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Rain Fade Compensation Alternatives for Ka Band Communication Satellites

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RAIN FADE COMPENSATION ALTERNATIVES FOR KA BAND COMMUNICATION SATELLITES

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1.0 Introduction

Future satellite communications systems operating in Ka-band frequency band are subject to degradation produced by the troposphere which is much more severe than those found at lower frequency bands. These impairments include signal absorption by rain, clouds and gases, and amplitude scintillation's arising from refractive index irregularities. For example, rain attenuation at 20 GHz is almost three times that at 11 GHz. Although some of these impairments can be overcome by oversizing the ground station antennas and high power amplifiers, the current trend is using small (< 20 inches apertures), low-cost ground stations (< $1000.0) that can be easily deployed at user premises. As a consequence, most Ka-band systems are expected to employ different forms of fade mitigation that can be implemented relatively easily and at modest cost.

The rain fade mitigation approaches are defined by three types of Ka-band communications systems – a low service rate (< 1.5 Mb/s), a moderate service rate (1.5 to 6 Mb/s) system and a high service rate (>43 Mb/s) system. The ACTS VSAT network, which includes an adaptive rain fade technique, is an example of a moderate service rate.

2.0 Propagation Factors at Ka-band

Propagation considerations applicable for open-loop or closed loop rain fade compensation are discussed in this section. Typically the control signal for the compensation system is derived from direct measurements on the downlink signal (20 Ghz) that will allow estimation of the up-link fade (30 GHz). The control accuracy is largely determined by the frequency translation issues associated with the various propagation factors.

Propagation factors that affect Ka-band satellite links include:

- rain attenuation
- antenna wetting
- depolarization due to rain and ice
- gaseous absorption
- cloud attenuation
- melting layer attenuation
- troposphere scintillation

In general rain fade compensation approaches must consider at least three characteristics of the above propagation factors: range of signal fading (dB's), rate of signal fluctuations (dB/sec), and frequency dependence (scaling). Propagation measurements conducted with the ACTS beacons can provide most of the required information.

2.1 Rain Attenuation

Rain attenuation is the dominant propagation impairment at Ka-band frequencies. Rain attenuation is a function of frequency, elevation angle, polarization angle, rain intensity, rain drop size distribution and rain drop temperature. Frequency scaling of rain attenuation is largely determined by the raindrop size distribution and the rain intensity, and as a consequence, the fade ratio is expected to vary with the type of rain. From the ACTS beacon data collected it is seen that fade ratio from light rain, which is mainly composed of smaller drops, tends to be large compared to heavy rain, which tends to have a higher proportion of larger drops. In general the fade ratio is a decreasing function of the fade depth. However, rapid variations in the rain intensity along the path can cause the instantaneous fade ratios to fluctuate considerably. The frequency dependence of rain attenuation has been found to follow the approximate relationship **(Ref.1)**

$$\frac{A_1}{A_2} \approx \left(\frac{f_1}{f_2}\right)^2 \qquad \textbf{(2)}$$

where A_1 and A_2 are attenuation (dB) at frequencies f_1 and f_2 , respectively.

The ACTS beacon data has shown that fade depth at 27.5 GHz under moderate elevation angles exceeds 20 dB for 0.1 % of a typical year. Fading becomes worse for low-elevations and or higher rainfall climates. Fade rates associated with rain attenuation are found to be distributed in a log-normal fashion with a median fade rate around 0.1 dB / sec. Fade rate increases with the depth of attenuation and can reach values as large as 1 dB / sec. Little difference exists between the fade rates on the increasing and decreasing side of an attenuation event.

One consideration for rain fade compensation design is the duration of fades. In order to distinguish between deep rain fades and beacon receiver failure or any other form of receiver malfunctions, are likely duration of fade events must be known. Fade duration has also been found to follow log-normal statistics with a median duration of approximately 5 minutes. A Deep fade may last up to 30 minutes; a shallow fade last for more than 24 hours.

2.2 Wet Antenna

The amount of water or snow in ground antenna systems can cause additional signal degradation from the expected propagation attenuation due to rain (See Figure 1.). This is one reason that the standard techniques for predicting rain fade using propagation models are not aligned with Ka-band RF beacon measurements (**Ref 2**). In certain climatic zones it will be necessary to take measures to remove wet snow and ice accumulation from the surfaces of antenna and feeds. Otherwise, prolonged periods with strong cross polarization and additional attenuation could occur which might dominate even the yearly cross polarization and propagation attenuation statistics.

In Ka-band communication system an additional margin should be included to account for the wetness of the antenna system. Preliminary measurements (by NASA Lewis Research Center) indicate that an additional contribution of several dB's more than predicted by propagation models (standard technique) can be found when the antenna is wet. In general these results showed that feed wetness are the main contributor to the system losses, with reflector wetness being a lesser factor .

The water in the feed aperture distorts the electric field's distribution of the feed creating a high perturbation on the feed standing wave ratio (SWR). The reflector losses can be explained by additional scattering losses due to rain drop's size at the surface of the reflector. This creates a distorted reflector surface that reduces the antenna gain by several dB's in the worst case. Frequency scaling may not seem to hold when the antenna is saturated with water, a factor that need's to be considered in a system design that employs fade compensation and frequency scaling.

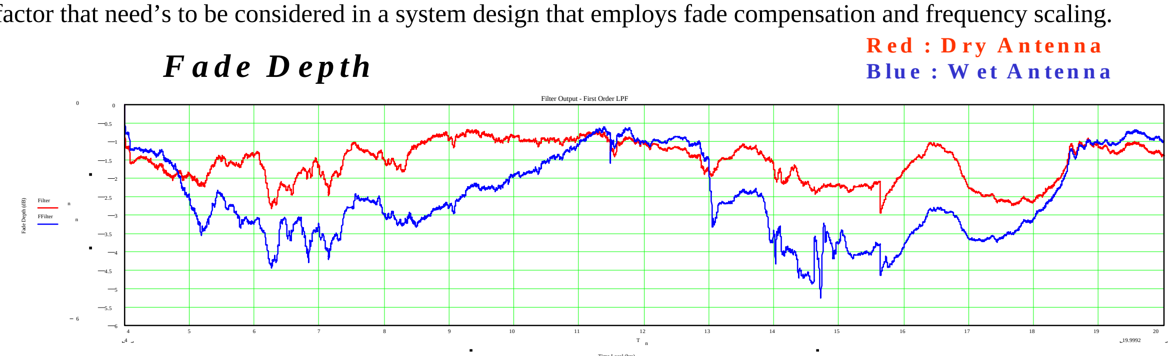


Figure 1. Dry Antenna vs. Wet Antenna (Ligth Rain Event < .1 mm/hr)

3.0 Rain Fade Characteristics

Fade compensation requires the following design consideration relating to rain fade:

- average rain time
- simultaneous rain fade over extended areas
- fade rates
- fade duration
- inter-fade intervals
- frequency scaling of fades

3.1 Average Rain Time

The average rain time for which the compensation must be applied is usually very small **(see table I).** Typically this may be less than 5 % -10% of time on an average year. As such, fade compensation through dynamic resource allocation is more cost effective.

Table I : Response Time for Fade Compensation

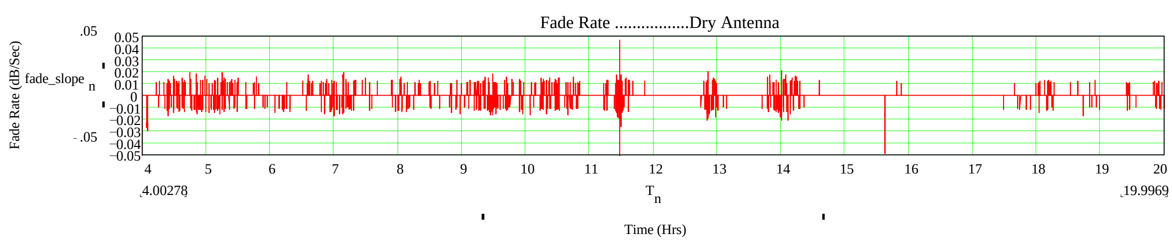
Margin (dB)	Fade Rate 0.5 dB/Sec	Fade Rate 1.0 dB / Sec	Fade Rate 1.5 dB / Sec
2	**T = 4 sec**	**T = 2 sec**	**T = 1.5 sec**
4	**T = 8 sec**	**T = 4 sec**	**T = 2.5 sec**
6	**T = 12 sec**	**T = 7 sec**	**T = 4 sec**

3.2 Simultaneous Rain Fade over Extended Areas

Simultaneous of rain events across extended areas can be studied using available databases. However, this type of information cannot be generalized easily. The results are system dependent (e.g., beam size) and need to be investigated for a particular satellite system. A preliminary look at the analysis indicates that rain events seen only for distances in excess of around 2000 Km are decorrelated. The rain databases can form the basis for optimizing antenna coverage and developing satellite resource allocation methodologies.

3.3 Rain Fade Rates

For most locations, rain fade rates rarely exceed 1 dB/sec **.** Amplitude scintillation riding on rain fade can produce faster fade rates. The account of scintillation effects must be taken in consideration when designing fade compensation techniques.



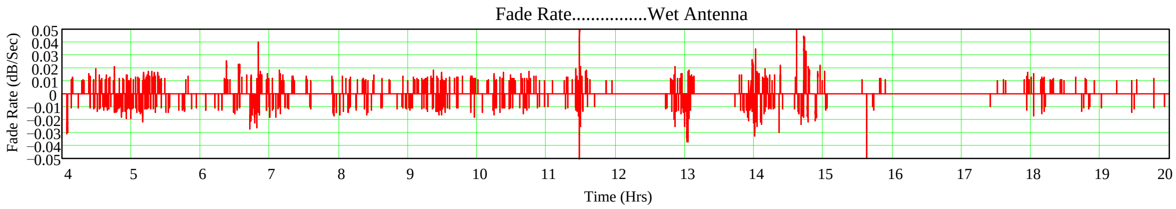


Figure 2: Fade Rates for Antenna vs. Wet Antenna

3.4 Fade Duration

Depending on the system margin, the selected duration over which fade compensation must be applied can last a few seconds to several hours. A suitable approach for estimating fade duration must be established.

3.5 Inter-fade intervals

Inter-fade intervals provide information on how frequently fade compensation must be invoked. Similar to fade duration, a suitable methodology to estimate inter-fade intervals must be developed.

3.6 Frequency Scaling

Uplink and downlink fades are generally correlated. The accuracy associated with the prediction of rain fade at one frequency based on the rain fade measured at another frequency is on the order of +/- 2 dB. Thus effective fade compensation requires fade measurements at only one frequency. An additional margin of 2 dB may be required.

4.0 Uplink Power Control - Bent Pipe Satellite

In the uplink power control (UPC) approach for dynamic allocation of additional power to the transmit carrier(s) at an earth station is used in order to compensate for rain attenuation.. Three types of power control techniques can be considered: open-loop, closed-loop, and feedback-loop.

1. Open-loop: One station receives its own transmit carrier and must rely on its measurement of beacon fading in the downlink in order to perform UPC.
2. Closed-loop: Two earth stations are in the same beam coverage and an earth station can receive its own transmit carrier. UPC based on this carrier is erroneous due to changes input and output backoffs under uplink and downlinks fading. UPC needs to be on the reception of a distinct carrier transmitted from another station.
3. Feedback loop: A central control station monitors the levels of all carriers it receives, and commands the affected earth stations to adjust their uplink powers accordingly. This technique has inherent control delays, and requires more earth segment and space segment resources.

4.1 Downlink Power Control - Bent Pipe Satellite

This technique allocates additional power to the transmit carrier(s) at the satellite in order to compensate for rain attenuation. As the downlink fading occurs, downlink carrier power degrades and sky noise temperature seen by the earth station increases. Power control correction of approximately 1.5 times fade is required to maintain carrier to noise ratio (C/N). If correction is applied at the satellite, the effective isotropic radiated power (e.i.r.p.) for the entire beam is increased, raising the signal level at both faded and non-faded earth stations For quasi-linear transponder operation, correction can be applied at the transmitting earth station. The TWTA's with variable output power levels can be commanded into high-power modes to counteract downlink fades. For beam diameters greater that rain cell diameter, correction should be applied only when a certain percentage of terminals within the beam exceeds an attenuation threshold. This technique must ensure that power flux density limits are not exceeded at non-faded terminals. The system design must ensure that the communications channel is not interrupted during power level changes.

4.2 Uplink Power Control - On-board Processing Satellite

With an on-board processing spacecraft, for a link transmitting from point A and receiving at point B, the received information bit error rate at point B is given by:

$$BER_B \equiv BER_{Uplink} + BER_{Downlink} \qquad \textbf{(1)}$$

where,

BER_{Uplink}	= uplink information bit error rate = FU(BER_{Uplink})
$BER_{Dwnlink}$	= downlink information bit error rate = FD($BER_{Downlink}$)
FU ( ) or FD ( )	= function describing relationship between uplink (or downlink) information BER and uplink (or downlink) channel BER.

The spacecraft need to monitor the levels of all carriers it receives in the uplink, and command the affected earth stations to adjust their uplink carrier powers accordingly.

4.3 Bit Rate Reduction and FEC Code Rate Change - Bent Pipe

In general the system design in this case can only consider power efficient modulation and coding techniques for all weather conditions. In frequency division multiple access (FDMA) or code division multiple access (CDMA) systems, one of the simplest compensation approaches would be to keep the carrier power, transmission rate and occupied bandwidth fixed. For example, a clear-sky 64 K bit/sec rate and **3/4** FEC carrier can be switched, under rain fades, to a 32 K bit/sec rate and a **3/8** FEC carrier. In continuos transmission, it is difficult to coordinate this switching at transmit and receive terminals, and the service may not be seamless.

In time division multiple access (TDMA), the reserved time slots to be used by carriers suffering fades can be allocated either at the end of each burst or at the end of the frame. In the previous example, in order to keep the information rate constant at 64 K bit/sec for this link, twice the number of time slots will be needed from the reserved time slots.

4.4 Bit Rate Reduction and FEC Code Rate Change - On-board Processing

Since the on-board processing architecture has not been specified in detail, it is not simple to evaluate the fade compensation technique for this case. However, in TDMA, the received time slots to be used by carriers suffering fades can be allocated either at the end of each burst or at the end of the frame. In order to keep the information rate constant when the fade compensation is applied, additional time slots will be needed from the reserved time slots.

4.5 Site Diversity - Bent Pipe or On-board Processing Satellite

This technique involves tandem operation of two earth stations, and exploits the finite size of rain cells (5 km to 10 km).Fading at sites separated by distances exceeding the average rain cell size are expected to be uncorrelated. Diversity gain or the reduction in link margin depends on site separation, frequency, elevation angle, and baseline orientation angle. Diversity gain calculation assumes ideal switching in which the least affected site is always selected.

Site diversity is very effective in combating rain fades. On the other hand, the cost of the second site, dedicated terrestrial interconnection, service interruptions, required data buffering and site synchronization are considered significant system overhead or major disadvantages. In general this technique is best suitable for network control centers and major gateways, amd not applicable for low-cost earth stations unless applied with public switched networks to interconnect the terminals.

A special case of site diversity can be classified as network diversity. In this approach, earth station resources in the same network can be pooled together to combat fading. The assumption is that each earth station in the network has some spare capacity that can be allocated to other earth stations that are experiencing outages. The main advantages is the optimal use of ground segment resources without the use of dedicated terrestrial interconnections. The main disadvantage is the non-standard network protocols.

4.6 Terrestrial Backups

In its simplest form terrestrial backup involves replacing the satellite connection by a terrestrial connection. In general, rain fade mitigation using terrestrial backup is not a practical option. This is especially true for satellite networks involving low-cost earth terminals.

This technique can also be describe in the context of site diversity. Organizations using multiple low-cost earth station sites in the same local calling area can benefit from terrestrial backup. The main advantage is the low cost terrestrial interconnection and the main disadvantage is that the high date rate may not be supported.

4.7 Built-in Link Margins - Bent Pipe Satellite

The achievable transponder capacity depends on factors such as earth station antenna size, high power amplifiers size; satellite e.i.r.p. ,G/T , saturation flux density, gain setting carrier modulation, coding, and interference environment. For a specified system margin M, a transponder capacity C is achieved. When M decreases, C increases and vice versa. The relationship between M and C depends on the above factors, and is highly nonlinear. It is very complex when carriers with different required margins are transmitted through the same transponder.

In multicarrier operation, the uplink margin is normally equal to system margin since an uplink fade would affect almost equally the uplink C/N, uplink carrier to interferer ratio (C/I), downlink C/I, and downlink C/N. For a downlink fade, the downlink margin is normally much larger than the system margin since only the last two components are affected.

In single-carrier-per-transponder operation, the uplink margin is normally larger than the system margin since an uplink fade would not equally affected the uplink C/N, C/I, downlink C/I and downlink C/N. For a downlink fade, the downlink margin is also normally much larger than the system margin since only the last two components are affected.

4.8 Built-in Link Margin - On-board processing Satellite

With the on-board processing spacecraft, the uplink margin and downlink margin directly affect the uplink BER and downlink BER, respectively. For a simple pencil beam antenna terminals at beam center may enjoy up to a 3dB advantage in downlinks C/N's compared to those at beam edge.

5.0 ACTS Adaptive Rain Fade Compensation Technique

The ACTS very small aperture terminal (VSAT) links require that the VSAT be located within a spot beam's 3 dB contour. Given this geometry, the uplink and downlink Bit Error Rate (BER) performance should not degrade below $5x10^{-7}$ in uplink rain fades of up to 15 dB. To support this fade requirement, the link generally operate with a 5 dB and 3 dB of uplink and downlink margin, respectively and makes use of the ACTS adaptive rain fade compensation process. ACTS adaptive rain fade compensation is the process whereby a VSAT's data channel BER performance is automatically enhance during a period of signal loss due to rain attenuation. The rain fade compensation protocol provides 10 dB of margin by reducing the burst by half and invoking one-half forward error correction coding. This allows the sharing of the spacecraft's decoding capacity. The decision process makes use of the downlink signal level and the onset and cessation thresholds identified for each VSAT. Each VSAT measures its downlink signal and transmits it to the network control station. Based on the thresholds, the control station instructs affected VSATs to operate coded or uncoded as appropriate. The implementation of coded vs uncoded operation is expected to accommodate a fade rate of at least 0.25 dB per second, to have no impact on VSAT throughput and to be smooth in the transition from uncoded to coded operation and back ***(Ref. 3).*** The performance status of the ACTS adaptive rain fade compensation can be summarized as follows; the rain fade protocol is functional in detecting fades, providing an additional 10 dB of margin and seamless transitions to and from coded operation. The stabilization of the link margins and the optimization of rain fade decision thresholds has resulted in improved BER performance. Characterization of the Fade Compensation Algorithm and its implementation with ACTS is still on-going.

5.1 Evaluation ACTS Up-Link Power Control Technique

The main objective of this of the rain fade compensation study is to develop tools for the mitigation of propagation impairments. One such technique, open-loop uplink power control, has been evaluated by NASA engineer and Comsat Labs using the ACTS system ***(Ref 4).***

Open-loop power control entails the estimation of the uplink fade at the ground station using a downlink signal and increasing the transmit power of the carrier to compensate for the uplink fade. Two key factors that determine the effectiveness of the open-loop power control are the detection of the correct downlink signal fade and the frequency scaling of this value to the uplink frequency.

An experiment was conducted using the ACTS satellite to investigate the limitations of the open-loop power at an IF stage using a linearized PIN diode attenuator. A power-controlled pilot carrier was transmitted from the NASA ground station in Cleveland, Ohio, and received at Comsat Lab. in Clarksburg, MD. The power-control algorithm takes into account equipment-induced errors as well as those attributed to the propagation environment. The test period lasted about six months during which a sufficient number of rain events were encountered to evaluate the controller performance. It was found that under most conditions the power control accuracy could be maintained within approximately +/- 2.5 dB.

The accuracy of the control system is measured by comparing the observed power of the 20 GHz pilot signal with the observed power of the 20 GHz beacon signal at the receive end of the experiment. The difference between the two power values constitutes the control error. The error statistics generated for the duration of the experiment was within +/- 2.5 dB. Results show that atmospheric effects at the receive site are transparent to the experiment because the received pilot is compared to the received beacon signal. These two signals are of 20 GHz frequency with a small frequency separation to allow interference-free detection.

6.0 Final Remarks

The ACTS satellite system has been instrumental in the successful evaluation of at least two different rain compensation techniques. Rain fade compensation techniques will play a critical role in future commercial exploitation of the Ka-band frequencies. The research conducted using ACTS on rain fade compensation to date has proved that that coding gain and power control can be quite effective in combating rain fading. Currently ACTS researchers are designing technology evaluation experiments on rain fade compensation that will help low cost implementations for Ka-band systems.

There are several area which has not been received closed attention by previous work in this area and these includes:

- Controller reaction to scintillation events

- Dynamic of the power control performance. The rapidity with which the controller reacts to different rates of onset and decay of events, as well as level and duration of power control over-shoots and under-shoots.
- Use of adaptive frequency scaling factor
- Inclusion of gaseous absorption and cloud attenuation for power control.
- Effect on sampling rate on the power control accuracy.
- Complete evaluation to system availability using rain fade compensation
- Low cost implementation of coding and power control
- Seamless operation of rain fade compensation

The Lewis Research Center Space Communication Office- ACTS is currently conducting an aggressive program to investigate all aspects of rain fade compensation including low cost implementation for future Ka-band systems.

7.0 References

(1) ITU - Radio Communications Sector Recommendations 618, 1992.

(2) NAPEX XVI, Washington, DC, November, 1996

(3) T. Coney and C. Cox, "ACTS VSAT downlink signal fade data for 1995, Ka-band Utilization Conference Florence Italy 1996

(4) Final Report - " ACTS Up-link Power Control Experiment,"NAS 326402, March 1995

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13. ABSTRACT ***(Maximum 200 words)***

Future satellite communications systems operating in Ka-band frequency band are subject to degradation produced by the troposphere which is much more severe than those found at lower frequency bands. These impairments include signal absorption by rain, clouds and gases, and amplitude scintillation's arising from refractive index irregularities. For example, rain attenuation at 20 GHz is almost three times that at 11 GHz. Although some of these impairments can be overcome by oversizing the ground station antennas and high power amplifiers, the current trend is using small (< 20 inches apertures), low-cost ground stations (< $1000.0) that can be easily deployed at user premises. As a consequence, most Ka-band systems are expected to employ different forms of fade mitigation that can be implemented relatively easily and at modest cost. The rain fade mitigation approaches are defined by three types of Ka-band communications systems – a low service rate (< 1.5 Mb/s), a moderate service rate (1.5 to 6 Mb/s) system and a high service rate (>43 Mb/s) system. The ACTS VSAT network, which includes an adaptive rain fade technique, is an example of a moderate service rate.

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