ADVANCED COMMUNICATIONS TECHNOLOGY SATELLITE ADAPTIVE RAIN FADE COMPENSATION PROTOCOL PERFORMANCE

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Abstract

Communication satellite operation at the Ka Band or higher frequencies, and the resultant signal fades caused by rain, have a significant impact on satellite system design. The NASA Advanced Communications Technology Satellite (ACTS), launched in September 1993, provided an opportunity to test and evaluate an adaptive rain fade compensation protocol for a communication system operating at the Ka Band. To date the ACTS protocol has performed exceptionally well in responding to and compensating for fades which without the compensation would have adversely impacted a network ground station's communication channel bit error rate (BER) performance. Other studies have addressed the statistical performance of the protocol over a period of 2 to 3 years. This paper characterizes the performance of the protocol as a function of fade rate, response time, signal filtering and the ACTS Time Division Multiple Access framing structure.

Introduction

The ACTS Baseband Processor (BBP) Mode system consists of the ACTS spacecraft, a network control station (NCS) and two large traffic terminals located at NASA's Lewis Research Center, Cleveland, Ohio and 19 Very Small Aperture Terminals (VSAT) located at various sites in the continental USA.

Spacecraft Architecture - BBP Mode[1]

The ACTS operates in the Ka band; the downlink frequency is 19.44 GHz, and the two uplink frequencies are 29.291 GHz and 29.236 GHz. The downlink burst rate is normally 110 Mbps and the uplink burst rates are normally 110 and 27.5 Mbps. There are two hopping spot beams interconnected by a baseband processor in a Time Division Multiple Access (TDMA) environment. A TDMA frame is 1 ms in duration. The uplink burst is demodulated to baseband and stored in one TDMA frame, routed according to real time traffic demand and stored again in the next frame, then remodulated and transmitted on the downlink in the third frame.

The two hopping beams visit up to 48 narrow spots. They are approximately 200 km in diameter at the 3 dB contour. The two beams interconnect multiple users on a rapidly reconfigurable and on-demand basis. During a 1 millisecond TDMA frame, all beams with active T1 VSATs are visited, with the beam dwelling long enough in each beam to transmit and receive the required traffic. An adaptive rain fade compensation protocol provides signal enhancement during signal fades caused by rain.

Adaptive Rain Fade Compensation Protocol

ACTS adaptive rain fade compensation is the process whereby a VSAT's data channel BER performance is automatically enhanced during a period of signal loss due to rain attenuation. The rain fade compensation protocol provides 10 dB of margin by reducing burst rates by half and invoking rate 1/2, constraint length 5 Forward Error Correction coding. The result is a reduction of the 110 Mbps burst rates to 55 Mbps and the 27.5 Mbps burst rates to 13.75 Mbps. The protocol is adaptive in that it includes a decision process so that fade compensation is implemented only when needed. This allows the sharing of the spacecraft's decoding capacity. The decision process, which determines the need for compensation in real time, makes use of the downlink signal level, a FADED threshold and a CLEAR threshold. Two thresholds are used to account for noise in the signal level measurement and to add stability to the decision process. The FADED and CLEAR thresholds are set individually per VSAT based on each VSAT's BER performance.

A downlink signal level measurement is made by each VSAT[4] and transmitted to the NCS. Hardware and software in the VSAT samples the demodulator "eye" pattern of the center bit of 1's and 0's triplets in the downlink burst 9600 times in a 75 ms superframe. The Mean To Variance method is then applied to the samples resulting in an estimated value of the signal level once every 75 ms. Each estimated value is stored in a first in first out register. The signal level reported to the NCS is the average of 13 estimated values; i. e., it is a 1 second sliding average that is reported once every 150 ms.

The reported signal levels, the two threshold settings and a smoothing function constitute the NCS fade compensation decision process. The NCS instructs affected VSATs to operate in either the FADED mode or the CLEAR mode as appropriate based on this decision process. The NCS applies a smoothing function to the downlink signal level data. The smoothing function, a first order tracking filter, is represented by the equation:

$$y_k = y_{k-1} + a(x_k - y_{k-1})$$

where

x_k = input signal level
y_k = output signal level
a (the filter constant) = $2\pi B t$
B = filter bandwidth in Hz
t = time between samples (150ms)

The filter bandwidth, B, is an operational variable which determines decision delay in reacting to a fade event. Its impact is addressed later in this paper. The output of this filter is used to determine the need for compensation. If the output drops below the predefined FADE threshold, the NCS orders compensation to be implemented for that VSAT. Compensation remains implemented until the output of the NCS filter rises above the CLEAR threshold (usually set about 1 dB higher than the FADED threshold). When this level is crossed, the fade event is assumed over and compensation is removed. It should be noted that the decision to implement compensation on the uplink is based on the downlink signal level. Therefore, compensation is always implemented or removed simultaneously from both the uplink and downlink. Only downlink VSAT signal level data is available for analysis. Therefore, all Eb/N0 values referenced in this paper refer to the VSAT downlink signal level.

The ACTS adaptive rain fade compensation protocol was designed to ensure a T1 VSAT bit error rate of no worse than 5E-7 99.5% of the time. T1 VSATs are designed to operate with 5 and 3 dB of uplink and downlink margin, respectively. The implementation of FADED or CLEAR operation is designed to accommodate a fade rate of at least .25 dB per second, to have no impact on VSAT throughput and to be "hitless" in the transition from CLEAR to FADED operation and back. A statistically significant number of transition events were logged in previous testing leading to the conclusion that the rain fade compensation protocol is fully functional having no impact on throughput and introducing no bit errors. The throughput experienced by the user is not affected by the application of compensation because the burst duration is doubled to account for the halved burst rate and doubled again to account for the rate ½ FEC.

TDMA Frame Architecture

The 1 millisecond TDMA frame is divided into 1,728 equal time slots, each corresponding to the time required to transmit one 64-bit word at the 110 Mbps clock rate. A T1 VSAT can transmit up to 28 64 kbps traffic channels, providing for a maximum throughput of 1.792 Mbps. Figure 1 shows a schematic of a single 1 ms TDMA downlink frame.

The frame is divided into two regions: the CLEAR and FADED regions. The CLEAR region carries the timing information and traffic for each VSAT operating in the CLEAR mode; i.e., the no rain condition. The FADED region is a "reserved" region, the size of which is set by NCS operators at system startup and is generally around 1000 slots. It consists of the "fade pool", which is used to carry the timing information and traffic of VSATs operating in the FADED mode, as well as the VSAT Acquisition Window, which is used to bring VSATs into the network. The position and duration of all bursts to and from T1 VSATs within these two sections is determined by the NCS based on the number of T1 VSATs and their operational requirements (mode of operation and number of traffic channels). This operational schedule is called the Burst Time Plan (BTP). It is modified by the NCS each time there is a change in traffic or a VSAT requires rain fade compensation. This fixed fade pool architecture was used to reduce the differences between FADED and CLEAR BTPs and thus to reduce the calculations performed by the NCS CPU. This in turn resulted in a faster implementation of fade compensation over an architecture that uses no fade pool, for example.

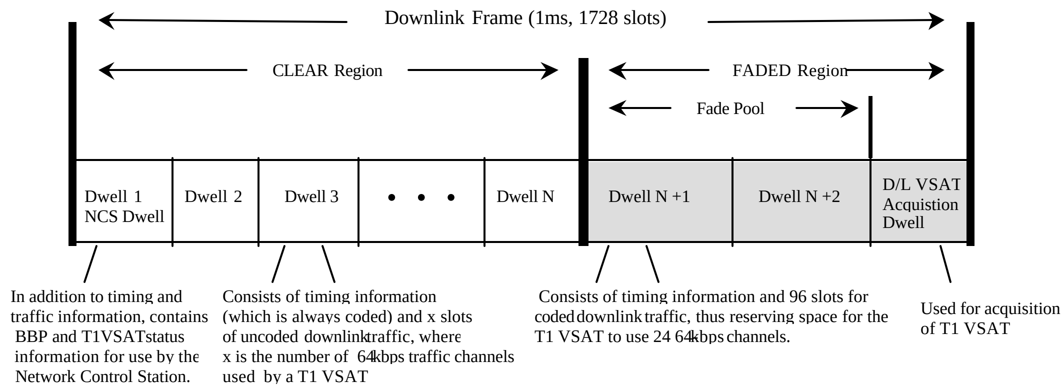

Figure 1. ACTS Downlink TDMA Frame Architecture

The amount of time a spot beam dwells on a given T1 VSAT is dependent upon the number of traffic channels, which the VSAT is using. In the CLEAR region, the dwell time to number of traffic channels ratio is 1:1. So the amount of time spent on a given VSAT within a dwell is equal to the sum of the slots of timing information plus one slot for each 64 kbps traffic channel utilized by the VSAT. In the FADED mode of operation (which also includes coding and burst rate reduction), the number of slots necessary to provide the same throughput is 4 times the number of traffic channels being utilized by the VSAT. The first factor of two compensates for the burst rate reduction, and the second factor of two accounts for the reduced *information rate* resulting from encoding. By lingering on a FADED VSAT 4 times as long as a CLEAR VSAT using the same number of channels, the effective throughput of a VSAT operating with fade compensation remains unchanged. A more detailed explanation of the frame architecture can be found in references 2 and 3.

Analysis

VSAT downlink signal fade data was analyzed to characterize the performance of the ACTS Adaptive Rain Fade Compensation Protocol. Due to the tremendous volumes of data generated, the NCS nominal reporting interval for signal data is 1 minute with a maximum, minimum and average fade value specified for each 1-minute period. However, to more precisely characterize the fade compensation protocol, special selections of data at 150 millisecond intervals were obtained. A total of 16 rain event data samples were examined for this paper. A given rain event can include multiple threshold crossings due to the varying nature of rain. All data samples examined pertained to VSAT 11, located in Boca Raton, Florida, as this location was subject to heavy rainfalls. The 150 ms data used are the raw, unfiltered signal level data, which is reported to the NCS by the VSATS. It is this raw data which is input into the NCS decision filter protocol. A model of this protocol was created using the NCS tracking filter equation to reproduce the filter output on which the decision to make a change in compensation status is based. This allowed filter bandwidth (decision response time) and compensation threshold settings to be varied in order to either reproduce the NCS response to an event based on actual operational settings, or to determine how the system would have reacted had these settings been varied. A first order digital low pass filter function (shown below) was incorporated into the model so that signal variations due to scintillation could be filtered out of the signal level data.

$$y_k = \alpha y_k + (1-\alpha)/2 * (x_k + y_{k-1})$$

where

$\alpha = (1-\sin(a))/\cos(a)$
$a = 2\pi Bt$
B = 3 dB cut-off frequency in Hz
t = sampling interval (150 ms)

This method was applied to all data samples. For all data analyzed for this paper, the 3 dB cut-off frequency was set to .01 Hz since most scintillation effects are removed at this value.

Results and Discussion

Protocol Performance as a Function of Fade Rates

Only the fade rate at the point of threshold crossing is significant in assessing the response of the ACTS fade compensation protocol to various fade rates. Once compensation is enabled the fade rate becomes relevant only in determining how quickly the signal will degrade to a point at which the VSAT cannot maintain synchronization.

The NCS filter function was used to establish the time at which the decision was made that the signal was below the FADED threshold. The low pass filter function was used to calculate fade rates using a 2 second rolling average. All 16 events were processed in this manner. For all events the FADED threshold was set at 14.3 dB and the CLEAR threshold was 15.3 dB. Of the 16 rain events examined, the steepest fade rate at the level of the FADED threshold crossing was –0.068 dB/sec. The average of all FADED threshold crossings (a total of 39) was –0.031 dB/sec. The ACTS system was designed to react to a fade as steep as .25 dB/sec, however, rates approaching this limit are rarely, if ever, seen at the FADED threshold level settings optimal for ACTS VSAT links.

As observed in the samples studied, rain events tend to have a slow varying "shoulder" leading into a steep, faster decline in signal level. The design requirement for the decision response time and the implementation response time is a function of where on the fade slope curve the minimum BER operating point is located. For ACTS this point was typically near the "shoulder" region. The threshold settings for the ACTS VSATs are based on each VSAT's link margin relative to the 5E-7 BER operating point and the requirement that the BER not degrade below 5E-7 for fades of 15 dB or less. Operational data for VSAT 11 indicates that the Eb/N0 resulting in a BER of 5E-7 is approximately 12.5 dB. All 16 events were input into the model, with the FADED threshold set to this value. The average fade rate of all FADED threshold crossings rose to -. 047 dB/sec, with a maximum threshold crossing rate of -. 12 dB/sec. This threshold level, which represents the limit at which acceptable BER performance is expected, appears to fall just at the edge of the "shoulder" area of most rain events. Beyond this point the fade rates increased more significantly. However, even in the regions of steep fade, rates of .25 dB/sec are not common. Figure 2 illustrates a rain event for VSAT 11 on May 29, 1997 between approximately 0250 and 0300 GMT. This event includes the steepest fade rate experienced in all of the events examined. Between 0253 and 0254 GMT the fade rate reached its peak of -.27dB/sec.

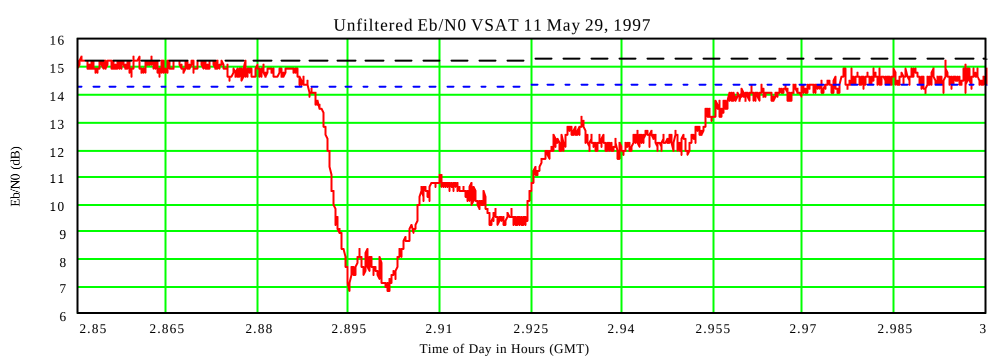

Figure 2. The unfiltered, incoming VSAT 11 Eb/N0 data for May 29, 1997. The dotted line represents the FADED threshold and the dashed line represents the CLEAR threshold.

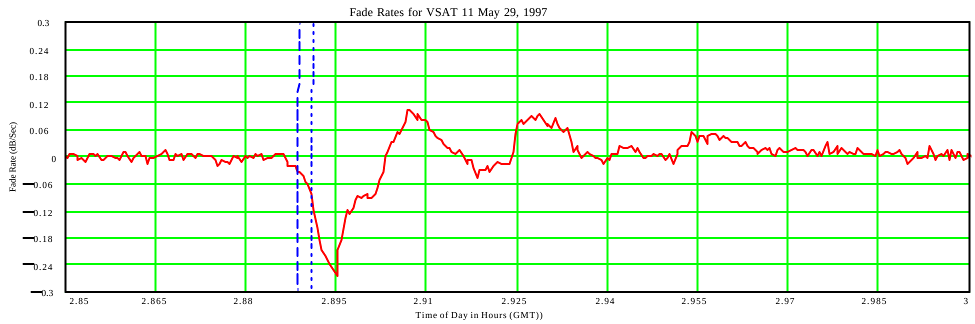

Figure 3. The fade rates for VSAT 11 for May 29, 1997. The dashed line represents the FADED threshold crossing point. The dotted line represents the 5E-7 BER operating level crossing point.

Figure 3 shows the fade rates corresponding to this event along with the threshold crossings for both the operational setting of 14.3 dB and the 5E-7 BER operating point at 12.5 dB. The fade rate at the operational threshold crossing is -. 03 dB/sec while the rate at the 5E-7 BER threshold increases to -. 10 dB/sec. Beyond this point (past the "shoulder") even steeper fade rates are experienced. The results of this analysis for ACTS suggest that threshold margins for maintaining optimal BER performance tend to lie in the "shoulder" region and that the ACTS .25 dB/sec fade rate design specification could be significantly reduced.

Protocol Performance as a Function of NCS Filter Bandwidth

The amount of filtering applied to the incoming VSAT signal dramatically impacts the response of the fade compensation protocol. Reducing the filter bandwidth results in less signal fluctuation due to scintillation but results in a slower system response to a rain fade. Increasing the filter bandwidth allows for more scintillation to be included in the filter output, but causes less delay in tracking a rain fade. With limited fade pool resources, a balance must be struck between being too conservative in applying compensation in order to preserve limited resources and maintaining an acceptable VSAT BER by implementing compensation prior to degraded VSAT performance. Of course, the level at which the thresholds are set also impacts the system's response to a fade event. To illustrate the impact of filter bandwidth, the fade event depicted in Figure 4 was examined using 3 different filter bandwidths: 1.06 which was the operational setting, .01 which is the lowest allowable value, and .21 which represents a state in between the two limits. This sample represents a rain event encountered at VSAT 11 on May 11, 1997 between approximately 0810 and 0917 GMT. The unfiltered, incoming VSAT signal level as well as the threshold settings are illustrated. The FADED threshold was set at 14.3 dB and the CLEAR threshold was set at 15.3 dB. During this rain event the VSAT lost synchronization at 08:43 due to high fade, but was reacquired at 08:46 with compensation immediately installed.

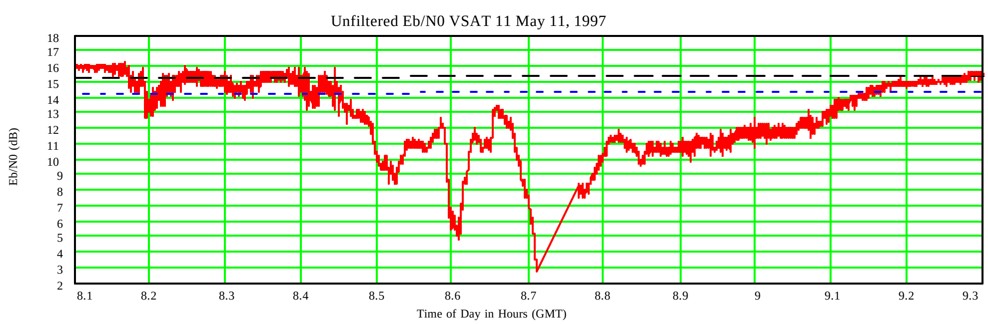

Figure 4. A rain event at VSAT 11 on May 11, 1997 during which the fast-varying nature of the signal caused the VSAT to switch between FADED and CLEAR modes numerous times.

In the first instance, setting the filter bandwidth equal to 1.06 results in a filter constant of 1. Hence, the output of the NCS filter equaled the input. Table 1 lists the resulting changes in compensation documented by the alarms received by the NCS. Column 2 lists the time of the NCS alarm indicating a change in status and column 3 indicates whether compensation was implemented or disabled. Of the 30 total changes in compensation status, most occurred during the onset of the rain event. In the 17 minute span between 08:10, when compensation was first implemented, through 08:27, when compensation was last applied prior to the loss of synchronization, compensation status changed 28 times. This includes a 43 second period between 08:23:54 and 08:24:37 when compensation status changed 8 times. The rapid reconfiguration of compensation status is due partly to scintillation causing the signal to bounce between the thresholds, but also due to the fact that the threshold settings were at the "shoulder" of the rain event. The signal stayed in this region for a relatively long time before degrading at a more rapid rate. Setting the threshold levels in this area ensures that the VSAT BER does not drop below the design specification value of 5E-7 before compensation is enabled. For this event no bit errors were encountered on the downlink. (At 8:23:56 and 8:24:18 it appears as if coding were removed twice consecutively without an implementation. However, system information indicates that some NCS alarms were lost during this interval. What appears as two consecutive implementations of coding at 8:26:44 and 8:46:05 is the result of the VSAT losing synchronization while compensated due to the large fade, then being reacquired during the fade event with compensation automatically implemented upon acquisition.)

VSAT fade data for the same event was next input into the model with a filter bandwidth of .01. This represents the lowest valid input for filter bandwidth. At narrower bandwidths, the effects of scintillation become less significant, but since the system is now responding to a signal with little fluctuation, the point at which the threshold is crossed will be delayed. Table 2 shows the changes in status times related to the event shown in Figure 4 with the .01 filter bandwidth. Since this data was not operationally obtained, no corresponding NCS alarm messages exist to support the calculated threshold crossing times. In this case compensation status is only altered 4 times for the entire event. Only one case of implementation and removal of compensation occurred in the "shoulder" of the rain event prior to the steep fade portion of the event. This configuration is less taxing on the NCS CPU. That is, fewer BTPs must be calculated. However, the fade pool is occupied continually for a longer period of time, and the VSAT operates without compensation for certain periods in which compensation was applied in the previous example. Table 3 shows a third example with a filter bandwidth of .21. In this case the system changes compensation status 12 times during the event. This represents a performance between the two extremes. This allows a balance between BER performance and the utilization of satellite FEC decoding resources.

Protocol Performance as a Function of Total Response Time

As mentioned previously, the NCS decision model was employed to calculate the times when a threshold was crossed causing a change in compensation status. It should be emphasized that not every threshold crossing causes a change in compensation status. If the FADED threshold is crossed AND compensation is enabled, the signal can then fluctuate back and forth across the FADED threshold without causing a change in status. Only when the signal increases enough to cross the CLEAR threshold will a change in status occur. The times at which threshold crossings dictated a change in status were calculated for the 16 events. To determine the response time of the compensation protocol, these times were then compared to status messages ("alarms") generated by the NCS which indicate when compensation was implemented or removed from a given VSAT; i.e., a new BTP was calculated. The total response time for the ACTS adaptive rain fade compensation protocol was consistently within 1 second of the actual threshold crossing fade. Table 1 shows the threshold crossing times compared with the NCS alarm times indicating a new BTP for the May 11, 1997 rain event discussed in the last section. Column 1 lists the threshold crossing times based on the NCS model, while column 2 shows the times for the corresponding NCS alarm messages. It may appear, in certain cases, that the status of compensation was changed prior to the threshold crossing. This is due to the fact that the NCS alarms are truncated to the second, while the threshold crossing times (based on 150 ms data) are calculated to fractions of seconds. Because of the quick, 1-second response time of the protocol, BER performance is never degraded between threshold crossing and implementation.

Protocol Performance as a Function of TDMA Framing Structure

A disadvantage of a fixed fade pool is that the fade pool can become full preventing additional VSATs that may experience rain fades from receiving fade compensation. This occurs when no unused capacity exists within the TDMA frame. However, this type of failure of the protocol occurred only 19 times in three years of operations.

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Summary of Conclusions

The ACTS adaptive rain fade compensation protocol performance has exceeded all expectations. To date the protocol has performed without error in accommodating all rain fade rates experienced at the FADED threshold crossing point. The 1 second response time indicates that the protocol could accommodate the specification fade rate of .25 dB/sec assuming the FADED threshold provides at least ¼ dB margin above the minimum BER operating level. The decision process can be adjusted, using the filter bandwidth, to optimize the satellite decoding resources and still maintain a 5E-7 BER availability of 99.5%. While there is an impact resulting from the use of a fixed fade pool architecture, it has only a very small affect on VSAT operational availability. VSAT BER performances at BERs worse than 5E-7 have been the result of out of specification links.

It is recognized that this paper analyzed only the downlink; the performance of the protocol at 20 GHz. The results, however, are directly applicable to the uplink. One need only recognize and model the differences between 20 and 30 GHz rain fade characteristics.

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Threshold Crossing Time	MCS Alarm Time	Compensation Action
8:10:39.18	8:10:39	Installed
8:10:40.68	8:10:41	Removed
8:10:52.15	8:10:52	Installed
8:11:13.45	8:11:13	Removed
8:11:34.53	8:11:35	Installed
8:13:05.05	8:13:05	Removed
8:13:07.30	8:13:07	Installed
8:13:30.78	8:13:31	Removed
8:13:34.68	8:13:35	Installed
8:14:29.80	8:14:30	Removed
8:14:36.85	8:14:37	Installed
8:14:40.30	8:14:40	Removed
8:17:57.40	8:17:57	Installed
8:17:58.15	8:17:58	Removed
8:18:04.90	8:18:05	Installed
8:20:48.70	8:20:49	Removed
8:23:53.80	8:23:54	Installed
8:23:55.90	8:23:56	Removed
8:24:00.09	no MCS alarm	Installed
8:24:17.79	8:24:18	Removed
8:24:19.37	8:24:19	Installed
8:24:27.78	8:24:28	Removed
8:24:30.62	8:24:31	Installed
8:24:35.57	8:24:35	Removed
8:24:37.22	8:24:37	Installed
8:25:57.25	8:25:57	Removed
8:26:02.65	8:26:03	Installed
8:26:41.79	8:26:42	Removed
8:26:43.74	8:26:44	Installed
n/a	8:46:05	Reacquired/CodingInstalled
9:16:42.76	9:16:43	Removed

Table 1

May 11, 1997 VSAT 11 Rain Event
Filter Bandwidth = 1.06

Threshold Crossing Time	Compensation Action
8:11:50	Compensation Installed
8:21:56	Compensation Removed
8:24:52	Compensation Installed
9:19:42	Compensation Removed

Table 2

May 11, 1997 VSAT 11 Rain Event - Filter

Threshold Crossing Time	Compensation Action
8:11:10	Compensation Installed
8:11:27	Compensation Removed
8:11:35	Compensation Installed
8:14:42	Compensation Removed
8:18:43	Compensation Installed
8:20:49	Compensation Removed
8:24:14	Compensation Installed
8:24:18	Compensation Removed
8:24:25	Compensation Installed
8:25:57	Compensation Removed
8:26:22	Compensation Installed
9:16:56	Compensation Removed

Table 3

May 11, 1997 VSAT 11 Rain Event - Filter Bandwidth = .21