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Data Acquisition and Control System for the OLYMPUS Propagation Experiments

by

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Abstract

A data acquisition and control system (DACS) has been designed and constructed for use during propagation experiments with the OLYMPUS satellite. OLYMPUS is a European Space Agency experimental satellite that broadcasts coherent beacons at 12, 20 and 30 GHz and is viewed from Blacksburg, Virginia at an elevation angle of 13.9°. This low elevation angle yields a relatively long atmospheric path which serves to accentuate propagation effects.

The DACS is a custom design which collects propagation, environmental and status information and periodically calibrates external equipment. Beacon signal strength is measured via a hybrid analog/digital receiver. The analog portion of the receiver utilizes the coherency of the satellite beacons to track the 20 and 30 GHz signals to the noise floor. The digital portion of the receiver is contained within the DACS and consists of a stand-alone microprocessor which filters the beacon signal to determine the power in a 3 Hz bandwidth. Additional DACS circuitry collects analog and digital input channels and controls external devices through digital output channels. Digital outputs are used to reference the collected data to known levels by performing periodic calibrations on external equipment. Analog input channels are used to measure quantities including external temperature, wind speed and wind direction, while digital inputs monitor alarm conditions.

The VIEW program utility permits an operator to graphically view data in real time. In addition, collected data is stored to tape without an interruption in data collection. DACS operation has been virtually continuous since data collection was started on August 3, 1990.

Acknowledgements

First and foremost, I am indebted to my parents for their love, understanding and encouragement.

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I would also like to thank all of the Satellite Communications Group members associated with the OLYMPUS project. In particular, Dennis Sweeney for his help in implementing the I and Q detector and William Sylvester for writing VIEW, the real time graphical display program used with the data acquisition and control system.

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Chapter 1

OLYMPUS Propagation Experiments

Transferring wideband information between distant locations on the earth can be accomplished by either a physical connection or by radio. Physical connections include fiber optic cable, coaxial transmission line and submarine cable. Radio based links typically operate in the microwave frequency range and include relays between telephone exchanges and communications satellites. Microwave frequencies are utilized in radio links because the communications spectrum below about 900 MHz has been allocated for other uses. An additional advantage of microwaves is that a relatively small, and therefore inexpensive, antenna can transmit or receive a directional signal which allows multiple users to operate within one geographic area without interference.

Microwave signals require a line-of-sight path between transmitter and receiver. Therefore, the maximum transmission distance for a terrestrial link is physically limited by the earth's curvature. As an example, transmit and receive antenna located 150 feet above average terrain yield a maximum distance between transmitter and receiver of 30 miles. Hilly terrain can increase the distance to several hundred miles yet it is not possible to fulfill transcontinental communications needs. A physical connection is one solution for transcontinental communications.

Physical connections can cover a virtually unlimited distance provided that repeaters are placed in the link to periodically boost the signal. Maintaining a physical

link is relatively simple since a technician can locate the faulty section and repair it. However, if a physical link is required to pass under an ocean, maintenance costs increase tremendously because accessing the cable is more difficult. Another caveat of physical links is that adding another site to the network requires the placement of new cable. One must consider the cost of the additional cable as well as labor and right-of-way costs for the passage of cable through property owned by others. Radio communications offers an attractive alternative: locate a transmitter at one point and a receiver at a second and communications can be established. There are, however, additional problems associated with radio link design. Radio communications is inherently less reliable than a physical link because of signal attenuation from ever changing atmospheric propagation characteristics. However through careful link design, the reliability of a radio link can approach that of a physical link.

Since a microwave link requires a line-of-sight path, geosynchronous communications satellites offer an attractive alternative to overseas and some intracontinental communications. In general, a communications satellite receives a signal from an earth station at an uplink frequency, mixes the received signal to a downlink frequency and retransmits an amplified version of this signal toward the earth. The most common uplink and downlink frequency pairs are 6/4 GHz (C band) and 14/11 GHz (K_u band). To simplify earth station design and to provide continuous availability, communications satellites are placed in geosynchronous orbit. This places the satellite in an orbit approximately 35,780 km above the equator. Viewed from the earth, the ensemble of geosynchronous satellites takes the form of an arc. The number of satellites that can be placed in geosynchronous orbit and which utilize a given set of frequencies is primarily limited by antenna design constraints. A signal transmitted from an earth to a particular satellite must not interfere with adjacent satellites. Presently, the portion of the geostationary arc visible from the United States is virtually saturated with satellites operating at C band while K_u band is becoming increasing utilized. As such, future communications satellites will need to use other frequency allocations, namely

the 30/20 GHz K_a band. Unfortunately, atmospheric propagation effects which are minimal at C band and tolerable at K_u band become very significant at K_a band.

1.1 Atmospheric Effects

A signal transmitted to or received from a satellite travels roughly 40,000 km. Yet only the 20 km of the path directly above the surface of the earth significantly affects the signal[1]. The received signal level varies because of atmospheric phenomena such as stratified layering, gaseous absorption, and rain. Figure 1.1 illustrates several of these effects.

Stratified layering of the atmosphere is responsible for rapid signal fluctuations known as scintillations. As shown in Figure 1.1 scintillations result in both signal enhancement and attenuation. Scintillation amplitude tends to increase with frequency and is also affected by weather conditions. During the early afternoon hours, atmospheric heating causes instabilities within the atmosphere. The subsequent changes in the atmospheric refractive index and effective path length give rise to high scintillation activity. In contrast to scintillations, gaseous absorption is always present.

Gaseous absorption is caused by the interaction of the microwave signal and atmospheric gases and generally results in 1-2 dB of attenuation in the 10-30 GHz frequency range[2]. The primary attenuating mechanism in the frequency range of interest is water vapor resonating at 22.235 GHz. Excluding a 0.25 dB peak at this frequency, gaseous absorption increases from about 0.05 dB at 10 GHz to 0.20 dB at 30 GHz[1]. High levels of humidity and clouds present on the signal path may add an additional 1-2 dB of attenuation. Very high levels of signal attenuation result from the absorption and scattering of microwave signals by rain.

During periods of heavy rain microwave signals can become attenuated to the point where reception is no longer possible. For example, during the rain fade shown in the received signal data of Figure 1.1 the 20 GHz and 30 GHz signals are attenuated by more than 30 dB for longer than 10 minutes during an afternoon thunderstorm.

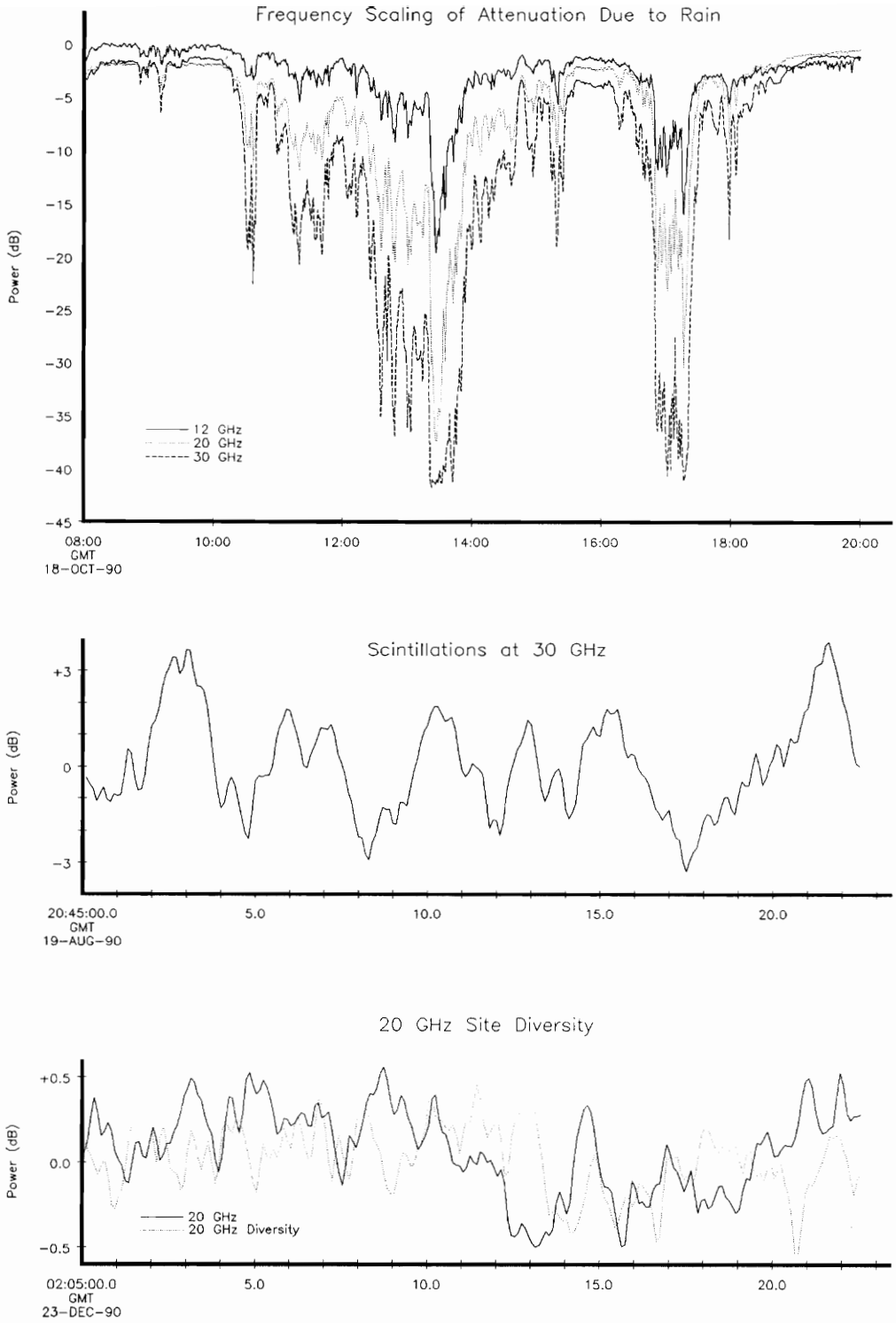

Figure 1.1. Several atmospheric signal attenuation effects observed during the OLYMPUS propagation experiments. Displays were generated from unprocessed raw data. Top graph consists of one minute averages; bottom two show all collected data points.

While this may seem to be a short period of time, downtime on a commercial data link during business hours is at best highly inconvenient and possibly quite costly. Moreover, Very Small Aperture Terminals (VSATs) – which are earth stations with relatively small dish antennas and low cost electronics with minimal reserve power – are gaining acceptance as an inexpensive method of communications for low data rate users. Most VSATs operate at K_u or K_a band with perhaps only a 3 dB margin. Thus, 3 dB of atmospheric attenuation can render a VSAT link useless. Figure 1.1 illustrates an event of this magnitude from a hot and humid August afternoon. Since scintillations can produce short term fades of more than 3 dB, and because almost no statistical data are available for short term fades, additional research is necessary.

The third graph in Figure 1.1 demonstrates site diversity. Site diversity relies on the fact that the atmosphere is non-uniform. Thus two separated terminals each receive a slightly different signal from the satellite. The data shown in Figure 1.1 was collected on an overcast day with two 20 GHz terminals separated by approximately 190 feet. Note that short term differences of 1 dB are clearly visible. The difference between the two signal levels is known as diversity gain. Characterization of diversity gain versus terminal baseline separation for distances of less than several hundred feet is an area requiring study.

Most of the previous work at K_u and K_a band is not suitable for modeling short term fade statistics[3]. Observations were performed at high elevation angles where the atmospheric path is relatively short. Additionally, the time resolution of the data from previous experiments is not adequate for the generation of accurate fade depth and fade duration statistics. A satellite with K_u and K_a band beacons viewed from a low elevation angle would provide the signals needed to generate the statistics mentioned above. The OLYMPUS satellite provides just such an opportunity.

1.2 OLYMPUS Satellite

The OLYMPUS satellite is a European Space Agency (ESA) three-axis stabilized experimental satellite that was launched on July 12, 1989 and placed in geosynchronous orbit at 19° West longitude. In this orbital slot, the satellite is viewed from Blacksburg, Virginia at an elevation angle of 13.9°. This low elevation angle increases the magnitude of atmospheric propagation effects since the signal travels through a large volume of atmosphere.

Four payloads are carried on OLYMPUS. A 12/14 GHz specialized services payload is provided for advanced communications experiments between small earth terminals (VSATs). A television direct broadcast payload with two channels, one for Italian use and one for European use is also carried on-board. Another package, a 20/30 GHz communications payload, is used for point-to-point and multipoint teleconferences and other experimental applications. The final payload is a 12/20/30 GHz propagation package to aid propagation research in the higher frequency ranges[4]. Of these payloads, the 12/20/30 GHz propagation package provides a unique opportunity to study atmospheric propagation effects.

As shown in Figure 1.2 the three beacons provided by the propagation package have the property of being coherent by virtue of a common frequency source. This coherency is extremely valuable for researching the 20 GHz and 30 GHz frequency bands during periods of heavy rain. Since the beacons are coherent, the receiving earth station hardware can be designed to lock to the less fade prone 12 GHz signal and track the 20 GHz and 30 GHz signals down to the noise floor of their respective receivers.

1.3 Desired Experimental Results

The Virginia Tech Satellite Communications Group has identified numerous statistics to be generated from collected data[5]. Of primary importance are fade duration, fade

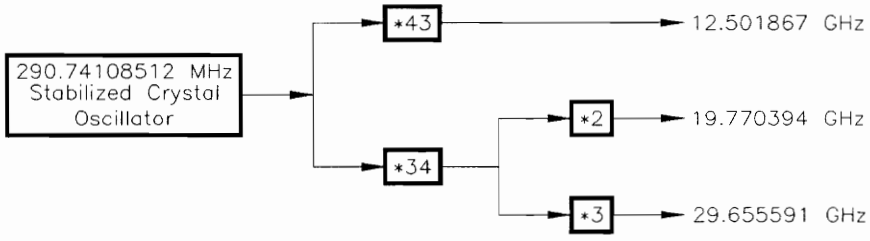

Figure 1.2. OLYMPUS satellite 12/20/30 GHz propagation package frequency plan.

interval, fade slope, and frequency scaling of attenuation. In addition, site diversity, scintillation effects, and uplink power control studies will also be conducted. Even though many analyses will be performed, relatively few data channels need to be collected to generate these statistics. Received beacon signal strength, sky noise temperature and rain rate are the primary data channels needed for analysis.

The major components of the Virginia Tech OLYMPUS experiment are shown in Figure 1.3. The experimental configuration consists primarily of four beacon receivers, four radiometers and two tipping bucket rain gauges. Each receiver outputs a signal representative of the received beacon signal strength. Because the beacon phase noise is quite low, the signal is only several Hertz wide[4]. Therefore, to maximize the signal to noise ratio, the output power is measured in a 3 Hz bandwidth. Under clear air conditions, the output of the beacon receiver is at a nominal level of 0 dB. Signal enhancement, such as that resulting from scintillations, increases the receiver output while rain decreases the output. Even though the receiver outputs a level of 0 dB in clear air, there is still some atmospheric attenuation. This attenuation is measured through the use of a radiometer.

The radiometers chosen for the OLYMPUS experiments are total power radiometers. The radiometer measures the noise power in a frequency band slightly removed from the beacon signal. The noise is assumed to be generated by radiation from molecules in the atmosphere and provides a measure of the absorption by atmospheric gases and water vapor, and hence the attenuation along the signal path. Using calibration information, the noise power is converted to attenuation. This attenuation is then used to calibrate the beacon signal such that 0 dB corresponds to zero atmospheric attenuation. Both the radiometers and the front end RF equipment are highly sensitive to temperature changes and were therefore placed in temperature controlled cabinets. Periodic recording of cabinet temperatures and weather conditions is helpful during data analysis.

Environmental information such as wind speed, wind direction, temperature, rain

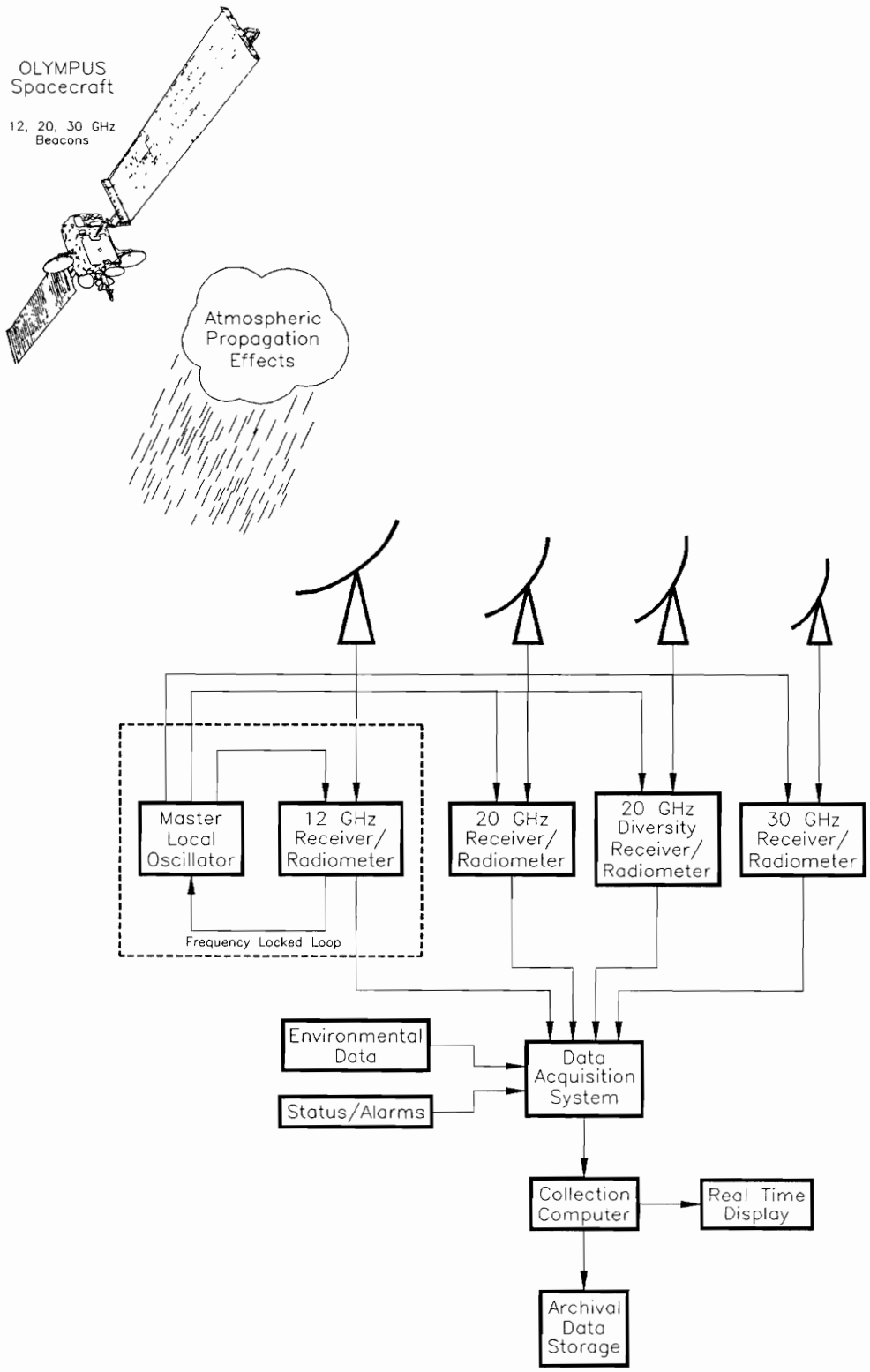

Figure 1.3. Overview of the Virginia Tech OLYMPUS propagation experiment hardware.

temperature, barometric pressure, and humidity is monitored primarily to indicate the passage of storms. Through the synchronous collection of signal and weather information, an expected correlation between scintillation amplitude and weather conditions can be examined. System health is verified by monitoring temperature controlled cabinets, PLO alarms and other status signals. Collection of the data channels described above for future analysis and for control of automated calibration procedures is the responsibility of the data acquisition and control system (DACS).

Figure 1.4 is an overview of data flow in the Virginia Tech OLYMPUS propagation experiments. Experimental data is collected by the DACS and may be displayed in real time. Archived data is input to the preprocessing software which applies calibration information to and locates and flags irregularities in the data. Analysis software then generates numerous statisitical graphs and displays.

1.4 Data Acquisition System

This thesis is primarily concerned with the design, construction, testing, and operation of the DACS for the OLYMPUS propagation experiments. Two tasks are assigned to the DACS: collection of data and execution of timed events. The data collection task continuously acquires and stores beacon strength, radiometer output, system status, and environmental conditions. To reference the collected data to known levels, periodic calibrations are required. These calibrations are considered timed events and are controlled by the DACS. The history of the DACS from its initial design to its present operational state is examined in the remainder of this thesis.

1.5 Overview

This chapter has provided a brief overview of atmospheric effects on satellite communications systems. Rain was shown to be the primary concern in link design for most geosynchronous earth stations. Scintillations are a primary concern for VSAT

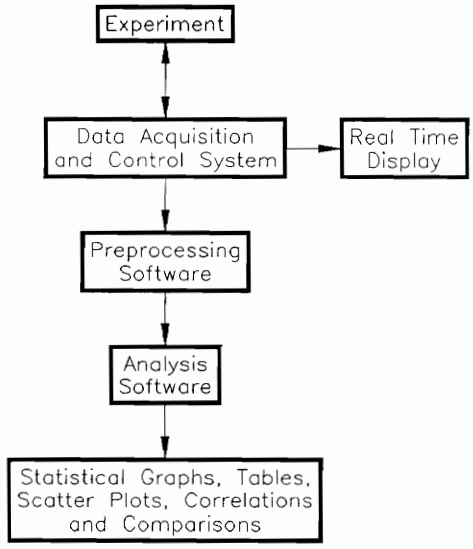

Figure 1.4. Overview of data flow in the Virginia Tech OLYMPUS propagation experiment.

terminals. As a result, future communications links at K_a band will require accurate modeling of short term signal behavior to allow link designers to take appropriate steps to ensure adequate link availability. ESA's OLYMPUS satellite has been chosen as a signal source for Virginia Tech's propagation experiments at 12/20/30 GHz. The OLYMPUS satellite's beacon coherency is used in Virginia Tech's receiver system to keep the 20 GHz and 30 GHz channels locked when their signal level drops into the noise.

Accurately characterizing the effects of rain and scintillations on K_a band signals requires a precise and stable data collection system. The second chapter in this thesis examines the system requirements for the DACS. Initially a list of data channels is presented as well as their respective sampling rates and resolutions. A method of acquisition is then determined for these data. System reliability concerns are addressed and specific design criteria are established. The chapter concludes with a comparison between commercially available data acquisition products and a custom design. The comparison indicates that a custom design is required to obtain accurate beacon signal strength measurements.

Chapter three provides an in-depth description of the DACS hardware beginning with a short history of the hardware development. System-wide design criteria are then established. In addition to the criteria established at the beginning of this project, design techniques subsequently incorporated into the system are presented. A detailed examination of each circuit board and the electrical systems in the DACS is then presented. For each item the complete design requirements are presented. These requirements include functionality, physical size, interface specifications and overvoltage protection. A functional block diagram is then presented. From this diagram and the given requirements, a suitable circuit was derived to meet the design criteria and it is presented in schematic form. An operational description of the circuit is then presented. The discussion of each card concludes with recommendations for future designs.

Software development for the DACS is examined in the fourth chapter. The C programming language along with a minimal amount of 80286 assembly code was chosen for all programs. Functional requirements for each program are then presented. Programming techniques are chosen for each program subfunction and a diagram depicting software flow is presented.

Chapter 5 begins with an operational history of the DACS. Dates when subsystems and functions were added are given with the hope that they may be useful in determining development and construction times for future projects. Uptime statistics are then presented as a measure of system reliability. The thesis concludes by providing recommendations for both improvement to the current design and the design of future data acquisition and control systems.

Chapter 2

System Requirements

Modeling atmospheric effects on 30/20 GHz (K_a band) signals is an area of intense research. Presently, OLYMPUS is the only spacecraft broadcasting coherent beacons both at K_u and K_a band. NASA, however, is scheduled to launch the Advanced Communications Technology Satellite (ACTS) in the second quarter of 1992. ACTS will allow research at K_a band as it carries beacons at nominal frequencies of 20 and 27 GHz[3]. When the satellite becomes operational, NASA intends to fund a number of experimental sites across the U.S. to collect K_a propagation data. To correlate the data measured between experimenters, the experimental sites will be configured identically and maintain accurate time reference by using WWV receivers. Since there will be many sites monitoring the ACTS beacons, distribution of incorrect hardware designs to ACTS experimenters would be costly in terms of time and money. To avoid problems such as these, the Jet Propulsion Lab (JPL), with NASA funding, contracted Virginia Tech to design, construct and operate a propagation measurement system for use with OLYMPUS. Once fully operational, the hardware from the OLYMPUS experiment will be modified for use with ACTS. This system will be replicated and distributed to ACTS experimenters throughout the U.S.

In its OLYMPUS experiment, Virginia Tech is contractually obligated to[6]:

- Measure attenuation of the OLYMPUS 12, 20 and 30 GHz beacons with sufficient accuracy for testing uplink power control algorithms proposed for the ACTS program.

- Measure and characterize site-diversity reception at 20 GHz.
- Collect rain rate information from two tipping bucket rain gauges.
- Operate continuously for one calendar year.

From these requirements, one might assume that only received signal strength and rain rate need to be monitored. However, a number of additional measurements are required to reference the collected data to known levels and to monitor system health and environmental conditions. The next section identifies each of the data channels to be interfaced to the DACS.

2.1 Original Proposal

The Virginia Tech OLYMPUS experiment began in January of 1989 with a contract to produce a system design for a propagation measurement system. The system description which resulted from this contract is different than the presently operational system[7]. The original system specification and the present system are described in this section.

Initially, Virginia Tech proposed to monitor the OLYMPUS propagation beacons with five terminals: 12 GHz, 20 GHz, 30 GHz, 20 GHz diversity and 30 GHz sidescatter. Each terminal was to include an analog receiver and a radiometer. Additionally, a prototype digital receiver designed by Virginia Tech was to be connected to the 12 GHz, 20 GHz and 30 GHz terminals. Digital receivers manufactured by Signal Processors Limited (SPL) were to be connected to the 20 GHz and 30 GHz terminals. Included in the system were instruments to monitor rain, wind velocity, and barometric pressure. Because of budget cuts at JPL, the sidescatter experiment and the purchase of the SPL receivers were deleted from the contract. During 1989 and the beginning of 1990 several system configurations were evaluated. A number of design/redesign cycles were required and in some cases operational circuit boards were scrapped. By the Spring of 1990 a stable system configuration was reached. This thesis examines the design and construction of this final configuration.