New Challenges in Earth-Satellite Propagation Research

Faramaz Davarian
Jet Propulsion Laboratory
California Institute of Technology

Abstract

Slant path propagation research contributes to new developments in satellite communications. The satellite communications' market share is being reduced in trunked point-to-point applications. However, business is growing for new applications such as mobile/personal, broadcasting, and low-traffic communications.

This paper examines the propagation needs of the satellite communication services, and presents research topics for the propagation community. In addition to service-oriented problems, regulatory issues are also addressed. The frequency bands considered by this paper are from 100 MHz to above 30 GHz.

1. Introduction

Earth/space propagation research in the United States is tied to new developments in satellite communications. In spite of the fiber optics competition for trunked point-to-point communications, a host of emerging services are discovering the great potential of satellites for wireless communications. The use of satellites in radio communications appears to grow with a rapid pace in the areas of mobile/personal and thin-route (low-traffic) applications.

An important factor influencing the future of satellite communications is the congestion of the spectral slots at K_u- and lower bands.[1] This heavy usage of the spectrum gives rise to conflicts among the users and occasionally forces regulatory organizations to relocate frequency assignments —a decision that, for obvious reasons, is unpopular with the

[1] Because there is no standard on band designators accepted worldwide, for convenience the author loosely defines frequencies from 12-30 GHz as K-band. The first portion of this band, 12-17 GHz, is called K_u and the rest is called K_a.

relocated service. The 1992 World Administrative Radio Conference (WARC '92) was held in Torremolinos, Spain, in early 1992 to consider reallocating the electromagnetic spectrum for a host of new communications technologies. As a result of WARC '92 decisions, some established radio systems residing in the reallocated bands may have to be moved if new systems cannot share frequencies without interference. For example, the 13.75-14.0 GHz band was reallocated to the Fixed-Satellite Service (Earth-space). This in turn caused the National Aeronautics and Space Administration (NASA) to move the operating frequency of its scatterometer from 13.9995 GHz to a lower frequency at considerable cost.

Because of a radio spectrum shortage below about 17 GHz, frequencies in K_a- and higher spectral bands are currently viewed as good candidates for Earth-space communications in the future.

New challenges in propagation research include the characterization of mobile/personal links and the investigation of higher bands for satellite communications. Figure 1 depicts an example of the above radiowave propagation scenarios. In this figure, the mobile terminal, with a low-gain antenna, operates in frequencies below 10 GHz and is faced with propagation anomalies due to shadowing, Doppler, and multipath effects. The fixed terminal, with a high-gain antenna, operates at frequencies above 10 GHz and suffers from atmospheric effects.

This paper briefly reviews the current challenges of propagation research and provides some of the study plans in the U.S.

2. Mobile and Personal Applications

The world's first operational land mobile satellite system will begin its voice and data service in Australia shortly [1]. However, the use of satellites for mobile communications is not a new idea. Initial investigations took place in the 1970s. During the 1980s, however, a major effort was carried out by NASA's Mobile Satellite Experiment (MSAT-X) at the Jet Propulsion Laboratory [2]. It was soon realized that a good understanding of the channel characteristics is fundamental to the planning of mobile satellite systems. To support the MSAT-X and the emerging mobile satellite technologies, the NASA Propagation Program funded a number of studies to examine the propagation effects of land mobile satellite channels. In addition to analytical work, these efforts included a considerable number of field measurements. In the early years of the endeavor, data were collected using simulated space platforms, such as balloons and helicopters [3], and in the later years, satellite transmissions were used [4, 5]. The mobile experiments in the U.S. were conducted primarily at UHF and L-bands, and they mostly employed omnidirectional ground antennas. Studies conducted in the U.S. assumed a geostationary satellite orbit.

It is worth noting that, in parallel with NASA's efforts, propagation researchers in other countries also investigated the vagaries of the mobile satellite channel. Notable efforts took place in Canada [6], Europe [7], and Japan [8]. Work on nongeostationary systems was reported by European researchers [9]. Some of these investigations also included aeronautical and maritime mobile satellite links [10,11]. A compendium of results for land mobile satellite systems can be found in [12], and two recommendations from the Radiocommunication Sector[2] of the International Telecommunications Union (ITU) address propagation in aeronautical and maritime mobile satellite systems [13].

Three recent events have influenced the future of mobile/personal applications.

First, in the 1980s Voice of America recognized the value of satellites in direct radio broadcasting to augment the less reliable shortwave broadcasting [14]. More recently, the commercial use of the direct satellite broadcast radio (DBS-R) has attracted much attention both in the U.S. [15] and abroad [16].

Second, many potential service providers have lately considered the use of satellites for personal communications [17-21]. Much attention is now being given to low-earth-orbit (LEO) satellite applications as well as geostationary-earth-orbit (GEO) applications.

Third, the 1992 World Administrative Radio Conference (WARC '92) deliberated mobile/personal applications and opened new regions of the spectrum for them. Although the L- and S-bands presently are the most popular spectral slots, allocation as low as 150 MHz[3] and as high as 30 GHz exist for slant path mobile/personal applications, and most of these frequencies are likely to be used sometime in the future.[4]

---

[2]Previously known as CCIR.

[3]Several newly formed telecommunications companies in North America are planning to use frequencies slightly below 150 MHz for LEO transmissions.

[4]L-band refers to frequencies between 1 and 2 GHz. S-band refers to frequencies between 2 and 4 GHz.

The task that faces propagation researchers is the characterization of a vast region of the spectrum for mobile/personal links. This assignment is particularly challenging because the mobile channel demonstrates a nonstationary behavior. Note that mobile/personal receivers may operate in a variety of propagation environments, including reception with or without a clear view (i.e., tree shadowing, blockage). In addition to the above effects, the Doppler-induced dynamics of the signal should also be taken into account.

Currently, data availability is limited to a few selected frequencies with only a limited number of physical and environmental attributes; therefore, future efforts should concentrate on expanding the existing propagation data base to all the bands of interest and include a broader selection of environmental parameters. It is also important that a diversity of satellite orbits —i.e., GEO, LEO, and highly elliptical orbit (HEO)— be considered in the future studies. The following is a partial list of topics in propagation research that need to be addressed:

- Conduct propagation measurements into buildings to determine the spatial, spectral, and temporal signal structure for indoor reception.

- Perform mobile measurements in urban, suburban, and rural environments to derive statistical information, determine model parameters, and obtain data for channel simulation. Measurements through trees must receive attention. Improved methods for describing and specifying the local environment are needed.

- Make stationary and mobile measurements of the delay spread to model the wideband behavior of mobile/personal channels. Sites in city centers and mountainous areas are of special interest.

In addition to the above items, land mobile satellite service providers need detailed statistics on regions of interest to them. However, the collection of detailed information on all the regions of interest will be prohibitively expensive. A good compromise is presented in the fourth item below:

- Optical blockage and shadowing measurements should be made to provide statistics on a given environment; for example, a given region, a particular highway, etc. It has been shown that optically based sensing systems can predict radio propagation impairments resulting from signal blockage and shadowing [22].

- Develop service contour maps that depend on such parameters as frequency, orbit, land environment, and coverage area.

- Develop a systematic method for evaluating ITU-allotted spectral slots for different applications.

- To enhance system performance, propagation effects should be mitigated or reduced. Examples are adaptive coding, power control, and smart antennas that can adapt their performance to match the propagation characteristics of the channel (multipath reception).

- For applications near equatorial regions, information is needed on the morphology of ionospheric scintillation at low latitudes, particularly as it affects L-through C-bands, because these bands will soon be used by DBS-R and aeronautical services.[5]

The above studies should also consider the effect of polarization and antenna type.

In the future, the designers of mobile/personal satellite-based networks are likely to employ simulation schemes for system design and evaluation applications. Therefore, propagation data and models are needed to develop simulation tools. For such applications, time series data or data generated locally using known signal statistics can be used. Future propagation research should support the development of simulation tools.

3. Rain and Cloud Effects

Most rain attenuation prediction procedures depend on rain climate models. Most available climate models are now about 15 years old, have not been updated in a consistent way to incorporate new observations, and are not dependent on measurable parameters such as annual and monthly rain accumulation, number of days with rain, and synoptic conditions to be associated with rain. Once the relationship between rain attenuation model and measurable climatological data is known, maps of the latter can be used to generate maps of the expected attenuation to be exceeded for a given fraction of time on a specific type of path such as from a mobile vehicle to a geostationary satellite. Future propagation research should include a revision of current rain

[5] C-band refers to frequencies between 4 and 8 GHz.

climate models, similar to the work conducted by Crane [23]. Furthermore, rain-rate distribution models should be expanded to represent seasonal behavior of the rain process. The annual/worst-month distribution relationships depend on the seasonality of the process, as do any models developed to explain the variability of the process.

Because most of the available data have been, or will be, used to provide the parameters for model distributions, more samples are needed to provide an independent data set to test the models. Samples should include the rain rate distributions for locations where observations have been made as well as data for new locations

An important component of most rain attenuation models is the rain height which is dependent on geographic region, e.g., latitude and longitude, season, and storm type. Although the rain height is not always equal to the 0^{o} isotherm height, it is offend associated with the altitude of the 0^{o} isotherm out of convenience. Simultaneous radar and attenuation observations of Goldhirsh have demonstrated that when the precipitation is stratiform, optimum agreement is obtained for heights corresponding to the 0^{o} isotherm [24]. However, dual-polarized radar measurements have shown that the above statement is not valid for convective rain [25]. In general, rain height statistics are best obtained by combining dual polarization radar observations with beacon measurements [26].

For many applications the assumption of a fixed rain height is not realistic; therefore, statistics on the variation of rain height with day, season, time of day, location within a storm, etc., are needed. For applications such as aeronautical mobile, the stochastic approach to rain height modeling is imperative. It is also important for receiver terminals in the mountains.

Some rain attenuation models depend on the expected correlation between rain rates at different locations along a path. For such applications an improved model for the correlation structure of rain rate can be useful.

By ignoring the microstructure of rain, the available models give rise to errors in signal attenuation prediction and discrepancies in frequency scaling. These problems become more important for frequencies above about 17 GHz because of the sensitivity of these frequencies to changes in the drop size distribution at the smaller drop sizes. A basic problem lies in the difficulty of making reasonable drop size distribution measurements. Employing measurements at the higher frequencies (i.e., the 90- and 120-GHz windows) simultaneously with measurements at lower frequencies may unravel this problem. Rain drop size distribution can also be measured by radars and disdrometers [27, 28]. Efforts to improve and simplify disdrometer measurement techniques should be considered. The microstructure problem is one that affects our ability to do real-time "frequency scaling," an important component of the uplink power control problem.

Although the influence of clouds can be ignored for the lower frequencies, their effect is important at higher frequencies. Multi-frequency radiometers, similar to the ones operated by the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado, are practical and a relatively inexpensive means of cloud sensing [29]. Since radiometers cannot determine the atmospheric liquid water versus distance, data from other remote sensing measurements may need to be combined with radiometric data for cloud modeling. Clouds may be characterized with high-power, high-resolution radars operating at the longer wavelength, e.g., S-band or C-band. Radars operating at shorter wavelengths, e.g., X- and K- bands, have also been utilized, including those with multiple polarization and Doppler capability [30]. For propagation modeling this is virgin territory with no adequate models and very little data.

4. Characterization of the Spectral Bands Above About 17 GHz

The congestion of the spectrum for radio communications will inevitably push some services to bands beyond 17 GHz, i. e. K_a-band and above. Radiowave propagation at frequencies above 17 GHz is plagued with rain-induced signal attenuation, a factor that for small probability levels can be very large. Therefore, services that require a low to moderate degree of link availability are likely to be attracted to frequencies above 17 GHz sooner than those demanding a very small probability of outage. The aeronautical mobile satellite service can use the K_a-band to its advantage considering that the cruising altitudes of most flights are high enough to either eliminate or considerably reduce the rain attenuation problem. Links in parts of the world with a low annual rainfall can use frequencies above about 17 GHz without significantly compromising link availability. For example, feeder links of mobile satellite systems can be placed in the relatively dry regions of the country to minimize rain attenuation at frequencies above about 17 GHz.

Link availability can be improved via the use of some form of fade mitigation technology. Hence, if tools to offset rain-induced effects are employed, the K_a-band can be used for services that require a moderate degree of link availability but cannot afford a large power margin. Lately, the VSAT industry is showing much interest in the K_a-band. A low-margin VSAT can transmit in the K_a-band by either reducing its demand on link availability or employing a fade mitigation technique.

5. ACTS Propagation Campaign

To accommodate low margin systems, future propagation research in the U.S. includes a measurement campaign using NASA's Advanced Communications Technology Satellite (ACTS) [31]. An experimental spacecraft, ACTS provides transponders and propagation beacons at 20- and 30-GHz bands. ACTS will also be used for K_a-band mobile/personal experiments. Plans for future research at the K_a-band call for the expansion of the current knowledge on K_a-band propagation with a focus on the following efforts [32]:

- Develop attenuation prediction models for atmosphere-induced effects with attention to high-occurrence, low-attenuation factors, such as light rain, clouds, and fog.
- Refine the existing climatological maps.
- Develop fade mitigation methods.
- Develop a model for large-scale diversity.
- Provide a means of real-time frequency scaling of propagation impairments.
- Investigate propagation characteristics of land, sea, and aeronautical mobile channels.
- Develop models for predicting impaired operation and outage duration statistics and the mean time between outages or impairments during a rain event.

The measurement phase of the ACTS campaign is likely to last four years with a total campaign period of five years, 1993 to 1998. Several sites, all equipped with dual-frequency beacon receivers and radiometers, will collect data. Considering the complexity of the campaign, much thought has been given to data archiving logistics. Data archiving and dissemination will take place by a single organization, known as the ACTS Propagation Data Center, located at the University of Texas, Austin [33]. Table 1 shows the ACTS propagation measurement sites.

Table 1. Sites for ACTS Propagation Terminals

LOCATION	CCIR Rain Zone	LATITUDE (NORTH) Deg	LONGITUDE (WEST) Deg	AZIMUTH from North Deg	PATH EL Deg	SLANT RANGE Km
Vancouver, BC	D	49	123	150	30	38777
Ft. Collins, CO	E	40	105	173	43	37654
Fairbanks, AK	C	65	148	129	9	40905
Clarksburg, MD	K	39	077	214	39	37971
Las Cruces, NM	M/E	32	107	168	51	37075
Norman, OK	M	35	097	184	49	37242
Tampa, FL	N	28	082	214	52	37060
Montreal, PB	K	45	074	215	31	38583
Montreal, PB	K	46	075	214	31	38582

Since the ultimate goal is to provide design tools for system engineers, the ACTS campaign emphasizes interaction between the experimenters and industry. A forum known as the ACTS Propagation Studies Workshop, formed in 1990, annually brings together experts from industry, academia, and elsewhere to develop plans for the ACTS propagation campaign [34].

6. Regulatory Issues

The increased use of satellites by today's emerging services will result in new demands for the already scarce resource of the radiowave spectrum. These demands will inevitably result in a more aggressive approach by the ITU toward revising existing allocations and generating new ones. Therefore, regulatory bodies around the world will need propagation data even more than before. Hence, future propagation research should support regulatory organizations with an emphasis given to:

- Active participation in the efforts of the Radiocommunications Sector of the ITU, particularly Study Group 5.

- Support of the ITU in providing spectrum for services that employ satellites for communications.

- Cooperation with other regulatory organizations, such as the National Telecommunications and Information Administration (NTIA), Federal Communications Commission (FCC), Space Frequency Coordination Group (SFCG), and Consultative Committee on Space Data Systems (CCSDS).

Study Group 5 of the ITU Radiocommunications Sector specializes on propagation in non-ionized media. The activities of this study group entail mainly the development of recommendations for predicting propagation anomalies in communications systems. Many of these recommendations can be expanded to better serve system and design engineers. In particular, recommendations dealing with propagation in mobile satellite channels (Rec. 680, 681, and 682 [13]), can greatly benefit from propagation research. For example, these recommendations would be enhanced by providing prediction models for signal attenuation, depolarization, and delay spread at all bands of interest with the elevation angle and the antenna type as parameters.

The inclusion of environmental descriptors in a model for mobile/personal applications is an important factor for the successful use of a prediction tool by system engineers. Examples are the terrain type in land applications, the state of the sea surface in maritime applications, and the cruising altitude in aeronautical applications. More work by ITU members to develop meaningful, easy-to-use environmental descriptors is needed. Furthermore, Radiocommunication Sector recommendations should be expanded to include models that accurately predict the propagation phenomena for the application of interest at the coverage of interest. Future efforts should include LEO and HEO configurations in addition to the GEO systems.

To predict slant path rain attenuation, the Radiocommunication Sector provides prediction models and rain climate maps. These rain climate maps are in need of improvement; for example, the map for the U.S. places New Mexico, with its arid climate, in the same rain climate region as South Carolina, which has subtropical weather. Clearly, future propagation research should correct such discrepancies [23].

Microclimatology is an important factor in the design and planning of fixed and broadcast services. Radiocommunication Sector models are generally too crude to account for this effect and hence give rise to prediction inaccuracies. Examples include errors in estimating link availability for areas prone to microclimatological effects when prediction models are used. This problem can be remedied by observing climatic statistics at a higher special resolution than previously has been done, when potential for microclimate exists. This topic needs to be addressed by propagation researchers, and the resulting data should be provided to the Radiocommunication Sector.

7. Data Dissemination and Representation

The sophisticated satellite networks of the present day require automated techniques for link calculation and planning. Propagation prediction tools should be presented to the system engineer in an intelligible and easy-to-use format. It is desirable that data and models be incorporated with computerized link calculation programs to save time. Therefore, the propagation community should provide engineers with user-friendly propagation software that can be easily implemented on popular personal computer systems and readily interfaced to the user's design control tables; an example of which is given in [35].

Simulation techniques are playing an increasingly important role in the planning, design validation, and implementation of communication systems. Since the collection of propagation data is often a time-consuming effort, an alternate approach may be needed to meet the propagation needs of a system under design. In such a case, simulation can be an attractive alternative, assuming that adequate prior data can be applied to the system under consideration. Therefore, schemes to simulate propagation effects should be developed and provided to system designers. Again, to enjoy widespread acceptance a simulation tool should use modern software technology and be capable of running on a personal computer.

Handbooks are useful tools for educational and system design purposes. In the U.S., NASA has published and maintains two handbooks on slant path propagation effects [36, 37]. NASA handbooks have been used by U.S. industry for many years. Currently Study Group 5 of the Radiocommunication Sector is also working on a handbook to complement some of its recommendations. Efforts to publish and update handbooks should continue and expand in the future. Such handbooks should be evolving documents with frequent revisions to ensure their utility and vitality.

8. Conclusions

Areas in need of further research include:

- Mobile/personal links in all the ITU-allotted bands, including the relevant choices of the propagation environment, ground antenna type, and satellite orbit configuration as parameters.

- Rain climatology, including microstructure and seasonal effects.

- Rain attenuation models, including event duration distributions.

- Fade mitigation technology.

- Cloud effects for frequencies above about 30 GHz.

- Bands above about 17 GHz, with emphasis given to low-margin applications.

- Low-latitude ionospheric scintillation effects for lower frequency bands (direct broadcast and aeronautical applications).

- Spectrum allocation for satellite applications via participation in regulatory processes.

- Computerized models for the prediction of propagation effects.

- Tools for the simulation of propagation effects.

- Maintenance and periodic revision of handbooks on slant path propagation

The propagation community must stay abreast of the changing trends in the satellite communications market. This can be achieved by an ongoing dialogue with system planners and design engineers of satellite communication networks. The success of propagation research in the future will depend largely on how well the needs of the systems and engineering community are communicated to the propagation experts and experimenters, and how effectively the propagation community responds to the challenges.

9. Acknowledgment

The research conducted in this paper was funded by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The author would like to thank many of the members of the NASA Propagation Program for providing him with data and useful comments.

10. References

1. P. Cooper and L. Crawley, "Mobilesat -- A World First," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 273-277, June 16-18, 1993.

2. K. Dessouky and M. Sue, *MSAT-X: A Technical Introduction and Status Report,"* JPL Publication 88-12, April 15, 1988.

3. J. W. Vogel and U. S. Hong, "Measurement and Modeling of Land Mobile Satellite Propagation at UHF and L-bands," *IEEE Trans. Antennas Propagat.*, Vol. AP-36, No. 5, pp. 707-719, May 1988.

4. J. W. Vogel and J. Goldhirsh, "Mobile Satellite System Propagation Measurements at L-Band Using MARECS-B2," *IEEE Trans. Antennas Propagat.*, Vol. AP-38, No. 2, pp. 259-264, February 1990.

5. J. W. Vogel, J. Goldhirsh, and Y. Hase, "Land Mobile Satellite Fade Measurements in Australia," *AIAA Journal of Spacecraft and Rockets*, August 1991.

6. J. S. Butterworth, "Propagation Measurements for Land Mobile Satellite at 1542 MHz," *Communication Research Center*, Ottawa, Canada Tech. Note 723, August 1984.

7. E. Lutz, W. Papke, and E. Ploechinger, "Land Mobile Satellite Communications Channel Model, Modulation and Error Control," *Seventh International Conference on Digital Satellite Communications*, pp. 537-543, May 1986.

8. H. Wakana, "A Propagation Model for Land-Mobile-Satellite Communication," *1991 North American Radio Science Meeting and IEEE/APS Symposium*, The University of Western Ontario, London, Ontario, Canada, June 24-28, 1991.

9. V. S. M. Renduchintala, H. Smith, J. G. Gardiner, and I. Stromberg, "Communications Service Provision to Land Mobiles in Northern Europe by Satellites in High Elevation Orbits -- Propagation Aspects," *Proceedings of the 40th International Conference on Vehicular Technology*, Orlando, Florida, May 6-9, 1993.

10. F. Davarian et al., "A CCIR Aeronautical Mobile Satellite Report," *Proceedings of the Thirteenth NASA Propagation Experimenters Meeting*, San Jose, California, JPL Publication 89-26, pp. 70-86, August 15, 1989.

11. Y. Karasawa and T. Shiokawa, "Characteristics of L-Band Multipath Fading due to Sea Surface Reflection," *IEEE Trans. Ant. Prop.*, Vol. AP-32, No. 6, pp. 618-623, 1984.

12. J. Goldhirsh and W. Vogel, *Propagation Effects for Land Mobile Satellite Systems: Overview of Experimental and Modeling Results*, NASA Reference Publication 1274, February 1992.

13. *Recommendations of the CCIR*, International Radio Consultative Committee, Geneva, Switzerland, Vol. V, 1990.

14. D. Messer, "BSS (Sound) Receiver Development Activities by the USA Government," paper presented at CITEL, August 24-28, 1992, Mexico City, Mexico.

15. D. Marcus, "Five More Companies Seek Audio Satellite Licenses from FCC," *Space News*, Jan 4-10, 1993.

16. P. L. Galbo, J. Benedicto, and R. Viola, "ESA Personal Communications and Digital Audio Broadcasting Systems Based on Non-Geostationary Satellite," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 9-14, June 16-18, 1993.

17. G. A. Johnson, "Implementation of a System to Provide Mobile Satellite Service in North America," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 279-284, June 16-18, 1993.

18. J. E. Hatlelid and L. Casey, "The Iridium System: Personal Communications Anytime, Anyplace," *Proceedings of the Third*

International Mobile Satellite Conference, Pasadena, California, pp. 285-290, June 16-18, 1993.

19. R. A. Wiedeman, "The Globalstar Mobile Satellite System for Worldwide Personal Communications," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 291-296, June 16-18, 1993.

20. C. Spitzer, "Odyssey Personal Communications Satellite System," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 297-302, June 16-18, 1993.

21. N. Hart, H. Haugli, P. Poskett, and K. Smith, "Inmarsat's Personal Communications System," *Proceedings of the Third International Mobile Satellite Conference*, Pasadena, California, pp. 303-304, June 16-18, 1993.

22. W. Vogel, and U. Hong, "Measurements and Modeling of Land Mobile Satellite Propagation at UHF and L-band," *IEEE Trans on Ant. and Prop.*, Vol 36, No. 5, May 1988, pp 707-719.

23. R. K. Crane, "Rain Rate-Data Base Development and Rain-Rate Climate Analysis," *Proceedings of the Seventeenth NASA Propagation Experimenters Meeting and the Advanced Communications Technology Satellite Miniworkshop*, Pasadena, CA, JPL Publication 93-21, pp. 105-128, August 1, 1993.

24. J. Goldhirsh, "Predictive Methods for Rain Attenuation Using Radar and In-Situ Measurements Tested Against the 28-GHz COMSTAR Beacon Signal," IEEE Trans. on Ant. and Prop., Vol. AP-27, pp. 398-406, 1979.

25. M. J. Leitao and P. A. Watson, "A New Method for the Prediction of Slant Path Attenuation at 10-30 GHz using Detailed Knowledge of the Micro-Physical Structure of the Rainstorm," IEE Conf. Pub. 219, (ant. and prop.), pp. 73-78, 1983.

26. M. J. Leitao and P. A. Watson, "Methods for Prediction of Attenuation on Earth-Space Links based on Radar Measurement of the Physical Structure of Rainfall," IEE Proc., Vol. 133, No 4, pp. 429- 440, July 1986.

27. J. Goldhirsh and B. Musiani, "Radar, Disdrometer, and Raingauge Measurements for Improving Radar Estimation of Rain Rates," *Proceedings of NAPEX XI,* Blacksburg, Virginia, JPL D-4647, pp. 76-81, June 19, 1987.

28. J. Goldhirsh and B. H. Musiani, "Rain Core Structure Statistics Derived from Radar and Disdrometer Measurements in the Mid-Atlantic Coast of the U.S.," *Proceedings of the Thirteenth NASA Propagation Experimenters Meeting*, San Jose, California, pp. 130-137, August 15, 1989.

29. E. R. Westwater, J. B. Snider, and M. J. Falls, "Ground-Based Radiometric Observations of Atmospheric Emission and Attenuation at 20.6, 31.65, and 90.0 GHz," *IEEE Trans. Ant. Prop.*, Vol. 38, No. 10, pp. 1569-1580, October 1990.

30. D. Atlas, *Radar in Meteorology: Battan Memorial and 40th Anniversary Radar Meteorology Conference,* American Meteorology Society, Boston, 1990.

31. D. A. Olmstead and R. J. Schertler, "Advance Communications Technology Satellite (ACTS)," *13th AIAA International Communications Satellite Systems Conference and Exhibit*, Los Angeles, California, pp. 522-528, March 11-15, 1990.

32. F. Davarian, "The ACTS Propagation Campaign," *Eight International Conference on Antennas and Propagation (ICAP)*, Edinburgh, UK, March 30 - April 2, 1993.

33. A. Syed and W. Vogel, "ACTS Data Center Status Report," *Proceedings of the Seventeenth NASA Propagation Experimenters Meeting and the Advanced Communications Technology Satellite Miniworkshop*, Pasadena, CA, JPL Publication 93-21, pp. 289-297 August 1, 1993.

34. F. Davarian, editor, *Presentations of the Fourth ACTS Propagation Studies Workshop,* Santa Monica, CA, JPL D-10393, December 1-2, 1992.

35. A. V. Kantak, K. Suwitra, and C. Le, "A Data Base for Propagation Models," *Proceedings of the Seventeenth NASA Propagation Experimenters Meeting and the Advanced Communications*

Technology Satellite Miniworkshop, Pasadena, CA, JPL Publication 93-21, pp. 129-141, August 1, 1993.

36. L. J. Ippolito, *Propagation Effects Handbook for Satellite Systems Design*, Fourth Edition, NASA Reference Publication 1082 (04), Feb. 1989.

37. W. L. Flock, *Propagation Effects on Satellite Systems at Frequencies Below 10 GHz*, Second Edition, NASA Reference Publication 1108 (02), 1987.

FIGURE 1. Radiowave Propagation in Earth-Space Links