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1.3 - T1 VSAT Fade Compensation Statistical Results

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Abstract

New satellite communication systems are steadily seeking to use higher frequency bands to accommodate the requirements for additional capacity. At these higher frequencies, propagation impairments that did not significantly affect the signal at lower frequencies begin to have considerable impact. In Ka-band, the next logical commercial frequency band to be used for satellite communication, attenuation of the signal due to rain is a primary concern. An experimental satellite built by NASA, the Advanced Communication Technology Satellite (ACTS), launched in September 1993, is the first U.S. communication satellite operating in the Ka-band. In addition to higher carrier frequencies, a number of other new technologies, including on-board baseband processing, multiple beam antennas, and rain fade detection and compensation techniques, were designed into the ACTS. Verification experiments have been conducted since the launch to characterize the new technologies.

The focus of this paper is to characterize the method used by the ACTS T1 Very Small Aperture Terminal (T1 VSAT) ground stations in detecting the presence of fade in the communication signal and to adaptively compensate for it by the addition of burst rate reduction and forward error correction. Measured data obtained from the ACTS program was used to validate the compensation technique. A software process was developed and demonstrated to statistically characterize the increased availability achieved by the compensation techniques in terms of the bit error rate time enhancement factor. Several improvements to the ACTS technique are discussed and possible implementations for future Ka band system are offered.

ACTS Compensation Experiment

An experiment was conducted by NASA to specifically characterize the performance of the ACTS T1 VSAT compensation technique. Two ACTS T1 VSATs were located next to each other at the NASA Glenn Research Center in Cleveland, Ohio. Adaptive coding was enabled on one of the T1 VSATs and disabled on the other. Fade and BER data was collected between May 1999 and February 2000. Seven parameters were collected over the 10 months (3 on each T1 VSAT and rain data) providing 6 station years of data for analysis. Only days with recorded rain events are used in the analysis [1]. This is the first time that two T1 VSATs were dedicated to rain fade compensation data collection. Locating the two T1 VSATs in the same location and collecting data during the same conditions allowed for the opportunity to directly compare the affect of coding.

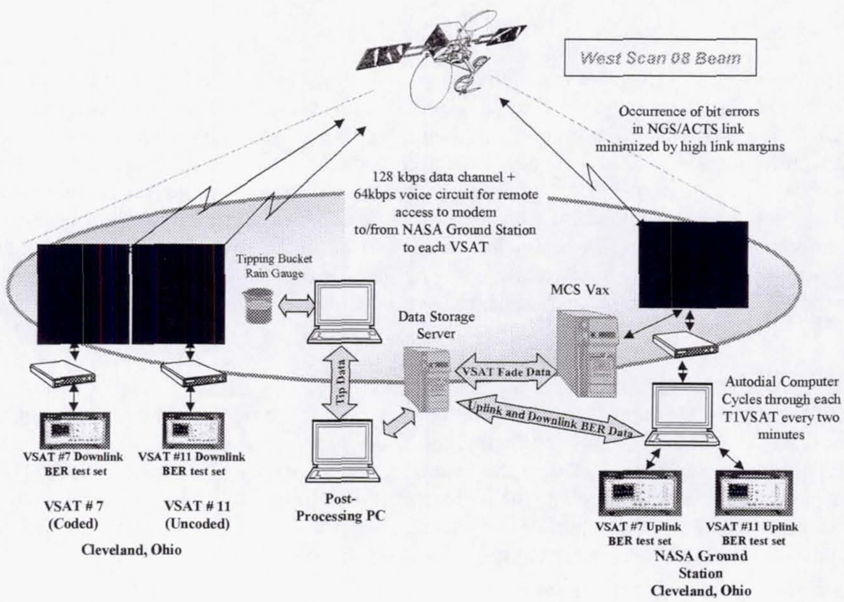
T1 VSAT and ACTS Fade Compensation Description

The T1 VSATs operate with uplink frequencies of 29.236 and 29.291 GHz and a downlink frequency of 19.440 GHz [2], [3]. The rain fade compensation protocol provides 10 dB of margin by reducing burst rates by half and invoking rate ½, constraint length 5 Forward Error Correction (FEC) Convolutional Coding and Viterbi decoding [4], [5]. The result is a reduction of the 110 Mbps burst rates to 55 Msps and the 27.5 Mbps burst rates to 13.75 Msps. The protocol is adaptive in that it includes a decision process so that fade compensation is implemented only when needed using ONSET and CESSATION thresholds. This allows for the sharing of the spacecraft's decoding capacity. The theoretical fixed margin for a T1 VSAT operating in Cleveland, Ohio at a BER of 5×10^{-7} is 3.541 dB for the uplink signal and 7.866 dB for the downlink signal.

Hardware Connectivity

Figure 1 depicts the layout of the equipment and the flow of the data for the compensation experiment. Two ACTS T1 VSATs, labeled T1 VSAT #7 and T1 VSAT #11, were used. Each T1 VSAT was connected locally to an HP 3770B T1 bit error rate test set. A duplicate test set for each T1 VSAT was located at the ACTS Master Control Station (MCS). Whenever these T1 VSATs were configured to operate within the ACTS Baseband Processor (BBP) network, a 6 channel, 2-way data connection (384 kbps) was placed between the test set at the MCS and the test set at the T1 VSAT site. This allowed the uplink and downlink BER to be monitored between the MCS and the T1 VSAT through the satellite. Every two minutes, the BER at the T1 VSAT site (downlink BER) and at the MCS (uplink BER) was recorded on a computer located at the MCS. The downlink BER was obtained remotely by placing a call through the satellite to the BER test set, through the T1 VSAT modem. After these values were recorded, the BER test sets were reset.

Figure 1. HARDWARE CONFIGURATION FOR BER MEASUREMENT



T1 VSAT #7 was configured to operate in the coded mode with an ONSET threshold of 14.25 dB and a CESSATION threshold of 15.35 dB. Compensation was disabled for T1 VSAT #11. Also co-located with the T1 VSATs was a tipping bucket to collect rain. When the water level reaches 1/100" the bucket tipped, and a time stamp recording the time of the tip was stored on a PC.

Compensation Experiment Data Analysis

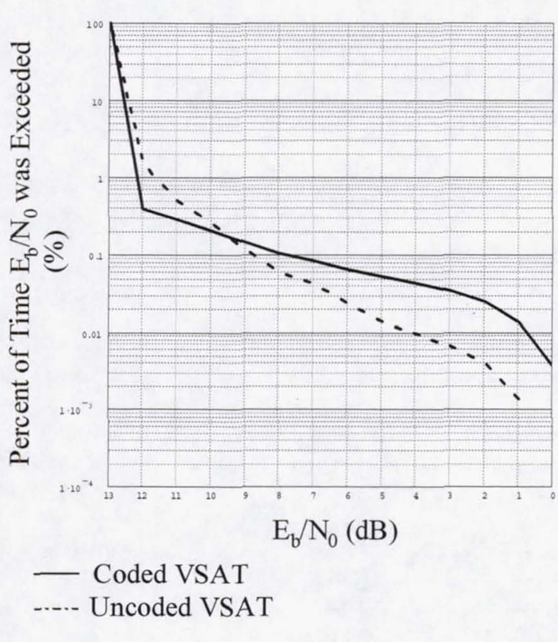
Statistical and time series analysis was performed with the data. Limitations in the experiment configurations and the T1 VSAT operating abilities restricted the range and accuracy of the results. Any E_b/N_0 above 13 dB will have such a high BER that no bit errors will be experienced, so the BER reading during the two minute interval will be equal to zero. This zero value is changed to 5×10^{-9} in the BER database. When the uplink BER reaches 10^{-2}, the T1 VSAT generally looses synchronization, invalidating any BER data. The downlink BER from the remote test set is downloaded to the control station via a modem using the satellite link to the T1 VSAT. When the downlink BER exceeds 10^{-4}, the uplink is so degraded that the BER modem can no longer obtain data. This results in only obtaining downlink BER up to a value of 10^{-4}. Therefore, the valid range of E_b/N_0 (and corresponding uncoded BER) is limited to 6 to 13 dB, which corresponds to an uncoded BER of approximately 10^{-4} to 10^{-9}.

Statistical Results

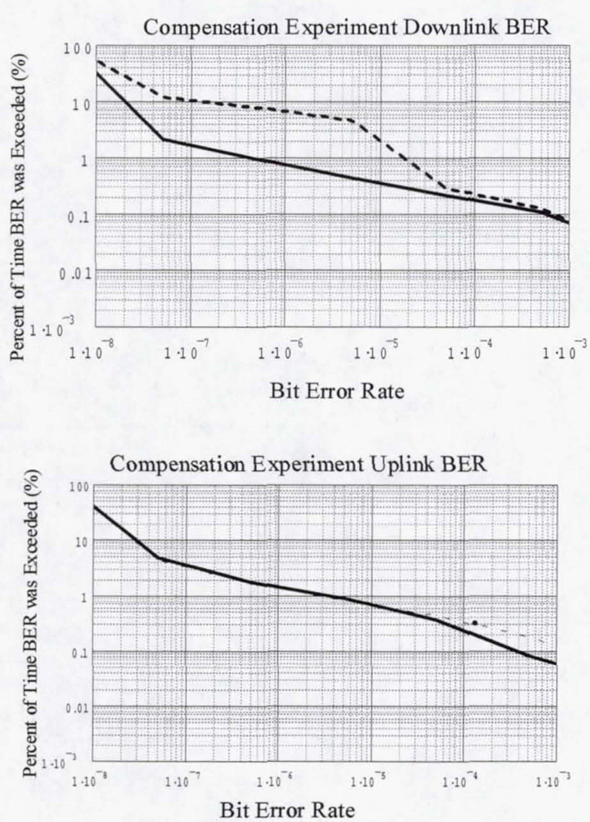
Figures 2 and 3 show the statistical results from the compensation experiment. From Figure 2 it is observed that the dynamic range of the coded T1 VSAT is approximately 6 dB higher than the dynamic range of the uncoded T1 VSAT. This is because the inbound orderwire, used to determine synchronization with the network, is not coded unless the T1 VSAT is in the coded mode. For this reason, the coded T1 VSAT can remain acquired with the BBP network for an additional 6 dB over the uncoded T1 VSAT. Approximately 1 dB difference in fades in the low fade regions is observed. This is due to the different operational characteristics of the hardware. For clarification, it should be noted that the experimental fade distribution should not be compared to that of a typical medium rain zone fade distribution due to the fact that only days with observed rain events are included. This limitation allows for a better opportunity to examine the characteristics of the T1 VSATs compensation technique.

Figure 3 shows the distribution of the downlink and uplink BER for the compensation experiment. The downlink BER improvement in the low ranges exceeds 6% between the coded and uncoded values. Hardware anomalies on the coded T1 VSAT #7 produced bit errors in the downlink signal temporarily when no errors should have occurred. Once the failing units were replaced, the BER returned to its expected value. If all subsystems are operating correctly, the coded T1 VSAT should experience very few downlink bit errors in the limited range which it operates. Also, the characteristics of the measurement system, causing the uplink signal to lose synchronization first, and the limitations of the BER collection modem, reduce the accuracy of the BER distribution results.

Figure 2. DISTRIBUTION OF FADE



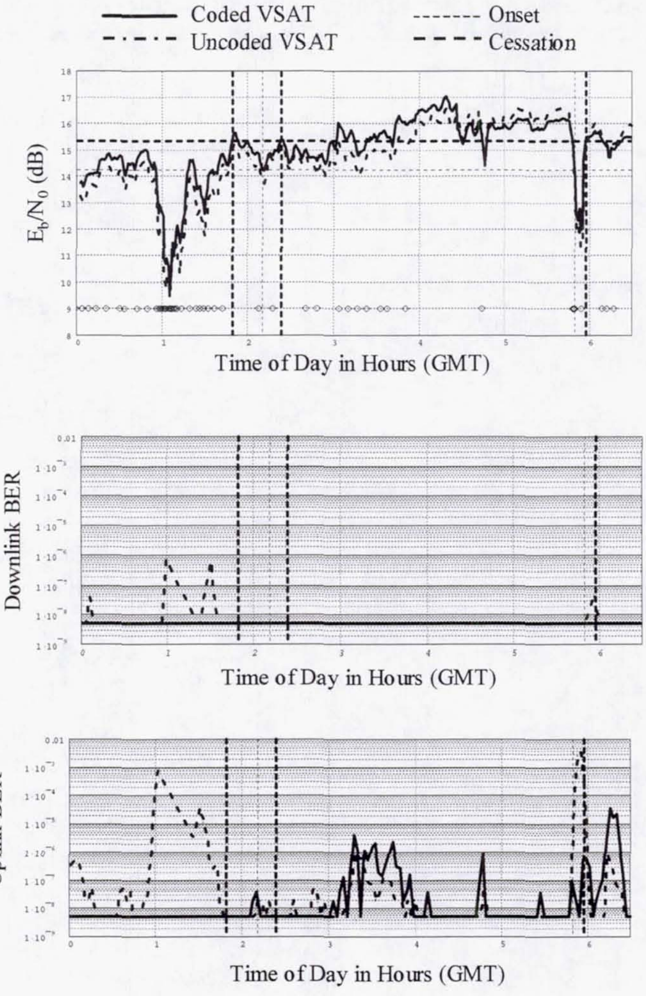
Figures 3a & b. Distribution of Downlink and Uplink BER



Time Series Results

Figures 4 depicts the fade and BER during a typical rain event in a time series representation. The onset and cessation times (shown as vertical dashed lines) are approximations. The ability of the coded T1 VSAT to correct for bit errors can be observed from this figure. Extremely close correlation between the uplink and downlink BER, E_b/N_0, and tip times (shown with a diamond on the top figure) are can be seen. From time 0 to approximately time 1.6, coding is enabled for T1 VSAT #7. Although the downlink BER of the uncoded T1 VSAT reached 10^{-6}, the coded T1 VSAT did not experience any measurable errors in the downlink. In the uplink, the coded BER remained error-free during the rain event occurring between 0 to 2 hours. Once coding is removed at hour 2.25, the uplink channel experienced errors until the E_b/N_0 exceeded approximately 16.5 dB. This shows the effect of setting the thresholds on the downlink E_b/N_0 value. Increasing the downlink thresholds or the use of an additional compensation technique on future satellite systems, such as uplink power control, could be used to compensate for the lower signal in the uplink. Overall performance during rain events shows that there are no anomalies and system specifications are met.

Figure 4: EB/N0, DOWNLINK AND UPLINK BER FOR RAIN FADE EVENT (MAY 24, 1999)



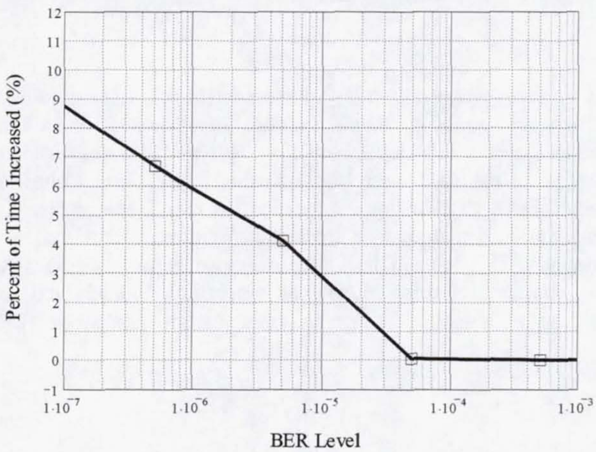
Bit Error Rate Time Enhancement Factor

The bit error rate time enhancement factor is the additional percent of time which a coded link will maintain or exceed a given BER level over a link that is not coded. Once the BER cumulative distribution function for coded and uncoded operation is obtained, the BER time enhancement factor can be obtained by subtracting the availability of the coded system from the availability of the uncoded system at selected bit error rates.

Experimental BER Time Enhancement Factor

The measured BER distribution has been obtained using the compensation experiment and is shown in Figure 4. The experimental uplink BER time enhancement factor is approximately 0 in the range of interest because the T1 VSAT uplink availability was not increased considerably due to the addition of coding, especially in the lower BER values. This was as expected because the decision to enact coding and the threshold limitations are based on the downlink BER. The uplink BER has already exceeded the lower BER values when this decision is implemented. The downlink BER, on the other hand, was greatly enhanced by the addition of coding. Most observed anomalies in the BER values were removed, such as inaccurate values when the T1 VSAT first synchronizes with the network. Some invalid points do remain. If all invalid points were determined and removed, there would be very few coded BER points greater than 10^{-7}, and the enhancement factor for BER values in the 10^{-7} to 10^{-4} range would be approximately equal to the uncoded BER availability.

Figure 5: EXPERIMENTAL BER TIME ENHANCEMENT FACTOR



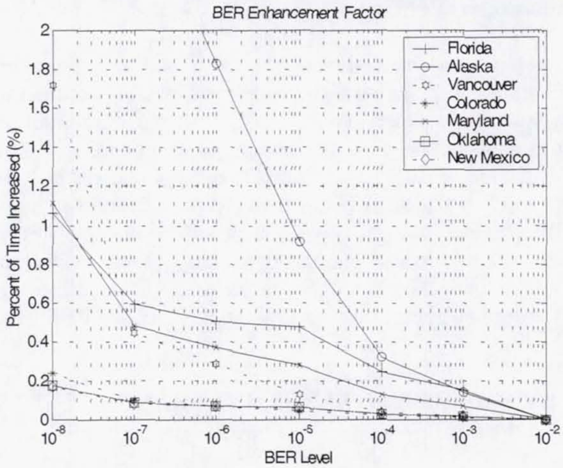
BER Time Enhancement Factor Software Model

The BER cumulative distribution function can also be derived from the fade cumulative distribution function and the performance curves. A software model has been developed to determine the BER time enhancement factor based on the particular environment, modulation and compensation technique. This allows the system engineer to determine whether adding compensation to a system can improve the availability to meet required specifications. This model requires as inputs the measured or propagation model of the fade CDF; the link calculation for the clear sky E_b/N_0 value; and the probability of error for the coded and uncoded modulation. Given this input, the BER enhancement factor is created by first generating a 4^{th} order polynomial for the coded and uncoded functions for the range of E_b/N_0 values that are being evaluated. Then the fade from the fade CDF is converted to E_b/N_0 by subtracting the fade value from the clear sky E_b/N_0. Using the polynomials (or the performance equation if available), the corresponding coded and uncoded BER distribution using the fade distribution is obtained from the system curves. For the range of BER enhancements being considered, the expected coded and uncoded availability is found and the BER time enhancement factor for the selected values of error is obtained by subtracting the coded BER availability from the uncoded BER availability value.

Results from Software Model using APT Data

Using the measured fade CDFs from the ACTS propagation campaign [6], [7], the BER time enhancement factors for each site is derived and the results are shown in Figure 8. BPSK with rate ½, Constraint Length 5 Convolutional Coding and a clear sky E_b/N_0 of 15.3 dB is assumed.

Figure 6: BER TIME ENHANCEMENT FACTOR USING ACTS PROPAGATION TERMINALS



From this figure, it can be shown that coding only adds approximately 0.2 percent additional availability for bit error rates exceeding 10^{-8} for dry rain zones such as Colorado, New Mexico, and Oklahoma. It appears that coding can greatly enhance the availability in Alaska; however, the types of fades experienced in Alaska are due largely to the low elevation angle to the ACTS satellite. At this low elevation angle a terminal experiences greater scintillation in the fade than a CONUS based terminal. Scintillation effects cannot be corrected by adaptive coding, and adjusting the fixed margin to compensate for these events may be a waste of resources. The ACTS Propagation Terminal (APT) located in Vancouver also experiences this phenomena. This result demonstrates that sites in mid-Atlantic and sub-tropical rain zones such as Maryland and Florida, can best be enhanced by coding. With coding implemented in similar zones, the occurrences of BER values exceeding 10^{-8} will be reduced by 1.5%.

Conclusion

The results from the compensation experiment show that the ACTS rain fade compensation technique complies with its design specification with no observed anomalies [6], [7]. The 10 dB of adaptive link margin provided by data compensation provides 6% additional downlink BER availability in the region of interest (10^{-6}). Additional uplink BER availability is provided at the higher BERs because of its higher carrier frequency. The results also show that the fixed margin of approximately 3 dB in the downlink and 5 dB in the uplink is adequate for most rain fades.

The process developed for this paper can assist satellite system engineers in choosing the type of modulation and coding techniques to be incorporated for mitigation of rain fade in their system. With this technique, future system engineers can rely on estimating the expected performance based on the system specifications that they are using. If additional margin is required to meet the demands of the system, additional fixed margin or other adaptive techniques can then be incorporated.

Suggestions for Improvement

The method used to estimate the signal to noise ratio of the ACTS T1 VSAT inherently has limitations and non-linearities. The E_b/N_0 detection method must be reliable between units for mass production in order to allow for reliable transfer of data. Variances of less than 0.5 dB are acceptable, but the ACTS system experienced variances of up to 2 dB between production units which created inaccuracies. The E_b/N_0 detection system must be able to detect the E_b/N_0 value in less than 0.25 seconds to compensate for fades greater than 10 dB..

Additional adaptive compensation techniques, such as uplink power control, would mitigate the number of uplink errors experienced when the downlink data is used to enact coding. Because the technique used to derive the BER time enhancement factor is based on proven theory, the results stated using measured data from the ACTS Propagation Campaign are mathematically accurate. A more controlled experiment to validate the results would be useful in the future. In this future experiment, a number of variables that existed in the past experiment, such as the BER collection method and hardware anomolies, should be eliminated. In addition, known BER performance curves for coded and uncoded operation must be measured.

Suggestions for Implementation on Future Communication Systems

The technique used by ACTS with the suggested improvements would benefit the operation of future satellite systems intending to operate in Ka-band and beyond. These proposed systems, such as Teledesic, Astrolink, and Spaceway, use many of the technologies that allow them to make use of the ACTS techniques. The additional costs required to design and build an adaptive data compensation technique similar to ACTS is minor compared with the cost of adding the same amount of fixed margin. The experiments conducted on ACTS have proven that the quality of the data will not be degraded due to adaptive compensation. If configured properly, employing adaptive compensation will not overload the traffic of the system. These methods, combined with other techniques such as site diversity, can meet most availability requirements in all rain regions.

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1.3 - T1 VSAT Fade Compensation Statistical Results

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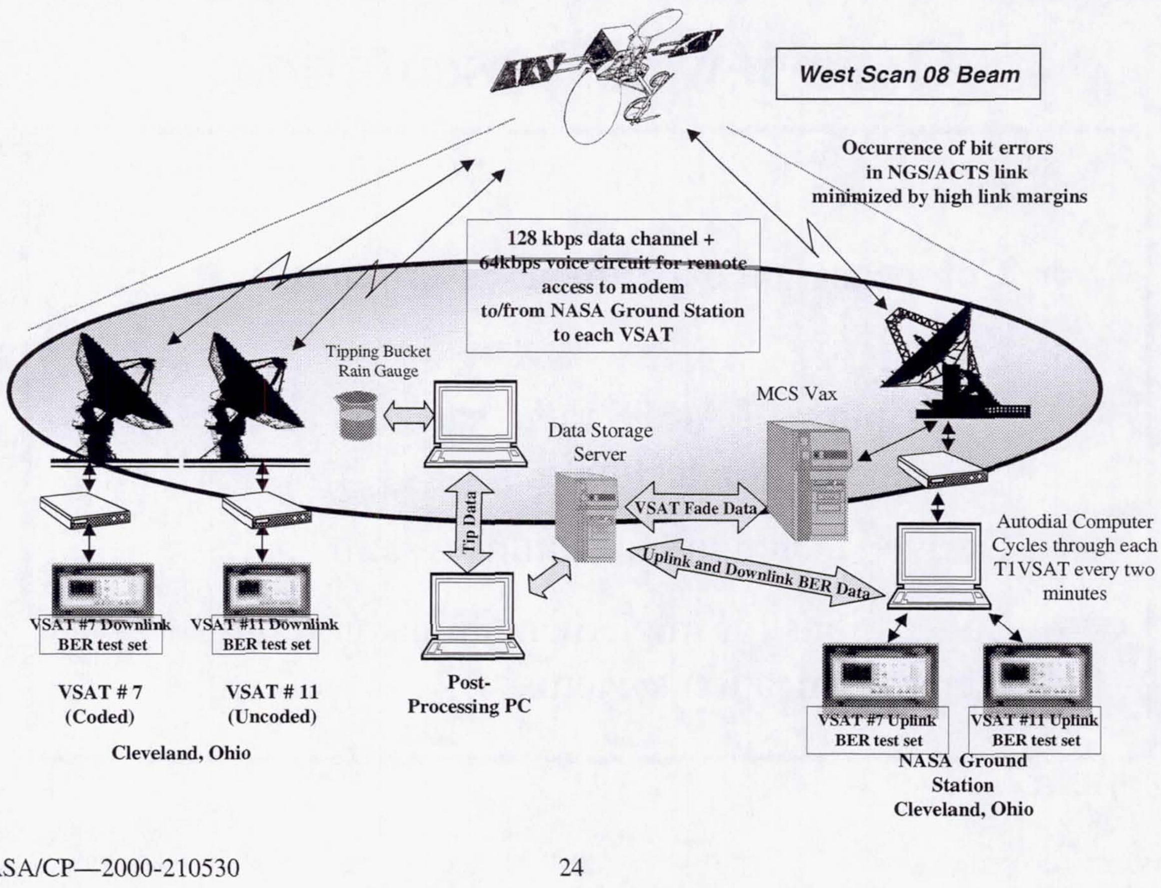
Overview of Presentation

- Objective
- Compensation experiment description and analysis
- Description of ACTS fade detection and compensation technique
- Derived technique for future system analysis
- Suggestions for implementations on future communication systems

Objective

- Perform a statistical investigation and validation of the rain fade detection and compensation algorithm in an end-to-end Ka-band satellite system
- Provide analysis and results from this investigation
- Develop an algorithm to determine the impact of data compensation techniques, which can be used for future system analysis

Compensation Experiment Hardware Connectivity



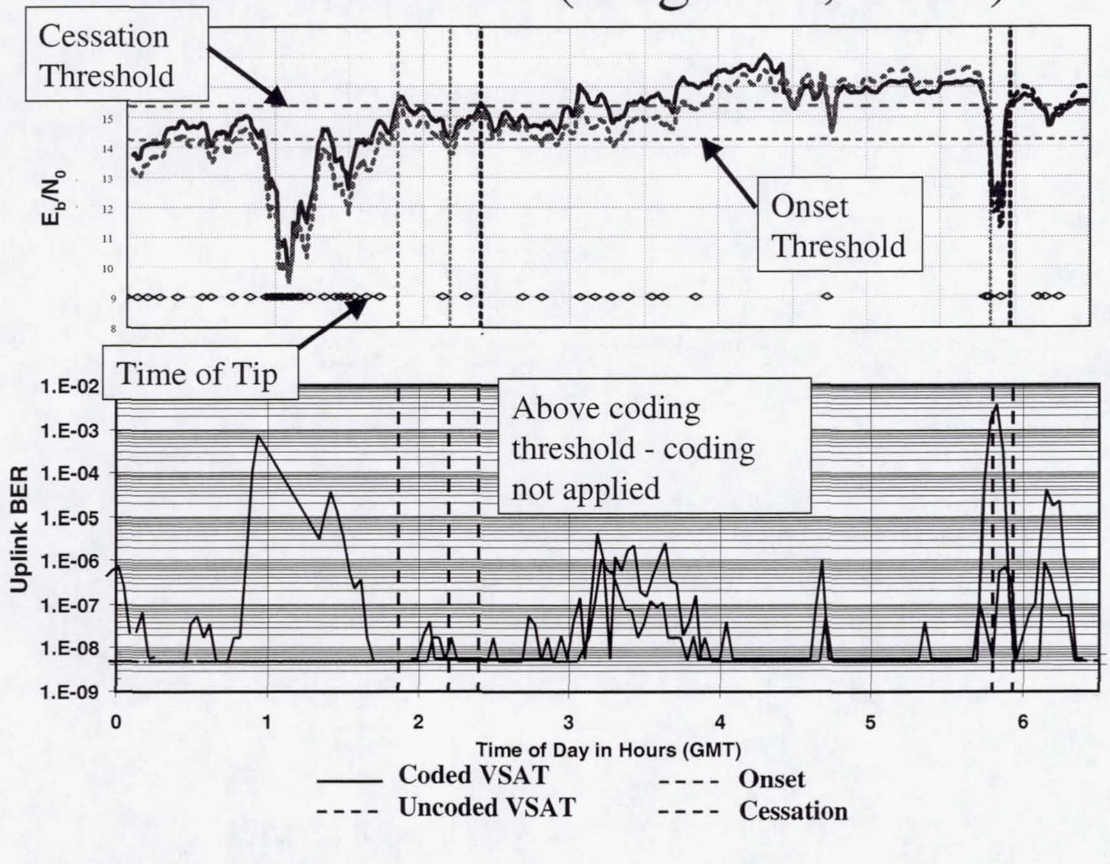
ACTS Fade Detection and Compensation Techniques

- **Fade is measured by determining the quality of the communications link**

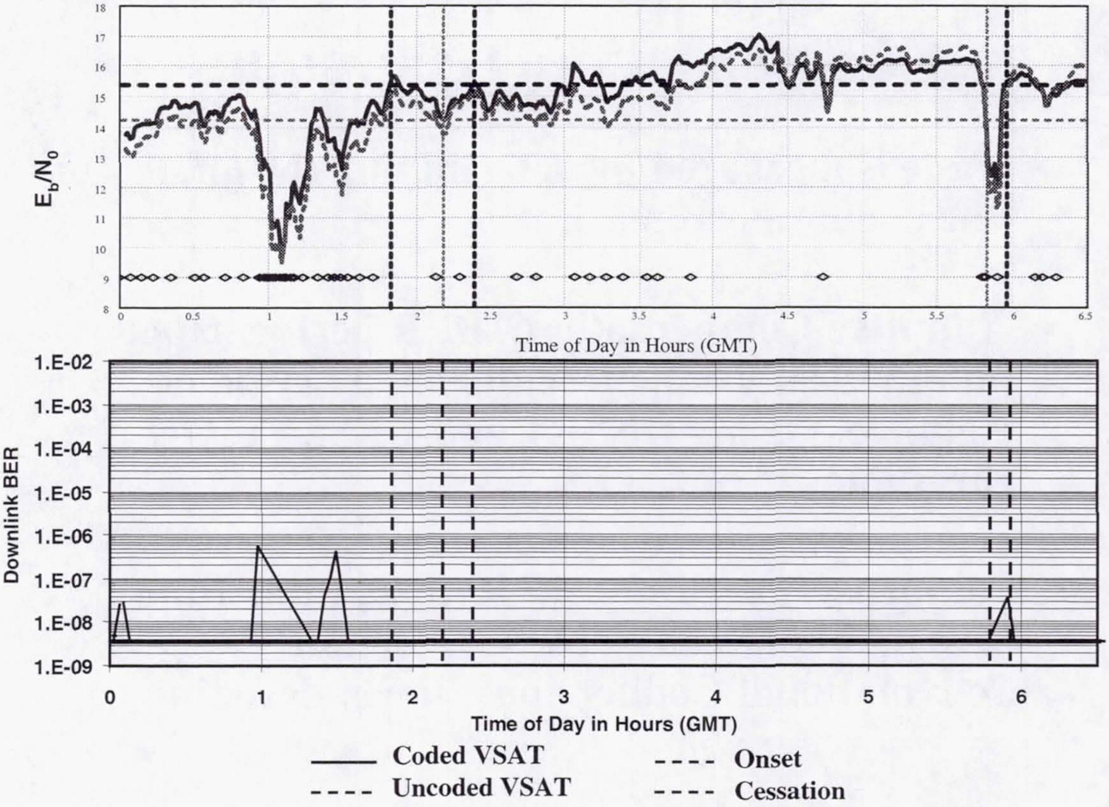
- **Adaptive Compensation: BER performance automatically enhanced during a period of signal loss using ONSET and CESSATION thresholds**

- **Compensation Protocol: Rate ½, Constraint Length 5 Forward Error Correction Convolutional Coding and Viterbi decoding**

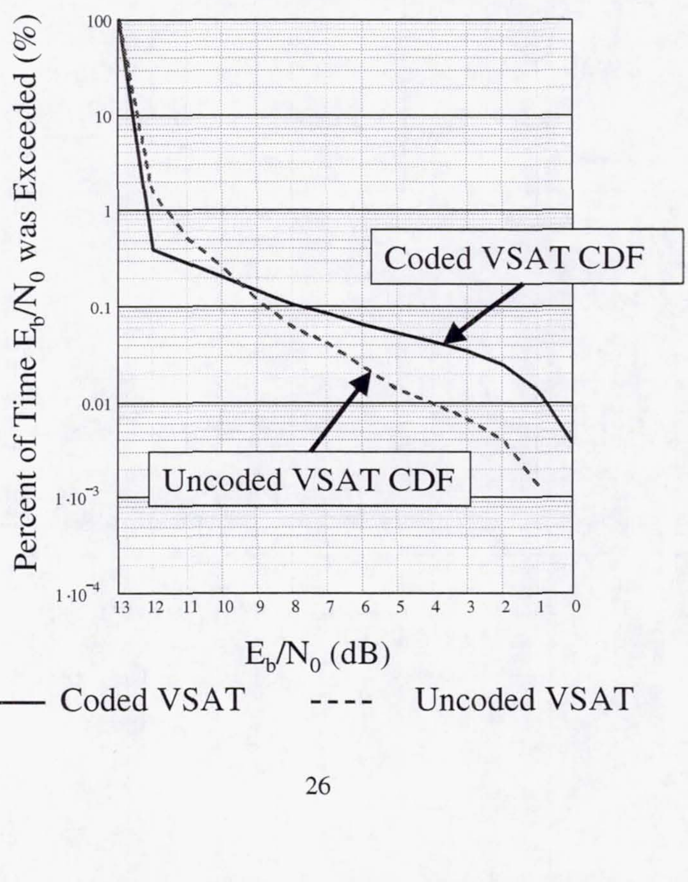
Rain Fade Event (August 8, 1999)



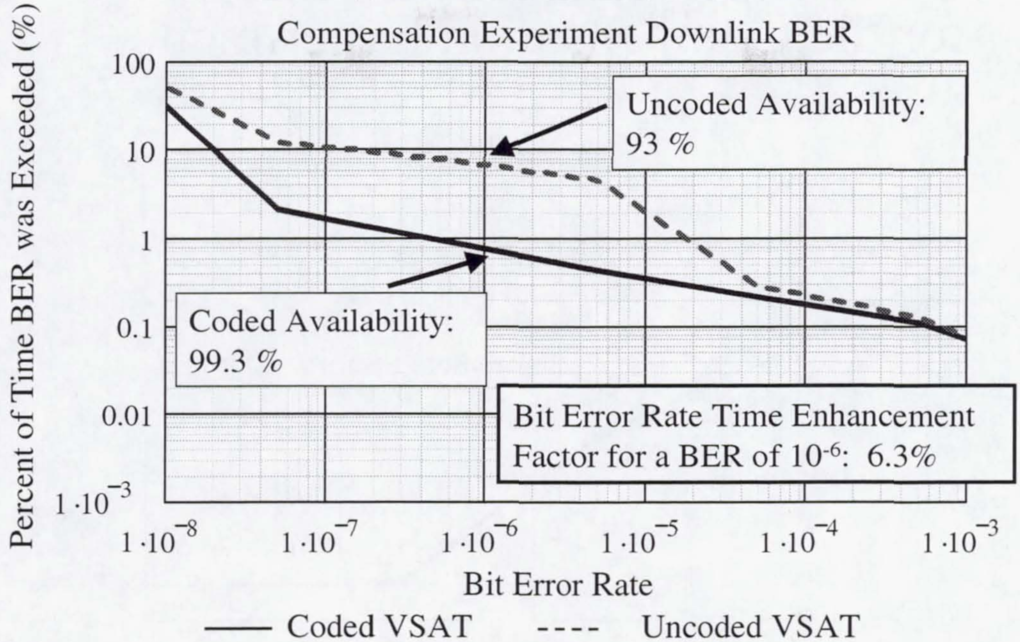
Rain Fade Event (August 8, 1999)



Compensation Experiment Statistical Results

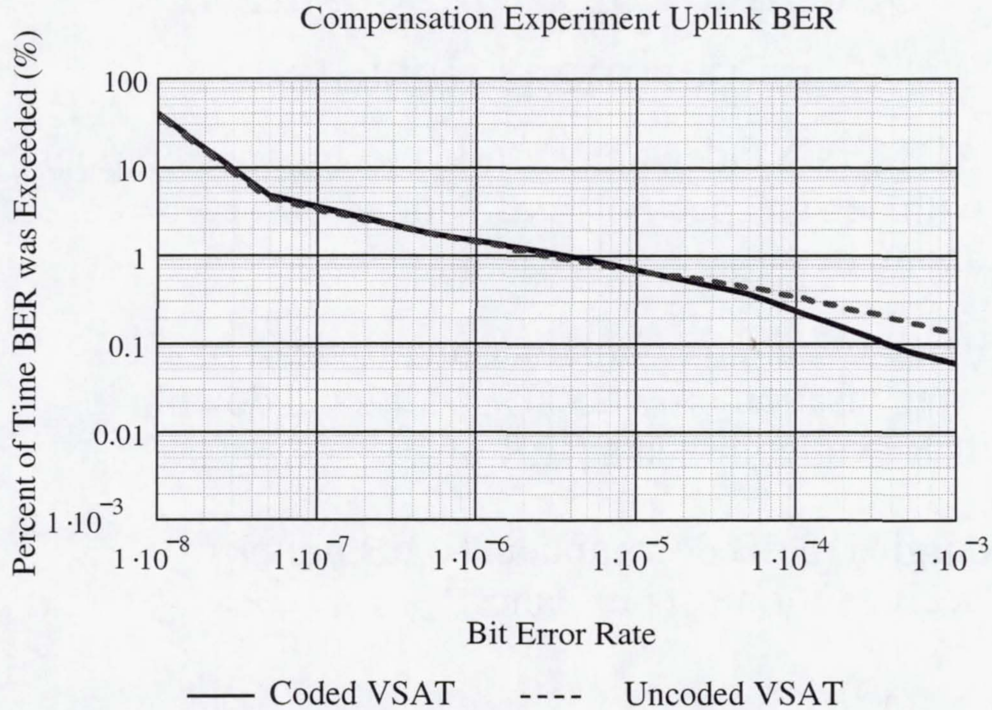


Compensation Experiment Downlink BER CDF

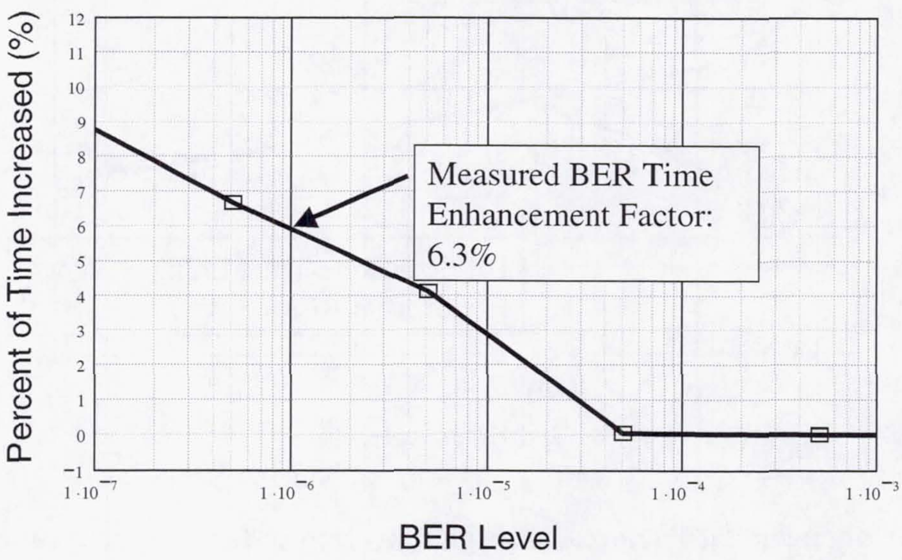


BER Time Enhancement Factor: Additional percent of time which a coded link will maintain or exceed a given BER level over a link system that is not coded.

Compensation Experiment Uplink BER CDF



Measured BER Time Enhancement Factor for the Compensation Experiment



Summary of Compensation Experiment Results

- ACTS rain fade compensation technique complies with design specifications with no observed anomalies
- 10 dB of adaptive link margin provided by data compensation provides 6% additional downlink BER availability at a BER of 10^{-6}
- Margins (3 dB downlink and 5 dB uplink) adequate for most rain fades.

Derived Technique for Future System Analysis

Bit Error Rate Time Enhancement Factor

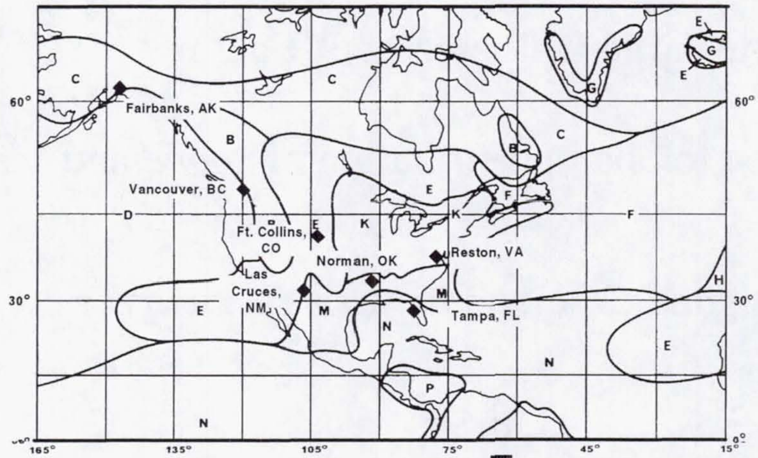
⇒ Measured: Need to obtain distribution of *coded* and *uncoded* BER

⇒ Derived: Using *fade CDF* and *performance curves*

Input to Derived Technique for Computing BER Time Enhancement Factor

- Measured or model data of the fade CDF
- Link calculation for clear sky E_b/N_0
- Probability of error for coded and uncoded modulation scheme (through equation or simulation)

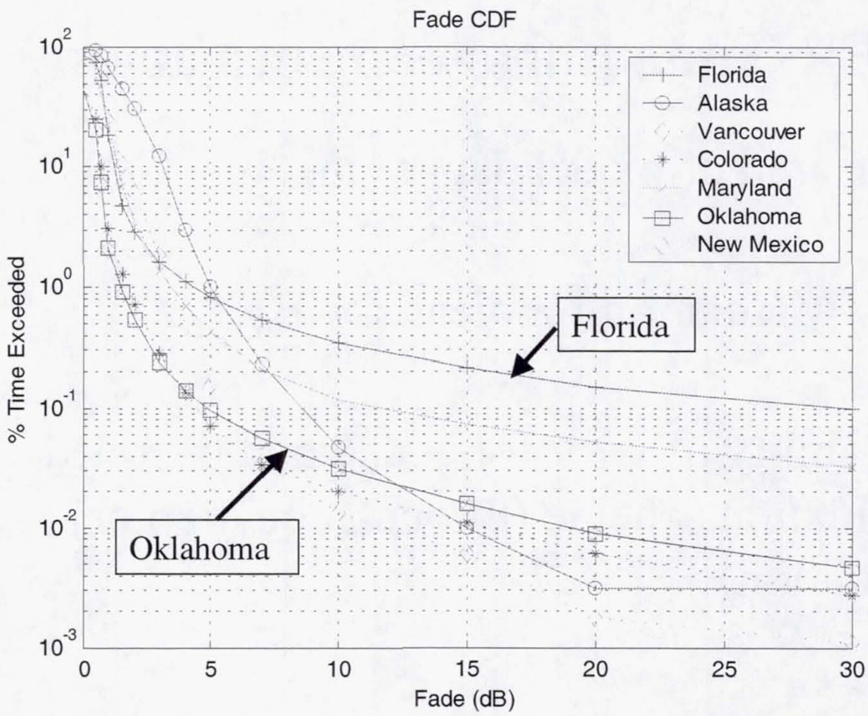
BER Time Enhancement Factor Simulation Example



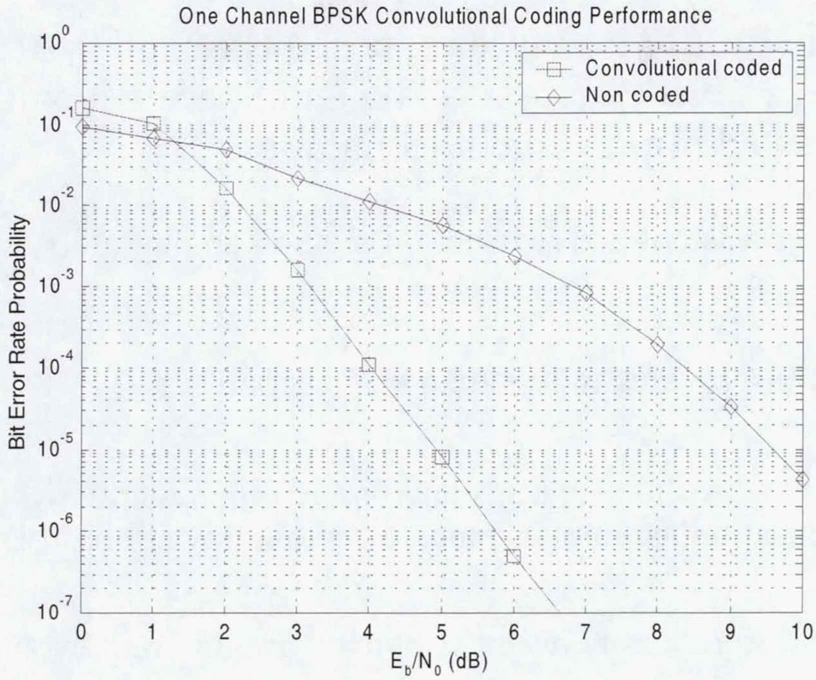
Location of 7 ACTS Propagation Terminals for the ACTS Propagation Campaign

Location	ITU-R Rain Zone	Lat. (North), deg.	Long. (West), deg.	Az. From North, deg	Path Elevation deg.
Vancouver, BC	D	49	123	150	30
Ft. Collins, CO	E	40	105	173	43
Fairbanks, AL	C	65	148	129	9
Reston, VA	K	39	77	214	39
Las Cruces, NM	M/E	32	107	168	51
Norman, OK	M	35	97	184	49
Tampa, FL	N	28	82	214	52

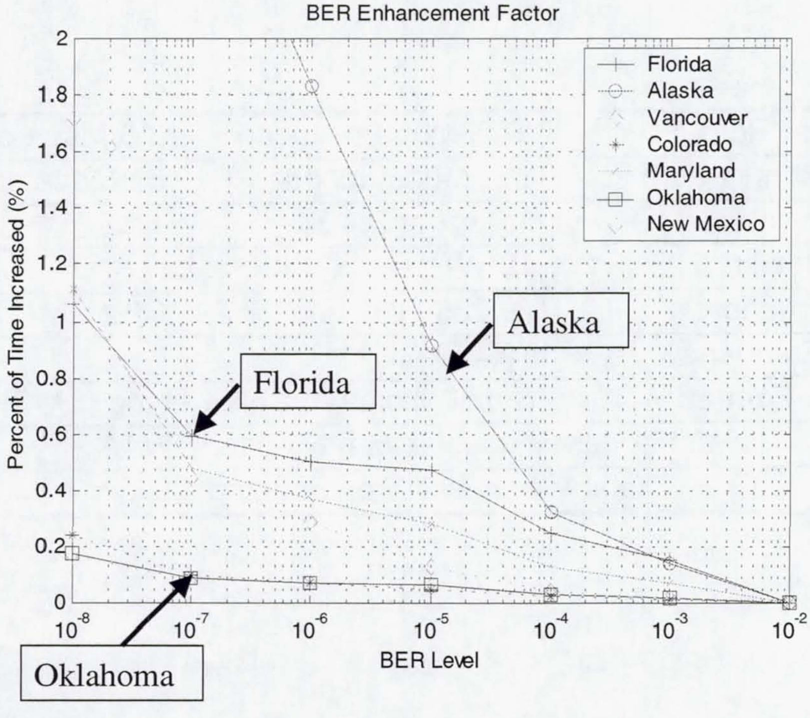
Fade CDF for Simulation Example



Performance of Uncoded and Coded BPSK



BER Time Enhancement Factor Results for Simulation Example



Suggestions for Implementations on Future Communication Systems

Suitable for use in future proposed Ka-band systems such as Teledesic, Astrolink, and Spaceway with suggested improvement techniques:

- Insure consistent E_b/N_0 detection method among units for mass production
- Detect E_b/N_0 value in less than 0.25 seconds
- Optimize threshold settings and/or add other adaptive compensation techniques (such as uplink power control)
- Detect differences between system events and rain events

T1 VSAT Operational Features

Uplink Burst Rate:	27.5 Mbps uncoded 13.5 Msps coded
Downlink Burst Rate:	110 Mbps uncoded 55 Msps coded
Antenna size:	1.2 m or 2.4 m
Transmit Power:	12 W
Uplink Frequency:	29.236 GHz and 29.291 GHz
Downlink Frequency:	19.440 GHz
Modulation Format:	Serial Minimum Shift Keying (SMSK)
Power frequency doubler with Ku-band TWTA	
Dialable bandwidth on demand	

Summary of Compensation Experiment Results

- Limitations of ACTS technique and experiment setup restrict measurable results
  - Limited dynamic range of T1 VSAT
  - 1 minute averaging of fade vs. 2 minute averaging of BER
  - Inaccuracies of E_b/N_0 detection and estimation process
  - Uplink E_b/N_0 not measured
  - Thresholds optimized for downlink
  - BER downlink collection method via satellite