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Propagation Effects Handbook for Satellite Systems Design

Fifth Edition

Section 3 Applications

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PREFACE

This Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design continues the long process of a continuing NASA commitment to provide a comprehensive reference document which provides the latest information on atmospheric propagation effects and how they impact satellite communications system design and performance. The First Edition of the Handbook was published in March 1980, the Second Edition in December 1981, the Third Edition in June 1983, and the Fourth Edition in February 1989. I have been fortunate to have been involved with the Propagation Handbook project since its inception, and this Fifth Edition continues on with the process.

I would like to acknowledge the contributions of the many members of the staff at Stanford Telecom who helped with the development of this handbook. The contributions of Dr. Lynn Ailes, Glenn Feldhake, Dr. Frank Hastings, Chris Pearson, Jennifer Pinder, and John Weinfield are gratefully appreciated. The contributions of previous members of the staff, Jay Gible, Julie Feil, and Chris Hofer are also acknowledged. The assistance of Ivy Cooper and Marian Montigny in the production of the handbook is also appreciated.

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PREFACE TO REVISION 1

This first revision, REV. 01, of the Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design, incorporates the results of a peer review process on the original Fifth Edition, published in October 1998. Revisions consisted, for the most part, of misspellings, omissions and corrections to the original text and graphics. In addition, clarifications and further discussions were added where indicated in the peer review.

Section 1, Background, had revisions to 16 pages, out of the total of 119 pages. Section 2, Prediction, had revisions to 104 pages out of the total of 226 pages. Four missing exhibits were added to Section 2. The reference lists for both Sections have been completely updated and reformatted. Corrected pages are indicated by an 'R1' in the file name on the right side of the page footer. Section 3, Applications, was not revised at this time.

I would like to thank the reviewers for their thoroughness and diligence in the review process. A special thanks goes to Dr. Ernest K. Smith for his excellent comprehensive review and comments. I also would like to acknowledge the contributions of Warren Flock, Ken Davies, and Glen Feldake to the review process.

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INTRODUCTION

I.1 INTRODUCTION TO THE HANDBOOK

The Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design provides, in one complete reference source, the latest information on atmospheric propagation effects and how they impact satellite communications system design and performance. The National Aeronautics and Space Administration, NASA, which has supported a large part of the experimental work in radiowave propagation on space communications links, recognized the need for a reference handbook of this type, and initiated a program in the late 1970's to develop and update a document that will meet this need. This Fifth Edition provides, in a single document, an update to two previous NASA handbooks; the fourth edition of a handbook which focused on propagation effects from 10 to 100 GHz (Ippolito, 1989), and the second edition of a companion handbook which covered propagation effects on satellite systems at frequencies below 10 GHz (Flock, 1987). This Fifth Edition covers the full range of radiowave frequencies that are in use or allocated for space communications and services, from nominally 100 MHz up to 100 GHz.

The basic intention of the Fifth Edition is to combine the scope of the previous handbooks into a single document, with elimination of duplication as much as possible. This Fifth Edition has a completely new outline, different from either of the two previous handbooks. The intent is to provide a more cohesive structure for the reader. The handbook incorporates a unique, new concept with several levels of "entrance" into the handbook.

Several major developments in satellite communications and the study of propagation effects have occurred since publication of the prior NASA handbooks. New propagation measurement campaigns have been completed or are in progress, providing new data for the evaluation of link degradations on satellite links. New propagation models and prediction techniques are available, covering the traditional propagation effects along with several new areas. New satellite applications have been thrust into the forefront of the satellite communications industry, requiring new approaches for the evaluation of propagation effects. The proliferation of new and competing applications in the frequency bands allocated to space communications has increased the importance and priority of understanding spectrum sharing and interference mitigation. Propagation conditions are a critical component of a viable sharing and interference process.

Section I.2 describes the handbook structure. Section I.3 describes how to apply the handbook for the most efficient use of the resource, depending on the readers' needs and level of interest.

I.2 HANDBOOK STRUCTURE

The Propagation Effects Handbook for Satellite Systems Design, Fifth Edition, is divided into three sections. Section 1 provides the background, historical development, theory, and basic concepts of the propagation effects of concern to the satellite systems engineer. The prediction techniques developed to address the critical propagation effects are presented in Section 2. Information on how to apply the prediction methods for specific satellite systems applications is provided in Section 3.

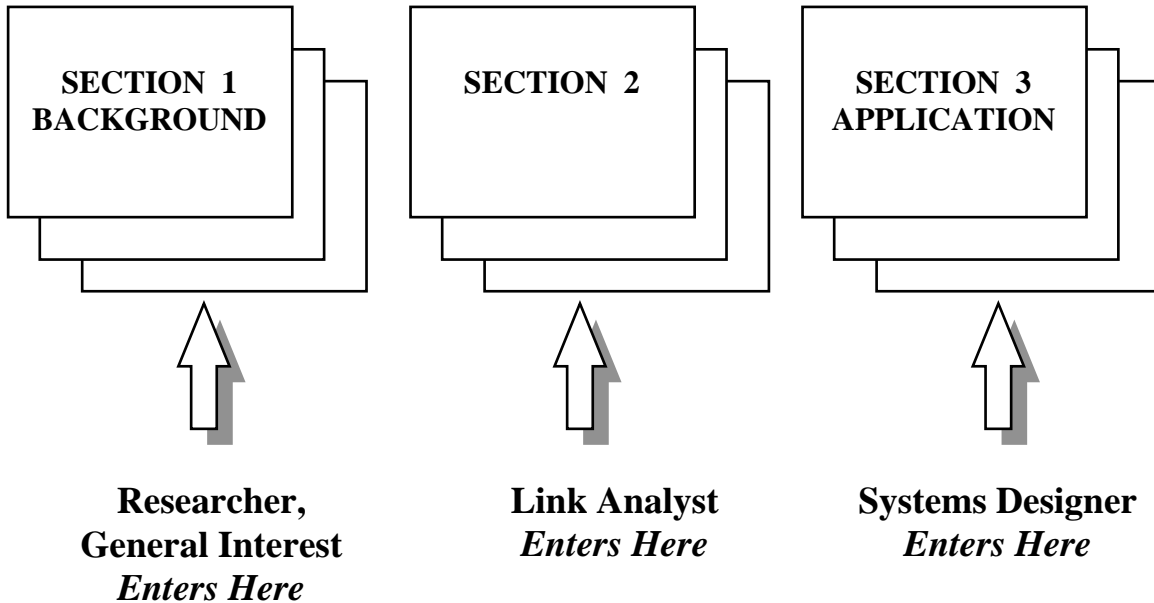
Section 1 begins with an overview of propagation effects on satellite communications. The propagation effects are then introduced and background theory and developments are described. The frequency dependence of radiowave propagation is recognized, and the effects are divided into two groups; ionospheric effects, influencing systems operating at frequencies below about 3 GHz, and tropospheric effects, influencing systems operating at frequencies above about 3 GHz. Radio noise, which can affect satellite systems in all operating bands, is then described. The section concludes with a comprehensive description of propagation databases, including points of contact and electronic addresses.

Section 2 provides descriptions of prediction models and techniques for the evaluation of propagation degradation on satellite links. Step-by-step procedures are provided where available. The first two subsections present propagation effects for ionospheric effects and for tropospheric effects, respectively. The third subsection presents prediction methods for radio noise. The fourth subsection describes several general modeling procedures, including statistical considerations, frequency scaling and elevation angle scaling. The final subsection presents models for the restoration of links subject to propagation impairments, including site diversity, orbit diversity and adaptive FEC.

Section 3 provides roadmaps for the application of the prediction models given in Section 2 to specific satellite systems and applications. Suggested approaches to evaluating link propagation effects and their impact on system design and performance are provided.

I.3 HOW TO USE THE HANDBOOK

The Fifth Edition of the Propagation Effects Handbook for Satellite Systems Design is intended for the systems engineer and link designer who is interested in the latest and most accurate methodology available for the evaluation of radiowave propagation effects on satellite communications. The handbook is structured with several levels of “entrance” into the handbook, as highlighted by the chart below.



The general researcher or someone new to the subject who may not have a full awareness of the background and history of propagation effects and their impact on satellite communications could enter in Section 1, which provides an overview of propagation effects and the background theory involved in the prediction methodology. Section 1 also provides an extensive listing of resources for additional information and backup data important to the area of propagation effects and satellite communications.

The link analyst or engineer who is familiar with propagation and satellite communications issues and knows which propagation effects are of interest would enter into Section 2 where concise step-by-step procedures for each effect are available. Section 2 also includes general modeling procedures, including statistical considerations, frequency scaling and elevation angle scaling. Section 2, in addition, presents models for the restoration of links subject to propagation impairments, including site diversity, orbit diversity and adaptive FEC.

The system designer who has a good understanding of the system aspects of satellite communications but may not know just which propagation impairments are important to the particular system or application under consideration would enter through Section 3. Here the reader will find roadmaps for the application of the prediction models given in Section 2 to specific satellite systems and applications. Suggested approaches to evaluating link propagation effects and their impact on system design and performance are also provided in Section 3.

These entrance levels are only suggestions for the reader, to avoid unnecessary reading and to optimize the use of the handbook. Suggestions on ways to improve the document structure, or on specific additional information that would be useful to the reader to include in later editions of the handbook, are always welcome by the author.

Propagation Effects Handbook for Satellite Systems Design

Section 3 Applications

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SECTION 3 APPLICATIONS

3. INTRODUCTION TO SECTION 3

A wide array of new satellite applications has appeared in the decade since publication of the last handbooks. Each application has unique design and performance characteristics requiring new approaches for the evaluation of propagation effects. Also, the extension of satellite communications to non-geosynchronous orbit (NGSO) constellations has added a new level of concern on the proper evaluation of link conditions for proper system operation.

The last decade has seen a proliferation of VSAT (very small aperture terminal) systems in the Ku-band, designed primarily for data applications. The VSAT typically are low margin systems, with margins of 1 to 3 dB. VSAT networks can be global, and operate in the domestic and international fixed satellite service (FSS) bands.

Direct Broadcast Satellites (DBS) also operating in the Ku-band provide direct-to-home entertainment video services. DBS systems are one of the fastest growing segments of the satellite industry. They are multi-channel digital systems with small (0.6m) rooftop type antennas. DBS systems are deployed in the U.S., Europe, Japan.

The past few years have also seen the initiation of rapid development of the Ka-band for a range of applications. Ka-band systems filed with the U.S. Federal Communications Commission (FCC) number fourteen employing geosynchronous orbit (GSO) satellites and three employing non-geosynchronous orbit (NGSO) satellites. Ka-band applications to the International Telecommunications Union Radiocommunications Sector (ITU-R) have been tendered by twenty-one countries, with over 380 GSO satellites and eight countries have filed for over 200 satellites in NGSO constellations. The Ka-band is also allocated for feeder links for NGSO systems, including NGSO/FSS, NGSO/FSS/MSS, and NGSO/MSS services.

Another area of rapid development involves “Big LEO” mobile satellite personal communications systems. The big LEO systems are NGSO constellations, with 10 to 66 satellites, and operate in low earth orbit (LEO), medium earth orbit (MEO) and elliptical earth orbit (HEO). The primary service of the Big LEO systems is personal voice communications. The service links operate in the bands 1610-1626.5 MHz (uplink) and 2483.5-2500 MHz (downlink). They operate with multiple satellite antenna beams, and employ CDMA or TDMA/FDMA access techniques

“Little LEO” mobile satellites systems are smaller in size and in capabilities than the big LEO systems. They provide lower rate services including paging, messaging, and position location (no voice). They operate in NGSO (LEO) constellations of 20 to 24 satellites. The service links operate in the 137-138, 148-149.9, 400-401 MHz bands.

The last year has seen the first interest in satellite systems operating in the so-called Q-band or Q/V-band. These systems operate in the FSS allocated bands of 37.5 - 40.5 GHz (downlink) and 47.2 - 50.2 GHz (uplink). Twelve organizations filed fourteen Q/V-band systems with the FCC in September 1997. These systems are designed to provide broadband multimedia services, VSAT and direct to home services. Q/V-band systems typically have higher data rates than Ku or Ka band systems, with data rates of up to 3 GBPS being considered. The proposed systems include GSO, NGSO, and mixed constellations.

Each of these applications has unique propagation characteristics. Section 2 of this handbook provides the tools to evaluate the propagation degradations of these systems, and this section, Section 3, offers “roadmaps” to adequately identify and analyze the specific propagation factors important to the application.

Another area where recent developments have changed the “playing field” in satellite communications is the increased emphasis on spectrum sharing and interference mitigation. The explosion in global satellite systems has required the system designer to include spectrum sharing as a critical part of the system design. The radio spectrum is a fixed and limited resource, and the available bandwidth in most of the bands allocated for satellite applications is not adequate for all of the systems under consideration for deployment. Sharing is required, and often, if band segmentation cannot be employed, mitigation techniques including power control and exclusion zones have to be evaluated. Also, the sharing of GSO and NGSO systems operating in the same allocated bands adds another critical element to the spectrum sharing process.

The inclusion of the appropriate propagation effects in the desired and the interfering links is essential to an acceptable solution. The models and procedures described in this handbook are elements of a comprehensive spectrum sharing process that often includes simulations and analytic procedures of the full range of applications and satellite orbits.

Section 3 begins with an overview of general link analysis procedures for satellite communications systems. Design considerations and recommendations for the selection of a rain attenuation prediction model are included. Section 3.2 covers propagation effects on systems operating below 3 GHz. Sections then follow on Ku-band systems, Ka-band systems, Q/V-band systems, and direct broadcast systems. A discussion on propagation considerations for non-geosynchronous (NGSO) is also included.

The principal topics and associated subsection numbers for Section 3 are listed below.

Section	Topic
3.0	INTRODUCTION TO SECTION 3
3.1	APPLICATION OF PREDICTION MODELS TO SYSTEM DESIGN AND PERFORMANCE
3.2	PROPAGATION EFFECTS ON SATELLITE SYSTEMS OPERATING BELOW 3 GHZ
3.3	PROPAGATION EFFECTS ON KU-BAND SYSTEMS
3.4	PROPAGATION EFFECTS ON KA-BAND SYSTEMS
3.5	PROPAGATION EFFECTS ON Q/V-BAND SYSTEMS
3.6	PROPAGATION EFFECTS DIRECT BROADCAST SATELLITE SYSTEMS
3.7	PROPAGATION EFFECTS CONSIDERATIONS FOR NGSO SYSTEMS
3.8	REFERENCES – SECTION 3

3.1 APPLICATION OF PREDICTION MODELS TO SYSTEM DESIGN AND PERFORMANCE

3.1.1 General Link Analysis Procedures

This section provided an overview of the general procedures to be followed in the evaluation of a satellite communications link subject to propagation problems. The systems designer is generally interested in determining system design or link performance requirements of the system based on overall performance criteria for the end-to-end performance of the system. The inclusion of propagation effects usually enters into the analysis in the power budget or “link budget” portion of the system design.

The relevance of propagation effects and the impact of the propagation degradations will differ greatly, depending on several factors. One of the most critical factors is the free space path frequency of operation, which determines the particular set of propagation effects that will hamper communications. Another is the particular type of service or application being provided, which often dictates system parameters such as antenna size, beamwidth, bandwidth of operation, and physical and operational constraints.

In this section a general system design process for a satellite communications link is described, with emphasis on how the propagation analysis enters into the process. Later sections will focus on specific satellite applications and frequency bands and the unique propagation analysis considerations required for each.

The systems designer integrates in propagation and other technical data to achieve a system design that will meet end-to-end requirements specified by the user. These requirements are specified in terms of a gross quantitative need (e.g., number of channels, acceptable voice or video quality, type of access scheme), or quantitative expression of performance (e.g., required c/n or E_b/N_o for a specified percent of time availability), and, sometimes, more qualitative expressions (e.g., "highly reliable"). The step-by-step process to go from overall system requirements to system design parameters is iterative, and often requires several ‘trys’ to converge on an acceptable solution. The steps necessary to go from this set of performance requirements and propagation effects information to a system design are shown in Exhibit 3.1.1-1, and summarized below:

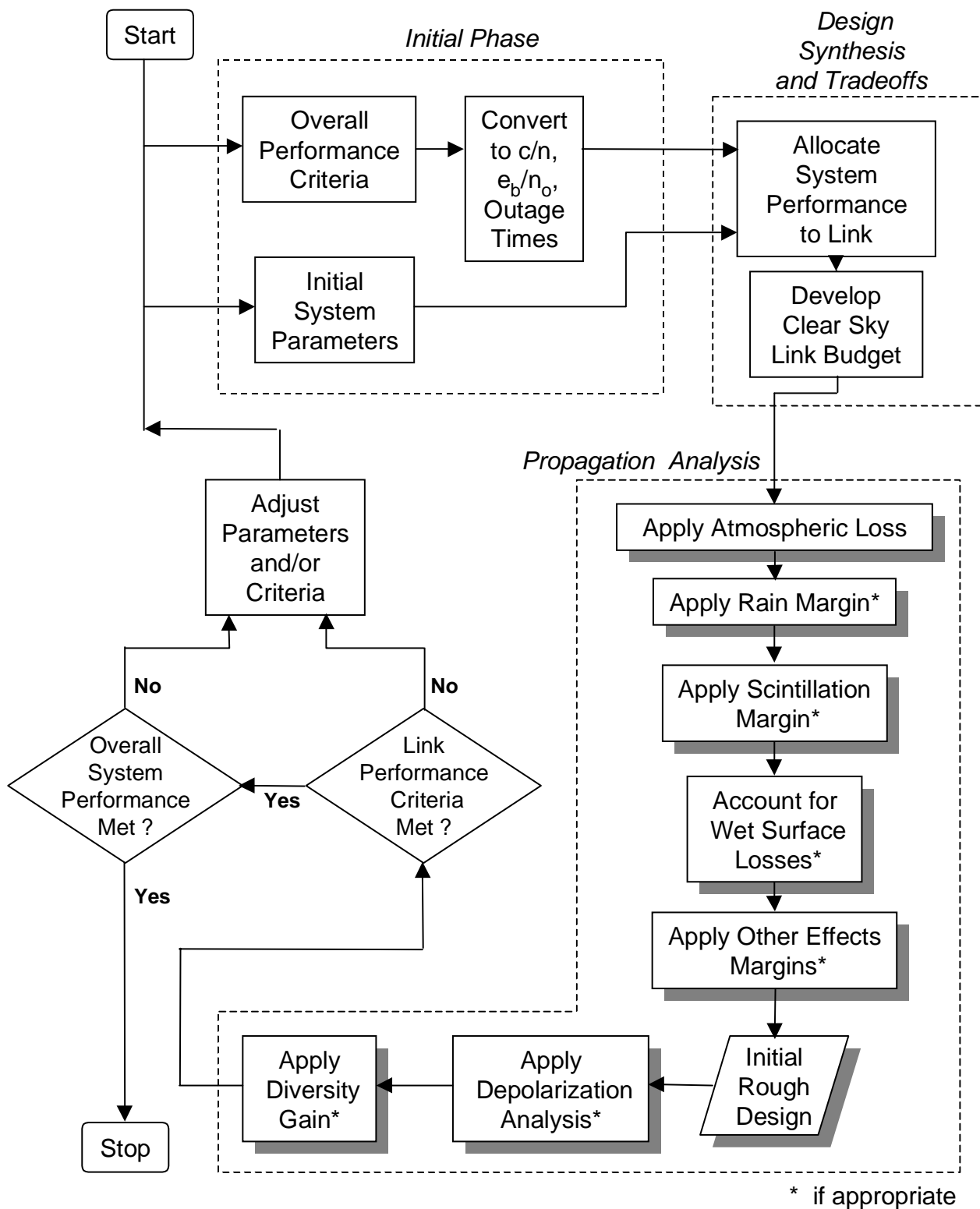


Exhibit 3.1.1-1
System Design Process

The *Initial Phase* of the process consists of the establishment of system performance requirements from the given overall performance criteria (, link availability, outage times) and an initial set of assumed system parameters (antenna size, beamwidth, transmit power, etc). The performance criteria, if not already in system performance parameter terms, must be converted to power allocation factors such as c/n , c/n_o , or e_b/n_o (for the specified link availability).

The performance parameters and initial system parameters are then input to the *Design Synthesis and Tradeoffs* phase. Here, the total system performance parameters are allocated to each element of the system and those allocated to the satellite link(s) are noted. For example, the total performance power margin could be apportioned to:

- uplink ground terminal,
- uplink satellite path (airlink),
- satellite transponder,
- downlink satellite path (airlink), and
- downlink receiver.

The uplink and downlink airlink allocations are of interest for evaluation of propagation effects. The type of satellite transponder is also important to the process. A non-regenerative ('bent-pipe') satellite results in a contribution of the uplink degradations on the downlink. A regenerative ('on-board processing') satellite can be treated as two independent links. Once the link performance parameters have been specified, a clear sky link power budget for each link is developed. Other factors which must be considered are: system architecture (single beam, multiple beam, switched beams, etc.) and modulation/multiple access technique (TDMA, CDMA, DAMA, etc.).

The *Propagation Analysis* phase consists of a systematic application of the appropriate prediction models and methods to estimate the degradation, in the form of additional power margin required or additional noise added to the system. These are the models and procedures provided in Section 2 of this handbook. An initial rough design is developed with the combined effects of all contributing propagation effects. Depolarization effects are added if the system employs frequency reuse, and diversity gain is added to the system if site diversity or orbit diversity is desired.

The initial design from the Propagation Analysis Phase is then tested for two conditions; first does the design meet the link performance criteria, and does the design meet the overall system performance criteria? If the answer is yes to both, the design process is complete and an acceptable design has been developed. If the answer to either is no, parameters and/or criteria must be adjusted and another iteration through the process is initiated.

3.1.2 Design Considerations

Systems operating above about 10 GHz will experience rain induced attenuation as the most severe propagation effect. The rain margin may be the 'driver' for the system design. If the system uses site diversity, some of this rain margin may be offset by "diversity gain." The remaining margin is then applied to the initial system parameters. Typically, the margin is applied as an increase in power; but it is also possible to increase antenna gains or modify the modulation parameters. At this point, a rough design has been achieved. This level of detail and accuracy may be sufficient if the objective is only to determine system feasibility. For more accurate results, the effects of other propagation phenomena must be considered. Except for depolarization, these effects are generally additive in terms of margin. Loss in cross-polarization isolation (usually termed "depolarization") can be accommodated as an additive term whenever the interference component is small relative to thermal noise and other interference sources. Thus, small degradations such as those due to depolarization from ice are treated as part of the system margin computation. The more severe degradations in cross polarization such as those caused by rain cannot be counteracted by margin increases. These events will usually be severe enough to cause an outage. Therefore, in systems employing cross polarization isolation, the depolarization phenomenon may reduce or limit the system availability.

3.1.3 Selection of a Rain Attenuation Prediction Model

The selection of an appropriate rain attenuation prediction model from the many published versions available to the systems designer is perhaps the most perplexing issue related to propagation effects and satellite systems. This handbook presents, in Section 2.2.4, five of the more popular “step-by-step” procedures for the determination of annual rain attenuation statistics for global locations. Each has some merit and each has been validated to some extent by direct comparison with measured path attenuation data.

All of the available models, however, even those with the best validation history, still do no better than 35% to 40% (RMS dB error) in predicting rain attenuation. This means that a prediction of 10 dB has an RMS error of ± 3.5 to 4.0 dB, for the average year, for the location of interest. This uncertainty is often overlooked in specifying rain margins based on a rain model prediction.

With this in mind, which model or models should be applied for the particular system under consideration? This section summarizes studies that were done to quantify and compare the RMS and mean errors for nearly a dozen published rain models and concludes with a recommendation on which models appear to give somewhat better performance.

The ITU-R, at Working Party 3M, in June of 1996, reported on the results of an exhaustive study of a comparison of several rain attenuation models with 186 station years of earth-space path measurements contained in the ITU-R database (ITU-R, 1996). The ten models evaluated by the ITU-R were:

Models Provided in Section 2 of this Handbook

- | | |
|---|-------------------|
| 1. ITU-R Rain Model | [Section 2.2.4.1] |
| 2. Crane Two-Component Model | [Section 2.2.4.3] |
| 3. DAH Model (“USA Model”) | [Section 2.2.4.4] |
| 4. ExCell Rain Attenuation Model | [Section 2.2.4.5] |

Other Models Included in the Evaluation

- | | |
|-------------------------------|----------------------------|
| 5. Leitao-Watson Model | (Leitao & Watson, 1986) |
| 6. Misme-Waltdeufel | (Misme&Waltdeufel, 1980) |
| 7. CCIR | (CCIR, 1986) |
| 8. Japan | (Karasawa & Matsudo, 1990) |
| 9. Spain | (Lopez et al, 1988) |
| 10. Brazil | (CCIR, 1992) |

The data base consisted of satellite beacon measurements, radiometer measurements, beacon and radiometer measurements, with frequencies from 11.6 GHz to 34.5 GHz. Comparisons were made by grouping the data sets by specific link parameters and conditions. The groupings were:

Frequency:	≥ 10 and < 15 GHz ≥ 15 and ≤ 35 GHz
Rain Rate:	> 0 and ≤ 10 mm/h > 10 and ≤ 20 mm/h > 20 mm/h
Latitude:	$\geq -22.5^0$ and $\leq 22.5^0$ $\geq -30^0$ and $\leq 30^0$ $< -30^0$ and $> 30^0$
Elevation Angle:	$\leq 10^0$ $> 10^0$ and $\leq 20^0$ $> 20^0$ and $\leq 30^0$ $> 30^0$ and $\leq 40^0$ $> 40^0$ and $\leq 60^0$ $> 60^0$

The results showed that the DAH and the ITU-R models were consistently in the top four or five in performance through most of the groupings, based on RMS error and Mean error. The ExCell Model also tended to fall in the upper end, for frequencies above 15 GHz. Typical RMS errors ranged in the 30% to 40% range, however, even for the best performing. The mean error ranged in the 20% to 25% range for the top performers.

A later study by Feldhake and Ailes-Sengers (1997) extended the comparisons with 21 additional station years of measurements with the Advanced Communications Technology Satellite (ACTS) in North America. The ACTS data was collected at 20.185 GHz and 27.505 GHz. Elevation angles for the sites ranged from 9^0 (Fairbanks Alaska) to 52^0 (Tampa, Florida). An additional model, the Simple Attenuation Model (SAM), developed by Stutzman & Dishman (1982), was also added to the evaluation. A similar range of RMS and Mean Errors was observed. The ranking of the models also varied extensively with location and with frequency. There was no single model that stood out as the top performer, however, again the DAH, ITU-R and ExCell models were at the higher ends of the rankings.

Exhibit 3.1.3 summarizes the performance rankings of the models from the ITU-R Evaluation and the Feldhake/Ailes analysis (designated ACTS Evaluation). The models are listed by overall ITU-R ranking, as well as the rankings for specified frequencies. The rankings are based on RMS percent error.

Model	ITU-R Evaluation		ACTS Evaluation	
	Overall	15 – 35 GHz	20 GHz	27 GHz
DAH	1	2	1	1
ITU-R	2	3	3	4
ExCell	3	8	2	2
Japan	4	5	8	8
Brazil	5	6	6	6
CCIR	6	7	5	5
Leitao-Watson	7	4	11	11
Misme-Waltdeufel	8	10	N/A	N/A
Two-Component	9	9	4	3
Spain	10	1	9	9
Global	N/A	N/A	7	7
SAM	N/A	N/A	10	10

Exhibit 3.1.3
Comparison of Performance of Rain Attenuation Prediction Models
[Source: Felkhake & Ailes-Sengers, 1997]

The comparisons and rankings are not by any means conclusive, since the range of RMS errors from the highest to the lowest rankings were in the range of 20 to 30 %. There does appear to be a tendency, however, for the DAH, ITU-R, ExCell models to be well performing for all frequency bands.

The recommendations which follow in Section 3 of the handbook will be based for the most part on the results from the comparative studies above. The DAH Rain Attenuation Model (sometimes referred to as the USA Model) is recommended for application to the general link and for a general location. If the reader is interested in specialized conditions, such as low elevation angle, or specific region or frequency of operation, referral to the ITU-R and ACTS studies is highly recommended, where further qualitative breakdowns of the comparisons are provided in great detail.

This recommendation is subject to revision and update as further data and studies become available.

3.2 PROPAGATION EFFECTS ON SATELLITE SYSTEMS OPERATING BELOW 3 GHZ

The significant effects observed in the frequency bands below about 3 GHz occur primarily in the ionosphere. The ionosphere is the region of ionized gas or plasma that extends from roughly 50km to a not very well defined upper limit of about 500 km to 2000 km about the Earth's surface. The ionosphere is ionized by solar radiation in the ultraviolet and x-ray frequency range and contains free electrons and positive ions so as to be electrically neutral. Only a fraction of the molecules, mainly oxygen and nitrogen, are ionized, and large numbers of neutral molecules are also present. It is the free electrons that affect electromagnetic wave propagation for satellite communications.

The complex nature of ionospheric physics and the interaction of communications system parameters affected by ionospheric effects cannot always be succinctly summarized in simple closed form analytical models or prediction methods. In many cases the only recourse available to the systems engineer is to review limited measured data if available, and attempt to summarize the effects into ranges or bounds for the expected degradations. The following section presents a process for the determination of general link propagation parameters that can be estimated reasonably well for typical ionospheric conditions.

3.2.1 General Link Propagation Parameters

This section presents recommended procedures for the determination of several important propagation parameters for satellite systems operating in the frequency bands below about 3 GHz. The procedures employ the prediction methods described in detail in Section 2 of this handbook. They are generally applicable to fixed slant path conditions, i.e. fixed satellite service (FSS), broadcast satellite service (BSS), space operations (SO), space research (SR), and other applications, employing fixed ground terminals¹.

The link parameters that are degraded by background ionization are:

- Faraday Rotation
- Group Delay
- Time Delay Dispersion

In addition, for conditions where ionospheric scintillation or absorption are expected (see handbook Section 1.2.3.2 for guidance) the following parameters are important:

¹ Recommendations for mobile satellite service (MSS) systems are discussed in the next section.

- Ionospheric Scintillation
- Auroral Absorption
- Polar Cap Absorption

The recommended propagation analysis procedure for general link parameters for satellite systems operating below about 3 GHz is summarized in the flow chart of Exhibit 3.2.1-1. The applicable Section 2 references from this handbook are indicated on the chart.

The system parameters required for the propagation analyses are:

- Frequency of operation, in GHz: f
- Percent of Time (or times) to achieve desired performance [on annual basis]
- Polarization tilt angle, in degrees: τ
- Elevation angle to the satellite, in degrees: θ
- Latitude of the ground station, in degrees N or S.: φ
- Longitude of the ground station, in degrees E or W: δ
- Altitude of the ground station above sea level, in km: h_s

Most of the parameters of interest for ionospheric propagation require a determination of total electron content (TEC) for the calculation, so that is the first step in the process. For satellite path effects prediction, the TEC value is usually quoted for a zenith path having a cross-section of 1 m^2 . The TEC of this vertical column can vary between 10^{16} and 10^{18} electrons/ m^2 , with the peak occurring during the sunlit portion of the day. For many purposes it is sufficient to estimate electron content by multiplication of the peak electron density with an equivalent slab thickness value of 300 km. Use the value given in the flow chart if no other information is available.

The conditions for ionospheric scintillation and absorption are discussed in Section 1.2.2.2. If appropriate calculate Peak-to-Peak Scintillation, Auroral Absorption and Polar Cap Absorption, as indicated on the flow chart.

The procedures presented above are suggestions for the determination of general link parameters for satellite systems operating below about 3 GHz. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

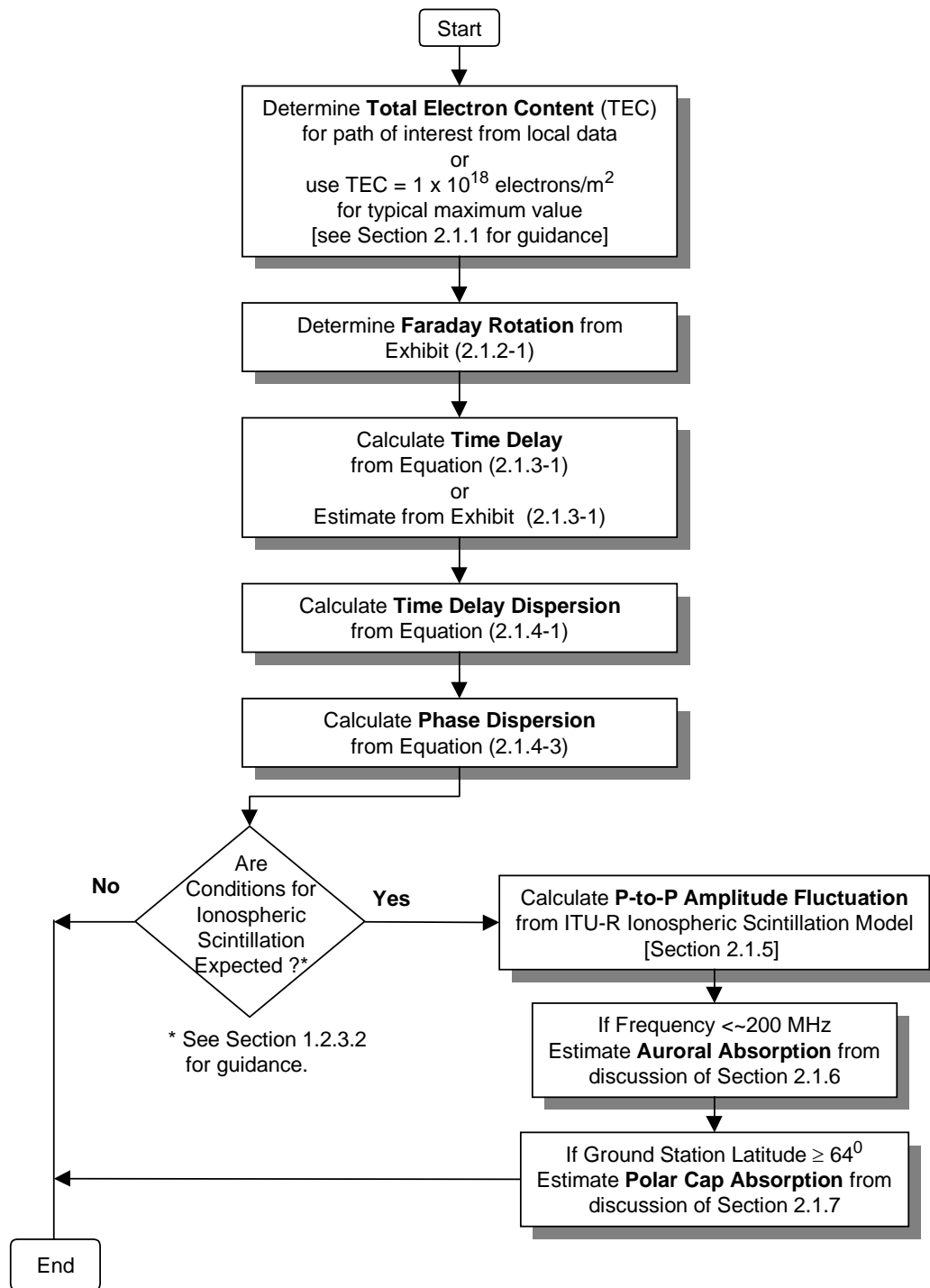


Exhibit 3.2.1-1
Propagation Analysis Procedure for Satellite Links Operating Below About 3 GHz

3.2.2 Mobile Satellite System Service Links

Propagation effects and modeling procedures for the service links of mobile satellite systems are described in companion NASA Handbooks published by Goldhirsh and Vogel (1992, 1998). The reader is referred to those documents for a complete compilation of propagation considerations for vehicular and personal mobile satellite systems operating in the frequency bands from UHF through K-band. This section provides a brief overview of the two documents and the subject areas covered.

Propagation Effects for Land Mobile Satellite Systems: Overview of Experimental and Modeling Results, NASA Reference Publication 1274, February 1992.

The first edition of the Handbook describes a systematic set of studies of propagation effects for land mobile satellite system (LMSS) for rural and suburban conditions in the United States. UHF and L-band links are included. Measurements were accomplished with a variety of signal sources, including balloons, remotely piloted aircraft, helicopters, and satellites (MARECS-B2, ETS-V, and INMARSAT). The contents of the handbook are:

Chapter

- 1 Introduction
- 2 Attenuation Due to Individual Trees: Static Case
- 3 Attenuation Due to Roadside Trees: Mobile Case
- 4 Signal Degradation for Line-of-Sight Communications
- 5 Fade and Non-Fade Durations and Phase Spreads
- 6 Propagation Effects Due to Cross Polarization, Gain, and Space Diversity
- 7 Investigations from Different Countries
- 8 Modeling for LMSS Scenarios

LMSS models are described for roadside shadowing, diversity operation, probability distributions, and object scattering. Extensive references are provided.

The complete handbook can be found on-line at the NASA JPL propagation home page;

<http://propagation.jpl.nasa.gov/TOC.html>

Propagation Effects for Vehicular and Personal Mobile Satellite Systems: Overview of Experimental and Modeling Results, *Second Edition*, NASA Reference Publication 1274, 1998.

This document provides updated measurements since the first edition and broadens the scope to additional frequency bands and to other mobile service geometries. Measurements at UHF, L-band and K-band are described. Propagation effects for personal communications systems

(PCS), maritime mobile satellite systems (AMSS), and propagation inside buildings are included. The contents of the handbook are:

Chapter

- 1 Introduction
- 2 Attenuation Due to Individual Trees: Static Case
- 3 Attenuation Due to Roadside Trees: Mobile Case
- 4 Signal Degradation for Line-of-Sight Communications
- 5 Fade and Non-Fade Durations and Phase Spreads
- 6 Polarization, Antenna Gain, and Diversity Considerations
- 7 Investigations from Different Countries
- 8 Earth-Satellite Propagation Effects Inside Buildings
- 9 Maritime-Mobile Satellite Propagation Effects
- 10 Optical methods for Assessing Fade Margins
- 11 Wideband Propagation Effects
- 12 Theoretical Modeling Considerations
- 13 Recommendations for Further Investigations

The handbook includes frequency-scaling considerations for frequencies at 870 MHz and L-band, 1 GHz to 4 GHz, and L-band to K-band. Several new empirical models for the evaluation of roadside shadowing are provided. An empirical multipath model for frequencies from 870 MHz to 20 GHz, and elevation angles from 8° to 60° is included. A novel optical imagery methodology for the evaluation of satellite diversity is described. Extensive references are provided.

The complete handbook can be found on-line at the University of Texas propagation home page; <http://www.utexas.edu/research/mopro/index.html>

Note: The uplink (**feederlink**) for mobile satellites can be at any of several of the bands allocated for that service. Current and planned mobile satellites operate with feeder links in the C-band, Ku-band, or Ka-band. Refer to the appropriate subsection in the APPLICATIONS section of this handbook for propagation considerations for that band.

3.3 PROPAGATION EFFECTS ON KU-BAND SYSTEMS

The Ku-band (nominally 14 GHz uplink / 12 GHz downlink) is the most popular band for VSAT (very small aperture terminal) systems, designed primarily for data applications. The VSAT typically are low margin systems, with margins of 1 to 3 dB. VSAT networks can be global, and operate in the domestic and international fixed satellite service (FSS) bands².

This section will consider propagation analysis procedures for the two general types of systems that are important segments of the Ku-band industry: FSS systems and low margin FSS systems. Each has unique propagation characteristics that impact system design and performance.

3.3.1 Ku-band FSS Systems

The application of propagation effects prediction models to the case of Ku-band fixed service systems proceeds with the establishment of system performance requirements from the given overall performance criteria (link availability, outage times) and an initial set of assumed system parameters (antenna size, beamwidth, transmit power, etc) [the *Initial Phase* described in Exhibit 3.1.1-1]. The performance criteria, if not already in system performance parameter terms, must be converted to power allocation factors such as c/n , c/n_o , or e_b/n_o (for the specified link availability).

The critical propagation effects that must be included in the evaluation of a general Ku-band fixed service links are:

- Atmospheric Gaseous Attenuation
- Rain Attenuation

In addition, if frequency reuse is employed:

- Rain Depolarization
- Ice Depolarization

If the Ku-band ground terminal is operating at low elevation angles (~ 20 degrees or less):

- Cloud Attenuation
- Tropospheric Scintillation

Finally, if link restoration techniques are employed, the appropriate procedure is followed to determine the final operating power margin or performance level.

² Direct broadcast service satellite service (BSS) is also provided at Ku-band. The propagation analysis procedure for direct broadcast satellite systems is discussed in Section 3.6.

The recommended propagation analysis procedure for Ku-Band FSS Links is summarized on the flow chart of Exhibit 3.3.1-1.

The system parameters required for the propagation analyses are:

- Percent of Time (or times) to achieve desired performance [on annual basis]
- Frequency of operation, in GHz: f
- Polarization tilt angle, in degrees: τ
- Elevation angle to the satellite, in degrees: θ
- Latitude of the ground station, in degrees N or S.: ϕ
- Altitude of the ground station above sea level, in km: h_s

For the case where the elevation angle is $\leq 20^\circ$, the additional parameters required are:

- Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)
- Antenna diameter, in meters: D
- Antenna Efficiency: η

If restoration techniques are employed, then refer to Exhibit 3.3.1-2 for the recommended handbook sections to complete the evaluation of the Ku-band link performance.

The procedures presented above are suggestions for a general Ku-Band link evaluation. They apply to either uplink or downlink situations. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

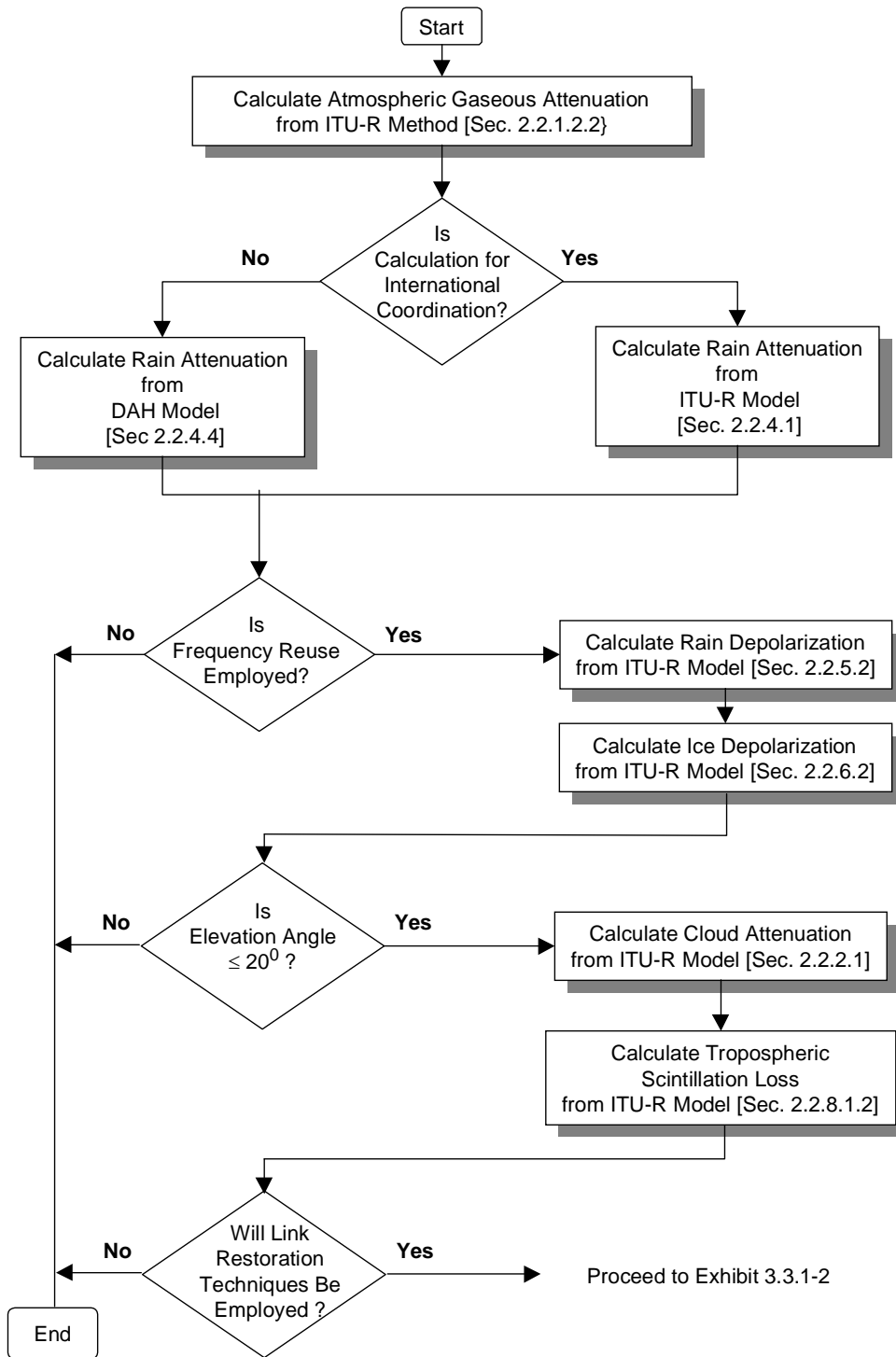


Exhibit 3.3.1-1
Propagation Analysis Procedure for Ku-Band FSS Links

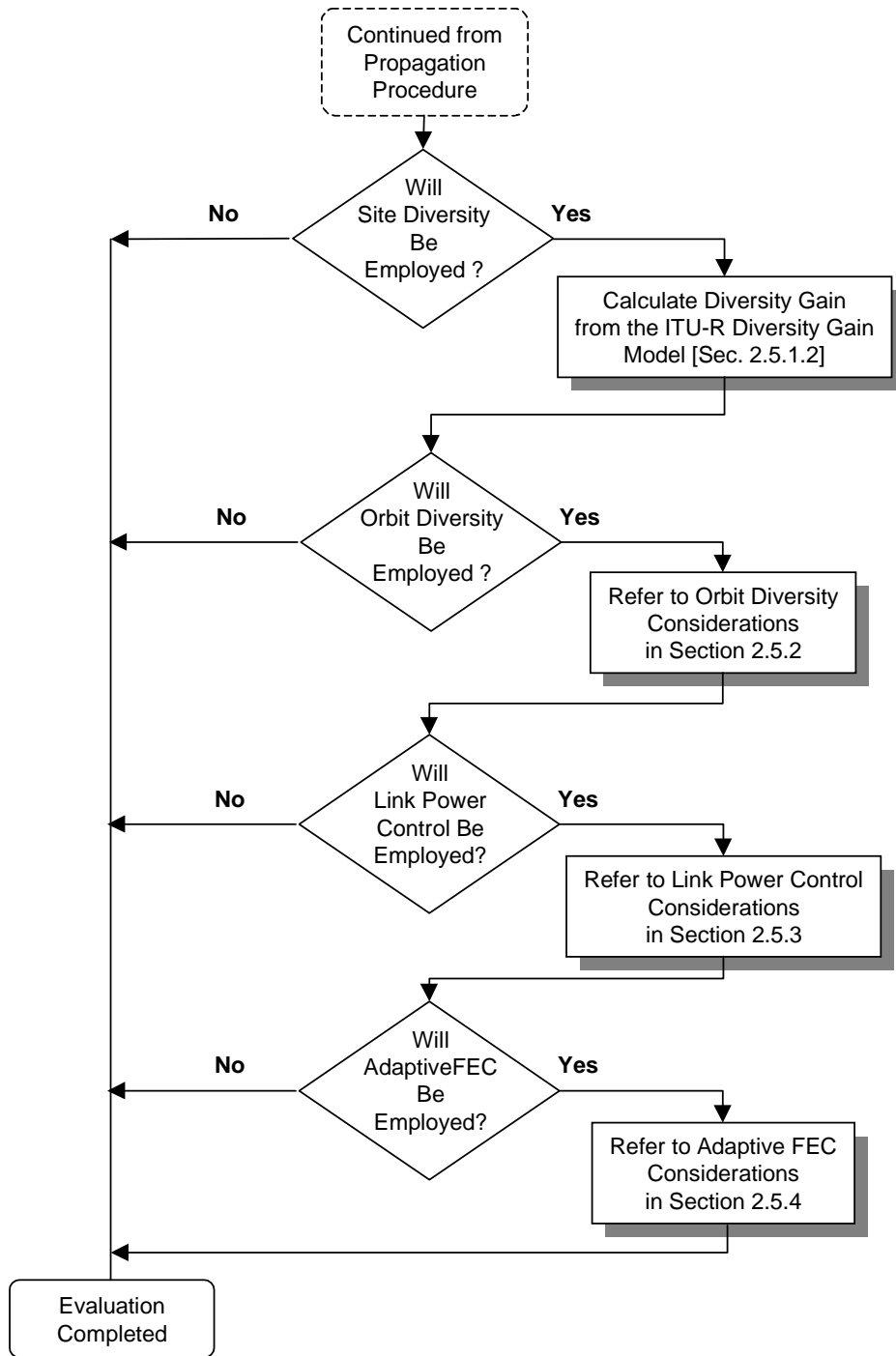


Exhibit 3.3.1-2
 Procedure for Evaluation of Link Restoration Techniques

3.3.2 Low Margin Ku-band Systems

The procedure described in Section 3.3.1 is applicable for any Ku-band link within the range of the prediction models, typically corresponding to a range of 95% to 99.99% annual link availability. If smaller VSAT type systems are involved, where the available link power margins may be 1 to 3 dB, corresponding to availabilities of ~ 99 % to 99.5%, additional effects must be added to the propagation analysis to insure that degradations that would be negligible for higher margin systems are accounted for.

All of the critical propagation effects specified in section 3.3.1 are applicable to the low margin systems. Additional propagation effects evaluated that should be evaluated for low margin Ku-band links are:

- Fog Attenuation
- Wet Surface Effects (optional – model results preliminary)
- Cloud Scintillation
- Combined Effects Statistics

A recommended propagation analysis procedure for Low Margin Ku-Band Links is summarized on the flow chart of Exhibit 3.3.2-1.

The system parameters required for the propagation analyses are:

Percent of Time (or times) to achieve desired performance [on annual basis]
Frequency of operation, in GHz: f
Polarization tilt angle, in degrees: τ
Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: ϕ
Altitude of the ground station above sea level, in km: h_s
Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)
Antenna Surface Parameters (optional)

For the case where the elevation angle is $\leq 20^\circ$, the additional parameters required are:

Antenna diameter, in meters: D
Antenna Efficiency: η
Visibility factor, in km: V (for fog attenuation calculation)

It is recommended that after the link propagation parameters are determined from the individual prediction procedures, a comparative analysis using the combined effects models described in Section 2.2.11 be performed (as indicated on Exhibit 3.3.2-1). The combined effects models tend to better account for the total statistical effects that would be present on a low-margin

system, where rain attenuation may not be the major contributor to periods when propagation outages are observed.

If restoration techniques are employed, then refer to Exhibit 3.3.1-2 for the recommended handbook sections to complete the evaluation of the Low Margin Ku-band link performance.

The procedures presented above are suggestions for low-margin Ku-Band link evaluation. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

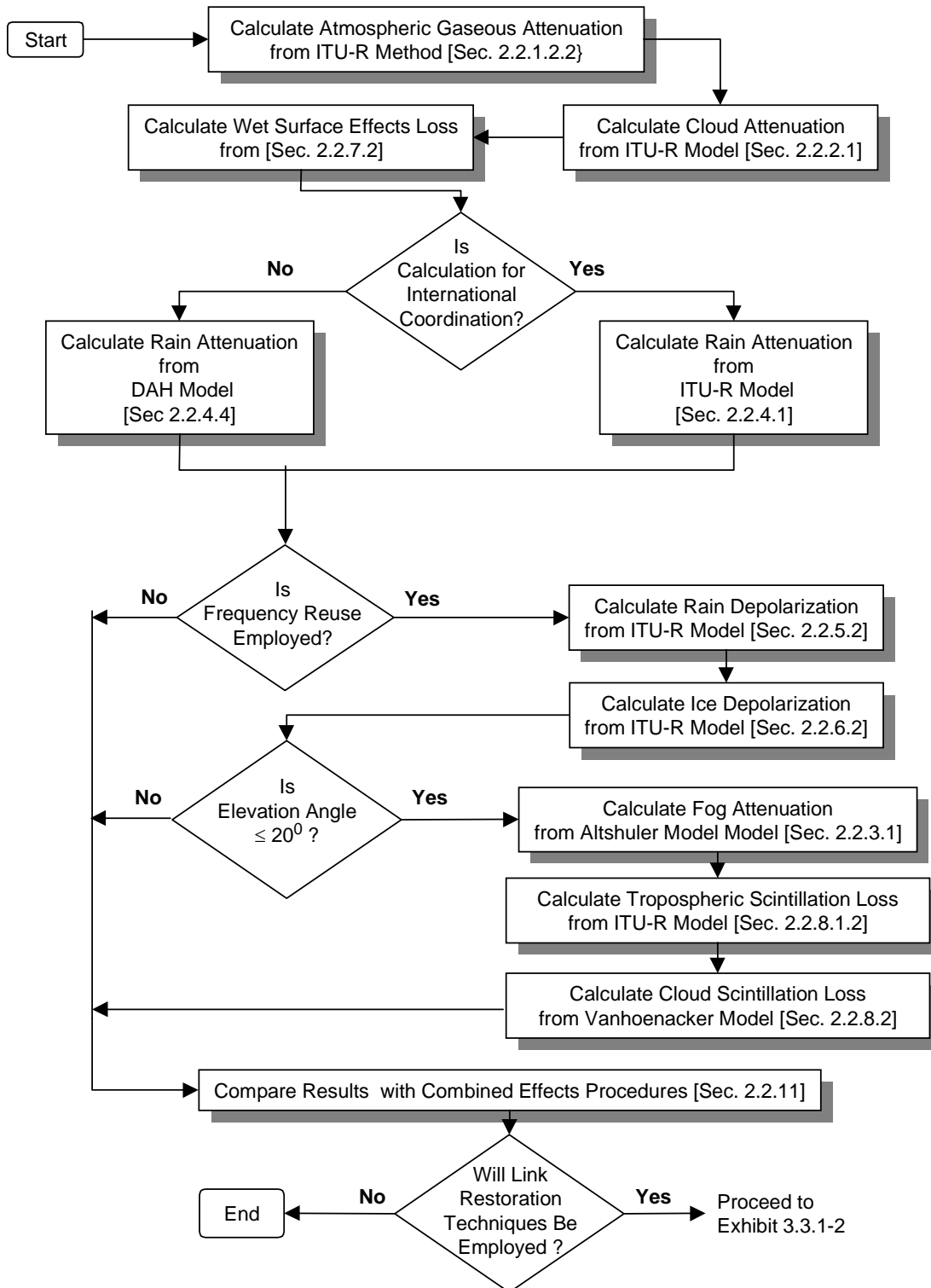


Exhibit 3.3.2-1
Propagation Analysis Procedure for Low Margin Ku-Band Links

3.4 PROPAGATION EFFECTS ON KA-BAND SYSTEMS

The Ka-band (nominally 30 GHz uplink / 20 GHz downlink) has seen a rapid growth for a wide range of applications. Ka-band systems are in development for fixed satellite service (FSS), some employing geosynchronous orbit (GSO) satellites and others non-geosynchronous orbit (NGSO) satellites. Ka-band applications to the International Telecommunications Union Radiocommunications Sector (ITU-R) through the end of WRC 97 have been tendered by twenty-one countries, with over 380 GSO satellites and eight countries have filed for over 200 satellites in NGSO constellations. The Ka-band is also allocated for feeder links for NGSO systems, including NGSO/FSS, NGSO/FSS/MSS, and NGSO/MSS services.

This section will consider the propagation analysis for four classes of systems that are important segments of the Ka-band industry:

- Ka-band FSS systems,
- Ka-band low margin FSS systems,
- Ka-band broadband systems, and
- Ka-band mobile service systems.

Each has unique propagation characteristics that impact system design and performance.

3.4.1 Ka-band FSS Systems

The application of propagation effects prediction models to the case of Ka-band fixed satellite service (FSS) systems proceeds with the establishment of system performance requirements from the given overall performance criteria (link availability, outage times) and an initial set of assumed system parameters (antenna size, beamwidth, transmit power, etc.) [the *Initial Phase* described in Exhibit 3.1.1-1]. The performance criteria, if not already in system performance parameter terms, must be converted to power allocation factors such as c/n , c/n_o , or e_b/n_o (for the specified link availability).

The critical propagation effects that must be included in the evaluation of a general Ka-band fixed service links are:

- Atmospheric Gaseous Attenuation
- Rain Attenuation
- Cloud Attenuation
- Tropospheric Scintillation

In addition, if frequency reuse is employed:

- Rain Depolarization
- Ice Depolarization

Finally, if link restoration techniques are employed, the appropriate procedure is followed to determine the final operating power margin or performance level.

The recommended propagation analysis procedure for Ka-Band FSS Links is summarized on the flow chart of Exhibit 3.4.1-1.

The system parameters required for the propagation analyses are:

- Percent of Time (or times) to achieve desired performance [on annual basis]
- Frequency of operation, in GHz: f
- Polarization tilt angle, in degrees: τ
- Elevation angle to the satellite, in degrees: θ
- Latitude of the ground station, in degrees N or S.: φ
- Altitude of the ground station above sea level, in km: h_s
- Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)
- Antenna diameter, in meters: D
- Antenna Efficiency: η

If restoration techniques are employed, then refer to Exhibit 3.3.1-2 for the recommended handbook sections to complete the evaluation of the Ku-band link performance.

The procedures presented above are suggestions for a general Ka-Band link evaluation. They apply to either uplink or downlink situations. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

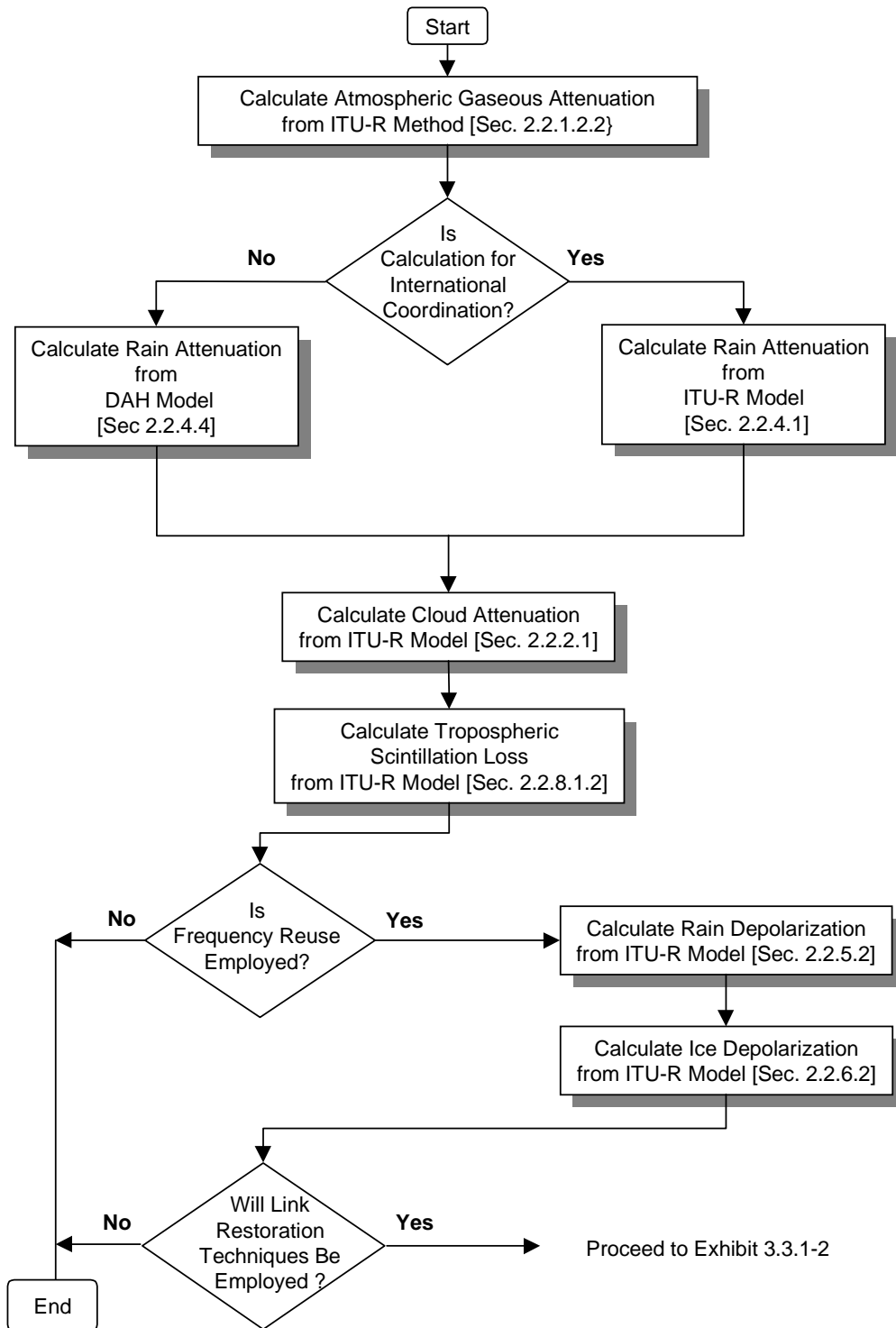


Exhibit 3.4.1-1
Propagation Analysis Procedure for Ka-Band FSS Links

3.4.2 Low Margin Ka-band Systems

The procedure described in Section 3.4.1 is applicable for any Ka-band link within the range of the prediction models, typically corresponding to a range of 95% to 99.99% annual link availability. If smaller VSAT type systems are involved, where the available link power margins may be 1 to 3 dB, corresponding to availability's of ~ 99 % to 99.5%, additional effects must be added to the propagation analysis to insure that degradations that would be negligible for higher margin systems are accounted for.

All of the critical propagation effects specified in section 3.4.1 are applicable to the low margin systems. Additional propagation effects evaluated that should be evaluated for low margin Ka-band links are:

- Fog Attenuation
- Cloud Scintillation
- Wet Surface Effects (optional – model results preliminary)
- Combined Effects Statistics

A recommended propagation analysis procedure for Low Margin Ka-Band Links is summarized on the flow chart of Exhibit 3.4.2-1.

The system parameters required for the propagation analyses are:

Percent of Time (or times) to achieve desired performance [on annual basis]
Frequency of operation, in GHz: f
Polarization tilt angle, in degrees: τ
Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: ϕ
Altitude of the ground station above sea level, in km: h_s
Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)
Antenna Surface Parameters (optional)
Antenna diameter, in meters: D
Antenna Efficiency: η
Visibility factor, in km: V (for fog attenuation calculation)

It is recommended that after the link propagation parameters are determined from the individual prediction procedures, a comparative analysis using the combined effects models described in Section 2.2.11 be performed (as indicated on Exhibit 3.4.2-1). The combined effects models tend to better account for the total statistical effects that would be present on a low-margin system, where rain attenuation may not be the major contributor to periods when propagation outages are observed.

If restoration techniques are employed, then refer to Exhibit 3.3.1-2 for the recommended handbook sections to complete the evaluation of the Low Margin Ku-band link performance.

The procedures presented above are suggestions for low-margin Ku-Band link evaluation. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc. are discussed in Section 2.4 of the handbook.

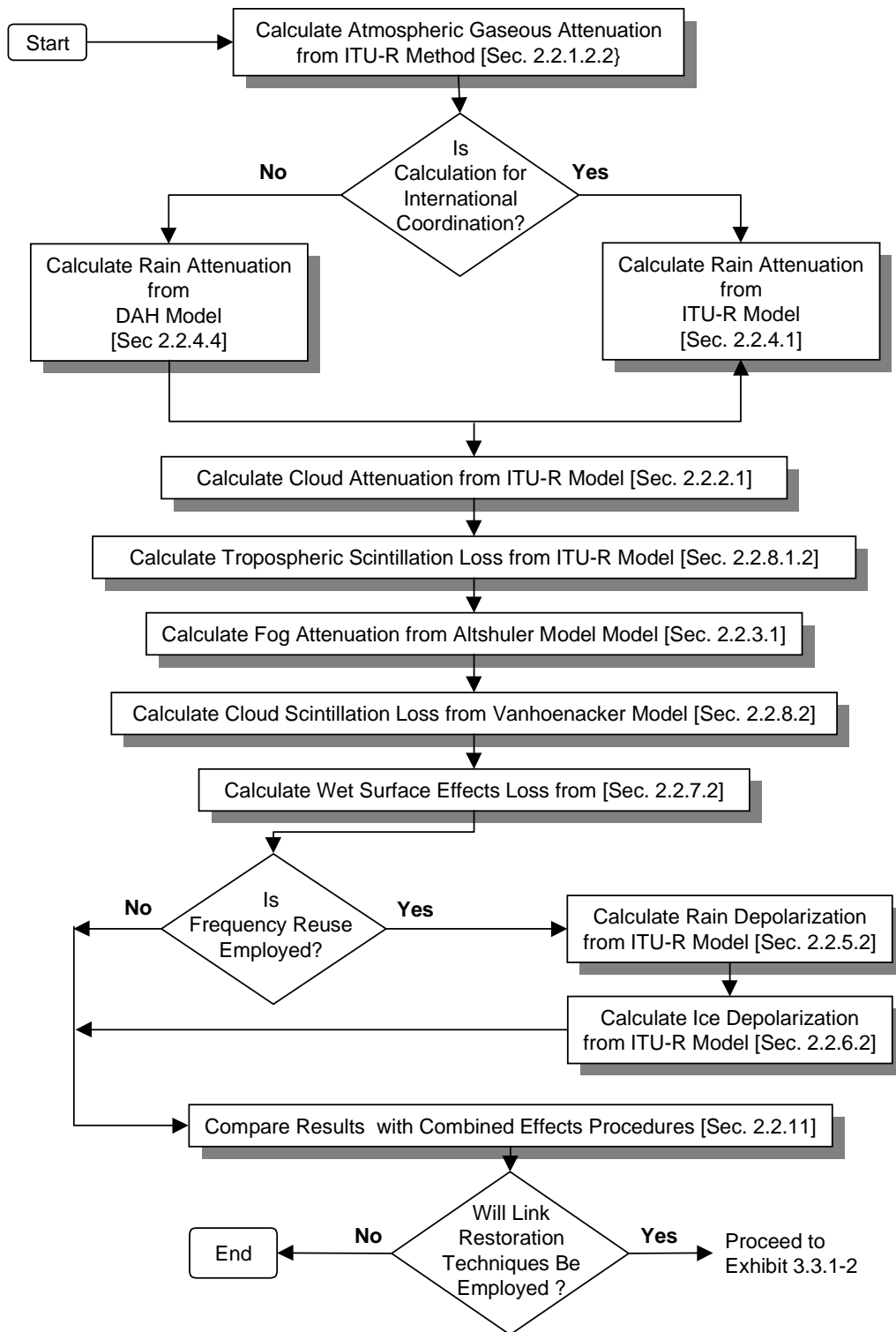


Exhibit 3.4.2-1
Propagation Analysis Procedure for Low Margin Ka-Band Links

3.5 PROPAGATION EFFECTS ON Q/V-BAND SYSTEMS

The past year has seen the first interest in satellite systems operating in the so-called Q-band or Q/V-band³. These systems operate in the FSS allocated bands of 37.5 - 40.5 GHz (downlink) and 47.2 - 50.2 GHz (uplink). These systems are designed to provide broadband multimedia services, VSAT and direct to home services. Q/V-band systems typically have higher data rates than Ku or Ka band systems, with data rates of up to 3 GBPS being considered.

This section provides a recommended propagation analysis procedure for the evaluation of links in the Q/V band. The majority of the propagation models provided in Section 2 have not been validated above 30 GHz. The major propagation degradation in this band is, of course, rain attenuation. A specific procedure for the evaluation of Q/V-band rain attenuation is described in Section 3.5.1.

The propagation effects that must be included in the evaluation of Q/V-band fixed service links are:

- Atmospheric Gaseous Attenuation
- Cloud Attenuation
- Tropospheric Scintillation
- Rain Attenuation

In addition, if frequency reuse is employed:

- Rain Depolarization
- Ice Depolarization

If the Q/V-band ground terminal is operating at low elevation angles (~ 20 degrees or less):

- Fog Attenuation
- Cloud Scintillation

The system parameters required for the Q/V-band propagation analyses are:

Percent of Time (or times) to achieve desired performance [on annual basis]
Frequency of operation, in GHz: f
Polarization tilt angle, in degrees: τ

³ The designation of this band is not consistent through the industry. The FCC, in Bulletin No. 70, July 1997, designates 33-50 GHz as “Q” band, 50-75 GHz as “V” band, and 75 –110 GHz as “W” band, with 40-60 GHz as “U” band. Most systems filed with the FCC refer to themselves as V-band. To further the confusion, we will refer to the bands as Q/V band, since, by the FCC definition, they should be called Q band.

Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: ϕ
Altitude of the ground station above sea level, in km: h_s
Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)

For the case where the elevation angle is $\leq 20^\circ$, the additional parameters required are:

Antenna diameter, in meters: D
Antenna Efficiency: η
Visibility factor, in km: V (for fog attenuation calculation)

The recommended propagation analysis procedure for Q/V-band Links is summarized on the flow chart of Exhibit 3.5-1. Refer to the next section (3.5.1) for the rain attenuation procedure referred to on the flow chart.

If restoration techniques are employed, then refer to Exhibit 3.3.1-2 for the recommended handbook sections to complete the evaluation of link performance.

The procedures presented above are suggestions for Q/V-Band link evaluation. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

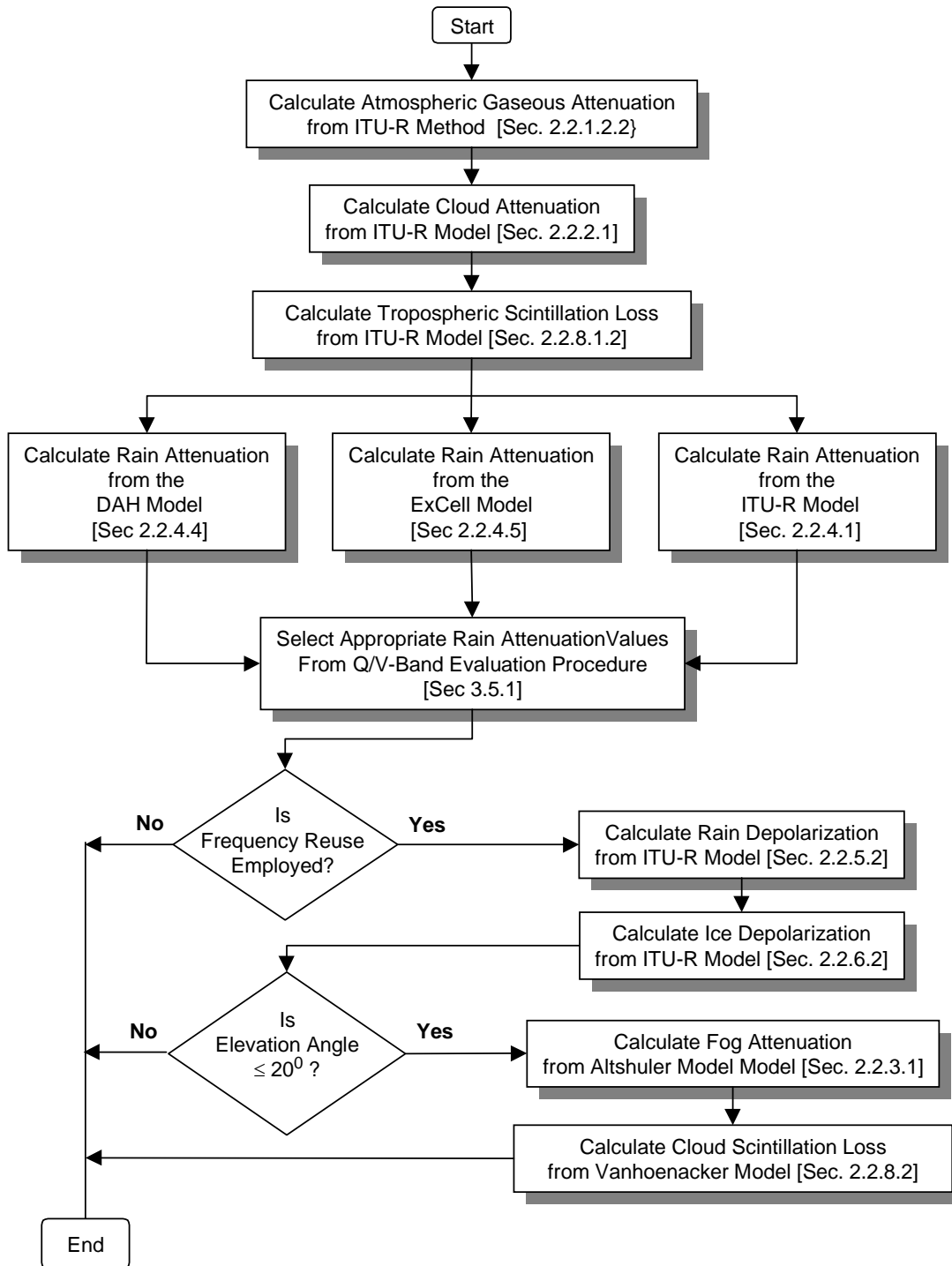


Exhibit 3.5-1
Propagation Analysis Procedure for Q/V-Band Links

3.5.1 Q/V-Band Rain Attenuation Evaluation Procedure

The rain attenuation prediction models described in Section 2.2.4 have not yet been fully validated in the bands above 30 GHz with directly measured data from satellite beacons or other sources. The only directly measured propagation statistics available to date for prediction model evaluation are measurements in Italy using ITALSAT beacons at 39.6 GHz and 49.5 GHz (Polonio and Rive, 1998). The authors state that annual rain attenuation statistics predictions obtained with the EXCELL and ITU-R models show ‘fairly good agreement’. The only other model tested was the DAH model. They also found that worst month statistics were underestimated with the ITU-R model.

Because of the preliminary nature of the validation of rain attenuation prediction procedures in the Q/V bands, a comparative approach, using the three better performing models (based on their performance for Ku and Ka band links) is recommended at this time. The recommended procedure, to be used with the flow chart of Exhibit 3.5-1, is given below.

Step 1

Calculate the predicted rain attenuation (in dB) for each link availability(s) using the three specified prediction models:

1. DAH Model (“USA” Model) [Section 2.2.4.4]
2. ExCell Rain Attenuation Model [Section 2.2.4.5]
3. ITU-R Rain Model [Section 2.2.4.1]

Step 2

Determine the average value (in dB) of the three values calculated in Step 1 for each link availability, A_{ave} :

$$A_{ave} = \frac{A_1 + A_2 + A_3}{3} \quad (\text{dB}) \quad (3.5.1-1)$$

where A_1 , A_2 , and A_3 are the three values calculated from Step 1, all in dB.

Step 3

If the difference between the maximum and minimum values calculated in Step 1 is $\leq 40\%$, in dB, then use A_{ave} as the predicted rain attenuation. If the difference between the maximum and minimum values calculated in Step 1 is $> 40\%$, then the predictions fall outside of the prediction uncertainty and a single predicted value cannot be assigned. In that case, the average value

could be used, with a notation that the prediction falls outside the prediction uncertainty range for rain attenuation prediction.

Example 1

The three values calculated from step 1 are 4 db, 4.5 dB, and 5.2 dB. Then

$$A_{ave} = \frac{4 + 4.5 + 5.2}{3} = 4.57 \text{ dB}$$

$$0.4 * 4.57 = 1.82 \text{ dB}$$

$$\text{Max} - \text{Min} = 5.2 - 4 = 1.2 \text{ dB}$$

Since the difference between the maximum and minimum values is less than 40 % of A_{ave} , use $A_{ave} = 4.57 \text{ dB}$.

Example 2

The three values calculated from step 1 are 3 db, 6 dB, and 6.5 dB. Then

$$A_{ave} = \frac{3 + 6 + 6.5}{3} = 5.16 \text{ dB}$$

$$0.4 * 5.16 = 2.06 \text{ dB}$$

$$\text{Max} - \text{Min} = 6.5 - 3 = 3.5 \text{ dB}$$

Since the difference between the maximum and minimum values is greater than 40 % of A_{ave} , the prediction exceeds the uncertainty range and A_{ave} should be used with caution.

3.6 PROPAGATION EFFECTS ON DIRECT BROADCAST SATELLITE SYSTEMS

The majority of current direct to home broadcast satellite services (BSS) operate into the home with a Ku-band downlink. The allocated bands are 11.7-12.5 GHz in Region 1, 12.2 - 12.7 GHz in Region 2, and 11.7 -12.2 GHz for Region 3. The uplinks (feeder links) generally operate in the 17.3 - 18.1 GHz band. This section will present a propagation analysis procedure for the Ku-band downlink. The uplink can be analyzed with the procedure described in Section 3.4.1, Ka-band FSS systems.

Direct to home systems generally operate with small aperture antennas, and are designed for unattended fixed pointed operation. BSS satellite EIRP for the downlink tends to be higher in power by 6 to 10 dB than for an FSS downlink. BSS system performance is often specified with reference to worst month link availability rather than an annual basis, and this must be taken into account in the propagation analysis.

The critical propagation effects that must be included in the evaluation of a Ku-band broadcast satellite service downlink are:

- Atmospheric Gaseous Attenuation
- Rain Attenuation
- Cloud Attenuation
- Wet Surface Effects (optional – model results preliminary)

In addition, Worst Month statistics must be considered, and a comparison with Combined Effects Statistics Modeling is recommended.

A recommended propagation analysis procedure for Ku-band Broadcast Satellite Service (BSS) Downlinks is provided by the flow chart of Exhibit 3.6-1.

The system parameters required for the propagation analyses are:

Percent of Time (or times) to achieve desired performance [on annual basis]
Frequency of operation, in GHz: f
Polarization tilt angle, in degrees: τ ($= 45^0$ if CP)
Elevation angle to the satellite, in degrees: θ
Latitude of the ground station, in degrees N or S.: ϕ
Altitude of the ground station above sea level, in km: h_s
Total columnar liquid water content of the cloud, in kg/m^2 : (available from Sec. 2.2.2.1)
Antenna Surface Parameters (optional)

If worst month statistics are desired, a procedure is provided for the conversion of annual statistics to worst month statistics for the specific location(s) of interest.

It is recommended that after the link propagation parameters are determined from the individual prediction procedures, a comparative analysis using the combined effects models described in Section 2.2.11 be performed. The combined effects models tend to better account for the total statistical effects that would be present on a low-margin system, where rain attenuation may not be the major contributor to periods when propagation outages are observed.

The procedures presented above are suggestions for Ku-band broadcast satellite service (BSS) downlink evaluation. Additional considerations such as application of statistical data, frequency scaling, elevation angle scaling, etc., are discussed in Section 2.4 of the handbook.

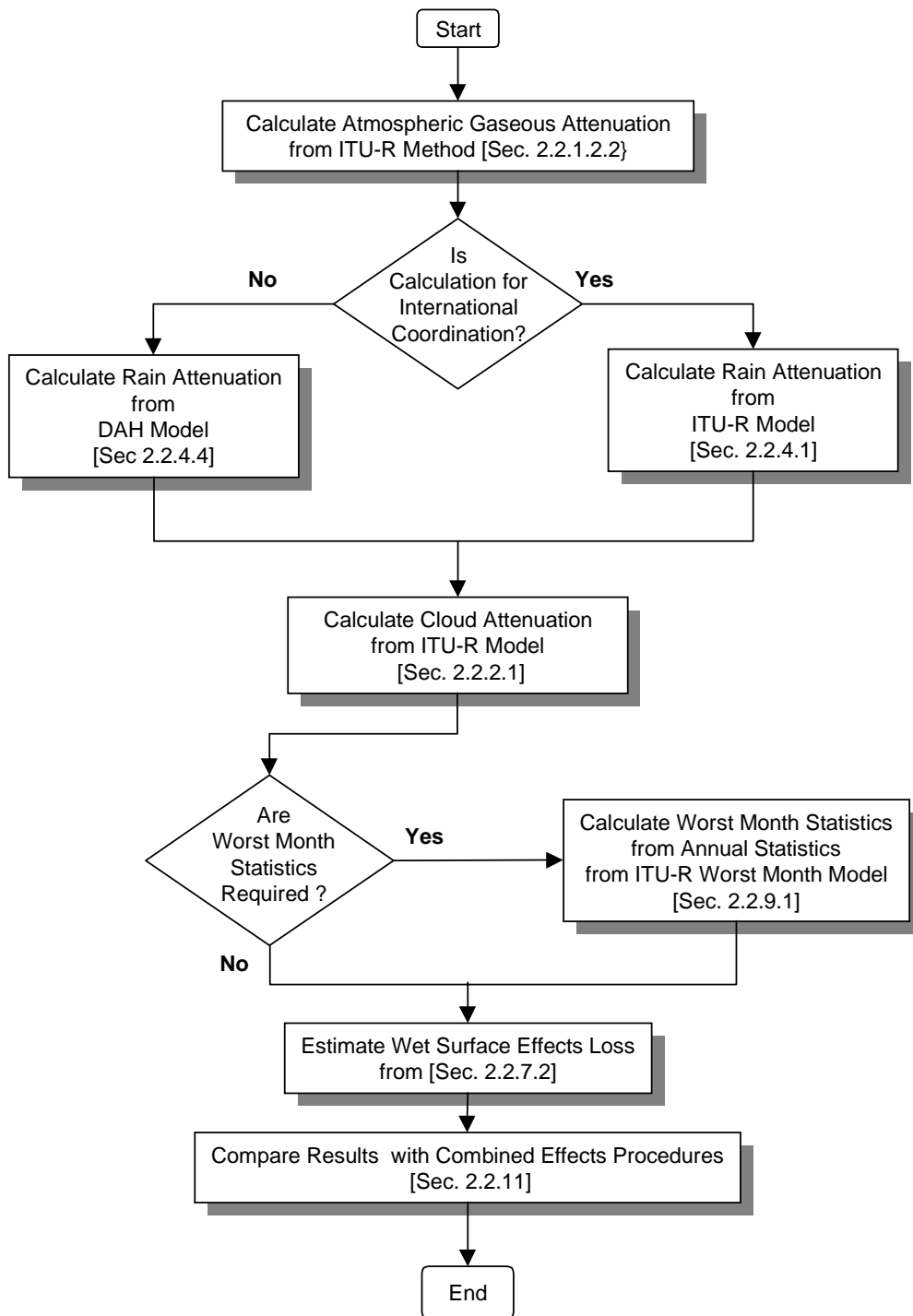


Exhibit 3.6-1
Propagation Analysis Procedure for Ku-band Broadcast Satellite Service (BSS) Downlinks

3.7 PROPAGATION EFFECTS CONSIDERATIONS FOR NGSO SYSTEMS

The past decade has seen a rapid increase in the interest in non-geosynchronous orbit (NGSO) constellations for the provision of communications services. The primary interest has been for mobile and personal communications with service links in the VHF/UHF (Little LEOs) and in the S- and L-bands (Big LEOs), however NGSO systems are also filed and being designed for Ku-band FSS, Ka-band FSS and MSS, and Q/V-band FSS services. Also, feeder links of the NGSO MSS systems operate in the C-, Ku-, and Ka-bands. Several types of NGSO orbits are utilized by these systems, including low earth orbit (LEO), medium earth orbit (MEO), high elliptical earth orbit (HEO), and quasi-GSO (QGSO) constellations.

The variation of path length (range) to the NGSO satellite changes as the satellite passes over the ground terminal, with the range at the maximum when the satellite rises and falls at the horizon and reaching a minimum at the midpoint of the pass. LEO satellites, for example, typically have orbital periods of 1.5 to 2 hours, and the satellite will ‘pass over’ an area on the Earth’s surface several times per day, and be in view of a ground terminal for 10 to 20 minutes per pass. The elevation angle statistics must therefore be integrated into the propagation prediction procedure to assure the proper evaluation of propagation margins is achieved. The free space path loss is at its maximum at the horizon points, and is a minimum at the midpoint of the pass. Unfortunately, the lower elevation angles occur at the horizon points, and the elevation angle is the highest at the midpoint of the pass. A system designed with a fixed power margin to account for path loss and for propagation effects losses will have LESS margin is available for propagation losses at the low elevation angles (where it is needed most).

3.7.1 NGSO Links and Rain Attenuation Statistics Evaluation

This section focuses on NGSO links that are impacted by rain attenuation, i.e. links operating above about 10 GHz. The considerations described here would apply to Ku-band, Ka-band, and Q/V-band. Propagation considerations for NGSO links operating in the bands below 3 GHz involve other considerations, and are not discussed here.

The evaluation of propagation effects involving NGSO satellites is complicated by the fact that the slant path to the satellite is no longer fixed, but is a time variable parameter (Ippolito & Russell, 1993). The statistical prediction models for rain attenuation, rain and ice depolarization, tropospheric scintillation, etc. provided in Section 2 all are based on a fixed elevation angle to the satellite. This will, of course, not be the case for NGSO satellite links. LEO satellites, for example, typically have orbital periods of 1.5 to 2 hours, and the satellite will ‘pass over’ an area on the Earth’s surface several times per day. The elevation angle statistics must therefore be integrated into the propagation prediction procedure to assure the proper evaluation of propagation margins is achieved.

The process for evaluation of propagation effects for NGSO links can best be described through the consideration of a specific example.

Consider a low earth orbit (LEO) satellite in a circular polar orbit at an altitude of 765 km, with an ascending node at 100°W. This is a typical orbit for a MSS Big LEO satellite. Let us assume the satellite has a feeder link operating in the Ka-band, with a feeder link terminal located at 106.6°W and 32.5°N latitude (White Sands, NM). Assume that the 20 GHz downlink has a fixed power margin of 74 dB available for free space path loss and propagation losses.

Exhibit 3.7-1 shows a plot of elevation angle and path loss with time for a single pass of the satellite over the ground terminal. The elevation angle (heavy solid line) reaches a maximum of about 60 degrees. The free space path loss (long dashed line) ranges from 70 dB at the horizon points to a minimum of 59 dB at the center of the pass, where the elevation angle is at the maximum. The light solid line shows the available power margin of 74 dB. The difference between the available margin and the path loss, (shown by the double arrow line), is the margin available for propagation losses. The propagation margin ranges from 4 dB at the horizon points to 15 dB at the midpoint of the pass.

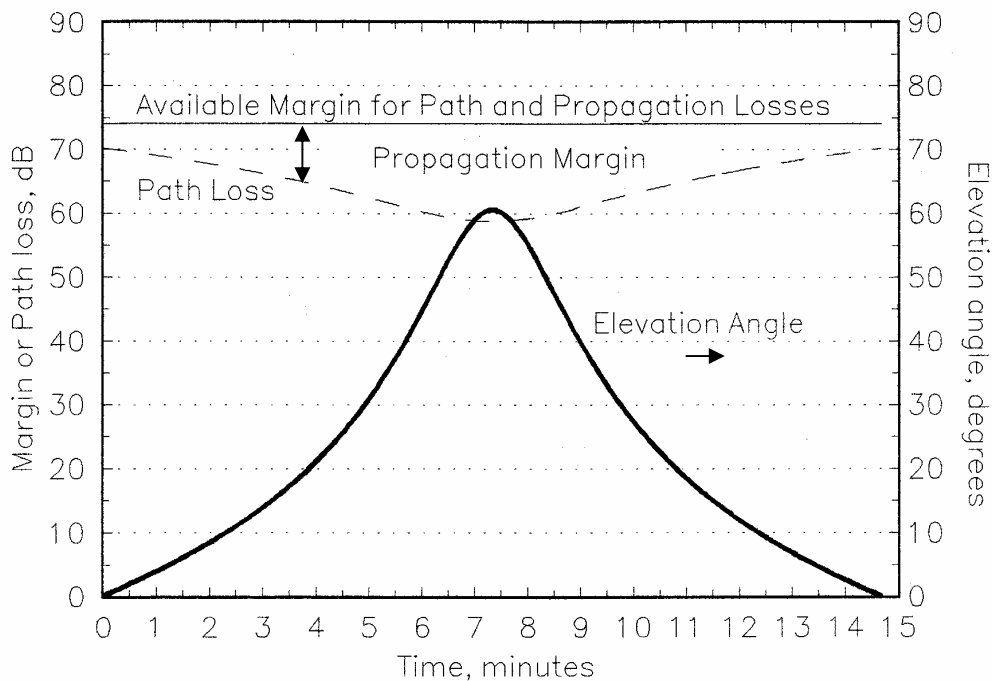


Exhibit 3.7-1
Elevation Angle and Path Losses for a Single Pass of a LEO Satellite
Frequency = 20 GHz, Altitude = 765 km

The next step in the evaluation process is to determine a reasonable estimation of the link availability from the time variable available propagation margin, which we found ranges from 4 to 15 dB. Let us assume that there are two propagation effects of concern for this location; gaseous attenuation and rain attenuation. If we assume a homogeneous atmosphere with a 7.5-g/m^3 water vapor density, the gaseous attenuation will vary only with path length.

Exhibit 3.7-2 shows the available propagation margin (solid line) for the example link as a function of time. The dotted line shows the gaseous attenuation determined from the ITU-R Gaseous Attenuation Model [Section 2.2.1.2.2]. The propagation margin minus the gaseous attenuation, which is the margin left for rain attenuation, is plotted as the dashed line labeled Rain Margin.

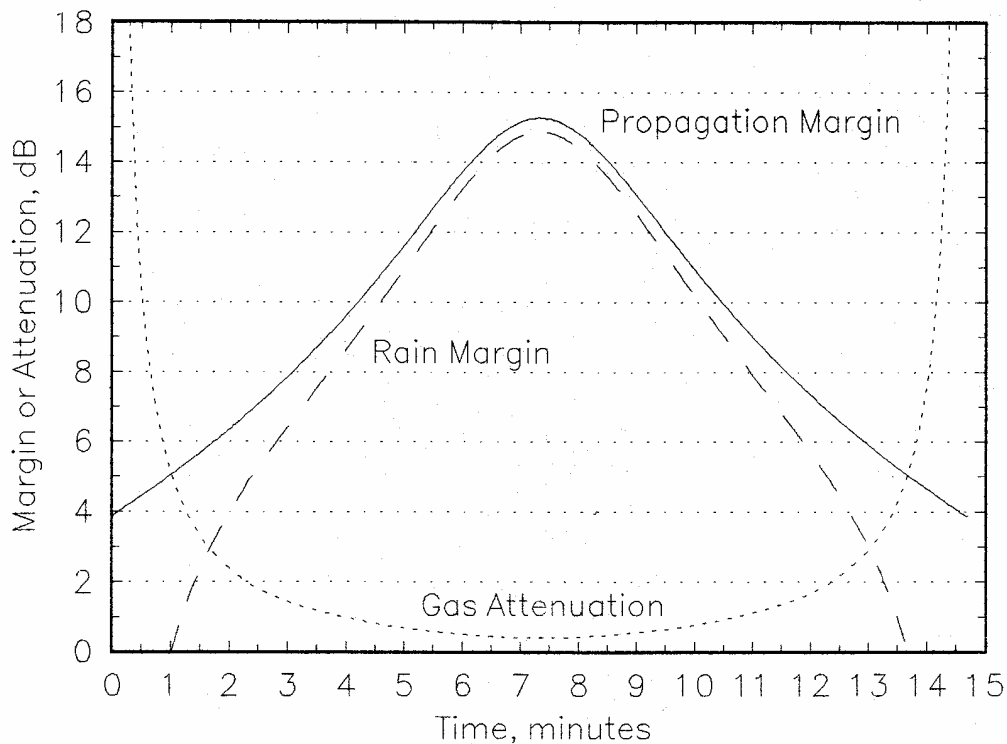


Exhibit 3.7-2
Total Propagation Margin and Allocation of Margin to Gaseous Attenuation and Rain Attenuation, for Single Pass of a LEO Satellite
Frequency = 20 GHz

The rain margin, also a variable with time, reaches a maximum value of 14.7 dB at the center point, and becomes negative for the first 2 minutes and last 2 minutes of the pass. This result

validates the comment made earlier that the system will have less margin at low elevation angles, where it is most needed.

The next step in the procedure is to determine expected rain attenuation outage statistics for the single pass, from the time variation of the rain margin. The rain attenuation prediction models in Section 2.2.4 of the handbook provide annual statistics of rain attenuation at a fixed elevation angle. The relative reliability at various portions of the LEO pass can be evaluated by applying the rain statistics from a prediction model to the time variable rain margin to determine an equivalent annualized outage probability for the link.

Exhibit 3.7-3 shows the annualized outage probability for the single LEO pass by application of the Global Model [Section 2.2.4.2] to the time varying Rain Margin shown in the previous plot. The ground station location is in Global Model Climate Region F (see Exhibit 2.2.4.2-1).

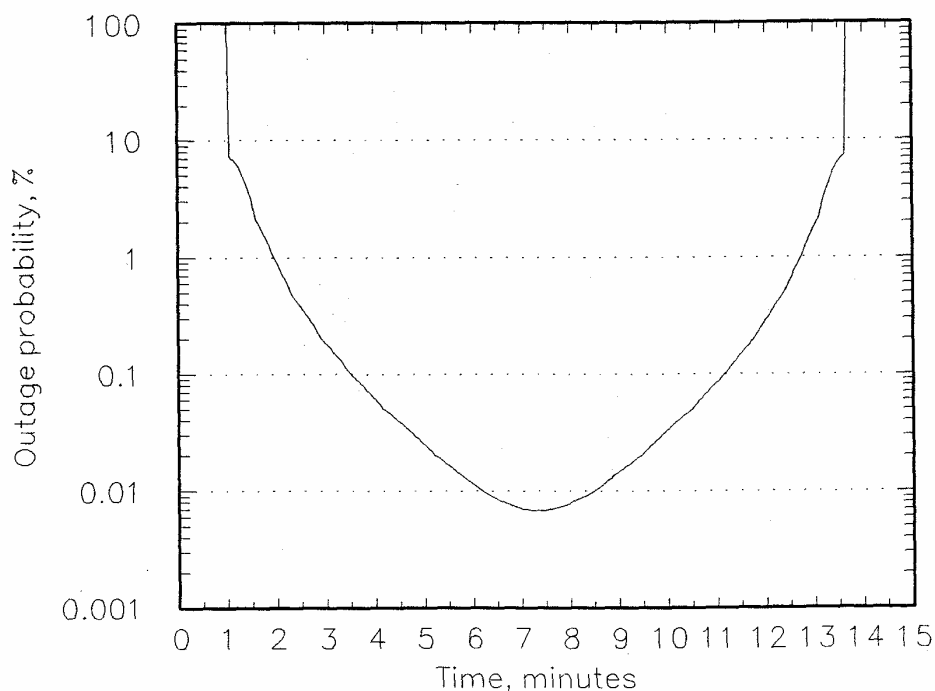


Exhibit 3.7-3
Annualized Outage Probability for a Single Pass of a LEO Satellite
Frequency = 20 GHz
ITU-R Gaseous Attenuation Model [Sec. 2.2.1.2.2]
Global Model [Sec 2.2.4.2]

The result shows that the link has less than 0.01% annual probability of outage (99.99% link availability) for three minutes in the midpoint of the pass. However, the link availability drops to 99% at ± 2 minutes into the pass. The link will not close for about 1 minute at the horizon points.

The average outage probability for the pass depends on the minimum elevation angle for link operation. The lower the allowable elevation angle the larger the coverage area for the satellite, therefore a low elevation angle is desired.

Exhibit 3.7-4 shows the cumulative statistics of the average outage probability over the pass for minimum elevation angles of 5, 7, 10 and 15 degrees and for a range of Available Margin from 65 to 85 dB. The dashed vertical line represents the operating point of the example above, 74 dB.

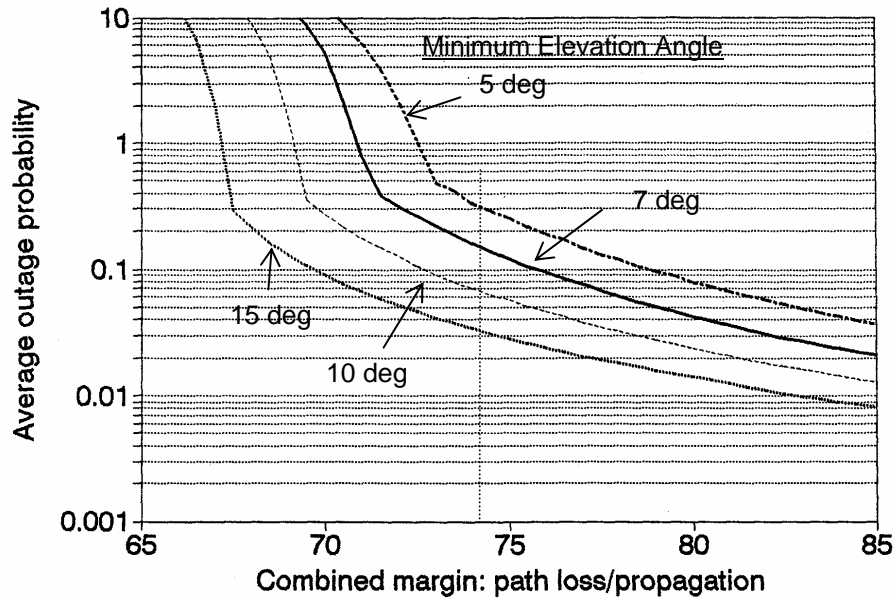


Exhibit 3.7-4
 Cumulative Statistics of Average Outage Probability over the Pass
 As a Function of Available Margin and Minimum Elevation Angle.
 Frequency: 20 GHz

The average outage probabilities at a margin of 74 dB for the four elevation angles are:

<u>Minimum Elevation Angle</u>	<u>Average Outage</u>
5 deg	0.38 %
7 deg	0.16 %
10 deg	0.075 %
15 deg	0.035 %

The results of the example evaluation show that the average outage probabilities are significantly different than the probabilities at the worst case of the pass (the horizon points).

The analysis has also shown the importance of a trade-off process between power margin designed into the system and the minimum elevation angle of operation. This trade also impacts the number of satellites required to meet a desired coverage area and quality of service.

A complete evaluation of the propagation margin requirements would require an analysis for the full constellation of satellites for each ground terminal of interest. The constellation average outage probability could be determined, and trades for minimum elevation angle and EIRP and other system parameters accomplished.

The validity of applying annual based statistical prediction models developed for fixed link conditions to links with time varying elevation angles requires an assumption of the interchangeability of temporal statistics and spatial statistics for the determination of expected link performance. There are good intuitive arguments for making this assumption, however further research is necessary for a complete validation. The first experimental links operating from NGSO platforms with payloads designed for the evaluation of propagation effects in the bands above 10 GHz are expected in the next few years, and they should shed new light on this important but perplexing problem.

3.8 REFERENCES – SECTION 3

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