Referências bibliográficas

[1] SILVA MELLO, L. A. R.; PONTES, M.; RODRIGUES DA COSTA, M. E., **Rádio Propagação.** Rio de Janeiro, 2000. Notas de Aula do Curso de Propagação Troposférica - Pós-Graduação da Pontifica Universidade Católica do Rio de Janeiro.

[2] ITU-R, Attenuation by Atmospheric Gases. **ITU-R Rec. P.676-5**, Genebra, 2001.

[3] CRANE, R.K., Comparative Evaluation of Several Rain Attenuation Predictions Models. **Radio Science**, v. 20, n. 3, p. 843-863, 1985.

[4] CRANE, R.K., A Local Model for the Prediction of Attenuation Caused by Rain. **Proc. of CLIMPARA 1998,** Otawa, Canadá, p. 53-56, 1998.

[5] CRANE, R.K., Modelling Attenuation by Rain in Tropical Regions. **Int. J. Satellite Communication**, v. 8, p. 197-210, 1990.

[6] ITU-R, Characteristics of Precipitation for Propagation Modelling. **ITU-R Rec. P.837-1**, Genebra, 1995.

[7] DA COSTA, A. T.; ASSIS, M. S., **Análise da Atenuação por Chuva em Regiões Tropicais e Equatoriais Aplicada ao Problema do Desempenho de Sistemas de Comunicações por Satélite em banda Ka.** Rio de Janeiro, 2002. Dissertação de Mestrado – Instituto Militar de Engenharia.

[8] GARCIA, P. N. A., **Modelamento de Efeitos de Atenuação por Chuvas em Enlaces Terrestres Ponto-a-Ponto e Ponto-Multiponto.** Rio de Janeiro, Junho 2003. Tese de Doutorado – Pontifica Universidade Católica do Rio de Janeiro.

[9] WATSON, P.A. at al., Prediction of Attenuation on Satellite Earth Links in the European Region. **IEE Proc.**, v. 134, pt. F, n. 6, p. 583-596, 1997.

[10] ITU-R, Characteristics of Precipitation for Propagation Modelling. **ITU-R Rec. P.837-3**, Genebra, 2001.

[11] BAPTISTA, J. P. V. P.; SALONEN, E. T., Review of Rainfall Rate Modelling and Mapping. **Proc. of CLIMPARA 1998,** Otawa, Canadá, p. 35-44, 1998.

[12] ITU-R, Characteristics of Precipitation for Propagation Modelling. **ITU-R Rec. P.837-4**, Genebra, 2003.

[13] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., Rain Attenuation Research in Amazon Region. **Proc. of XXVIIIth General Assembly of URSI 2005**, Nova Delhi, Indía, 2005.

[14] PAN, Q. Q., ALLNUT, J. E., 12-GHz Fade Durations and Intervals in the Tropics. **IEEE Trans. on Antennas and Propagation**, v. 52, n. 3, p. 693-700, Março, 2004.

[15] ESA, Reference Book on Radar. **Second Workshop of the OLIMPUS Propagation Experimenters**, v. 4, Noordwijk, Novembro de 1994.

[16] CRITCHFIELD, H. J.; **General Climatology**. 3ª edição, Editora Prentice Hall, Nova Jersey, E.U.A., 1974.

[17] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., An Exceptional Rainfall Event in the Amazon Region. **Proc. of CLIMDIFF 2005**, Cleveland, E.U.A, 2005.

[18] PAWLINA, A., Essential Knowledge of Rain Structure for Radio Applications Based on Available Data and Models. **Proc. of Radio Africa 99 – Radiocommunications Workshop** 99, Gaborone, Botswana, 1999.

[19] CAPSONI, C.; LUINI, L.; RIVA, C., A New Global Prediction Model of Rain Attenuation that Accounts for Separately Stratiform and Convective Rain. **Proc. of XXVIIIth General Assembly of URSI 2005**, Nova Delhi, Indía, 2005.

[20] SALONEN, E. T.; BAPTISTA, J. P. V., A New Global Rainfall Rate Model. **Tenth Int. Conf. on Antennas and Propagation,** IEE Conf. Publ. 436, v. 2, p. 2.182-2.185, 1997.

[21] DA COSTA, A. T.; ASSIS, M.S., Modelagem da Precipitação para Emprego no Cálculo da Atenuação em Enlaces Radioelétricos. **Proc. SBMO 2002**, Recife, Brasil, 2002.

[22] **http://www.cptec.inpe.br/products/climanalise.** Endereço Eletrônico na Internet da análise climática da região norte realizada pelo CPTEC do INPE, acessado em janeiro 2006.

[23] ECEPLAN, **Atlas Climatológico do Brasil.** Ministério da Agricultura – Escritório Central de Planejamento e Controle (ECEPALN), Rio de Janeiro, 1969.

[24] IBGE, **Anuário Estatístico do Brasil 1997 – Unidades Climáticas**. Diretoria de Geociência IBGE, 1997.

[25] INMET, **Normais Climatológicas 1961-1990**. Brasília, 1992.

[26] **http: // www.worldclimate.com**, acessado em setembro 2005.

[27] CHAVES, M. P., **Rádio Propagação em Sistemas de Comunicações Via Satélite.** Rio de Janeiro, Agosto 1996. Dissertação de Mestrado – Pontifica Universidade Católica do Rio de Janeiro.

[28] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., Precipitation Studies for Rain Attenuation Prediction in the Amazon Region. **Proc. of Int. Symposium on Antennas and Propagation - ISAP 2005**, Seul, Coreia, 2005.

[29] CRANE, R. K; DEBRUNNER, W. E., Worst Month Statistics. **Electonic Letters,** v. 14, n. 2, p. 38-40, 1978.

[30] ITU-R, The Concept of Worst Month. Statistics. **ITU-R Rec. P.581-2**, Genebra, 1994.

[31] HOUZE, R. A., Stratiform Rain in Regions of Convective: a Meteorological Paradox? **Bulletin of the Amarican Meteorological Society,** v. 3, p. 230-255, 1997.

[32] COUTO DE MIRANDA, E.; SILVA MELLO, L. A. R.; PONTES, M., Statistical Modelling of The Cumulative Probability Distribution Function of Rainfall Rate in Brazil. **Proc. of CLIMPARA 1998,** Otawa, Canadá, p. 77-80, 1998.

[33] ALLNUTT, J. E.; HAIDARA, F., Ku-band Diurnal Fade Characteristics and Fade Event Duration Data From Three, Two-Year, Earth-Space Radiometric Experiments in Equatorial Africa. **Int. J. Satellite Communication**, v. 18, p. 161-183, 2000.

[34] AJAYI, G. O., Handbook on Radiopropagation Related to Satellite Communications in Tropical and Subtropical Countries. **URSI Standing Committee on Developing Countries**, 1996.

[35] ITU-R, Probability Distributions Relevant to Radiowave Propagation Modelling. **ITU-R Rec. P.1057-1**, Genebra, 2001.

[36] FUKUCHI, H.; WATSON, P.A., AJAYI, G. O., Statistical Stability of Cumulative Distributions of Rainfall Rate in the UK. **IEE Proceedings**, v. 136, pt H, n. 2, Abril 1989.

[37] PAULSON, K., GIBBINS, C., Rain Models for the Prediction of Fade Durations at Millimetre Wavelengths. **IEE Proc-Microw. Antennas Propag.**, v. 147, n. 6, Dezembro 2000.

[38] GREMONT, B.; FILIP, M., Spatio–Temporal Rain Attenuation Model for Application to Fade Mitigation Techniques. **IEEE Transactions on Antennas and Propagation,** v. 52, n. 5, Maio 2004.

[39] ONG, J.T,; CHOO,Y.K.; ZHANG,S., Rain Rate and Attenuation Prediction Model for Singapore. **Proc. of ICAP 1995**, p. 81-84, 1995.

[40] MOUPFOUMA, F., Model of Rain Rate Distribution for Radio System Design. **IEE Proc.**, v. 134, pt. H, p. 527-537, 1987.

[41] MOUPFOUMA, F.; MARTIN, L., Point Rainfall Rate Cumulative Distribution Function Valid At Various Locations. **Electronic Letters**. v. 29, n. 17, p. 1503-1505, Agosto 1993.

[42] BAPTISTA, J. P. V. P.; SALONEN, E. T., Review of Rainfall Rate Modelling and Mapping. **Proc. of CLIMPARA 1998,** Otawa, Canadá, p. 35-44, 1998.

[43] ITU-R, Characteristics of Precipitation for Propagation Modelling. **ITU-R Rec. P.837-4**, Genebra, 2003.

[44] MOUPFOUMA, F.; DEREFFYE, J., Empirical Model for Rainfall Rate Distribution. **Electronic Letters,** v. 18, n. 11, p. 460-461, Maio 1982.

[45] MOUPFOUMA, F.; Distribution Statistique des Intensités de Pluie et des Affaiblissements dus à la Pluie en Climat Équatorial et Tropical. **Ann. Telecommunic.**, v.37, n.3, p.123-128, Março 1982.

[46] COUTO DE MIRANDA, E., SILVA MELLO, L.A.R., PONTES, M; SOUZA, R., Dynamics of Attenuation in Equatorial Brazil: 1-year Analysis of Three 12GHz Earth-Space Links. **Proc. of the IEEE Antennas and Propagation Symposium on Wireless Communications**, Waltham, 1998.

[47] PARABONI, A., MASINI, G. ; ELIA, A., The Effect of Precipitation on Microwave LMDS Networks—Performance Analysis Using a Physical Raincell Model. **IEEE Journal on Selected Areas in Communications**, v. 20, n. 3, p. 615-619, Abril 2002.

[48] DA COSTA, A. T.; ASSIS, M.S., Modelagem da Precipitação para Emprego no Cálculo da Atenuação em Enlaces Radioelétricos. **Proc. SBMO 2002**, Recife, Brasil, 2002.

[49] ITU-R, Conversion of Annual Statistics to Worst-Month Statistics. **ITU-R Rec. P.841-3**, Genebra, 2003.

[50] SINGH, M.; HASSAN, S. I.S.; ANSOR, M., Worth Month Rain Statistics Measurement in Malaysia. **Proc. of Student Conference on Research and Development 2002**, Shah Alam, Malasia, 2002.

[51] PONTES, M. S.; SILVA MELLO, L. A. R., MIGLIORA, C.G.S., Ku-Band Slant-Path Radiometric Measurements at Three Locations in Brazil. **International Journal of satellite Communications,** v. 8, p.239-249, 1990.

[52] COST255, **Radiowave Propagation Modelling for New Satcom Services Operating at Ku-band and Above.** ESA Pubications Division, Março 2002.

[53] CRANE, R. K., Rain Attenuation Measurements: Variability and Data Quality Assessment. **Radio Science**, v. 25, n. 4, p. 455-473, 1990.

[54] ORTGIES, G., Rain rate and its Temporal variability Measured at Darmstadt for a Period of Eight Years. **Proc. of CLIMPARA 1994**, Moscou, Rússia, p. 2.6.1 – 2.6.4, 1994.

[55] RIVA, C.; MAURI, M., Nine Years of Statistics of Meteorological Parameters at Spino D'Adda. **Proc. of CLIMPARA 2001**, Budapeste, Hungria, p. 151 – 155, 2001.

[56] SILVA MELLO, L. A. R. et al., Statistical Modelling of the Cumulative Probability Distribution Function of Rainfall rate in Brazil. **Proc. of CLIMPARA 1998**, Ottawa, Canáda, p. 77-80, 1998.

[57] PAPOULIS, A., **Probability, Random Variables and Stochastic Processes.** Mc Graw-Hill International Editions, 3ª Edição, Nova York, 1992.

[58] MISME, P., Affaiblissements dus a La Pluie – Resultats Experimentaux, Calculs et Previsons. **Ann. Telecommunic.**, v. 33, n. 9-10, p. 341-362, 1978.

[59] RICE, P.L.; HOLMBERG, N.R., Cumulative Time Statistics of Surface Point Rainfall Rates. **IEEE Trans. Comm.**, v. 21, p. 1131-1136, 1973.

[60] **http: // www.itu.int / ITU-R / study – groups / rsg3 / index.asp**. Endereço Eletrônico na Internet do Grupo de Estudo 3 do ITU-R, acessado em setembro 2005.

[61] SALONEN, E. T.; BAPTISTA, J. P. V., A New Global Rainfall Rate Model. **Tenth Int. Conf. on Antennas and Propagation,** IEE Conf. Publ. 436, v. 2, p. 2.182-2.185, 1997.

[62] EMILIANI, L. D. at al., Development of Rain-Attenuation and Rain-Rate Maps for Satellite System Design in the Ku and Ka Bands in Colombia. **IEEE Antennas and Propagation Magazine**, v. 46, n. 6, p. 54-68, Dezembro de 2004.

[63] ECEPLAN, **Atlas Climatológico do Brasil.** Ministério da Agricultura – Escritório Central de Planejamento e Controle (ECEPALN), Rio de Janeiro, 1969.

[64] PARABONI, A.; CAPSONI, C.; FEDI, F.; Data and Theory for a New Model of Horizontal Structure of Rain Cells for Propagation Applications. **Radio Science,** v. 22, n. 3, p. 395-404, 1987.

[65] ALLNUT, J., HAIDARA, F., Ku-Band Duration Data from Three, Two-Year, Earth-Space Experiments in Equatorial Africa. **Proc. of CLIMPARA 1998,** Ottawa, Canada, p. 163-166, Abril, 1998.

[66] PAULSON, K. S., KORMANYOS, Z., PEDERSEN, L., A Climate Variable Model for Rain Fade Duration Statistics. **Proc. of CLIMPARA 2001,** Budapeste, Hungria, p. 103-105, 2001.

[67] TIMOTHY, K. I., MONDAL, N. C., SARKAR, S.K., Dynamical Properties of Rainfall for Performance Assessment of Earth/Space Communication Links at Ku and Ka Bands. **International Journal of Satellite Communications**, n. 16, p. 53-57, 1998.

[68] PAULSON, K. S., High Temporal Resolution Rain Duration Statistics in the Southern UK. **IEE Proc. Microw. Antennas and Propagation**, v. 151, n. 4, pp. 375-380, Agosto, 2004.

[69] GOLDHIRSH, J. , Rain-Rate Duration Statistics over a Five-Year Period: a Toll for Assessing Slant Path Fade Durations. **IEEE Trans. on Antennas and Propagation**, v. 43, n. 5, pp. 435-439, Maio, 1995.

[70] LEKKLA, R., PRAPINMONGKOLKARN, P., Diurnal Variations in Rain Attenuation on Ku Band Earth-Space Paths. **International Journal of Satellite Communications**, n. 16, p. 219-236, 1998.

[71] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., Dynamic Characteristics of Rainfall Rate in the Amazon Region and their Effects on Satellite Link Design. **Proc. IMOC 2005**, Brasília, Brasil, 2005.

[72] OFOCHE, E. B. C., Duration of Tropical Rainfall Rate for Predicting Radiowave Attenuation. **Proc. of CLIMPARA 1990,** Rio de Janeiro, Brasil, p. 56-61, Dezembro, 1990.

[73] COUTO DE MIRANDA, E. C., SOUSA, R.S.L, SILVA MELLO, L.A.R., Dynamic Analysis of Attenuation on Five Converging Links at 15 GHz Located in the Great São Paulo Area, Brazil. **Proc. of 10th International Conf. on Antennas and Propagation,** Edimburgo, Inglaterra, p. 14-17, Abril 1997.

[74] COMA, J., GHALOUL, F., BENARROCH, A., Statistics of Rain Rate Variability for Spanish Regions: The Durations of Exceddances. **Proc. of CLIMPARA 1998,** Ottawa, Canada, p. 62-65, Abril, 1998.

[75] PARABONI, A., RIVA, C., A New Method for the Prediction of Fade Duration Statistics in Satellite Links above 10 GHZ. **Int. Jounal Sat. Comm.**, v. 12, p. 387-394, 1994.

[76] UIT-R, Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **ITU-R Rec. P.618-8**, Genebra, 2002.

[77] COUTO DE MIRANDA, E. C., SOUSA, R.S.L, SILVA MELLO, L.A.R., Dynamic Analysis of Attenuation for 12 GHz Satelitte Beacon Link in Brazil. **Proc. of 10th International Conf. on Antennas and Propagation,** Edimburgo, Inglaterra, p. 2251-2254, Abril 1997.

[78] BATTAN, L. J., **Radar Meteorology**. University of Chicago Press, Chicago, 1959.

[79] ROGERS, R. R., Statistical Rainstorm Models: Their Theoretical and Physical Foundations. **IEEE Trans. on Antennas and Propagations**, Turtorial Papers and Reviews, p. 547-566, Julho, 1976.

[80] GOLDHIRSH, J., Two-dimension Visualization of Rain Structures. **Radio Science**, v. 35, n. 3, p. 713-729, Maio-Junho, 2000.

[81] LAWS, J. O., PARSONS, D. A., The Relation of Raindrop-Size to Intensity. **Trans. Amer. Geophys.**, v. 24, p. 452-460, 1943.

[82] MARSHALL, J.S.; PALMER, W. M. K., The Distribution of Raindrops with Size., **J. Meteorology**, V. 5, P. 165-166, 1948.

[83] JOSS, J., THAMS, J.C., WALDVOGEL, A., The Variation of Raindrops Size Distribution at Locarno. **Proc. Int. Conf. Cloud Physics**, p. 369-373, 1968.

[84] OLSEN, R. L., ROGERS, D. V., HODGE, D. B., The aR^b Relation in the Calculation of Rain Attenuation. **IEEE Trans. on Antennas and Propagation**, v. 26, n. 2, p. 318-329, Março, 1978.

[85] HOGG, D. C., Rain, Radiometry and Radar. **IEEE Trans. on Geosc. and Remote Sensing**, v. 27, n. 5, p. 576- 585, Setembro 1989.

[86] KEENAN, T. D., CAREY, L. D., ZRNIC, D. S. , Sensitivity of 5-cm Wavelength Polarimetric Radar Variables to Raindrop Axial Ratio and Drop Size Distribution. **J. Appl. Meteorol.**, v. 40, p. 526 545, 2001.

[87] GIBBINS, C. J., WALDEN, C. J., A Study into the Derivation of Improved Rain Attenuation Regression Coefficients. **Radicommunications Agency Report** No. AY4359, 2003.

[88] ULBRICH, C. W., Natural Variations in the Analytical Form of the Raindrop Size Distribution. **J. of Climate ans App. Meteo.**, v. 22, n. 10, p. 1764-1775, Outubro, 1983.

[89] KATZ, I., A Rain Cell Model. **Proc. 17th Conference on Radar Meteorology**, Amer. Meteor. Soc., Boston, 442-447, 1976.

[90] PAWLINA, A. B., Essential Knowledge of Rain Structure for Radio Applications Based on Available Data and Models. **Radio Africa 99**, Radiocommunications Workshop, Gaborone, Botswana, Outubro 1999.

[91] HALL, M. P. M., GODDARD, J. W. F., Variation with Height of the Statistics of Radar Reflectivity Due to Hydrometeors. **Electron. Lett.**, v. 14, n. 7, p.224-225, 1978.

[92] LEITÃO, M.J., WATSON, P. A., Method for Predition of Attenuation on Earth-Space Links Based on radar Measurements of the Physical Structure of Rainfall. **IEE Proc.**, v. 133, n. 4, p. 429-440, 1986.

[93] CRANE, R. K., Modelling Attenuation by Rain in Tropical Regions. **Int. J. Sat. Commun.**, v. 8, p. 197-210, 1990.

[94] JOSS, J., PITTINI, A., The Climatology of Vertical Profiles of Radar Reflectivity. **Proc. 25th Conf. Radar Meteorology**, p. 828-832, Junho ,1991.

[95] DINKU, T., ANAGNOSTOU, E. N., BORGA, M., Improving Radar-Based Estimation of Rainfall over Complex Terrain. **Journal of Applied Metereorology**, Amer. Met. Soc., v. 41, p. 1163-1178, Dezembro de 2002.

[96] ANAGNOSTOU, E. N., KRAJEWSKI, W., SMITH, J., Uncertainty Quantification of Mean-Areal radar rainfall Estimates. **Journal of Atmospheric and Oceanic Tech.,** v. 16, p. 206-215, Fevereiro, 1999.

[97] ZAWADZKI, I., Factors Affecting the Precision of radar measurements of Rain. **Proc. 22 nd Conf. on Radar Meteorology**, Zurique, pp.251-256. Setembro, 1988.

[98] CALHEIROS, R. V., ZAWADZKI, I., Reflectivity-Rain rate Relationships for Radar Hydrology in Brazil. **Journal of Climate and Applied Meteorology**, v. 26, n.1, p. 118-132, Janeiro de 1987.

[99] MAITRA, A., CHAKRAVARTY, K., Raindrop Size Distribution Measurements and Associates Rain Parameters at a Tropical Location in the Indian Region. **Proc. of XXVIIIth General Assembly of URSI 2005**, Nova Delhi, Indía, 2005.

[100] ADHIKARI, K., SARKAR, B. K., Space-Time Variation of Raindrop Size Distribution. **Proc. of XXVIIIth General Assembly of URSI 2005**, Nova Delhi, Indía, 2005.

[101] AUSTIN, P. M., Relation between Measured Radar Refletivity and Surface Rainfall. **Mon. Wea. Rev.,** n. 115, p. 1053-1070, 1987.

[102] JOSS, J., VALDVOGEL, A., The Accuracy of Daily Rainfall Measurements by Radar. **13 th Radar Meteorology Conf.,** Montreal, p. 448-451, 828-832, Junho de 1991.

[103] PAWLINA, A., Some Features of Ground Rain Patterns Measured by radar in North Italy. **Radio Science**, v. 19, n.3, p. 855-861, 1984.

[104] PARABONI, A., CAPSONI, C. , FEDI, F. , A Comprehensive Meteorologically Oriented Methodology for Prediction of Wave Propagation Parameters in Telecommunication Applications beyond 10GHz. **Radio Science**, v. 22, n.3, p.387-393, 1987.

[105] PARABONI, A. ,CAPSONI, C. ,FEDI, F. ,Data and Theory for a New Model of Horizontal Structure of rain Cells for propagation Applications. **Radio Science**, v. 22, n.3, p. 395-404, 1987.

[106] DRUFUCA, G., Radar Derived Statistic on the Structure of Precipitation Patterns. **J. Appl. Meteor.**, v. 14, pp. 1419-1429, 1977.

[107] MILLER, J. R., A Climatological Z-R Relationship for Convective Storms in the Northern Great Plains. **Proc. of 15 th Radar Meteor. Conf.**, Boston, p. 153-154, 1972.

[108] WILSON, J. W., Radar-Raingage Precipitation Measurements: A Summary. **Proc. of First Conf. on Hydrometeorology**, Boston, p. 72-75, 1976.

[109] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., Spatial Variability of Rain in the Amazon Region with Application to Site Diversity in Earth-Satellite Paths. **Proc. of CLIMDIFF 2005**, Cleveland, E.U.A, 2005.

[110] CERQUEIRA, J.L.; ASSIS, M. S.; SILVA MELLO, L.A.R., Análise da Variação Espacial da Taxa de Precipitação com Aplicação em Diversidade de Sítio para Enlaces Terra-Satélite. **Anais do XXII Simpósio Brasileiro de Telecomunicações, SBrT 05**, Campinas, Brasil, Setembro, 2005.

[111] SEGAL, B., Analytical Examination of Mathematical Models for the Rainfall Rate Distribution Function. **Simpósio de Abertura URSI**, Lennoxville, Canadá, Maio, 1980.

[112] MISME, P., WALDTEUFEL, P., A Model for Attenuation by Precipitation on a Microwave Earth-Space Link. **Radio Science**, v. 15, n.3, p. 655-665, 1980.

[113] MISME, P., FIMBEL, J., Determination Theorique et Experimentale de L'Affaiblissement par la Pluie sur un Trajet Radioélectrique. **Ann. Telecommunic.**, v.30, n. 5-6, p. 149-158, 1975.

[114] ASSIS, M. S., EINLOFT, C. M., A Simple Method for Estimating Rain Attenuation Distribution. **Ann. Telecommunic.**,v. 32, n. 11-12, p. 478-480, 1977.

[115] DA COSTA, A. T.; ASSIS, M.S., The Concept of Path Length Factor in The Prediction of Rain Attenuation in Terrestrial Links. **Proc. of URSI Commision F Symposium**, Alemanha, 2002.

[116] PAWLINA, B., BINAGHI, M., Rain Distribution along the Path: New Statistics of Cells and Cells Separations from Radar Data. **Proc. of CLIMPARA 1998,** Otawa, Canadá, p. 81-84, 1998.

[117] GOLDHIRSH, J., Rain Cell Size Statistics as a Function of Rain Rate for Attenuation Modeling. **IEEE Trans. on Antennas and Propagation**, v. 31, n. 5, p. 799-801, Setembro, 1983.

[118] PAWLINA, B., Rain Areas on Horizontal Radar Rain Maps: New Collection, New Insight into Spatial Intensity Distribution. **Proc. of CLIMPARA 1994,** Moscou, Russia, p. 5.10.1 – 5.10.5, 1994.

[119] GOLDHIRSH, J., Rain-Rate Duration Statistics over a Five-Year Period: a Tool for Assessing Slant Path Fade Durations. **IEEE Trans. on Antennas and Propagation**, v. 43, n. 5, p. 435-439, Maio, 1995.

[120] GOLDHIRSH, J., Prediction Methods for Rain Attenuation Statistics at Variable Path Angles and Carrier Frequencies Between 13 a 100 GHz. **IEEE Trans. on Antennas and Propagation**, v. 23, n. 6, p. 786-791, Novembro, 1975.

[121] GOLDHIRSH, J., Path Attenuation Statistics Influenced by Orientation of rain Cells. **IEEE Trans. on Antennas and Propagation**, v. 24, n. 6, p. 792-799, Novembro, 1976.

[122] UIT-R, Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **ITU-R Rec. P.618-8**, Genebra, 2002.

[123] HODGE, D. B., An Improved Model for Diversity Gain on Earth-Space Propagation Paths. **Radio Science**, v. 17, p. 1393-1399, 1982.

[124] CCIR (atualmente UIT-R), Propagation Data Required for Space Telecommunication Systems. **Report 564,** XIV Plenary Assembly, Genebra, 1974.

[125] CCIR (atualmente UIT-R), Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **Report 564-2(Mod I)**, conclusão do Encontro do Grupo de estudo 5, Genebra, 1983.

[126] CCIR (atualmente UIT-R), Special Issue on the COST 205 Project on Earth-Satellite Radio Propagation Space Above 10 GHz. **Alta Frequenza**, v. 54, n. 3, p. 87-236, Maio e Junho, 1985.

[127] CCIR (atualmente UIT-R), Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **Report 564-3**, XVII Plenary Assembly, Genebra, 1986.

[128] CCIR (atualmente UIT-R), Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **Report 564-4**, XVIII Plenary Assembly, Genebra, 1990.

[129] CCIR (atualmente UIT-R), Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **Rec. P.618-2**, Genebra, 1992.

[130] UIT-R, Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunication Systems. **ITU-R Rec. P.618-5**,Genebra, 1997.

[131] DA COSTA, A. T.; ASSIS, M. S., Rain Height Behaviour in Low Latitude Areas. **URSI Commission F Symposium**, Garmirch, Alemanha, Fevereiro, 2002.

[132] UIT-R, Rain Height Model for Prediction Methods. **ITU-R Rec. P.839-3**,Genebra, 2002.

[133] FABRY, F., ZAWADZKI, I., The Vertical Structure of Precipitation: an Overview. **Proc. of CLIMPARA 1998,** Ottawa, Canadá, p. 131-136, Abril, 1998.

[134] BANDERA, J., PAPATSORIS, A.D., GODDARD, J. W., Vertical Variation of Reflectivity and Specif Attenuation in Stratiform and Convective Rainstorms. **Electronics Letters**, v. 35, n. 7, p. 599-600, Abril 1999.

[135] DISSANAYAKE, A.W., McEWAN, N.J., Radar and Attenuation Properties of Rain and Bright Band. **IEE Conference Publication on Antenna and Propagation**, p. 125-129, 1978.

[136] KHARADLY, M.N.Z., CHOI, A., A Simplified Approach to the Evaluation of EMW Propagation Characteristics in Rain and Melting Snow. **IEEE Trans. on Ant. and Prop. ,** v. 36, p. 282-296, 1988.

[137] KLAASSEN, W., Radar Observations and Simulation of the Melting Layer of Precipitation. **Journal of the Atmos. Scienc.**, v. 45, p. 3741-3753, 1988.

[138] SZYRMER, W., FABRY, F., ZAWADZKI, I., Meteorological and Electromagnetic Modeling of the Melting Layer. **28th Conference on Radar Meteorology**, American Meteorological Society, p. 534-535, 1997.

[139] ALLNUT, J., DISSANAYAKE, A., The Combination of Attenuation Phenomena ion Prediction Procedures for 10-50 GHz Satellite-to-Ground Path. **Proc. of CLIMPARA 1990**, Rio de Janeiro, Brasil, p. 183-190, Dezembro, 1990.

[140] ALLNUT, J., DISSANAYAKE, A., HAIDARA, F., A Prediction Model that Combines Rain Attenuation and Other Propagation Impairments along Earth-satellite paths. **IEEE Trans. Ant. and Prog.,** v. 45, n.10, p. 1546-1558, 1997.

Anexo A
Trabalhos Publicados

Neste anexo são incluídos os trabalhos publicados pelo autor e seus orientadores ao longo do desenvolvimento da tese:

a) *"Dynamic Characteristics of Rainfall Rate in the Amazon Region and their Effects on Satellite Link Design"*, apresentado no *International Microwave and Optoelectronics Conference*, realizada em Brasília, Brasil, Julho de 2005;

b) *"Precipitation Studies for Rain Attenuation Prediction in The Amazon Region"*, apresentado no *International Symposium on Antennas and Propagation* – ISAP 2005, realizado em Seul, Coréia do Sul, Agosto de 2005;

c) *"Spatial Variability of Rain in the Amazon Region with Application to Site Diversity in Earth-satellite Paths"*, apresentado no *ClimDiff 2005*, realizado em Cleveland, Estados Unidos, Setembro de 2005.

d) *"An Exceptional Rainfall Event in the Amazon Region"*, apresentado no *ClimDiff 2005*, realizado em Cleveland, Estados Unidos, Setembro de 2005.

e) *"Análise da Variação Espacial da Taxa de Precipitação com Aplicação em Diversidade de Sítio para Enlaces Terra-Satélite"*, apresentado no XXII Simpósio Brasileiro de Telecomunicações – SBrT 2005, realizado em Campinas, Brasil, Setembro de 2005;

f) *"Rain Attenuation Research in Brazil"*, apresentado na *XXVIIIth URSI General Assembly* – URSI 2005, realizada em Nova Delhi, Índia, Outubro de 2005;

Dynamic Characteristics of Rainfall Rate in the Amazon Region and their Effects on Satellite Link Design

Jorge L. Cerqueira (1), Mauro S. Assis (2) and Luiz A . Silva Mello (3)

(1)Pontifical Catholic University of Rio de Janeiro and Military Institute of Engineering, Rua Pinto Guedes 140 apt. 303 – Rio de Janeiro – RJ, 20511-320 – Brazil - jlcerq@terra.com.br

(2)Fluminense Federal University, Rua Coelho Neto, 17 apt. 301 – Rio de Janeiro – RJ, 22231-110 – Brazil - msassis@openlink.com.br

(3)Pontifical Catholic University of Rio de Janeiro - Centre for Telecommunication Studies, Rua Marques de São Vicente 225 – Rio de Janeiro – RJ, 22453-900 – Brazil - smello@cetuc.puc-rio.br

Abstract — **This paper deals with an investigation of dynamic characteristics of rainfall rate in the Amazon Region. Experimental data from 3 (three) selected locations pertaining to different climate subtypes identified in this tropical rainy region constitute the basis of the analysis carried out here. Details about the annual clock hourly rainfall accumulation and the average duration of rainfall events are presented, the relevance of their effects in satellite system design being pointed out.**

Index Terms — **Rain, precipitation rate, dynamics properties of rain, worst-month distribution, Köppen climatic classification, satellite communication systems.**

I. Introduction

The evaluation of fade margin due to rain is normally based on the annual cumulative distribution of precipitation rate corresponding to the area under study. This distribution is adequate for planning high availability systems, where large levels of fade margin are used. The same is not true for low availability links as broadcast satellite services (DTH – Direct To Home) or VSAT (Very Small Aperture Terminal) systems. In this situation, where an acceptable outage is around 0.3% of year, the time behaviour has an important impact on system design. Consequently, more detailed information on the dynamics of rain phenomenon is needed, the knowledge of seasonal and diurnal variation of fade duration statistics and fade interval characteristics being of fundamental relevance.

It is recognized that there is no accepted model for the conversion of rain rate duration to slant path duration statistics [1]. The main problem is the possibility of having more than one rain cell along the propagation path. However, according to Timothy at al. [2], for elevation angles higher than 30°, the measured rainfall rate threshold at a given probability level may be used to obtain the associated slant path attenuation. A study by Lekkla and Prapinmongkolkarn [3] corroborated the above conclusion. Of course, the accuracy of this procedure depends on the model used for the evaluation of rain attenuation. In this context, this paper discusses seasonal and diurnal measurements of rainfall rate carried out in the Amazon region. Rainfall data presented here correspond to preliminary results from a research program on rain attenuation which is being developed under the responsibility of the Military Institute of Engineering with financial support from the National Scientific and Technological Development Council (CNPq).

II. Climates in the Amazon Region

According to Köppen [4], the climate of Amazon region is a tropical rainy type (A) where 3 subtypes can be identified:

a) Rainy equatorial (Af) – with a large annual rainfall (over 2000 mm) and practically no dry season;

b) Monsoon tropical (Am) – the annual rainfall is equal to or larger than Af, but there is a short dry season (one to three months);

c) Wet-and-dry tropical (Aw) – where the rain and dry seasons are well defined.

Fig. 1 shows the geographical limits of these climatic subtypes and the rain gauge network implemented in the Amazon region. Tipping bucket gauges with 0.1 mm capacity and 1 minute integration time are being used. Typical average monthly rainfall amount (mm) from 3 selected locations (Cruzeiro do Sul – Af, Santarém – Am and Boa Vista – Aw) are depicted in Fig 2. It is clear from this figure that the subtype Am is a transition climate between Af and Aw.

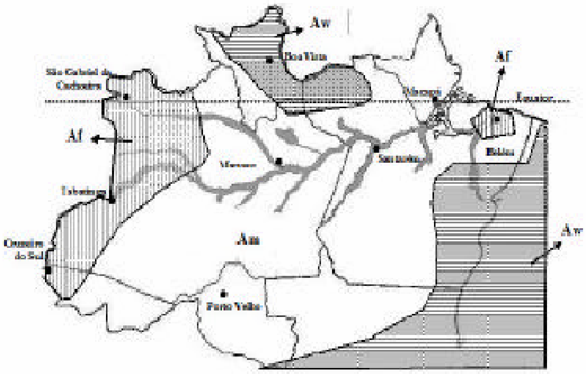


Fig. 1. Köppen climate classification in the Amazon region.

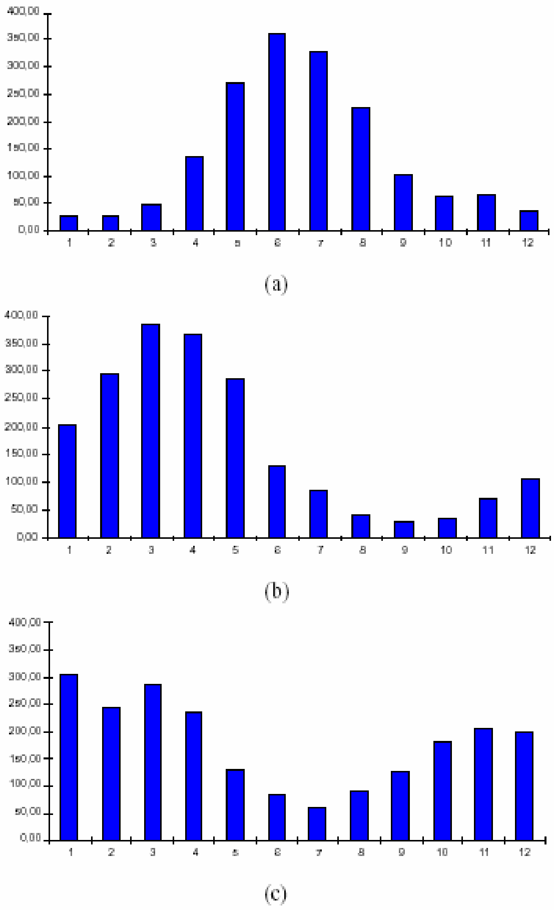


Fig. 2. Typical average monthly rainfall amount (mm) (a) Boa Vista (S 2.79 W 54.72); (b) Santarém (S 2.50 W 54.72); (c) Cruzeiro do Sul (S 7.61 W 72.68).

III. DYNAMIC BEHAVIOUR OF RAINFALL RATE

Besides the average annual outage due to fading, another criterion used in the planning of radio communication links is the average of worst month [5] statistics (see Fig. 3). According to this criterion, typical outages of low availability systems are around 1 to 0.1% of the worst month. It is observed in Fig. 3 that this percentage range corresponds to rainfall rates between 20 and 100 mm/h. In spite of being more rigorous with this procedure, as it will be shown below, the analysis of seasonal and diurnal variations should be taken also into account.

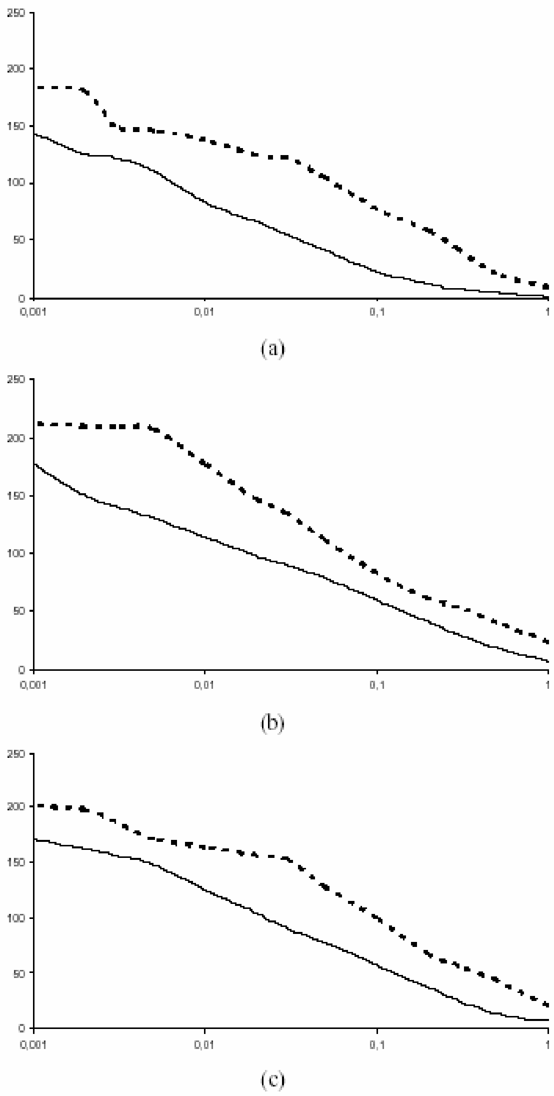


Fig. 3. Annual (——) and worst-month (- - -) rainfall rate distributions (mm/h).(a) Boa Vista; (b) Santarém; (c) Cruzeiro do Sul.

Fig. 4 shows the annual clock hourly rainfall accumulation for Cruzeiro do Sul, Santarém and Boa Vista. It is observed that the concentration of rain varies along the day from one location to another. Particularly important is the maximum accumulation in Cruzeiro do Sul, which occurs in the afternoon and early evening and Santarém from late evening to morning hours. Of course, depending on the service being planned, this behaviour may be quite important. For instance, intense rain in the morning or afternoon (business hours) affects commercial services, while the evening is the prime time for radio broadcasting. It should be pointed out that the precipitation accumulation along the day is directly connected to the clock hourly rainfall rate exceedance. An example is given in Fig. 5.

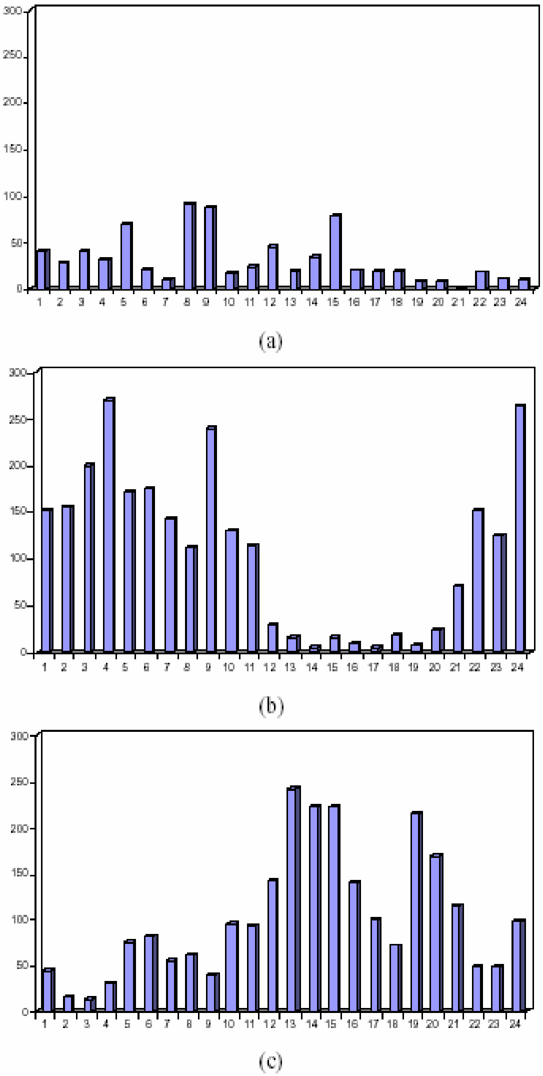


Fig. 4 Annual clock hourly rainfall accumulation (mm). (a) Boa Vista; (b) Santarém; (c) Cruzeiro do Sul.

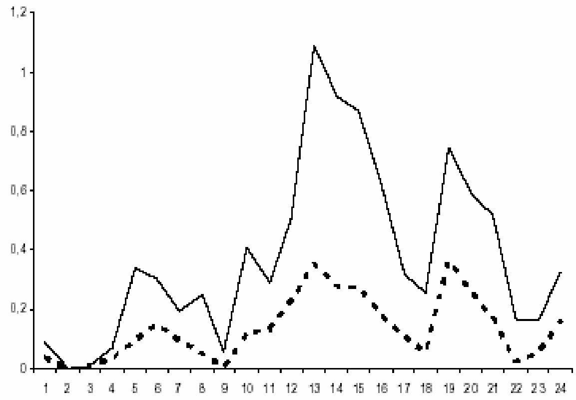
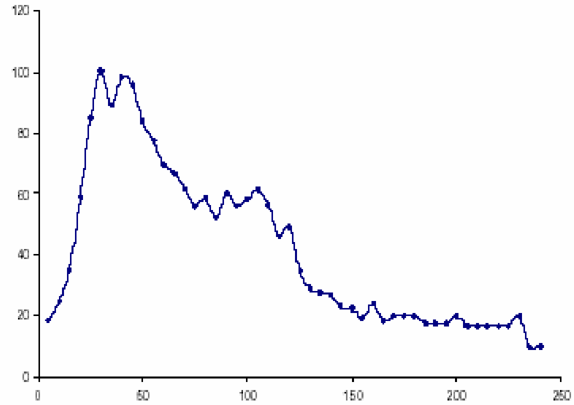
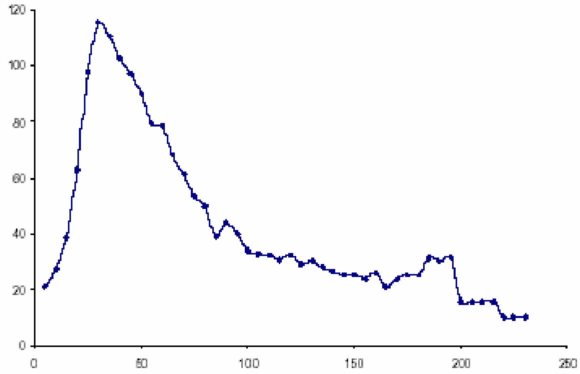


Fig. 5. Annual clock hourly exceedance (%) – Cruzeiro do Sul – 20 mm/h (——) and 50 mm/h (- - -).

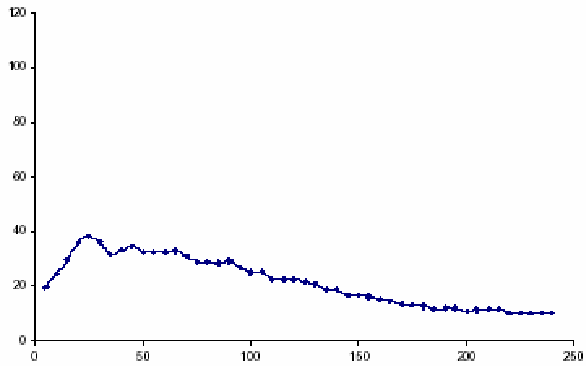
Fig. 6 depicts the average duration of rainfall events as a function of precipitation rate for the locations under study. In all locations, long events are concentrated from 20 to 70 mm/h. Incidentally, these values are within the range from 1 to 0.1% of the worst month statistics commented before (see Fig. 3). The design of mitigation techniques, as forward error correction codes (FEC), uplink power control, etc., normally used to overcome fading effects, should take these data into consideration. Other dynamic characteristics such as seasonal variations (wet and dry seasons) and the average interval between rainfall events, not shown here due to paper length limitation, are also important for satellite system planning.



(a)



(b)



(c)

Fig. 6. Average duration of rainfall events (s) as a function of precipitation rate (mm/h) (a) Boa Vista; (b) Santarém; (c) Cruzeiro do Sul.

IV. CONCLUDING REMARKS

Dynamic characteristics of rainfall rate in the Amazon region were investigated in this paper. The behaviour of precipitation in three locations pertaining to different climate subtypes identified in this tropical rainy region was described and some relevant aspects of interest for satellite system design were pointed out. The analysis carried out here was based on the hypothesis that, for high elevation angles, it possible to convert rain rate duration to slant path duration statistics. Fortunately, this is case of greatest interest in the Amazon region. Anyway, the research is progressing and more data will be published shortly, including comparison with rain attenuation measurements.

REFERENCES

[1] J. Goldhirsh, "Rain-rate duration statistics over a five-year period: a toll for assessing slant path fade durations", *IEEE Trans. on Antennas and Propagation,* vol. 43, no. 5, pp. 435-439, May 1995.

[2] K. I. Timothy, N.C. Mondal and S. K. Sarkar, "Dynamical properties of rainfall for performance assessment of earth/space communication links at Ku and Ka bands", *International Journal of Satellite Communications"*, no. 16, pp. 53-57, 1998.

[3] R. Lekkla, P. Prapinmongkolkarn, "Diurnal variations in Rain attenuation on Ku band earth-space paths", *International Journal of Satellite Communications"*, no. 16, pp. 219-236, 1998.

[4] H. J. Critchfield, General Climatology, Prentice-Hall, New Jersey, USA, 1974.

[5] ITU-R Recommendation P.581-2: "'The concept of worst-month", International Telecommunication Union, 1994.

PRECIPITATION STUDIES FOR RAIN ATTENUATION PREDICTION IN THE AMAZON REGION

Jorge L. Cerqueira(1), Mauro S. Assis (2), L.A.R. da Silva Mello(3)
(1) Pontifical Catholic University of Rio de Janeiro and Military Institute of Engineering
Rua Pinto Guedes 140 apt.303– Rio de Janeiro– RJ,20511-320 –Brazil –jlcerq@terra.com.br
(2) Fluminense Federal University, Rua Coelho Neto 17 apt. 301
Rio de Janeiro –RJ,22231-110 –Brazil – msassis@openlink.com.br
(3) Pontifical Catholic University of Rio de Janeiro, Rua Marques de São Vicente 225
Rio de Janeiro – RJ, 22453-900 – Brazil – smello@cetuc.puc-rio.br

1. Introduction

Rainfall rate is an essential input parameter in the prediction of rain attenuation. Mathematical models used in this prediction are function of precipitation rate distribution at a point in or near to the propagation path. However, such distributions are available for a limited number of locations. A solution to overcome this difficulty is the extrapolation from one point to another one belonging to the same climatic region. In this context, rainfall characteristics of the Amazon region is described in this paper. Rainfall data presented here correspond to preliminary results from a research program on rain attenuation which is being developed under the responsibility of the Military Institute of Engineering with financial support from the National Scientific and Technological Development Council (CNPq).

2. Köppen Climate Classification

The structure of Köppen climatic classification depends on temperature, precipitation and vegetation [1]. Once these meteorological factors can be related to the statistical distribution of rainfall rate, Köppen classification was adopted in this paper. According to this classification, the climate of Amazon region is a tropical rainy type (A) where 3 subtypes can be identified:

a) Rainy equatorial (Af) – with a large annual rainfall (over 2000 mm) and practically no dry season;
b) Monsoon tropical (Am) – the annual rainfall is equal to or larger than Af, but there is a short dry season (one to three months);
c) Wet-and-dry tropical (Aw) – where the rain and dry seasons are well defined.

Figure 1 shows the geographical limits of these climatic subtypes and the rain gauge network implemented in the Amazon region. Tipping bucket gauges with 0.1 mm capacity and 1 minute integration time are being used. Typical average monthly rainfall amount (mm) and temperature (^{0}C) from 3 selected locations (Boa Vista – Aw, Santarém – Am and Cruzeiro do Sul – Af), are shown in Figure 2 [2]. It is clear from this figure that the subtype Am is a transition climate between Af and Aw. However, as it will be commented in the next Section, due to higher rainfall rates in the rainy season, its effect on system availability is quite important.

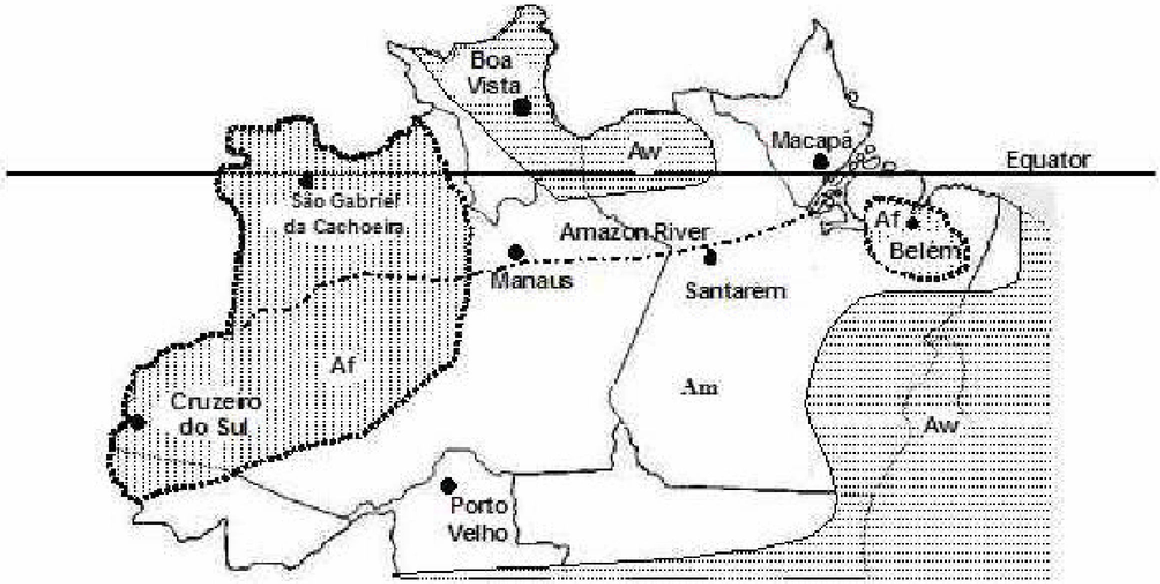
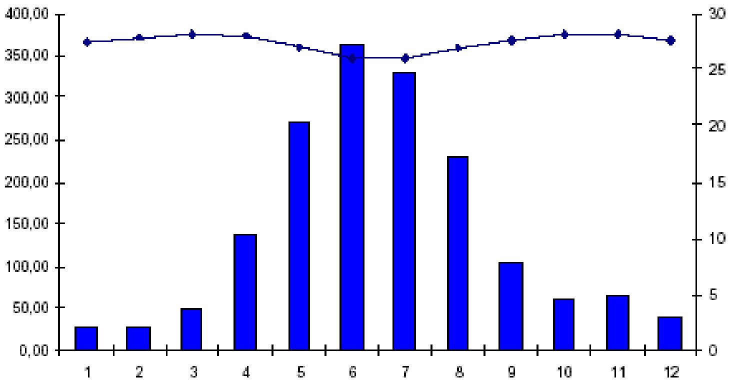
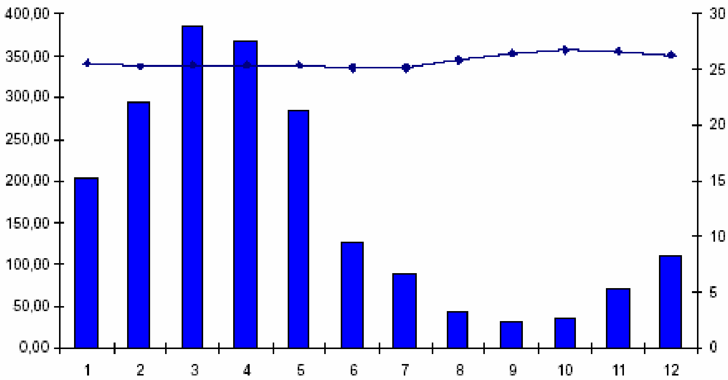


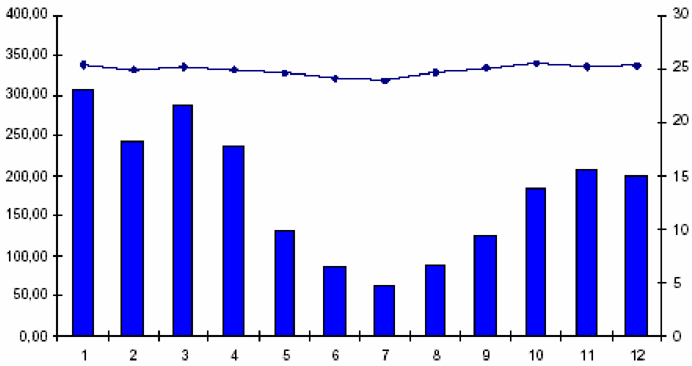
Figure 1 – Köppen climate classification in the Amazon region.



(a)



(b)



(c)

Figure 2 – Typical average monthly rainfall amount (mm) and temperature (^{0}C) in the Amazon region. (a) Aw - Boa Vista (S 2.79 W 54.72); (b) Am – Santarém (S 2.50 W 54.72); (c) Af – Cruzeiro do Sul (S 7.61 W 72.68).

3. Rainfall Characteristics in the Amazon Region

Figures 3 and 4 show the annual and the monthly cumulative distributions for the above cited locations. As expected, based on the total annual amount of rain (over 2000 mm for both Cruzeiro do Sul and Santarém), there is no significant difference in the annual cumulative distribution of rainfall rate between Af and Am subtypes. On the other hand, in the case of Boa Vista (subtype Aw) lower rain rates are observed.

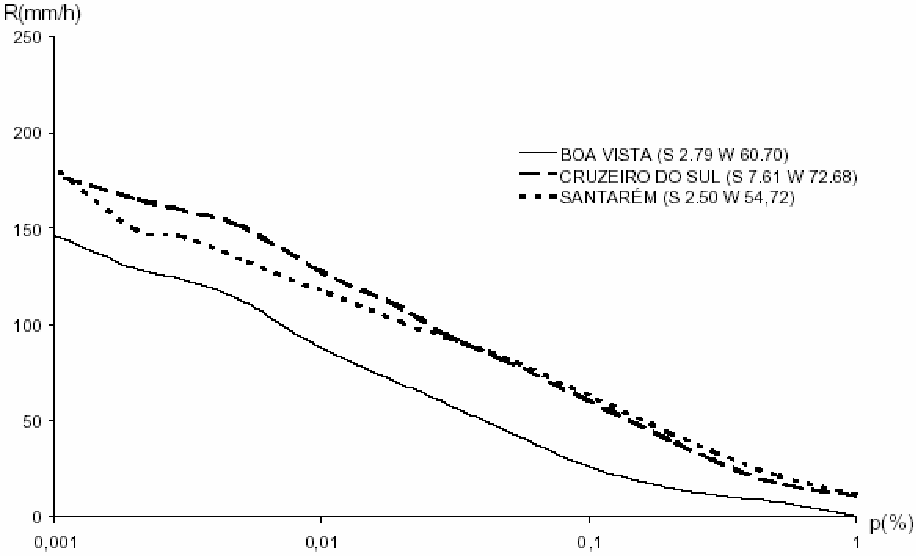


Figure 3 – Annual rainfall rate distributions.

The statistical behaviour is not the same when considering worth month distributions [3]. For relatively low rainfall rates, i.e. in the range from 1 to 0.1 percent of time, distributions for Af and Am subtypes are almost the same. This behaviour is of interest for low availability systems as, for instance, satellite broadcasting reception. However, from 0.01

to 0.001 percent of time, higher rainfall rates are observed in the subtype Am. In this subtype there is a large difference between dry and rainy seasons. When planning high availability communication systems in this climate, this behaviour should be take into account. A similar conclusion appears in the case of subtype Aw. Possibly, automatic transmission power control (ATPC) can be used as mitigation technique to compensate for such high rainfall rates.

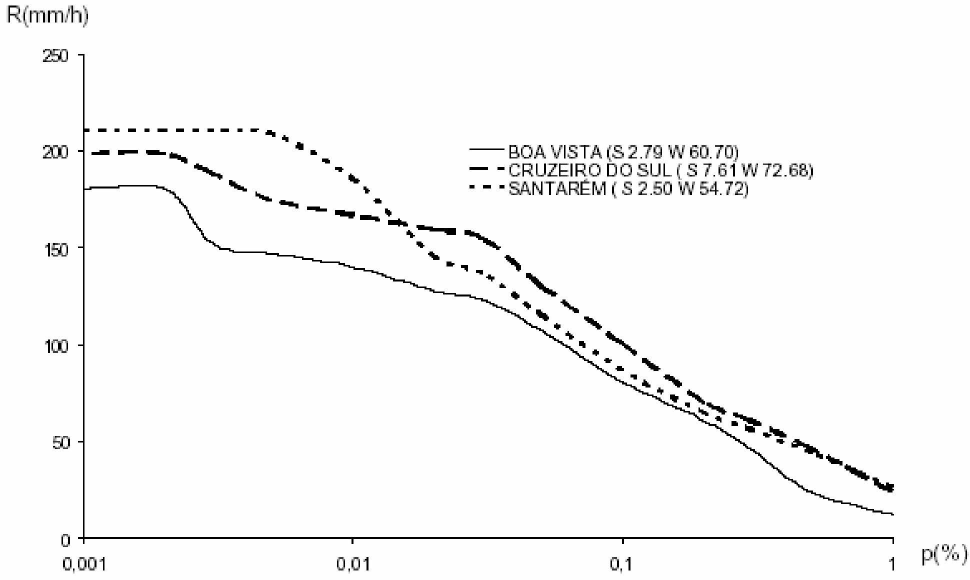


Figure 4 – Worst-month rainfall rate distributions.

4. Concluding Remarks

Based on Köppen climate classification, rainfall characteristics of Amazon region were described in this paper. In spite of being classified as a tropical rainy climate, 3 subtypes were identified (Af, Am and Aw). Under the practical point of view, the importance of each subtype depends on the particular aspect being considered. Although, regarding the annual cumulative distribution, each one follows the expected behaviour, the same is not true for the worst month distribution. In this context, different procedures should be taken into account when planning low or high availability communication systems.

5. References

[1] H.J.Critchfield, General Climatology, Prentice-Hall, New Jersey, USA, 1974.
[2] www.worldclimate.com, accessed on 02/21/2005.
[3] ITU-R Recommendation P.581-2: "'The concept of worst-month", International Telecommunication Union, Geneva, 1994.

Spatial Variability of Rain in the Amazon Region with Application to Site Diversity in Earth-Satellite Paths

Jorge L. Cerqueira
Pontifical Catholic University of Rio de Janeiro and Military Institute of Engineering
Rua Pinto Guedes 140 apt. 303 – RJ – RJ, 20511-320 – Brazil - jlcerq@terra.com.br
Mauro S. Assis
Fluminense Federal University - Rua Coelho Neto, 17 apt. 301 – Rio de Janeiro – RJ, 22231-110 – Brazil - msassis@openlink.com.br
L.A.R. da Silva Mello
Pontifical Catholic University of Rio de Janeiro - Rua Marques de São Vicente 225, Rio de Janeiro – RJ, 22453-900 – Brazil - smello@cetuc.puc-rio.br

Abstract

This paper deals with the spatial variability of rain rate in the Amazon region. Measurements from a meteorological radar located in Cruzeiro do Sul [7.36°S ; 72.46°W] were taken into account and a mathematical model for relating the statistical distribution of precipitation rate between two points separated by a given distance was developed. Data from a pluviograph installed near the radar was used in the derivation of a relationship between radar reflectivity and precipitation rate. Final results were promising enough. The behavior of the mathematical model has showed excellent agreement with site diversity gain curves from empirical models based on rain attenuation.

1. Introduction

This paper investigates the spatial variability of rain rate in the Amazon region aiming to derive a physical model to evaluate the performance of site diversity in earth-satellite paths. In this context, measurements from a meteorological radar located in Cruzeiro do Sul [7.36°S ; 72.46°W], in the state of Acre, Brazil, were taken into account and a mathematical model relating the statistical distribution of precipitation rate between two points separated by a given distance was developed. Data from a pluviograph installed near the radar was used in the derivation of a relationship between radar reflectivity and precipitation rate. Experimental data presented here are from a research program which is being developed under the responsibility of the Military Institute of Engineering (IME) with financial support from the National Scientific and Technological Development Council (CNPq). Figure 1 shows the rain gauge and radar stations used in this program, which are co-located and covering all the Amazon region.

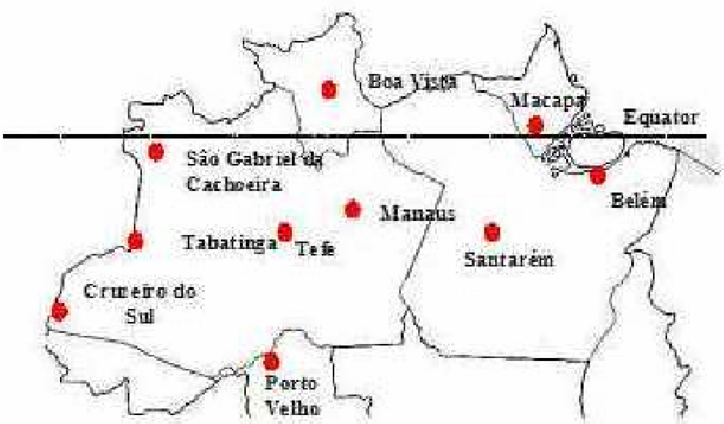


Figure 1. Amazon region – rain gauge and radar stations.

2. Mathematical model

The fundamental problem to be solved by this mathematical model is the evaluation of the separation distance L between two earth stations, in a site diversity configuration, aiming to minimize the rain effect and in accordance with a specified system availability criterion. This task can be performed having as statistical basis the probability of a rainfall rate R_0 be exceeded, simultaneously, in two points separated by L. This probability $P(R_1, R_2 > R_0)$ is given by,

$$P(R_1,R_2 > R_0) = P(R_2 > R_0/R_1>R_0).P(R_1 > R_0) \qquad (1)$$

where R_1 and R_2 are the rainfall rate in the stations 1 and 2, respectively; $P(R_1 > R_0)$ is the probability that R_0 be exceeded in the station 1, which corresponds to the cumulative statistical distribution of rain in station 1; and $P(R_2 > R_0/R_1 > R_0).P(R_1 > R_0)$ is the probability that R_0 be exceeded in station 2, once $R_1 > R_0$.

On the other hand, the conditional probability $P(R_2 > R_0/R_1 > R_0).P(R_1 > R_0)$ is related to the union of two events without intersection: the probability of the same rain cell is over station 1 and station 2 or the probability of one rain cell over station 1 and the other over station 2.

These probabilities are related to the following functions: i) $p(D_i, R_0)$ – joint probability density function of D_i and R_0; ii) $p(D_i)$ – probability density function corresponding to a rain cell with a diameter D_i in a position covering the two stations.

Based on the knowledge of the horizontal distribution of rain in the area under study, expression (1) can be written as,

$$P(R_1,R_2 > R_0) = \left\{ \sum_{D_i=L}^{\infty} p(D_i,R_0).p(D_i) + \left[\left(\sum_{D_i=0}^{L} p(D_i,R_0) + \sum_{D_i=L}^{\infty} [p(D_i,R_0).(1-p(D_i))] \right)^2 P_R(R_0) \right] \right\} P_R(R_0) \qquad (2)$$

where $P_R(R_0) = P(R_1 > R_0)$.

Two limit conditions can be used to validate expression (2). First, if L tends to zero, it is easy to show that $P(R_1, R_2 > R_0)$ tends to $P(R_1 > R_0)$. On the other hand, if L tends to ∞, $P(R_1, R_2 > R_0)$ tends to $[P(R_1 > R_0)]^2$.

3. Z–R relation

Radar reflectivity factor (Z) in mm^6/m^3 is related to rainfall rate (R) in mm/h through an empirical relation of type $Z= aR^b$. Based on rain gauge [7.36^{0}S ; 72.80^{0}W] and radar measurements [7.36^{0}S ; 71.56^{0}W] carried out in Cruzeiro do Sul, it was found the following values for the parameters a and b,

$$a = 207 \; ; \; b = 1.53$$

The relation $Z = 207\ R^{1.53}$ will be used throughout in this paper. Details about the derivation of "a" and "b" are being published elsewhere [1]. Figure 2 shows a comparison between the cumulative distribution of precipitation rate from rain gauge measurements and the corresponding distribution obtained by the conversion of radar data. An excellent agreement is observed for percentage of time up to 0.005 %. For smaller percentage the difference of values between the two procedures is probably due to rain gage saturation.

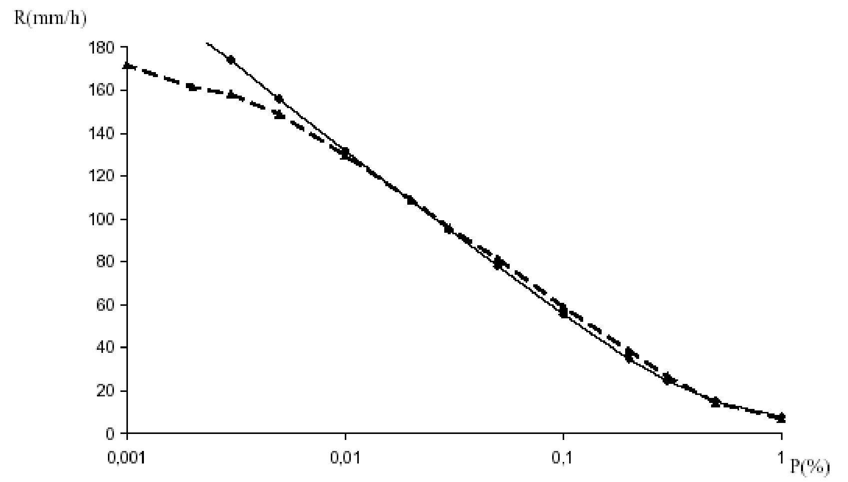


Figure 2. Comparison between cumulative distribution of precipitation rate from rain gauge (- - -) and radar data (—).

The analysis of the horizontal distribution of rain was based on the above relation between Z and R. The rain cell threshold was supposed to be 5 mm/h. First, it was derived the cumulative distribution of rain cell diameter for a given precipitation rate. This procedure allows to draw Figure 3, which shows the percentage of cells (vertical axis) with a diameter greater than the value indicated in the horizontal axis for $R \geq R_0$, being R_0 the reference for each curve.

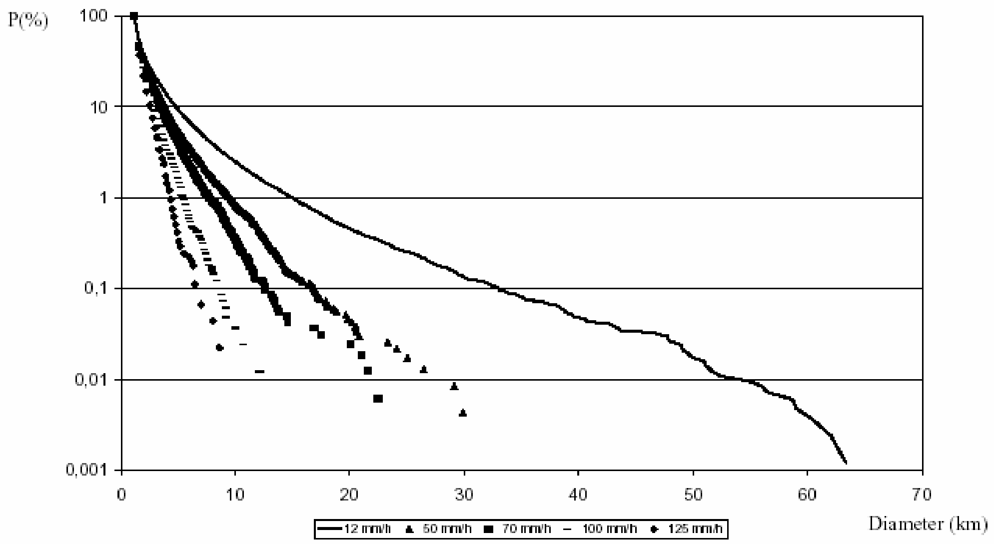


Figure 3. Rain cell diameter (km) exceeding a given precipitation rate (mm/h).

Finally, introducing the above results on equation (2), it was possible to draw the Figure 4, where it is shown the percentage of time that a precipitation rate greater than R_0 is exceeded in two stations separated by a given distance L. It is observed in this figure, for all curves, that a saturation occurs for distances between 10 and 15 km. This behavior is similar to site diversity gain curves empirically derived from rain attenuation measurements [2,3]. Once system parameters as, frequency, polarization and elevation angle, affect only the rain attenuation value, it is concluded that the saturation effect is due to rain correlation, which decreases as the separation between terminals increases.

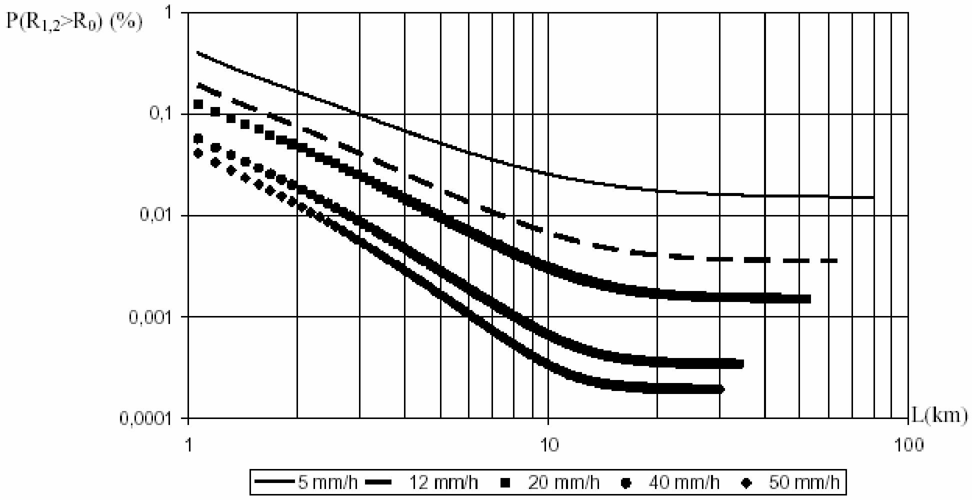


Figure 4. Percentage of time (%) that cumulative rain exceeding R_0(mm/h) at two earth stations in a site diversity configuration, with distance L(km).

Based on this result, it is possible to settle an expression relating the rainfall rate (R_A) exceeded in station 1 for a given time percentage (p) with the rainfall rate (R_B) exceeded in both stations for the same time percentage. As a preliminary proposal, it can be written,

$$R_A = R_B\,(12.5\,p + 1.1)\,L^{(0.42\log(p)+1.9)} \qquad (3)$$

R_A and R_B in mm/h, L in km and p in %.

This preliminary expression will be checked with data from other radar stations.

4. Concluding remarks

Having as reference measurements from radar and rain gauges carried out in Cruzeiro do Sul [7.36°S ; 72.46°W], this paper has investigated the problem of spatial variability of rain in the Amazon region. A mathematical model relating the statistical distribution of rainfall rate between two points separated by a given distance was developed. The behavior of this model is similar to site diversity gain curves empirically derived from rain attenuation measurements. Based on this result, it is being proposed a practical formula relating the point rainfall rate with the rainfall rate simultaneously exceeded in two stations, in a site diversity configuration, for the same percentage of time.

5. References

[1] Cerqueira, J. L., "Radiometereological studies in Amazon region" (in Portuguese) , PhD doctoral dissertation in phase of printing.

[2] UIT-R, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems", *Recommendation ITU-R P.618-8*, Genebra, 2002.

[3] D. B. Hodge, "An improved model for diversity gain on earth-space propagation paths", *Radio Science*, v. 17, p. 1393-1399, 1982.

An Exceptional Rainfall Event in the Amazon Region

Jorge L. Cerqueira
Pontifical Catholic University of Rio de Janeiro and Military Institute of Engineering
Rua Pinto Guedes 140 apt. 303 – RJ – RJ, 20511-320 – Brazil - jlcerq@terra.com.br
Mauro S. Assis
Fluminense Federal University - Rua Coelho Neto, 17 apt. 301 – Rio de Janeiro – RJ, 22231-110 – Brazil - msassis@openlink.com.br
L.A.R. da Silva Mello
Pontifical Catholic University of Rio de Janeiro - Rua Marques de São Vicente 225, Rio de Janeiro – RJ, 22453-900 – Brazil - smello@cetuc.puc-rio.br

Abstract

This paper describes an exceptional rainfall recorded at the radar station of Tefé [3.22°S ; 64.42°W] in the Amazon region. The rain cell dimension and rain height measured during this event show a large deviation from typical horizontal and vertical distributions . The effect on both terrestrial and slant paths is commented.

1. Introduction

The equatorial region is characterized by intense precipitation. Rainfall intensity levels around or above 100 mm/h are usually exceeded for more than 0.01% in the yearly cumulative distribution. However, this limit is, sometimes, surpassed with a very large margin and contributes for a non-expected behaviour in the small percentage of time range of the statistical distribution of rain. This paper describes an exceptional event where the horizontal distribution of rain covers a large area with very high intensity. The effect of this type of event on both terrestrial and slant paths are commented. Experimental data presented here are from a research program which is being developed under the responsibility of the Military Institute of Engineering (IME) with financial support from the National Scientific and Technological Development Council (CNPq). Figure 1 shows the rain gauge and radar networks used in this program, which are co-located and covering all the Amazon region.

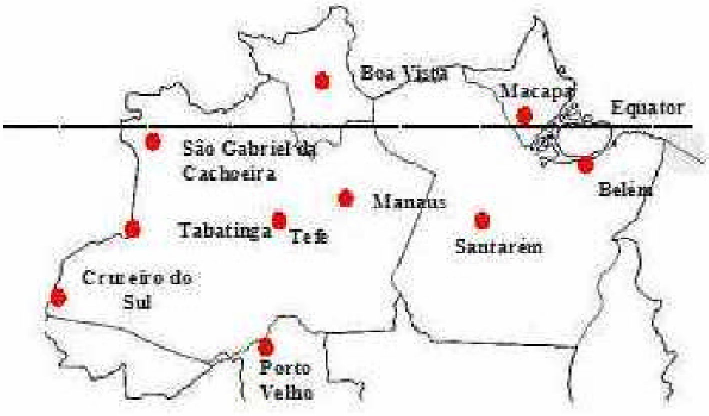


Figure 1. Amazon region – rain gauge and radar stations.

2. Horizontal distribution of rain

Figure 2 shows a convective rain cell structure measured at the radar station of Cruzeiro do Sul [7.36°S ; 72.46°W]. Once the dimension of each small square in this figure is 1x1km, the mean cell diameter for R = 100 mm/h is around 1.0 to 1.5 km. Similar results have been observed throughout the network shown in Figure 1, and can be considered as typical for low latitude areas. The conversion from radar reflectivity (Z) to rainfall rate (R) was based on the following equation [1],

$$Z(mm^6/m^3) = 207[R(mm/h)]^{1.53} \qquad (1)$$

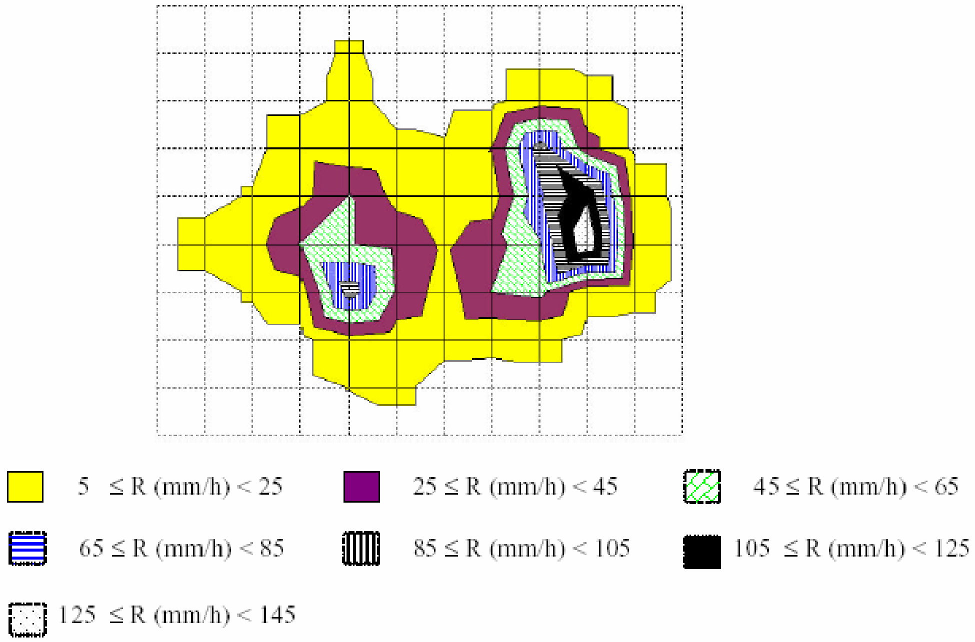


Figure 2. A typical example of the horizontal variability of rain.

Eventually, however, much higher rainfall rates, covering several km^2, can be recorded in the Amazon region. An example is given in Figure 3, which was registered on 10/18/2004 by the meteorological radar located in Tefé [3.22°S ; 64.42°W]. In this example, the rain is distributed over a very broad area with an intensity higher than 200 mm/h. On the other hand, it should be pointed out that the measure of such precipitation rates with a rain gauge is quite difficult due to instrument saturation.

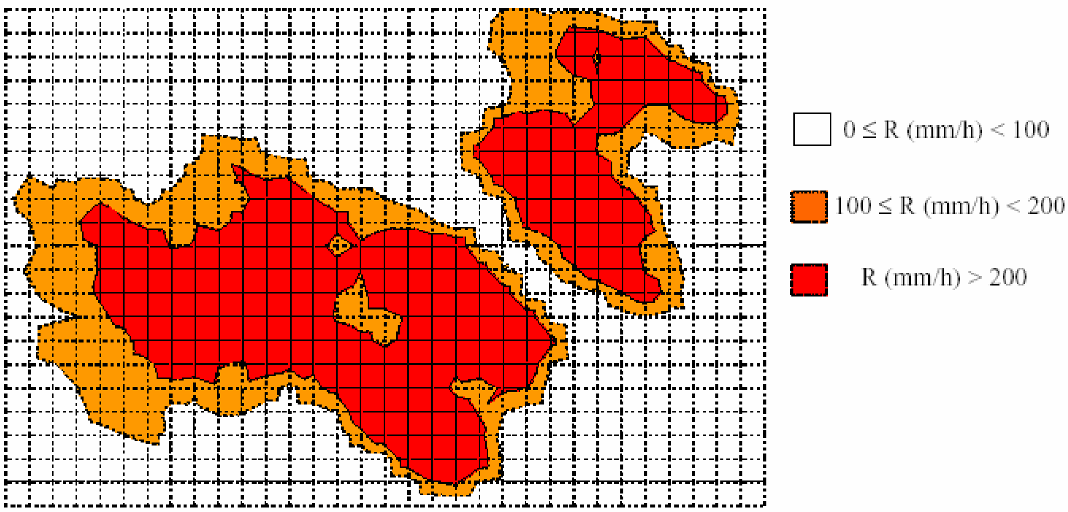


Figure 3. Horizontal distribution of an exceptional rainfall rate event.

3. Vertical distribution of rain

Along the years, the 0° isotherm h_0 has been used as reference for modeling the rain height. In general, experimental data available indicate that this reference has a sound basis. For instance, the profiles of radar reflectivity show in Figure 4 are in accordance with it. Sometimes, however, radar data point out the existence of heavy rain well above the 0° isotherm. An example is given in Figure 5 with data from the radar station of Tefé recorded also in the event of 10/18/2005. This figure shows vertical profiles of Z measured at 8 points separated by 250m in a range of 2km. Considering that h_0 is around 4.5km, the rain rate in this example is constant up to 9km.

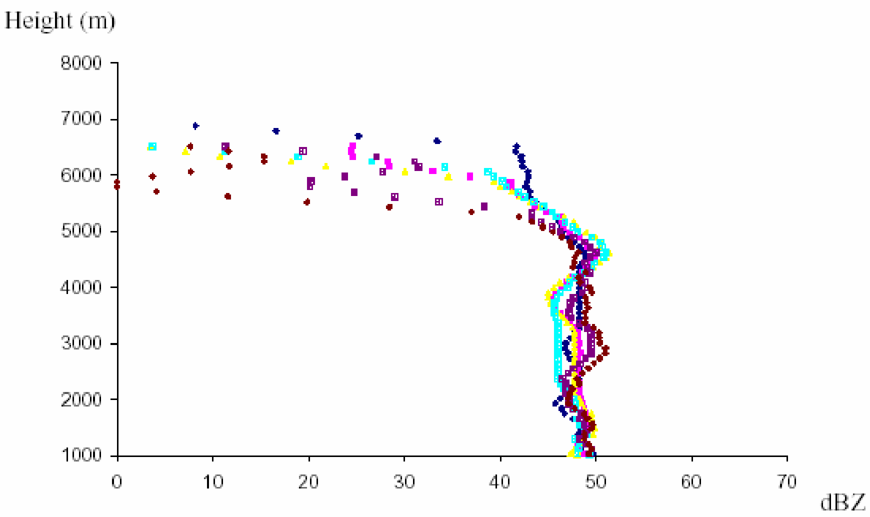


Figure 4. A typical example of the vertical distribution of rain.

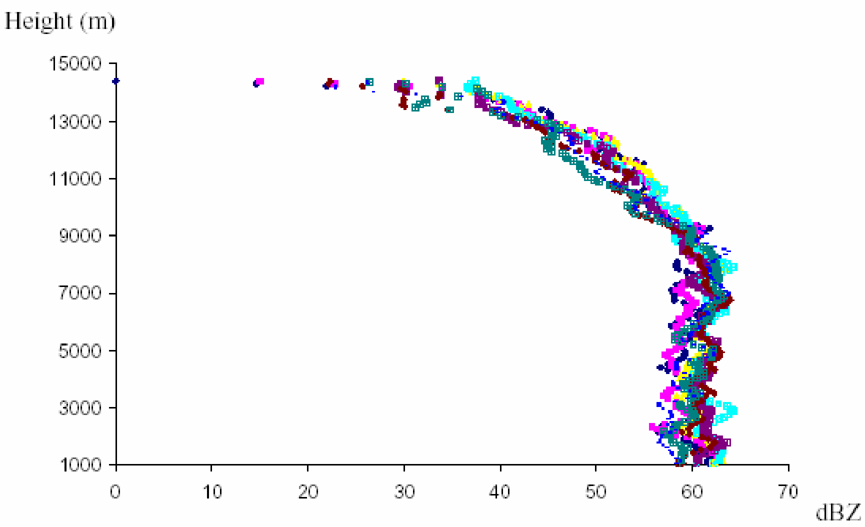


Figure 5. Vertical distribution of an exceptional rainfall event.

4. Effect on terrestrial and slant paths

Referring to terrestrial paths, when such type of event occurs, a very high attenuation level is noticed. Considering that the rain cell of Figure 3 covers a distance of more than 15km with a rain intensity higher than 200 mm/h, a typical radio link (5 ~ 10km) could be totally immersed on it.

On the other hand, a study by Timóteo da Costa and Assis [2] has shown large errors when comparing rain height corresponding to -2°C isotherm height, as adopted in the IUT-R model [3], with the effective rain height derived from experimental data measured in low latitude areas. Possibly, this disagreement is due to the vertical distribution of rain commented above.

5. References

[1] Cerqueira, J.L., "A radiometeorological study in the Amazon region" (in Portuguese), PhD doctoral dissertation in phase of printing;

[2] Timóteo da Costa, A. and M.S.Assis, "Rain height behavior in low latitude areas", Open Symposium on Propagation and Remote Sensing – URSI Commission F, Garmisch-Partenkirchen, Germany, February, 2002;

[3] ITU-R, "Propagation data and prediction methods required for the design of Earth-space telecommunication system", Recommendation ITU-R P.618-8, Geneva, 2002.

Análise da Variação Espacial da Taxa de Precipitação com Aplicação em Diversidade de Sítio para Enlaces Terra-Satélite

Jorge L. Cerqueira[1], Mauro S. Assis[2], L.A.R. da Silva Mello[3]

Resumo—**Este trabalho analisa a variação espacial da taxa de precipitação na região Amazônica. Foram utilizadas medidas de um radar meteorológico localizado Cruzeiro do Sul, AC, e desenvolvido um modelo matemático relacionando a distribuição estatística da chuva entre dois pontos separados por uma determinada distância. Adicionalmente, no estabelecimento da relação entre refletividade do radar e taxa de precipitação, dados provenientes de um pluviógrafo instalado nas vizinhanças do radar foram levados em conta. Os resultados finais do trabalho mostraram-se compatíveis com a forma de variação observada nas curvas de ganho da diversidade de sítio obtidas a partir de modelos empíricos com base na atenuação do sinal.**

Palavras-Chave— **taxa de precipitação, diversidade de sítio, região Amazônica, radar meteorológico, radiometeorologia,**

Abstract—**This paper deals with the spatial variability of rain rate in the Amazon region. Measurements from a meteorological radar located in Cruzeiro do Sul, AC, were taken into account and a mathematical model for relating the statistical distribution of precipitation rate between two points separated by a given distance was developed. Additionally, data from a pluviograph installed near the radar was also used in the derivation of a relationship between radar reflectivity and precipitation rate. Final results were promising enough. The behaviour of the mathematical model has showed excellent agreement with site diversity gain curves from empirical models based on rain attenuation.**

Keywords— **precipitation rate, site diversity, Amazon region, meteorological radar, radiometeorology.**

I. INTRODUÇÃO

A diversidade de sítio representa a solução técnica mais eficiente para compensar o efeito da atenuação por chuva em enlaces terra-satélite que operam em freqüências acima de 10 GHz. É claro que esta solução implica em maior custo na implementação do sistema. Entretanto, em locais onde o emprego de comunicações via satélite seja a melhor alternativa, a relação custo-benefício poderá justificar o investimento realizado. A Amazônia é um exemplo a ser citado, uma vez que as distâncias envolvidas e a barreira natural da floresta indicam o satélite como um caminho natural para resolver os problemas de comunicações. Por outro lado, o uso da banda Ku (12 – 18 GHz) nesta região poderá ser inviabilizado se não houver uma utilização criteriosa de técnicas que possibilitem a operação dentro de padrões aceitáveis de disponibilidade.

Com base em medidas de radar realizadas na localidade de Cruzeiro do Sul, divisa do Acre com Amazonas, este trabalho analisa o problema da variação espacial da chuva na região equatorial. Trata-se de um passo importante no sentido de desenvolver, a partir de uma sólida base física, um modelo que permita avaliar o desempenho da diversidade de sítio. A segunda parte desta pesquisa, em andamento, será estabelecer um procedimento de cálculo da atenuação por chuva aplicável nas condições de interesse na Amazônia, quais sejam, altas taxas de precipitação e ângulos de elevação acima de 60°. Cumpre ressaltar que, em tais condições, o modelo [1] adotado atualmente pelo Setor de Radiocomunicações da União Internacional de Telecomunicações (UIT-R) apresenta um comportamento aparentemente inadequado [2]. Esta questão está sendo investigada e os resultados obtidos serão publicados oportunamente.

Os dados experimentais aqui apresentados são provenientes de um amplo programa de pesquisa em radiometeorologia que está sendo realizado na região amazônica, sob a responsabilidade do Instituto Militar de Engenharia (IME), com apoio do Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), da Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio) e do Sistema de Proteção da Amazônia (SIPAM). Este programa tem como base de medidas a rede de radares e pluviógrafos mostrada na Figura 1.

II. FORMULAÇÃO MATEMÁTICA DO PROBLEMA

A questão fundamental que se apresenta é determinar a separação que deve existir entre as duas estações terrenas de uma configuração em diversidade para que o efeito da chuva seja minimizado e permita que a disponibilidade seja adequada

[1] Pontifícia Universidade Católica do Rio de Janeiro e Instituto Militar de Engenharia – Rio de Janeiro – RJ - jlcerq@terra.com.br

[2] Universidade Federal Fluminense – Niterói -RJ, msassis@openlink.com.br

[3] Pontifícia Universidade Católica do Rio de Janeiro – Rio de Janeiro – RJ - smello@cetuc.puc-rio.br

para o serviço que está sendo prestado. Para isto torna-se necessário avaliar a probabilidade de que uma determinada taxa de precipitação (R_0) seja excedida, simultaneamente, nas duas estações distanciadas por uma distância L_0.

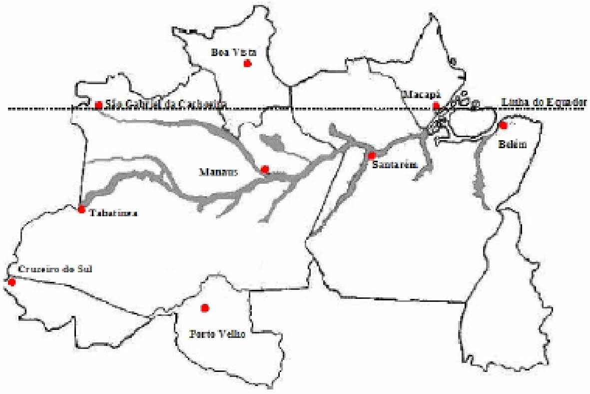


Fig. 1. Rede de Pluviógrafos e Radares Metereológicos.

Esta probabilidade pode ser determinada através de uma probabilidade condicional:

$$P(R_1 > R_0 \text{ e } R_2 > R_0) = P(R_2 > R_0 / R_1 > R_0).P(R_1 > R_0) \quad (1)$$

onde R_1 e R_2 são as taxas de precipitação na estação 1 e 2, respectivamente.

A probabilidade da chuva ser excedida na estação 1, $P(R_1>R_0)$, será dada pela função distribuição cumulativa da chuva na região, $F_R(R_0)$.

A probabilidade da chuva da estação 2 exceder a chuva especificada, dado que a chuva na estação 1 está excedida, $P(R_2>R_0 / R_1 > R_0)$, pode ser determinada pela união de dois eventos disjuntos, isso é, a probabilidade das estações 1 e 2 serem atingidas pela mesma célula de chuva (p_{mc}) ou a probabilidade de serem atingidas por células distintas (p_{cd}).

Nos cálculos destas probabilidades, leva-se em conta a função densidade de probabilidade do tamanho horizontal da célula de chuva para uma determinada taxa de chuva excedida, $f_D(D, R_0)$. Considerando a seção horizontal de uma célula de chuva como um círculo, este tamanho será definido pelo diâmetro da célula de chuva, D.

A probabilidade da estação 2 ser afetada pela mesma célula de chuva, excedendo R_0, que está atingindo a estação 1, será dada pelo produto entre probabilidade do diâmetro da célula ser D_i, $f_D(D_i,R_0)$, e a probabilidade do centro desta célula esteja em pontos específicos, isso é, pontos que permitam atingir ambas as estações simultaneamente, $p_1(D_i)$. O valor de $p_1(D_i)$ será dado por uma relação de áreas.

A probabilidade da estação 2 ser afetada por uma célula de chuva, excedendo R_0, distinta da que atinge a estação 1, será dada pelo produto entre a probabilidade de existir está nova célula de chuva, $\bar{F}_R(R_0)$, e a probabilidades de ambas as células apresentem diâmetros D_{i1} e D_{i2} e estejam em centros específicos de forma a não atingirem, cada uma, as duas estações.

Assim, a equação 1 será determinada por:

$$P(R_1 > R_0 \text{ e } R_2 > R_0) = \Big\{ \sum_{D_i=L_0}^{\infty} f_D(D_i, R_0).p_1(D_i) + \quad (2)$$

$$+\Big[\Big(\sum_{D_i=0}^{L_0} f_D(D_i, R_0) + \sum_{D_i=L_0}^{\infty} [f_D(D_i, R_0).(1 - p_1(D_i))] \Big) \bar{F}_R(R_0) \Big] \Big\} F_R(R_0)$$

Pode ser verificado que o valor da probabilidade dada pela equação (2) tende para $F_R(R_0)$ quando à distância entre as duas estações, L_0, tende para zero. Quando está distância tende para o infinito, isso é, para valores maiores que o diâmetro máximo de chuva encontrado na região, o valor da probabilidade dada pela equação (2) tende para o quadrado de $F_R(R_0)$.

III. Levantamento de Dados e Análise das Medidas

O primeiro passo para o cálculo das probabilidades associadas à estrutura horizontal da chuva, foi o de se estabelecer uma relação entre a refletividade (Z) do radar e a taxa de precipitação (R). Para isto, foram utilizadas medidas realizadas no período de agosto a dezembro de 2004, totalizando 6.908 imagens do tipo CAPPI ("Constant Altitude Plan Polar Indicator"), provenientes do radar de Cruzeiro do Sul, obtidas a uma altura em relação ao solo de 2 km e com uma distância máxima ao radar de 80 km. Este valor de altura foi utilizado por ser um valor intermediário entre o solo e a altura da célula de chuva, considerando também que a variação da refletividade (Z) com a altura no percurso da chuva não é relevante [3]. Ao final de uma varredura CAPPI dispõe-se de um valor de Z em cada quadrícula de dimensão 1 km x 1 km. De posse de tais medidas, utilizando como referência a relação de Marshall e Palmer [4], ou seja,

$$Z(mm^6/m^3) = 200[R(mm/h)]^{1,6} \quad (3)$$

e tendo como elemento de comparação à distribuição cumulativa da taxa de precipitação medida no pluviógrafo localizado nas vizinhanças do radar, chegou-se a

$$Z(mm^6/m^3) = 207[R(mm/h)]^{1,53} \quad (4)$$

Os detalhes da obtenção de (4) estão descritos em outra publicação [5]. Observa-se que a relação é muito próxima de Marshall e Palmer. Isto era esperado, uma vez que, para o objetivo pretendido neste trabalho, considerou-se o limiar da taxa de precipitação em 5 mm/h, abrangendo, desta forma, tanto chuva estratiforme, como chuva convectiva. A figura 2 apresenta a distribuição cumulativa da taxa de precipitação medida pelo pluviógrafo no período de janeiro a dezembro de 2004 e aquela obtida a partir da equação (4).

A seguir, associando a cada quadrícula o valor de R correspondente, considerou-se como chuva toda quadrícula com taxa de precipitação igual ou superior a 5 mm/h. Definiram-se as células de chuva excedendo R_0, como o conjunto de quadrículas, com $R > R_0$, que apresentasse ligação horizontal ou vertical entre seus lados. A área de cada célula foi determinada pelo número de quadriculas existentes.

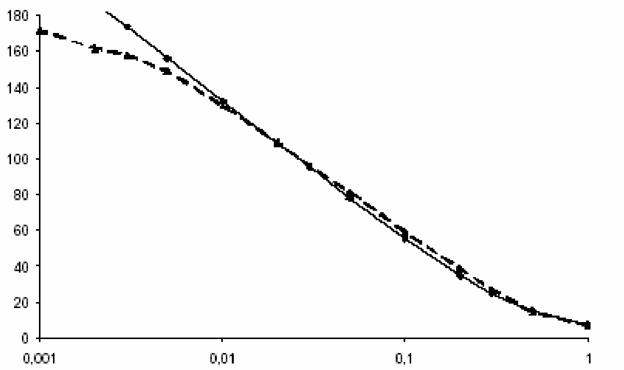


Fig. 2. Função distribuição acumulativa da chuva em Cruzeiro do Sul (F_R) medida pelo pluviógrafo (- - -) e através da equação 4 (—). Eixo horizontal marca a probabilidade (%) e o eixo vertical o valor da taxa de precipitação cumulativa excedida(mm/h).

Fazendo equivalência da área irregular assim obtida com uma circunferência, chegou-se a uma distribuição dos valores de diâmetro da célula para cada taxa de precipitação excedida. Assim foi possível traçar a Figura 3 que apresenta a percentagem do número de células (eixo vertical) com diâmetro superior ao valor indicado no eixo horizontal para $R \geq R_0$, sendo R_0 o limiar tomado como referência em cada curva.

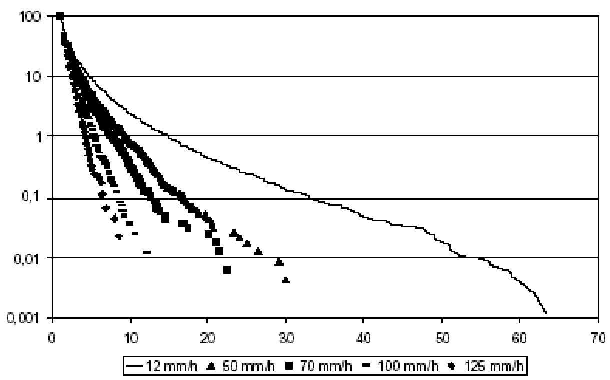


Fig. 3. Percentagem do número de células (%), eixo vertical, com diâmetro (km) superior ao valor indicado no eixo horizontal, para diversos valores de $R \geq R_0$, sendo R_0 o limiar tomado como referência em cada curva.

Por fim, baseado na equação (2), obtém-se então a Figura 4 que mostra a percentagem de tempo que uma taxa de precipitação acima de R_0 é excedida em duas estações separadas por uma determinada distância, L_0.

Verifica-se nesta figura que existe uma saturação das curvas entre 10 e 15 km. Este resultado é similar ao que se observa nas curvas de ganho de diversidade obtidos a partir de modelos empíricos que tem por base a atenuação do sinal [1,6]. Considerando que os parâmetros de sistema, tais como, freqüência, polarização e ângulo de elevação afetam unicamente o valor da atenuação, conclui-se que o efeito de saturação é função apenas da descorrelação da chuva à medida que aumenta a distância de separação entre os terminais.

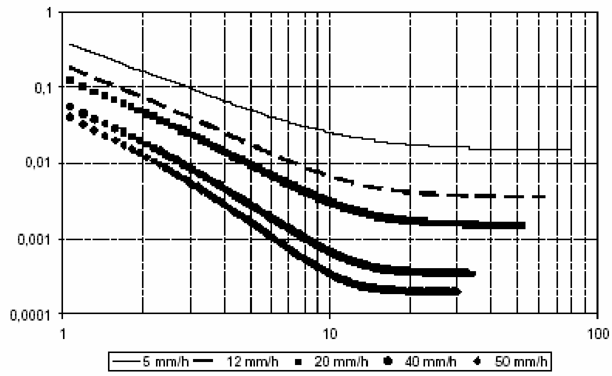


Fig. 4. Percentagem de tempo (%), eixo vertical, que uma taxa de precipitação acima de R_0(mm/h) é excedida em duas estações separadas por uma determinada distância L_0 (km), eixo horizontal.

Em vista deste resultado, procurou-se definir um relacionamento entre a taxa de chuva excedida em uma estação isoladamente (R_A) em uma dada percentagem de tempo (p) e o valor da taxa excedida simultaneamente em duas estações (R_B), separadas por uma distância da na mesma percentagem de tempo. O melhor ajuste correspondeu a,

$$R_A = R_B . (12{,}5\, p + 1{,}1)\, D^{(0{,}42 \log(p) + 1{,}9)} \qquad (5)$$

sendo R_A e R_B em mm/h, D em km e p em %.

A expressão (5) é considerada ainda preliminar, pois se pretende investigar dados de outras estações na mesma linha do que foi feito neste trabalho. Pode-se, no entanto, adiantar que se espera um comportamento similar, pois as características da chuva na região em estudo não apresentam variações significativas.

IV. Conclusões

Tendo por referência medidas (radar e pluviógrafo) realizadas em Cruzeiro do Sul, AC, este trabalho analisou o problema da variação espacial da taxa de precipitação na região Amazônica. A formulação matemática desenvolvida para modelar esta variação mostrou-se plenamente satisfatória. A saturação observada na figura 4 do trabalho é similar ao comportamento observado nas curvas empíricas de ganho de diversidade, demonstrando que o modelo definido pela equação (2) é adequado para análise da variação espacial da taxa de precipitação. Com base neste resultado foi proposta uma formula prática a ser utilizada no dimensionamento da separação entre terminais de um sistema de diversidade de sítio.

REFERÊNCIAS

[1] UIT-R, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems", *Recommendation ITU-R P.618-8*, Genebra, 2002.

[2] UIT-R, "Comments on Recommendation ITU-R P.618-7 - Propagation data and prediction methods required for the design of Earth-space telecommunication systems", *Doc. 3M-17* , WP-3M, Fortaleza, Brasil, 2003.

[3] P. Misme e P. Waldteufel, "A model for attenuation by precipitation on a microwave earth-space link", *Radio Science*, v. 15 , nr. 3, p. 655-665, Jul 1980.

[4] A. Pawlina, "Essential knowledge of rain structure for radio applications based on available data and models", *Radio Africa 99*, Gaborone, Botswana, 1999.

[5] Cerqueira, J. L., "Estudo radiometeorológico da região Amazônica", *Dissertação de Doutorado*, PUC - Rio, Brasil, (em preparação).

[6] D. B. Hodge, "An improved model for diversity gain on earth-space propagation paths", *Radio Science*, v. 17, p. 1393-1399, 1982.

RAIN ATTENUATION RESEARCH IN BRAZIL

Jorge L. Cerqueira(1), **Mauro S. Assis (2), L.A.R. da Silva Mello(3)**

(1) Pontifical Catholic University of Rio de Janeiro and Military Institute of Engineering
Rua Pinto Guedes 140 apt. 303 – Rio de Janeiro – RJ, 20511-320 – Brazil - **jlcerq@terra.com.br**

(2) Fluminense Federal University - Rua Coelho Neto, 17 apt. 301 – Rio de Janeiro – RJ, 22231-110 – Brazil - **msassis@openlink.com.br**

(3) Pontifical Catholic University of Rio de Janeiro - Centre for Telecommunication Studies
Rua Marques de São Vicente 225 – Rio de Janeiro – RJ, 22453-900 – Brazil- **smello@cetuc.puc-rio.br**

ABSTRACT

This paper describes some preliminary results and the activities in progress of a research program on rain attenuation in the Amazon region. This program is part of a broad project, named CT-Amazônia, covering different aspects of science and technology, which is being developed under the responsibility of the Military Institute of Engineering (IME) with financial support from the National Scientific and Technological Development Council (CNPq). The following topics are being investigated in this program: a) Precipitation rate behaviour based on rain gauge and radar measurements and b) Rain attenuation prediction modelling for terrestrial and slant paths.

INTRODUCTION

The research on rain attenuation in Brazil has started around 1970 [1]. Reference to the work prior to 1996 may be found in [2] and [3]. This paper presents some preliminary results related to rainfall characteristics, as well as, the research program now in progress. This research is the theme of the doctoral thesis of the first author and includes two main topics: a) Precipitation rate distribution and radar measurements in the Amazon region and b) Rain attenuation prediction models for terrestrial and slant propagation paths. Referring to rainfall rate studies, a very broad rain gauge network was implemented in the Amazon region. Figure 1 shows the locations where the gauges were placed. On other hand, considering the well-known relation between radar reflectivity and rain rate, measurements from a radar network is being used as a complement for these studies. This radar network belongs to SIPAM (Amazon system protection) and covers the same locations as the rain gauge network. Radar data will be also used in the definition of rain cell shape and dimension. With this procedure, it is hopped to derive an attenuation model closely fitted to physical reality of rain structure.

KÖPPEN CLIMATE CLASSIFICATION

According to preliminary results of this research program, the combined use of precipitation and radar data, Köppen climate classification [4] and the mathematical model adopted by the ITU-R Recommendation P.837-4 [5] appears to be an useful tool for the prediction of rainfall rate cumulative probability distribution. This approach can also be used to improve contours of homogeneous climatic areas, as well as to better characterize the transition between different climates.

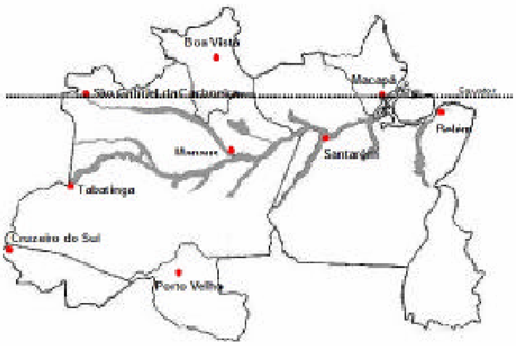


Fig. 1 Amazon region – rain gauge and radar networks.

Köppen classification was adopted because its structure depends on temperature, precipitation and vegetation, factors that can be related to the statistical distribution of rain in a given area. In the Amazon region only Köppen climate A (tropical rainy) can be identified with the following subtypes:

a) Rainy Equatorial (Af) - with a large annual rainfall (over 2000 mm) and practically no dry season;
b) Monsoon Tropical (Am) – the annual rainfall is equal to or larger than Af, but there is a short dry season (one to three months);
c) Wet-and-dry tropical (Aw) – where the rain and dry seasons are well defined.

PRECIPITATION RATE DISTRIBUTION

When there is no information about the local cumulative distribution of rain, an alternative is to use a mathematical model based on meteorological parameters available in the region under study. In this paper it was adopted the Salonen-Baptista model, which is the basis of the ITU-R Recommendation P.837-4 [5]. This model depends on the following parameters:

- Average annual convective rainfall amount, M_C (mm);
- Average annual stratiform rainfall amount, M_S (mm);
- Probability of rainy 6h periods, ***Pr6.***

which can be obtained from the data available in the Brazilian Meteorological Institute.

Taking this mathematical model together with precipitation and radar data, a detailed analysis of the cumulative distribution of rain in the Amazon region is being carried out. Figure 2 shows a comparison between the cumulative distribution measured at Cruzeiro do Sul, from January 2004 to December 2004, with the corresponding predicted values from the Salonen-Baptista model adjusted with meteorological local data. An acceptable agreement between the two curves is observed.

Z – R RELATION

Radar reflectivity factor (Z) in mm^6/mm^3 is related to rainfall rate (R) in mm/h through an empirical relation of the type $Z = aR^b$. Based on rain gauge [7.36^{0}S;72.80^{0}W] and radar measurements [7.36^{0}S ; 71.56^{0}W] carried out at Cruzeiro do Sul, it was found the following values for these parameters: a = 207 and b = 1.53.

The relation $Z = 207\ R^{1.53}$ will be used throughout in this paper. Details about the derivation of "a" and "b" are being published elsewhere [6]. Figure 3 shows a comparison between the cumulative distribution of precipitation rate from rain gauge measurements and the corresponding distribution obtained by the conversion of radar data. An excellent agreement is observed for percentage of time up to 0.005 %. For smaller percentages of time the difference of values between the two procedures is probably due to rain gage saturation.

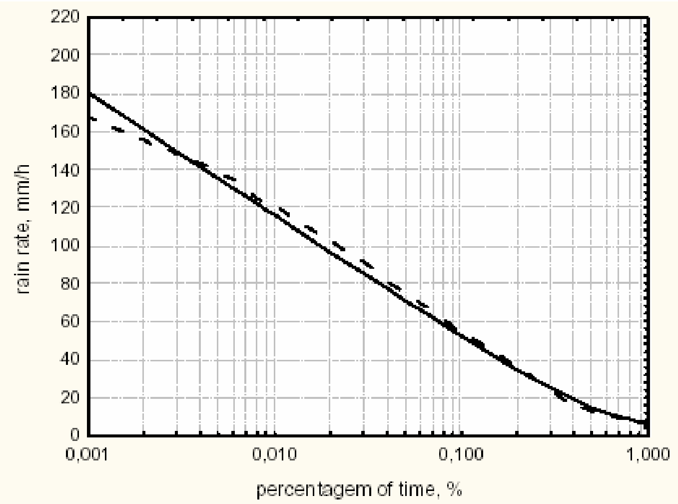


Fig. 2 Cumulative distribution of rainfall rate in Cruzeiro do Sul (7.36°S ; 72.80°W) - Comparison between rainfall rate measurements (—) and Salonen-Baptista prediction model (- - -).

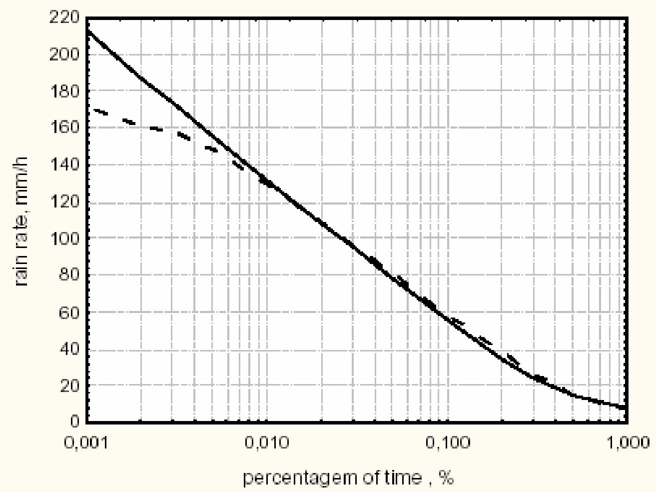


Fig. 3 - Cumulative distribution of rainfall rate in Cruzeiro do Sul - Comparison between rainfall rate measurements from rain gauge (- - -) and radar data (—)

PREDICTION OF RAIN ATTENUATION

An example of a rain cell measured at the radar station of Cruzeiro do Sul is given in Figure 4. Taking into account the non-uniform aspect of the rain cell shown in this figure, it is clear the difficulty to model it by a simple geometrical shape. Most of prediction models use the concept of path length factor (or distance factor) for solving the problem of non-uniformity of rain along the propagation path. However, considering that is not feasible to derive a rigorous mathematical expression for this factor, an alternative is the use of experimental data for fitting an empirical solution based on a given rain cell model. Taking as reference a truncated exponential rain cell, promising results were obtained by Timóteo da Costa and Assis [7]. An important reason for choosing this model was because, through a combination of cylindrical and exponential shapes, it is avoided the restriction associated to a measured path length factor greater than one, common to other predicting methods.

Observing Figure 4, once the rotational symmetry assumed above is not in accordance with the shape of the rain cell, a limitation to this model could be raised. However, a detailed analysis of the cell core, where precipitation is more intense, indicates that this approximation seems to be acceptable. There is not a good agreement in the tail of the rain cell, where the precipitation is low and, consequently, less important for rain attenuation.

On the other hand, weather radar observations [8] show that, on average, the rain intensity does not vary from the surface of the Earth up to the 0°C isotherm (h_o). Based on this result, h_o has been used along the years as reference for modelling the rain height. However, in the Amazon region (and probably in other low latitude locations) this point deserves a more detailed investigation, once radar data indicate the existence of heavy rain well above the 0°C isotherm. An example is given in Figure 6 with data from the radar station of Tefé [3.22^{0}S; 64.42^{0}W]. This figure shows vertical profiles of Z measured at 8 points separated by 250 m in a range of 2 km. Considering that the isotherm of 0°C is around 4500m, the rain is approximately constant up to 2 h_o, i. e. 9000m.

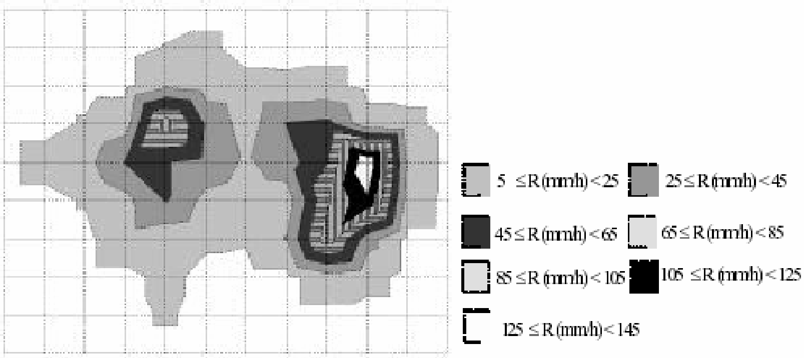


Fig. 4 – An example of the horizontal variability of rain

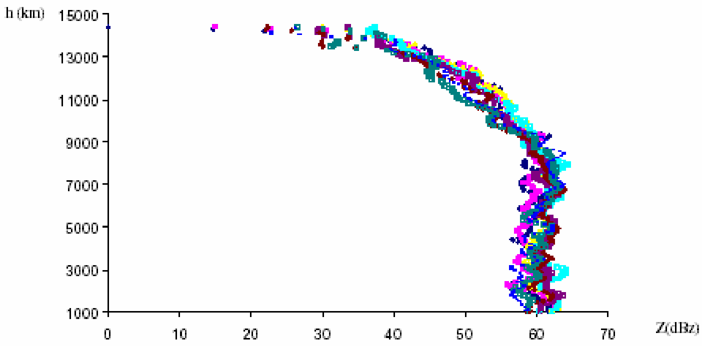


Fig. 5 An example of the vertical variability of rain.

The concept of equivalent rain height seems to be an adequate way to solve this question. However, as it was pointed out by Assis [9], this solution should be considered only after solving the problem of the horizontal distribution of rain. An study by Timóteo da Costa and Assis [10] has shown large errors when comparing rain height corresponding to -2°C isotherm height, as adopted in the ITU-R model [11] with the effective rain height derived from experimental data in latitudes between 30°N and 30°S.

CONCLUDING REMARKS

According to the preliminary results described in this paper, it is clear that the combined use of precipitation and radar data, Köppen climate classification and Salonen-Baptista mathematical model appears to be an useful tool for the prediction of rainfall rate cumulative distribution. This approach can also be used to improve contours of an homogeneous climatic area, as well as, to better characterize the transition between different climates. As expected for convective rain, the non-uniformity of precipitation in the horizontal plane constitutes an obstacle for modelling the cell. In spite of that, considering that the core of the rain cell can be treated as homogeneous, a model referenced by a truncated exponential rain cell is being investigated. Regarding vertical variability, once for convective precipitation radar signals can be detected well above the 0°C isotherm, the concept of effective rain height seems to be an adequate way to face the question. However, taking into account the totally empirical basis of this concept, it must be used only after the problem of horizontal distribution has been solved.

REFERENCES

[1] Assis, M. S. and A. A. Salles, "Some topics in the application of millimeter waves in tropical and equatorial regions", *International Symposium on Antennas and Propagation (ISAP)*, Sendai, Japan, September, 1971;
[2] Assis, M. S., "Rain attenuation in terrestrial paths: A review", *CLIMPARA'96*, Oslo, Norway, June, 1996;
[3] Silva Mello, L. A. R., M. S. Pontes and M. S. Assis, "Climatic parameters for prediction of radiowave propagation in South America", *XXVth General Assembly of URSI*, Lille, France, August, 1996;
[4] H.J.Critchfield, *General Climatology*, Prentice-Hall, New Jersey, USA, 1974;
[5] ITU-R, "Characteristics of precipitation for propagation modelling", *Recommendation ITU-R P.837-4*, Geneva, 2002;
[6] Cerqueira, J.L. *"Modelling rain attenuation in satellite links in tropical and equatorial regions" (in Portuguese)*, PhD doctoral dissertation in phase of printing;
[7] A. Timotéo da Costa and M. S. Assis, 'The concept of path length factor in the prediction of rain attenuation in terrestrial links", *XXVIIth General Assembly of URSI,* Maastricht, the Netherlands, August, 2002;
[8] Goldhirsh, J. and I. Katz, Useful experimental results for Earth-satellite rain attenuation modelling, *IEEE Trans. on Antennas and Propagation*, AP-27, pp. 413-415, May, 1978;
[9] Assis, M. S., "Some remarks on the spatial structure of rain in tropical and equatorial regions", *ISRP'93*, Beijing, China, August, 1993;
[10] Timotéo da Costa, A. and M. S. Assis, "Rain Height Behaviour in Low Latitude Areas", *Open Symposium on Propagation and Remote Sensing – URSI Commission F*, Garmisch – Partenkirchen, Germany, February, 2002;
[11] ITU-R, "Propagation data and prediction methods required for the design of Earth-space telecommunication system", *Recommendation ITU-R P.618-8*, Geneva, 2002.