a mesh network, all nodes in the network are able to communicate independent of the master earth station. Both services also offer data rates from 56 kbps to 2048 kbps, and higher. Switched Channel Services offer various features and capabilities through two service products, Metered Service and User Managed Service. Customized Networks include all those configurations that may require a departure from the standard services. Initially, all Channel Services had been full-time because satellite services were, in some cases, more cost effective than terrestrial lines, and the switching equipment was not available. However, today the majority of applications require switching.

Switched satellite services were created as a result of the development of network controllers capable of activating and deactivating satellite links desired by the user. Switched Channel Services are clear channel services which provide users access to satellite links on an occasional basis, either on-demand or prescheduled. Switching of satellite capacity is accomplished by transmission of commands to each of the earth stations in the network via either the standard terrestrial link or a satellite channel (only available as an option on User Managed Service). In simple networks the switching of satellite links normally takes one to two minutes from user command, with a maximum of fifteen minutes guaranteed by GTE Spacenet.

Switched Channel Services are offered in either private or public network mode. In the private network mode, the user has sole access to a specific satellite capacity. In the public network mode, the user has access to a pool of satellite capacity, available to a number of users and managed by GTE Spacenet. Access to satellite capacity in public network services is billed on a usage basis, while the private network users pay for the total capacity allocated to that network as a fixed monthly fee. Public Metered Services allow usage-based billing in minute increments (regular access option) or hour increments (Certain- access option). The User Managed Service allows the user to have direct control over the network through an on-premises network controller. This service is only offered under the private network mode.

Switched Channel Services have certain coverage limitations. In public mode, they are only offered in the Ku-band, and in the private mode, they are offered in both the C and Ku-bands.

In the public network mode, Metered Service is provided with two grades of service option: a higher access option and a regular access option. The higher access option, called Certain- "data rate" (i.e. Certain-T1, Certain-384, etc.), consists of assigning excess satellite channels to the space segment pool of a given regional area. This way, if an entire area suffers an outage, enough capacity exists to support every Certain- user in that area. This improves the probability of access to a satellite when needed since it is unlikely that two areas in the country will suffer outages at the same time. With satellite capacity limited, this option is only offered on a first-come basis. Billing for the Certain- option is done on an hourly basis, while billing for standard Metered Service is done on a minute basis.

The most simple configurations of the Channel Services are those required for Full-Time services since these are active all the time and are assigned a specific transponder capacity. Full-Time point-to-point earth stations require an antenna, an RF terminal and a satellite modem(s) at each node. Full-Time point-to-multipoint networks, where a hub earth station is required, are equipped with an antenna and an RF terminal which supports more than one satellite modem, depending on the number of channels used in the network.

Switched Channel Service networks are more complex because the satellite capacity is assigned on a dynamic basis, requiring additional equipment at each earth station location for switching and control. Switched Channel Services require that access to the satellite capacity be coordinated and controlled from a centralized location to ensure that the capacity allocated to these services is efficiently utilized, and that there is no interference between users sharing this capacity.

User Managed Service is designed for the user to have full control over the network resources by providing the network controller (NCS 1000) at the user's master earth station. Satellite capacity in the User Managed Service is fully dedicated to the user, and can be switched among nodes in a network of three or more earth stations. Typically, activation and deactivation of the links are made through telephone requests from the user nodes to the control operator at the master earth station. The usual practice is to have the operator receiving the call make the appropriate entry into the NCS 1000, and confirm to the requesting user (node) of the availability of the satellite channels at the requested time, either immediately or on a prescheduled basis. The network controller consists of an industrial grade personal computer with input/output cards to communicate with the network sites; an event printer that prints any change in configuration in the network; and, terrestrial dial-up or satellite modems to communicate with the rest of the network depending on the type of signaling channel, terrestrial or satellite, used in the network. A customer provided long distance telephone line is used to send commands to the network locations when terrestrial signaling is used. A 19.2 kbps satellite channel is used to broadcast commands when satellite signaling is used. At each network node is equipment similar to that used for full-time services and dial-up or satellite modems to communicate command information with the controller. The command information is directly fed into the control port of the satellite modem used to transmit the user application.

In Metered Services the user has access to link connectivity through a personal computer terminal located at each of the network locations. This Network Access Terminal, or NAT, allows direct interface into the Metered Service Controller, which verifies access to the pool of satellite capacity, and that the requested channel is available. In addition to the NAT at each site, an earth station similar to the Full-Time Services is used. A dial-up terrestrial modem is either contained in, or adjacent to, the NAT. This modem transmits switching requests to, and receives activation commands from, the Metered Service Controller located at the Network Operations Center in McLean, Virginia. A user provided long distance telephone line is required for this modem. The capability to use satellite for communications between the Metered Service Controller and the NAT is under development. This feature will require additional satellite modems and other hardware at each node, and consequently will be more costly. Table 10 outlines the different services and accompanying features. Tables 11 and 12 list the duties performed by GTE Spacenet and the customer, respectively, for earth station installation and satellite link access.

Table 10.
GTE Spacenet services and features.

Service	Feature
Switched Public Service	Low need for quick back-up, cost critical
"Certain-" Metered Service	Outage critical, will wait for technician
User Managed Service	Outage critical, immediate activation
User Managed Service	Full network control from central location
User Managed Service w/ sat	Space segment will be available as needed
Metered Service Public/Private	Network control/activation at any node
Switched Channel Services	Will wait 36 to 48 hours to restore service
Metered Service	Multipoint link w/immediate activation
Metered Service Private Mode	Multipoint time critical, C & Ku-band
Metered Service	Multipoint w/billing on a minute basis
User Managed Service	Multipoint w/usage exceeding 20 hr/month
Metered Service	Sporadic trans w/usage below 20 hr/month
User Managed Service	Multipoint same company nodes
Metered Service Public Mode	Multipoint to different companies, Ku only
Full Time	Multipoint regular and periodic

Table 11.
GTE Spacenet's installation responsibilities.

1) Site survey to determine the most appropriate location for the earth station.
2) Frequency coordination, if required.
3) Obtain FCC licenses for construction and operation of the earth stations and related equipment. These licenses are generally obtained in GTE Spacenet's name since they are the company operating the network.
4) Installation of earth stations and associated equipment in customer provided facilities.
5) Installing associated cables through customer provided and installed conduit.
6) Alignment of antenna and testing of earth stations.
7) End-to-end testing of link.
8) Provide brief orientation to customer personnel on operations and reporting procedures.
9) Provide site survey and preparation procedures and guidelines to user.

Table 12.
User's responsibilities for installation.

1) Designating a representative who shall serve as a point of contact with GTE Spacenet for coordination and decisions regarding installation matters.
2) Preparing site for installation, in accordance with specifications provided by GTE Spacenet, including: site selection, ensure adequate subsoil conditions exist, antenna foundations and pole mounts, cable conduits with 1/4 inch to 3/8 inch pull rope from foundation to indoor equipment room, site electrical power, and lightning protection at ground point.
3) Structural analysis for permit approvals.
4) Any building modifications.
5) Obtaining the necessary rights to access, owner consents, and building permits and zoning approvals for equipment to be placed on site.
6) Accepting delivery of equipment and storing it in secure locations.
7) Providing adequate electrical power (inside and outside), circuit breakers, and air conditioning.
8) Arranging for and allowing GTE Spacenet to have access to the premises during all reasonable times.
9) Coordinating with local telephone company for dedicated long distance line to the satellite modem or network controller.
10) Responsible for all local union labor if installation requires union labor.
11) If antenna is to be roof mounted, additional preparations including kingpost mounting plates and bolts, electrical power scheme, scaffolding, adequate protection from roof damage during installation, interim staging area during installation, and suitable roof access for test equipment and personnel.

PERFORMANCE GTE Spacenet measures the performance of Channel Services transmissions by link availability and bit error rate. The link availability is based on equipment reliability, the time to restore, and satellite link performance. The reliability is increased by maximizing the mean time between failures (MTBF) and reducing the mean time to restore (MTTR) when a failure does occur. The MTBF is an industry reliability standard and is a function of the equipment chosen. The MTTR is a function of how quickly a technician can deploy to the site, make corrections, and restore the service. In both cases, equipment redundancy can help to improve total system reliability by reducing the risk that a single component failure will affect the operation of the earth station, while giving the technician time to arrive and repair the failed component. The satellite link performance is based, in part, on the rain attenuation margins. Typical availability numbers for a single link are 99.5%, while earth stations with redundant equipment at both ends of the link reach 99.8% on an annual basis. Link availability is measured over long periods in order to gain statistical significance. Since Switched Channel Service is only active for a small percentage of the time, link availability cannot be used as a valid performance parameter.

Another parameter of link performance is the BER. If the BER becomes too high, the satellite modem will shut down. GTE Spacenet BERs are typically 1×10^{-7} for 99.5% of the time the system is available or operational.

Switching performance is based on switching time and blocking probability. Switching time is the period between the time the user requests a connection (through the NAT) and the time the circuit is actually established. GTE Spacenet guarantees a maximum switching time of 15 minutes. Blocking probability is applicable only to public services, where there might be competition for the satellite channels in the public pool. Switched Channel Services offer a 1% blocking probability, or a user is guaranteed a successful connection in 99% of the attempts, within four hours of when the connection was originally requested.

COST The following price information may be outdated by two years, but was provided to give an approximation of the costs seen in satellite communication. The satellite common carriers are highly competitive and consider pricing confidential information, to be given only for a contract bid. Although outdated, this information is considered a close approximation of current pricing. Market pricing is based on available satellite time, equipment costs, market competition, and other variables. The estimates provided only consider space segment time used, based on GTE Spacenet's charge, and cost of the maintenance agreement. Equipment costs were not available and are not part of this pricing. GTE Spacenet provides the equipment for purchase or in terms of three and five year lease agreements. Although GTE Spacenet does not manufacture the equipment, as part of the service package GTE Spacenet will repair or replace any defective equipment for the life of the service.

The space segment of Full-Time Services is typically more costly than for Switched Channel Services since it is expected to be in use more often. Access to satellite capacity in public network services is billed on a usage basis, while in private networks users pay for the total capacity allocated to that network as a fixed monthly fee. A mesh network that uses ten hours of public switched transmission per month will cost between $1,600 for 384 kbps to $2,400 for T1 per site based on a five node network. A mesh network using 50 hours per month of private switched transmission would cost between $1,400 for 384 kbps to $3,000 for T1 per site based on a five node network. This contradicts earlier presented information of private mode being more costly than public mode, however this information is from the same source. A dedicated star network of a hub and four remote sites (five nodes total) which has variable speed traffic to the hub and 56 kbps from the hub to the remote sites, would cost between $3,000 for 384 kbps to $6,500 for 768 kbps to $8,000 for T1 per channel. In addition to these fees, GTE Spacenet charges a monthly access fee of $500 per network, regardless of its size, for Metered Services, and a premium charge of $400 for every duplex link activated simultaneously for the "Certain-" option. User Managed Service using satellite control access vice terrestrial access will be charged extra for this use. Interpolating from the above information, the point-to-point Daytona Beach-to-Prescott link could cost between $1,000 to $1,500 per month, based on usage and service. It would be worth investigating if GTE Spacenet offers a reduced rate for non-profit educational institutions.

The space segment charge can be billed either monthly for User Managed and Metered Service private mode; or, hourly or by the minute for Metered Service public mode. "Certain-" service is billed only in hourly increments. Space segment hourly charges are capped at a maximum of 80 hours for a single event for every 7 day period, and a maximum of 200 hours for a single event in a given month. Time incurred past the maximum billing hours for a single event will not be charged.

APPENDIX H
EQUIPMENT LIST

Equipment List

Earth stations are the most tangible component of any satellite network. There is a wide variety of earth station configurations depending on the frequency band used, geographic location of the sites, number and data rates of the channels transmitted from each node, and the satellite and transponder selected for the service. General earth station equipment was presented in Chapter V. Equipment specific to the satellite links used in the GTE Spacenet system is presented here based on information from S. Dalrymple (GTE Spacenet) (personal communication, March 9, 1994 and K. Stevens (GTE Spacenet) (personal communication, January 20, 1994). Note that frequency band channel services are primarily provided using Ku-band capacity, but if the requirements call for use of C-band, it can be supported. Earth stations in C-band are usually larger than those used for Ku-band operation for the same traffic and performance parameters. C-band systems are typically used where Ku-band is not available or where the performance requirements cannot be met in Ku-band because of the variability in performance in Ku-band caused by precipitation. New C-band installations are generally avoided domestically because of the terrestrial interference. This may induce costly frequency coordination of the new sites. C-band earth stations are sometimes more costly than their Ku-band counter parts because of the sizes required for new equipment. However, a plethora of used equipment exists and may be obtained at lower cost than new Ku-band equipment.

Earth stations consist of three primary components: antenna, radio frequency (RF) terminal, and the satellite modem. Additionally, modem control equipment is used in switched service configurations. Earth stations are typically configured to support the specific capacity required by the user. Post installation expansion of capacity may be difficult and require equipment or antenna swap-outs. Therefore, it is important that future expansion requirements are reviewed when planning the earth station.

Antenna size selection is performed either to minimize the cost of the earth station, which includes installation and site preparation cost, or to minimize the cost of the network, including the space segment. GTE Spacenet use two suppliers for their antenna installations, Harris Delta Gain® and Vertex Communications Corporation. Both companies manufacture models for C and Ku-band operation, in a variety of sizes and feed mount types. Both companies also manufacture deicers for earth station locations where the antennas may be subject to interference caused by snow. Both company's antennas offer hub-mounted electronics for low RF noise. The Vertex antennas were arbitrarily chosen for this application.

GTE Spacenet uses several types of RF terminals, depending on the requirements of the transmission. Lower data rates, requiring less power, use solid state PAs with power outputs of 2, 4, 8, and 16 watts. Higher data rates, requiring greater power, use tube-based TWT amplifiers with power outputs of 50, 75, 125, and 300 watts. GTE Spacenet typically uses TWTs for video and multi-carrier operations. Standard configuration for GTE Spacenet RF equipment is to install the upconverter/downconverter, LNC, and PA behind the dish antenna in a hub-mounted canvas box. A waveguide from the LNC and PA travels from this box to the feedhorn, center mounted at the focal point of the dish antenna. Harrisat Alpha™ Terminal Series equipment was selected for this application. National ADL was chosen as the supplier for the feed horn.

The satellite modem is separate from the controller discussed in Chapter V. GTE Spacenet uses both BPSK and QPSK modulation techniques based on the user's network, and depending on the satellite modem chosen. These modems can support a variety of data rates, including both standard and non-standard rates used in most networks. For Switched Channel Service applications, a control port on the satellite modem allows an external system to control the activation/deactivation and selection of the transmit frequency of the channel. The various modem manufacturers select the protocol for the control function. GTE Spacenet uses two suppliers for satellite modems in their installations, Fairchild Communications Group and ComStream Corporation. The ComStream model CM701 was chosen for this application. The CM701 is a variable rate modem, supporting data rates from 9.6 kbps to 2.2 Mbps, both BPSK and QPSK modulation, FEC code rates of 1/2, 3/4, and 7/8, built-in-test capabilities, and auto switching of power supplies from 100 VAC to 240 VAC. The CM701 also has modular construction for flexible earth station setup and ease of repair in the field. This modular construction also allows expansion capability for a built-in multiplexer if further research shows that an earth station at a remote site should call for small multiplexed data requirements.

The CM701 satellite modem is configured for full-duplex operation of SCPC satellite communications. In the transmit mode, the CM701 accepts user data at the data interface module (Data I/O card), directs the data to the modulator where it is scrambled, differentially encoded, FEC convolutionally encoded, and PSK modulated on an IF carrier. This is output at the back of the unit to a standard BNC connector. In the receive mode the reverse occurs. The IF signal is input at a BNC connector, demodulated, decoded, descrambled, and output through the Data I/O card using any data interface card to accommodate RS-449, RS-422, V.35, DS-1, G.703, RS-232, or other interface modules.

The control equipment associated with Switched Channel Services varies slightly between Metered Service and User Managed Service. In User Managed Service configuration, the NCS 1000, a personal computer with proprietary software, is located at the control site. This unit controls network access, call set-up, and supports the reservation function. In addition, there is a dial-up terrestrial modem or satellite modem at the control location and at each node. For this application, Hayes® 2400 baud Smartmodems would be selected for both locations. These modems are connected to the network controller at the central location and to the control port of the satellite modem at each node. In Metered Service, there is a personal computer, or NAT, at each location. The NAT is an IBM PS2 386-based workstation, with at least one megabyte of memory, a 40 megabyte hard disk, a 1.44 megabyte floppy disc drive, and a VGA monochrome monitor. A 485/232 interface adapter by Blackbox Industries is required to link the satellite modem to the NAT. The NAT is connected to the control port of the application modem, and to a long distance telephone line via an internal or external Hayes® Smartmodem^{TM}. The Metered Service controller located in the network operations center in McLean, Virginia, controls network access, call set-up, and maintains billing records for the entire network.

Tables 13 and 14 detail the proposed equipment lists for the C and Ku-band links, respectively. In addition to the equipment listed, both systems would require proper antenna mounts, adequate indoor and outdoor power supply (115 VAC), and adequate cooling of indoor equipment. Determination of antenna location would dictate the required amount of RG-6 IFL. This cable would require a dual run, each for uplink and downlink. Also, the 300 feet nominally listed for the other IFL is control and low voltage power for ODU electronics.

Table 13.
Suggested equipment list for the preferred C-band link.

Multiplexer	Canoga Perkins 3140 T1 with A/D PCM modulator
Phone Modem	Hayes 2400 baud Smartmodem™ with dedicated long distance phone line and db-9 to db-25 cable to controller
Controller	IBM (or compatible) PS/2 personal computer with RS-232 connection to interface adapter
Interface Adapter	485/232 Blackbox adapter to RS-485 from SAT modem
Satellite Modem	ComStream CM 701 with 70 MHz output
Outdoor Unit	Harrisat Alpha Terminal/Integrated Data Terminal One Built-In: IF Unit (6/4 Ku-Band Freq.) Upconverter (6 GHz) Downconverter (4 GHz) Power Amplifier (16W max. GaAs FET) LNC (Hemt, NF < 40 °K)
Feedhorn	National ADL LPF-200 Dual Hybrid Mode Linear Polarized
Waveguide	Minimum ten feet from feed to ODU
Antenna	3.7 Meter Vertex
Cable	Minimum 300 feet of coaxial Heliax RG-6 IF line (IFL) between antenna ODU and SAT modem (2 runs) Minimum 300 feet of Belden multipair IFL to ODU Minimum 300 feet of Belden 8 stranded ground wire RS-422 for SAT modem to MUX link RS-485 for SAT modem to adapter link RS-232 for adapter to controller link DB-9 to DB-25 for controller to Smartmodem® link RJ-11 for telephone line
Additional	Five Gilbert 'N' connectors for IFL Two gallons of Vertex reflector paint for antenna/pedestal

Table 14.
Suggested equipment list for the Ku-band link.

Multiplexer	Canoga Perkins 3140 T1 with A/D PCM modulator
Phone Modem	Hayes 2400 baud Smartmodem™ with dedicated long distance phone line and db-9 to db-25 cable to controller
Controller	IBM (or compatible) PS/2 personal computer with RS-232 connection to interface adapter
Interface Adapter	485/232 Blackbox adapter to RS-485 from SAT modem
Satellite Modem	ComStream CM 701 with 70 MHz output
Outdoor Unit	Harrisat Alpha Terminal/Integrated Data Terminal One Built-In: IF Unit (14/12 Ku-Band Freq.) Upconverter (14 GHz) Downconverter (12 GHz) Power Amplifier (16W max. GaAs FET) LNC (Hemt, NF < 80 ^{o}K)
Feedhorn	National ADL LPF-200 Dual Hybrid Mode Linear Polarized; RPII-Ku 500
Waveguide	Minimum ten feet from feed to ODU
Antenna	2.4/3.7 Meter Vertex
Cable	Minimum 300 feet of coaxial Heliax RG-6 IF line (IFL) between antenna ODU and SAT modem (2 runs) Minimum 300 feet of Belden multipair IFL to ODU Minimum 300 feet of Belden 8 stranded ground wire RS-422 for SAT modem to MUX link RS-485 for SAT modem to adapter link RS-232 for adapter to controller link DB-9 to DB-25 for controller to Smartmodem® link RJ-11 for telephone line
Additional	Five Gilbert 'N' connectors for IFL Two gallons of Vertex reflector paint for antenna/pedestal