ALPHASAT SITE DIVERSITY EXPERIMENTS IN GREECE AND THE UK AT KA BAND: COMPARISON OF 2-YEARS' RESULTS

Apostolos Z. Papafragkakis[1], Spiros Ventouras [2], Charilaos I. Kourogiorgas[3], Athanasios D. Panagopoulos[4]

[1]School of Electrical & Computer Engineering, National Technical University of Athens, Athens, Greece
[2]STFC Rutherford Appleton Laboratory, RAL SPACE, Harwell, UK
[3]School of Electrical & Computer Engineering, National Technical University of Athens, Athens, Greece
[4]School of Electrical & Computer Engineering, National Technical University of Athens, Athens, Greece

Abstract –Satellite communications have already started to employ mmWave bands such as the Ka-band (20/30GHz) for broadcasting and broadband services; Ka-band is used either for backhauling (feeder links) or direct-to-user services. To enhance the propagation modeling and assist in the development of advanced satellite radio systems, two site diversity experiments are simultaneously conducted in Greece and in the UK using the satellite beacon transmitted by ALPHASAT. In this paper, the two years of collected experimental data are presented and evaluated in terms of first-order statistics. Considering the different climate of the two experiment locations, one in the Southern Mediterranean Sea (Greece) and one in the Northern Atlantic Sea (UK), a comparison between the two respective Ka-band long-term radio diversity channels is also performed. Several conclusions for the diversity system design are drawn that can be particularly significant towards the application of a smart gateway diversity concept in feeder links.

Keywords – ALPHASAT, exceedance probability, excess attenuation, joint statistics, Ka Band, satellite comunications, site diversity

1.   INTRODUCTION

In modern satellite communication systems the reliable design and system performance are constrained by the radio propagation effects, the interference and the noise, phenomena inherently present in every radio system. Currently, fixed satellite services using GEO satellites commonly employ [1] Ku (12/14GHz) and Ka (20/30GHz) bands. These frequency bands are used for both direct-to-user (DTU) and broadcasting applications, as well as for feeder links and satellite backhaul networks [2], [3]. New, data-rate intensive satellite applications have evolved and led to the adoption of higher frequency bands (such as Ka-band) for both fixed and mobile satellite networks. Despite the fact that the use of higher frequency bands bears many advantages (namely greater bandwidth and less interference), the signal propagation can be significantly affected by the various atmospheric phenomena (i.e. rain, clouds, gases, the melting layer and tropospheric turbulence).

In order to meet the elevated system performance requirements imposed by the new services and applications, feeder links design must provide a very high link availability, typically in the order of 99.9% or higher [1], [3]. Maintaining such a high link availability is a non-trivial task and cannot be

achieved by merely using a fade margin; more advanced Fading Mitigation Techniques (FMTs) have to be utilized.

A typical feeder link FMT is uplink power control, providing a few more dB of extra fade margin at the expense of bulkier gateway RF front-ends [4]. However, even such a technique might not be sufficient to provide the required availability level for the feeder links, particularly when the Q/V-bands are considered. At such frequencies rain effects can severely impair the signal and depending on the rain intensity and the elevation angle, can potentially cause attenuation in excess of 15 to 20 dB for a non-negligible percentage of time throughout the year.

Site Diversity (SD) is a well-known strategy to mitigate the impact of fading events in satellite feeder links by exploiting the temporal and spatial variability of the radio channel [1], [2], [5]. A gateway is complemented by a backup station within the same feeder beam at a suitable separation distance depending on the regional meteorological characteristics. Considering a properly configured station arrangement, the two locations should encounter severe radio propagation impairments at different times; in this case, switching to the site experiencing the least fading should considerably improve system

availability and performance. Of course the two stations need to be interconnected through a high capacity network to enable dynamic rerouting of the data traffic whenever a gateway switch occurs. Such an approach is quite practical for satellite networks characterized by one or a few beams since a second gateway greatly improves the availability at an acceptable cost increase and allows the use of smaller gateways to meet a particular availability.

The demand for a site diversity performance assessment before actual system deployment necessitates the development of accurate prediction models [1], [2]. However, reliable long-term measurements which could be used either for the design and modeling of site diversity (i.e. testing existing models [6], [7]) or the development of new prediction models (for regions where data is not available), are sparse, particularly at high frequency bands such as Ka and Q/V bands.

The novelty of this paper is that it evaluates and compares the statistical performance of the site diversity technique based on 2-year measurements at two vastly different climatic regions within Europe, Greece (Southern Mediterranean climate) and Southern England (North Atlantic climate). Greece is well known for its Mediterranean climate with irregular, whilst intense, rainfalls (convective precipitation) mainly during winter, as well as for its long and hot summers; in particular Greece has been known to suffer from heavy storms and rain commonly originating from the west because of its unique location and terrain morphology. On the other hand, the United Kingdom is characterized by frequent showers throughout the entire year (stratiform precipitation) with small temperature fluctuations between different seasons. For both regions the measurement data was aquired using the Alphasat SCIEX Ka band beacon signal in the framework of the European Space Agency (ESA) *ASALASCA* propagation experiment [8]. RAL Space, who led the *ASALASCA* consortium, is responsible for the site diversity experiment in England while the Radio and Satellite Communications Group at the National Technical University of Athens (NTUA), also member of the ASALASCA consortium, is responsible for the experimental campaign in Greece.

The remainder of this paper continues as follows: In section 2 the experimental campaigns (the architecture of the receivers, the preprocessing technique and the ancillary measurements) are briefly described. In section 3 the experimental

single and joint statistics in Greece and UK, as well as a brief, nonetheless rigorous discussion is given. Finally, section 4 concludes the paper and presents ideas for future work.

2. ALPHASAT PROPAGATION CAMPAIGN IN GREECE AND THE UK

In July 2013 the ALPHASAT satellite (commercial name Inmarsat-4A F4) has been developed and launched to 25.0ºE providing, among others, payloads for experimental purposes under the supervision and coordination of the European Space Agency (ESA). The so-called Aldo Paraboni Technology Demonstration Payload 5 (TDP#5), named after Professor Aldo Paraboni of Politecnico di Milano, who was principal investigator of this project but passed away in 2011 provides two coherent beacons at Ka- (19.701 GHz) and Q-band (39.402 GHz). The transmitted beacons have been utilized by many research groups around Europe to conduct propagation experiment campaigns, ultimately to enhance available propagation data and allow the development of new models and techniques. As already stated in the introduction, both NTUA and RAL Space are members of the relevant ESA consortium *ASALASCA* [8].

Table 1 – Experimental campaign receivers' sites

Locations	Longitude, Latitude	Altitude a.m.s.l.*	Azimuth Angle	Elev. Angle
Greece, Athens NTUA Campus	37.975 ºN 23.785 º E	0.21 km	178.03º	45.97º
Greece, Lavrion	37.723 º N 24.048 º E	0.02 km	178.44º	46.26º
UK, Chilbolton	51.15 º N 1.43 º W	0.1 km	147.45º	26.40º
UK, Chilton	51.57 º N 1.29 º W	0,1 km	147.77º	26.07º

*above mean sea level

2.1 Receivers' details

The ongoing experimental campaign described in this paper takes place at four sites in total, two in Greece (Athens and Lavrion, about 36.5 km apart) and two in the UK (Chilbolton, Chilton, 47.8 km apart); such a configuration enables the study of site diversity schemes in small and large scale distances. The Ka-band beacon signal transmitted by ALPHASAT is a constant power continuous wave (CW) (unmodulated signal) at 19.701 GHz. The ground terminals receive and measure the beacon

power to extract any induced signal attenuation. Due to the satellite's slightly inclined orbit, its apparent position as observed at the ground varies over time;nevertheless, its position is known at each time using Orbit Ephemeris Messages (OEM) files.

2.1.1 Receivers in Greece

NTUA has designed and deployed two identical Ka-band beacon receivers in Attica, Greece, one at the NTUA Campus in Athens and another one at the Lavrion Technological and Cultural Park. Both receivers are based on the Software Defined Radio (SDR) principle, making use of high-grade off-the-shelf parts allowing for lower procurement and service costs, as well as quicker provisioning.

The Ka-band receivers front-end consist of 1.2 m offset dishes. After undergoing filtering, amplification and down-conversion at the Low Noise Block (LNB) units, the signals are fed to a Universal Software Radio Peripheral (USRP) which further samples them, digitizes them and passes them to a single-board computer for further processing. The signal power estimation is done using a real-time Fast Fourier Transform (FFT) algorithm, providing 10 Hz of data measurement sampling rate and is built around the popular open-source GNU Radio framework. It is worth noting that apart from the beacon signal measurements, also the noise power in the same bandwidth is measured and recorded [9].

All oscillators used in the receiver chains are locked to external GPS Disciplined Oscillators (GPSDOs) to guarantee that extremely high frequency stability is achieved. Also, both antennas are equipped with an accurate tracking system developed in-house. The measured dynamic is in excess of 40 dB.

2.1.2 Receivers in the UK

RAL Space has deployed receivers targeting the Ka-band ALPHASAT's beacons at Chilbolton and Chilton. The measurement setup comprises of equipment already used successfully in past propagation measurement campaigns; all equipment is located indoors, in a specially adapted Portakabin with woven PTFE windows.

The antennas used are 50 cm in diameter lens horn type. Each antenna has its own (commercially procured) tracking system. The beacon reception is based on conventional techniques, i.e. Phase Locked Loop (PLL) envelope detection using a PLL tracking receiver. The receiver is configured with a noise

bandwidth of 300 Hz and a tracking range of 100 kHz. The output of the PLL receiver is fed to a computer-attached Analog to Digital Converter (ADC) for further processing (sampling, digitization etc).

The available measurement dynamic range is about 20 dB at a 10 Hz data output rate .

2.2 Ancillary equipment

Since the beginning of the campaign, collocated ancillary equipment has been deployed at all campaign locations allowing for in-situ meteorological measurements. All measurements are synchronized to the receivers and archived with the necessary meta-tags for later processing. The use of collocated meteorological instrumentation should allow for further study of the correlation between the fading statistics and the observed meteorological events.

2.3 Data preprocessing

NTUA and RAL Space monitor the data collection and visually inspect the obtained time series on a daily basis to ensure data consistency and integrity. Additionaly, data preprocessing is performed using the well established RAL method based on Fourier Series [10]. Data preprocessing is critical in any propagation experiment campaign and involves the following tasks:

- removal of the effect the ground equipment has on the received signal;
- identification of valid data;
- data merge from beacon receivers and ancillary instruments;
- raw and processed measurements archiving.

All measurements have timestamps synchronized to GPS time and are stored using a common format (netCDF) for further processing and evaluation. Apart from the actual propagation measurements, ancillary data is recorded to support the experiment with essential metadata (e.g. meteorological events).

3. ANALYSIS OF EXPERIMENTTAL RESULTS AND DISCUSSION

In the following the results obtained from the first two years of the campaign are analyzed and presented. The processed beacon data availability for the Greek campaign has been 96.11% for Athens and 95.99% for Lavrion; for the UK campaign the processed data availability has been 98.33% for

Chilton and 97.82% for Chilbolton. Regarding the processed rainfall data, NTUA has 100.00% availability for both locations while RAL Space has 98.93% availability for Chilton and 98.81% availability for Chilbolton.

3.1 Single site statistics receivers

Table 2 summarizes the annual measured rain characteristics in two locations in Greece and the UK. Rainfall data in mm have been converted to rainfall rate in mm/h using a 60 second integration window according to the methodology in [11]. The annual probability of (detectable) rain, i.e. the probability that the rain rate is greater than 0.25 mm/h, is higher in England than in Greece. As an example, there is detectable rain in Attica, Greece for about 365x24x0.01=87.6 hours/year on average whereas in the UK 365x24x0.04=350.4 hours/year. However, the rain rate used in the ITU-R Predictions Model (ITU-R Rec. P.618-13) [7], i.e. at 0.01% of the year or 52.56 minutes/year, is much higher in Greece. This is reflected in the attenuation statistics depicted in Figures 1 and 2.

The attenuation exceedance probabilities suggest that systems operating at Ka-band for a given availability, require a larger fade margin in Greece than in Southern England. For example for an annual availability of (100-0.01)%=99.99% the required fade margin in Attica, Greece must be at least 18 dB whereas in Southern England 12 dB; the fade margin values merely serve as a baseline as they refer to the received ALPHASAT unmodulated CW signals.

Table 2 – Rainfall rate data

Location	Exceedance time (%) of 0.25mm/hr	Rain rate at 0.01% (mm/hr)
Athens, GR	1.23	64,98
Lavrion, GR	1.06	70.27
Chilton, UK	3.99	19.67
Chilbolton, UK	4.70	20.82

In addition, the exceeded attenuation levels at the lower exceedance probability values experience a significant annual variability in both countries.

Figures 3 and 4 show the comparison of the average annual statistics with the ITU-R P.618-13 [7] model in the two locations, i.e. in Greece and the UK respectively. The annual attenuation statistics are the average annual over the observation period of two years. As can be seen in Figures 3 and 4, the ITU-R Model [7] for the prediction of the excess

attenuation, i.e. the combination of all the propagation impairments except for the gaseous attenuation, overestimates the actual measured values. This is more evident at the English sites where the elevation angles are lower compared to the Greek sites and therefore the former experience more cloud attenuation. In Figures 3 and 4 a modified methodology proposed in [8] for the calculation of in-excess attenuation using the ITU-R model is also shown. As can be observed it yields better results in all the campaign locations.
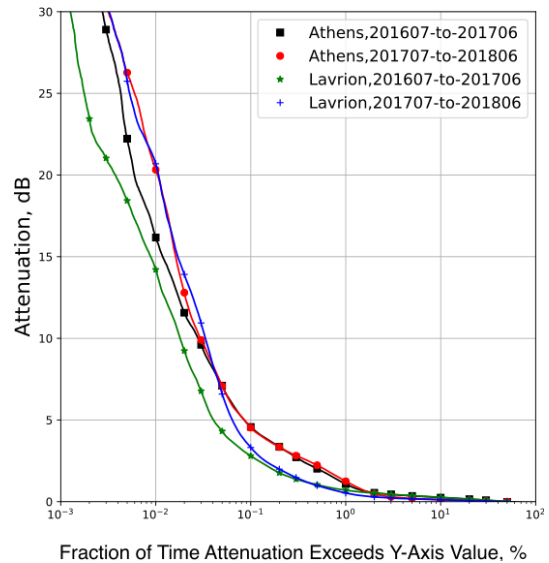

Fig. 1 - Measured annual complementary cumulative distribution of excess attenuation in Greece
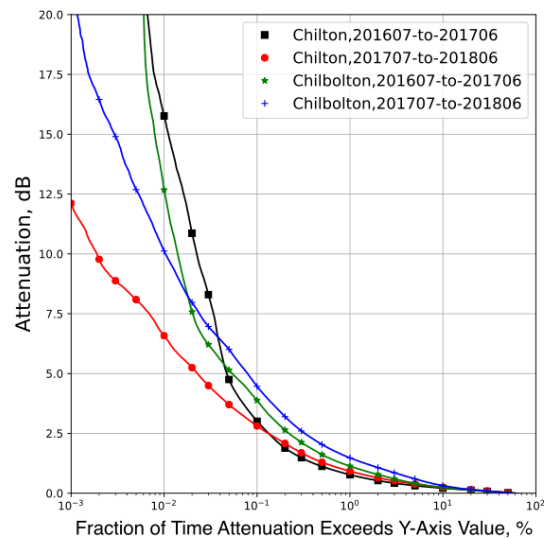

Fig. 2 - Measured annual complementary cumulative distribution of excess attenuation in the UK

3.2 Joint site diversity statistics

In Figures 5 and 6 the performance of the site diversity FMT, [1], [2], in Greece and the UK is evaluated against the ITU-R P.618-13 [7] predictions. The attenuation statistics are the

average annual over the observation period of two years. A very significant observation not yet mentioned anywhere in the literature is that for an annual availability of (100-0.01)%=99.99% the required fade margin using site diversity, despite the different radio propagation characteristics in England and Greece, for both countries is very similar and around 2.8 dB as shown in Figures 5, 6 and 7. This suggests that the diversity gain in Greece is much higher since the corresponding single link excess attenuation experienced at 0.01% of the time is also much greater than in the UK.
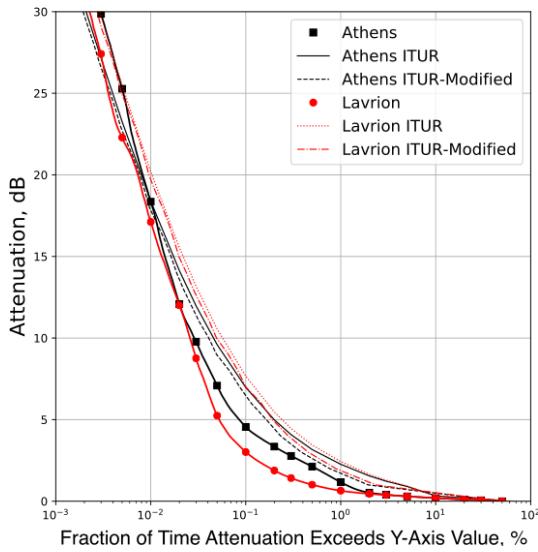
Fig. 3 - Average annual complementary cumulative distribution of excess attenuation in Greece in comparison with the ITU-R P.618-13 predictions
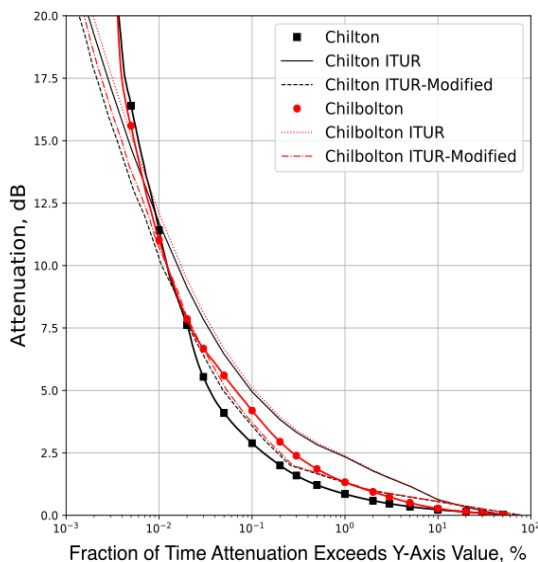

Fig. 4 - Average annual complementary cumulative distribution of excess attenuation in the UK in comparison with the ITU-R P.618-13 predictions
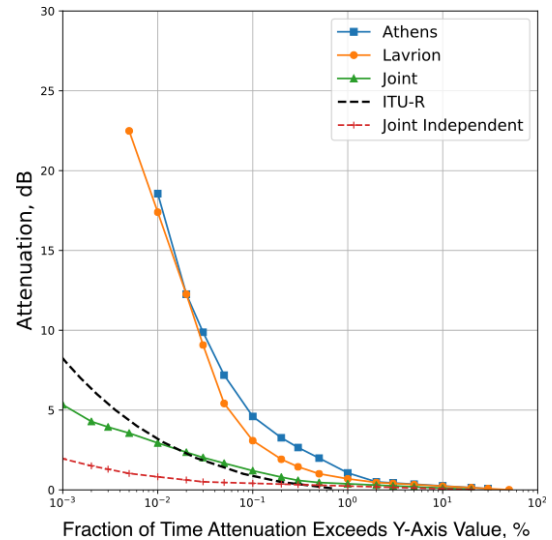

Fig. 5 - Average annual complementary cumulative distribution of excess attenuation in Greece in comparison with the ITU-R predictions
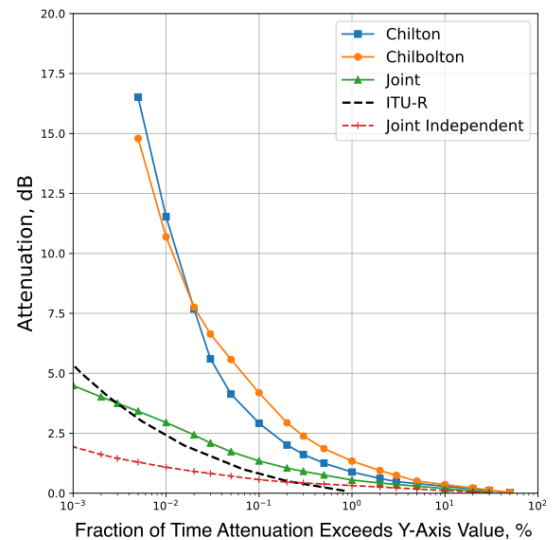

Fig. 6 - Average annual complementary cumulative distribution of excess attenuation in the UK in comparison with the ITU-R predictions

The independent joint attenuation cumulative attenuation statistics [12], i.e. the product of the single attenuation statistics, clearly shows that even for site separations of 36.5 km and 48 km, as is the case for the campaigns in Greece and the UK respectively, there is a significant dependence between the propagation effects at the two sites (Chilton-Chilbolton and Athens-Lavrion).
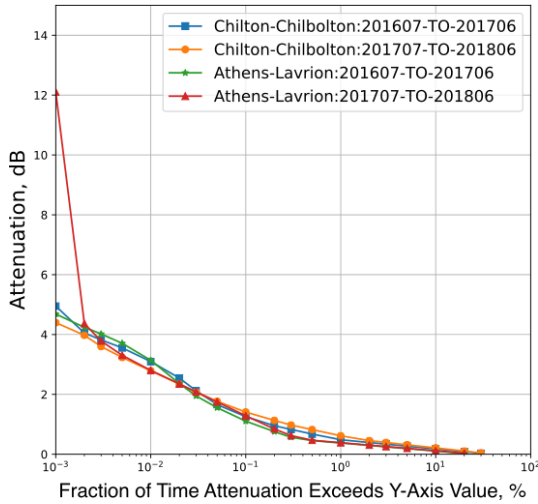
Fig. 7 - Measured annual joint complementary distribution of excess attenuation for Greece and the UK
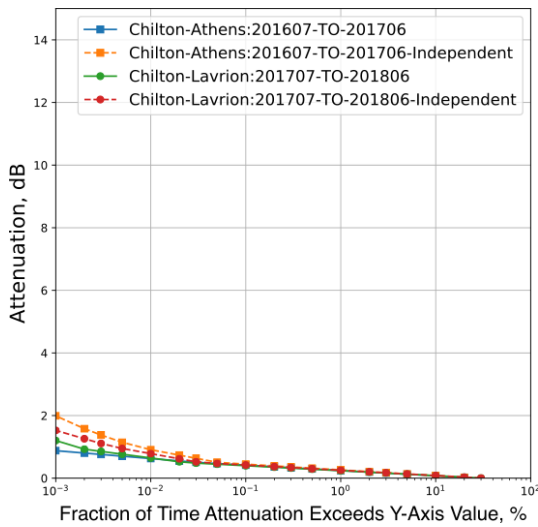

Fig. 8 - Measured annual joint complementary distribution of excess attenuation between Greece and the UK in comparison with the independent joint distributions

A significant observation can be made in Fig. 7; it is apparent that the measured annual joint complementary distribution of excess attenuation for both experiments in Greece and the UK share a very similar behavior and their lines almost overlap; this is an outstanding result that, despite potentially being a random effect, has to be noted. Finally, in Fig. 8 the results for the measured annual joint complementary distribution of excess attenuation between Greece and the UK are presented; these results are presented considering the application of the smart gateway diversity concept in feeder links [13].

There is a notable discrepancy in elevation angles across the two regions potentially influencing the derived results to some extent; the UK receivers operate at an elevation angle of approximately 26° while the Greek ones around 46°. However,

precisely quantifying the impact of such a difference is a non-trivial task, especially considering the substantially dissimilar meteorological conditions between Greece (more convective rain) and the UK (more stratiform rain). More details regarding the impact of the stratiform and convective type of precipitation on the site diversity gain can be found in [14], [15] and [16].

In order to better explain the impact the elevation angle has on the site diversity gain considering also the type of precipitation more experimental data in various climatic regions and in different separation distances are required [8], [17], [18]. In [19] an investigation of the factors that affect the site diversity gain has been conducted and it has shown that the dependence of the elevation angle on the diversity gain should in any case not be particularly pronounced.

As can be observed in figures 5-8, the effectiveness and practical value of a site diversity scheme becomes apparent at time exceedance probabilities less than <0.1%; above that value a dual antenna scheme could provide a solid 3 dB gain as mentioned in [20].

4. CONCLUSION

In this paper the results from the first two years of the ALPHASAT Ka-band site-diversity experiment in Greece and the UK are presented yielding interesting observations regarding both the small and the large scale site diversity scenarios (as can be seen in Fig. 8). The deployment of receivers at two sites per region enables the study and development of new site diversity techniques, based on the temporal and spatial distribution of statistics.

The campaign is still ongoing and future work has already been planned; ultimately, the processed time series should provide statistical evidence for modeling in-excess attenuation, total attenuation and scintillation, providing feedback that could be used by standardization bodies (e.g. ITU-R Study Group 3 – Propagation) in order to revise their recommendations (e.g. ITU-R P.618-12 [7], ITU-R P.1815-1[21], and ITU-R P.1853-1 [22]) and experimental databases as far as long and short-term statistics of atmospheric channels are concerned.

ACKNOWLEDGEMENT

REFERENCES

[1]   A. D. Panagopoulos, P.-D. M. Arapoglou, P. G. Cottis, "Satellite Communications at Ku, Ka and V Bands: Propagation Impairments and Mitigation Techniques", IEEE Communication Surveys and Tutorials, 2004.

[2]   A. D. Panagopoulos, "Propagation Phenomena and Fade Mitigation Techniques for Fixed Satellite Systems", Book Chapter in the Book "Radio Wave Propagation and Channel Modeling for Earth-Space Systems", Taylor and Francis CRC Press, May 2016.

[3]   Shree Krishna Sharma; Symeon Chatzinotas; Pantelis-Daniel Arapoglou. Satellite Communications in the 5G Era, 1st ed.; The Institution of Engineering and Technology: London, United Kingdom, 2018.

[4]   P. D. Arapoglou, K. P. Liolis, M. Bertinelli, A. D. Panagopoulos, P. G. Cottis, R. De Gaudenzi, " MIMO over Satellite: A Review", IEEE Communication Surveys and Tutorials, March 2011.

[5]   L. J. Ippolito, "Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance", John Wiley, 2008.

[6]   A. D. Panagopoulos, P. M. Arapoglou, J. D. Kanellopoulos and P. G. Cottis, "Long Term Rain Attenuation Probability and Site Diversity Gain Prediction Formulas", IEEE Transactions on Antennas and Propagation, vol. 53, no. 7, July 2005.

[7]   ITU-R P. 618-13, "Propagation data and prediction methods required for the design of Earth-space telecommunication systems", Geneva, 2017.

[8]   S. Ventouras, A. Martellucci, R. Reeves, et al. "Assessment of spatial and temporal properties of Ka/Q band earth-space radio channel across Europe using Alphasat Aldo Paraboni payload", Int J Satell Commun Network. 2019; 1- 25.

[9]   A. Z. Papafragkakis, A. D. Panagopoulos and S. Ventouras, "Combined beacon and noise satellite propagation measurements using software defined radio," *2017 11th European Conference on Antennas and Propagation (EUCAP)*, Paris, 2017, pp. 2356-2360.

[10]   S. Ventouras, S.A Callaghan, and C.L. Wrench, "Long-term statistics of tropospheric attenuation from the Ka/U band ITALSAT satellite experiment in the United Kingdom," Radio Science, Vol. 41, 2006.

[11]   E. Matricciani and C. Riva, "The search for the most reliable long-term rain attenuation CDF of a slant path and the impact on prediction models," IEEE Transactions on Antennas and Propagation, vol. 53, no. 9, pp. 3075–3079, 2005.

[12]   A. Papoulis, Athanasios; Pillai, S. Unnikrishna (2002). Probability, Random Variables and Stochastic Processes (4th ed.). Boston: McGraw Hill. ISBN 0-07-366011-6.A.

[13]   A. Gharanjik, B. Shankar M. R., P. Arapoglou and B. Ottersten, "Multiple Gateway Transmit Diversity in Q/V Band Feeder Links," in *IEEE Transactions on Communications*, vol. 63, no. 3, pp. 916-926, March 2015.

[14]   J. Goldhirsh, B. H. Musiani, A. W. Dissanayake and Kuan-Ting Lin, "Three-site space-diversity experiment at 20 GHz using ACTS in the Eastern United States," in Proceedings of the IEEE, vol. 85, no. 6, pp. 970-980, June 1997.

[15]   R. K. Crane, Propagation Handbook for Wireless Communication System Design. Boca Raton, FL, USA: CRC Press, 2003.

[16]   E. Matricciani, "Prediction of site diversity performance in satellite communications systems affected by rain attenuation: Extension of the two-layer rain model. European Transactions on Telecommunications 5(3): 327-336, 1994.

[17]   G. A. Karagiannis, A. D. Panagopoulos and J. D. Kanellopoulos, "Multidimensional Rain Attenuation Stochastic Dynamic Modeling: Application to Earth–Space Diversity Systems," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 11, pp. 5400-5411, Nov. 2012.

[18]   C. I. Kourogiorgas, A. D. Panagopoulos and J. D. Kanellopoulos, "On the Earth-Space Site Diversity Modeling: A Novel Physical-Mathematical Outage Prediction Model," in IEEE Transactions on Antennas and Propagation, vol. 60, no. 9, pp. 4391-4397, Sept. 2012.

[19]   A. D. Panagopoulos, P. -. M. Arapoglou, J. D. Kanellopoulos and P. G. Cottis, "Long-term rain attenuation probability and site diversity gain prediction formulas," in *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 7, pp. 2307-2313, July 2005.

[20]   E. Matricciani, "Micro scale site diversity in satellite and tropospheric communication systems affected by rain attenuation" Space Communications. 19. 83-90, April 2003.

[21]   ITU-R P. 1815-1, "Differential Rain Attenuation", Geneva, 2009.

[22]   ITU-R P.1853-1, "Tropospheric attenuation time series synthesis", Geneva, 2012.