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Site- and Time-Diversity Experimental Statistics at Ka and Q Bands in Attica, Greece, Using *Alphasat*

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Abstract – In this article, one year of concurrent Ka- and Q-band experimental data from *Alphasat* obtained by the National Technical University of Athens satellite beacon receivers are analyzed and evaluated. The signal attenuation due to various atmospheric effects—particularly pronounced at the Ka and Q bands—is a serious bottleneck in system performance and has to be carefully addressed. The annual results presented here for Attica, Greece, provide a better insight into the system-design requirements and limitations of satellite communication at these bands. Finally, site- and time-diversity fading mitigation techniques are tested for their effectiveness against real propagation data, revealing their upper performance bound.

1. Introduction

It is known that satellite links operating at the Ka band and above, despite their greater bandwidth advantage, are notoriously prone to propagation effects arising from various atmospheric phenomena, particularly rainfall/precipitation [1–4]. Such impairments constitute a serious design limitation and have to be compensated for using appropriate fading mitigation techniques (FMTs) to reduce downtime and outages [1–4]; the sole use of a conventional fade margin is generally insufficient, as signal fading could be in excess of 15 dB to 20 dB for a nonnegligible fraction of time. The application of FMTs, however, requires knowledge of the channel conditions or accurate signal modeling. In the past few years, a substantial effort has been made to collect propagation data by means of experimental propagation campaigns. The launch of the *Alphasat* satellite has facilitated this endeavor tremendously, motivating researchers around Europe to conduct new, more accurate measurements using state-of-the-art techniques. *Alphasat* (commercial name *Inmarsat-4A F4*) offers payloads for experimental purposes under the coordination of the European Space Agency [5]. One of them, the so-called Technology Demonstration Payload 5, offers two fully coherent beacons at Ka and Q bands (19.701 GHz and 39.402 GHz, respectively). The National Technical University of Athens (NTUA) is among the institutions that actively participate in obtaining new measurements [6], having deployed satellite beacon receivers targeting *Alphasat* at two locations in Attica, Greece, in order to collect propagation data. This article focuses exclusively on the actual experimental data; in the following sections, the receivers' architecture is outlined; a first batch of experimental results spanning across a full year (1 July 2017 to 30 June 2018) is analyzed and presented in terms of long-term statistics; and time- and frequency-diversity techniques are tested and investigated. The article concludes with a few interesting conclusions and our plans for future work.

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2. The Experimental Campaign

As mentioned in the introduction, the NTUA Radio and Satellite Communications Group has deployed and maintains satellite beacon receivers at two locations in Attica, Greece, approximately 36.5 km apart. The first one is located inside the NTUA campus in Athens, and the other is at the Lavrion Technological and Cultural Park (LTCP) near the town of Lavrion.

At each site, one Ka-band and one Q-band receiver targeting the *Alphasat* satellite are installed. The Ka-band receivers use 1.2 m offset parabolic antennas, while the Q-band ones use 0.6 m parabolic shrouded antennas, as depicted in Figure 1. The antennas together with the necessary front-end components are mounted outdoors, while the rest of the equipment is mounted in custom-made enclosures or racks. Each antenna uses its own custom-made open-loop tracking system, responsible for maintaining a pointing accuracy better than 0.05° in the elevation plane (the azimuth plane does not require a tracking system). The tracking systems utilize linear actuators and digital inclinometers to align the antenna to the correct direction based on calculations on Orbit Ephemeris Messages for *Alphasat*. The latter orbits the Earth at a slightly inclined plane (probably in order to prolong its life span), and therefore a tracking system is essential to account for small deviations in its apparent position as observed from the ground stations.

After each signal is received at the antenna, it is fed to a high-performance low-noise block to filter it, amplify it, and down-convert it to a lower intermediate frequency. After further filtering and amplification, the signal is ultimately fed to a software-defined radio device, namely a USRP B200, where it is sampled, quantized, and digitized. The digital samples are forwarded to a colocated single-board computer where signal power estimation takes place. The estimation is based on the fast Fourier transform using libraries from the very popular GNU Radio framework; using similar techniques, the signal noise floor is also estimated and recorded [7]. The data are recorded and stored using

Figure 1. Overview of the Ka-band (right) and Q-band (left) front ends located at the NTUA campus in Athens.

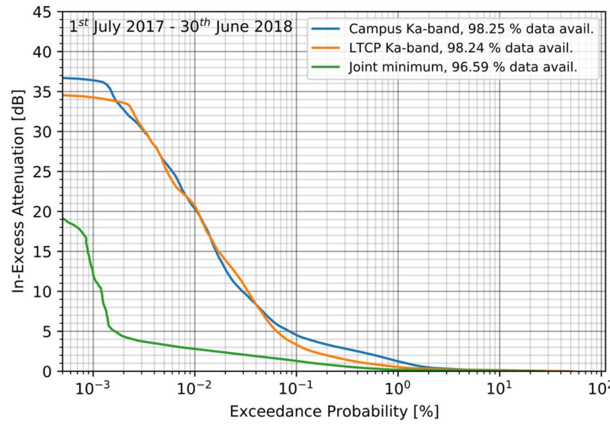

Figure 2. Long-term complimentary cumulative distribution function of excess attenuation for Ka band at the two locations and their joint minimum—ideal site-diversity technique.

time stamps and all the relevant metadata to allow for further processing and analysis. In order to establish fully coherent measurements, all oscillators are locked to a common GPS-disciplined oscillator installed at each location, including the computer, whose real time clock is constantly adjusted using pulse-per-second signals from the GPS. This ensures minimal frequency drift and phase noise in the measurements. The dynamic range for the Ka-band receivers is in excess of 40 dB while for the Q-band receivers it is greater than 35 dB.

At each location, relevant ancillary equipment is also installed in order to monitor various meteorological phenomena such as rain precipitation, temperature, wind speed and direction, humidity, and atmospheric pressure; regarding the estimation of rain precipitation, which plays the most significant role in signal degradation, tipping-bucket rain gauges are installed at each site, offering an accuracy of 0.2 mm per tip at a frequency of 1 Hz. The use of this meteorological equipment allows for the correlation of the atmospheric effects with the signal effects as recorded by the beacon receivers. More information on the receivers, as well as a first statistical evaluation for the Ka band, can be found in [7, 8].

Before statistical analysis, the obtained signal data undergo both automatic and manual preprocessing and inspection. In the absence of a radiometer, the main preprocessing technique involves the definition of the clear-sky signal level, after which the excess attenuation can be determined. To this end, the well-established method in [9] is used, based on a Fourier series fitting technique. Additionally, the manual preprocessing and visual inspection of the time series ensures that wind loading effects, random software hiccups, and any other non-propagation-related variations in signal power level are removed.

3. Long-Term and Site-Diversity Evaluation

In the following, results from one full year are analyzed and evaluated in order to obtain a picture of the long-term system performance. In Figure 2, the system performance is presented in terms of the complimentary cumulative distribution function of excess attenuation of the Ka-band receivers, while in Figure 3 the corresponding results for the Q band are shown.

Regarding the Ka-band case, very substantial signal fading was recorded for 0.01% of the total time. At this fraction of the total observation time, an excess attenuation value greater than 20 dB was experienced consistently at both locations. Such a value cannot be compensated using conventional techniques, and unless carefully addressed, it will lead to intolerable system downtime.

In the case of the Q band things become even worse, as the whole figure appears to be shifted to the right, corresponding to much greater attenuation for the same fraction of the total time. More particularly, at 0.01% of the total time, an excess attenuation value of approximately 32 dB is to be anticipated. The 10 dB level is crossed at 0.2% of the time, whereas at the Ka

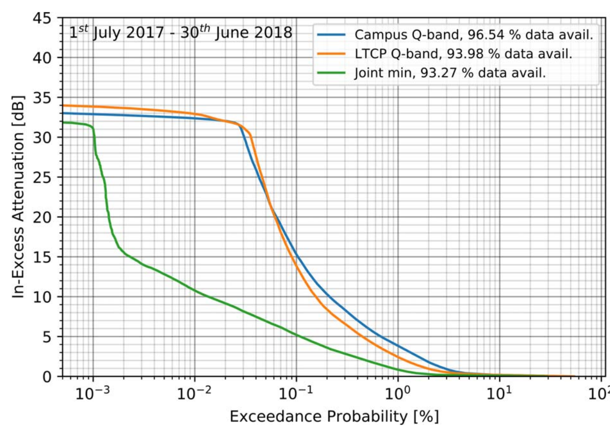

Figure 3. Long-term complimentary cumulative distribution function of excess attenuation for Q band at the two locations and their joint minimum—ideal site-diversity technique.

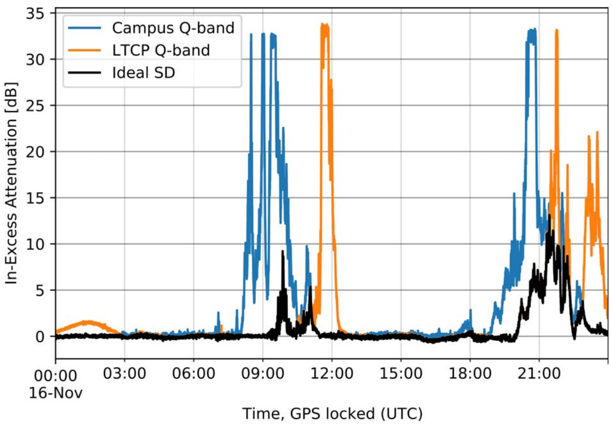

Figure 4. Example of the idealized site-diversity technique for Q band on a rainy day.

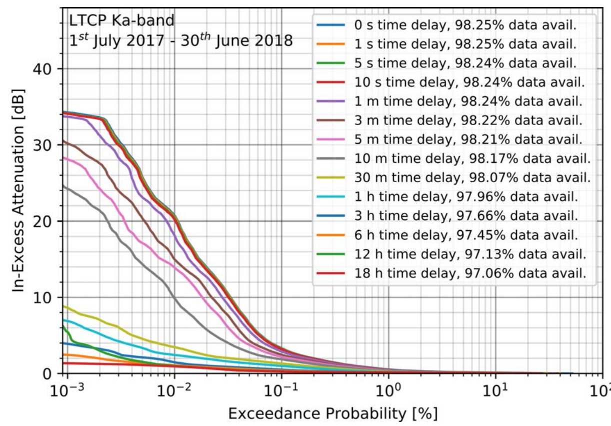

Figure 6. Time-diversity evaluation for Ka band at NTUA LTCP for different time delays.

band the same level is exceeded at 0.02% of the total time—that is, a discrepancy of one order of magnitude.

In each of the two figures, the joint-minimum line is also included, representing an ideal site-diversity scenario. Although not practically realizable, as it would require instantaneous switching from one ground station to the other (whichever experiences the least attenuation at each time instant), it offers an indication (the upper bound) of what an efficient site-diversity scheme could theoretically achieve. It is obvious that a well-implemented site-diversity architecture could decrease attenuation values to about 10 dB for 0.001% of the total time at the Ka band, and the same value could ideally be accomplished for 0.01% of the time for the Q band. In both cases, the gain is appreciable and should minimize downtime, especially when combined with a fade margin and other FMTs; of course, the use of additional (more than two) ground stations should offer even better performance, albeit at a much higher cost.

In Figure 4 an exemplary application of the idealized site-diversity selection-combining technique $\min(A_1, A_2)$ is depicted using the recorded Q-band time series for a rainy day on 16 November 2017.

4. Time-Diversity Evaluation

Another proposed FMT is the time-diversity technique: a link affected by a propagation impairment leading to outage merely retransmits the signal after a scheduled time delay. This technique is therefore appropriate for time-delay-tolerant (i.e., non-real-time) applications and services, such as data transfer. A noteworthy advantage of time diversity over other FMTs is that it makes use of only one single link—the very same propagation channel—but delayed in time [10–12]. The time-diversity statistics for a time delay TD are derived from the measured excess attenuation statistics based on the definition

$$P(A(t) \geq a, A(t + \mathrm{TD}) \geq a),$$

where $P(.)$ is the probability that both attenuation values $A(t)$ and $A(t + \mathrm{TD})$ at the instants t and $t + \mathrm{TD}$ accordingly exceed the attenuation threshold a. The

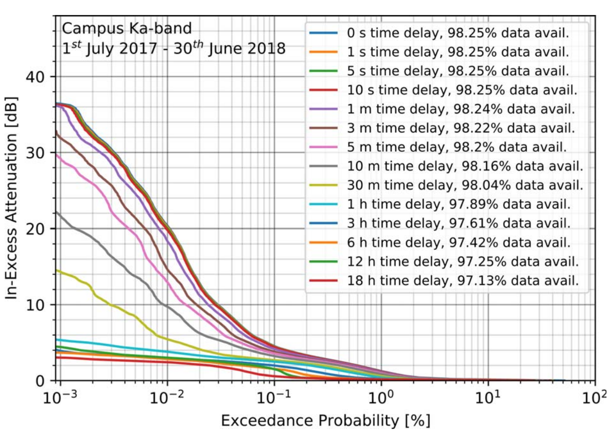

Figure 5. Time-diversity evaluation for Ka band at NTUA campus for different time delays.

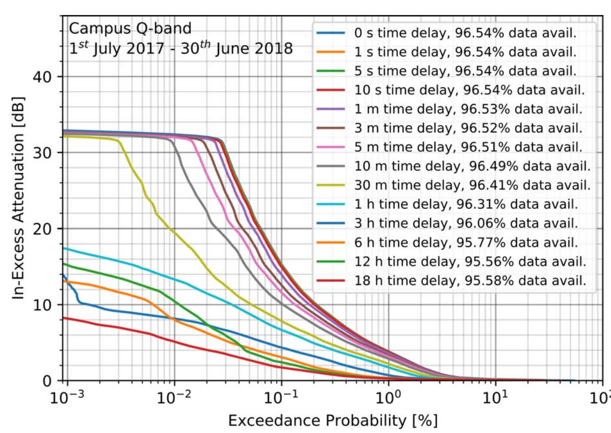

Figure 7. Time-diversity evaluation for Q band at NTUA campus for different time delays.

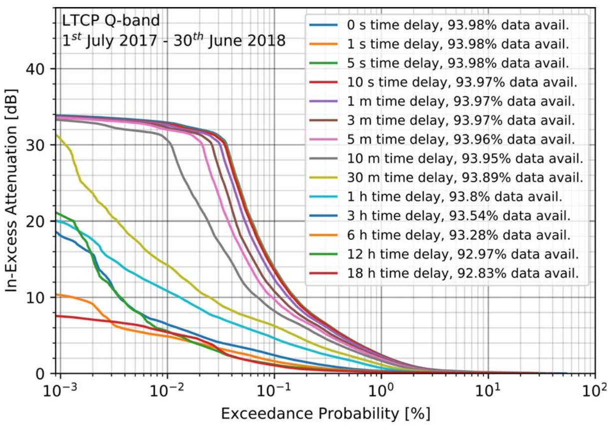

Figure 8. Time-diversity evaluation for Q band at NTUA LTCP for different time delays.

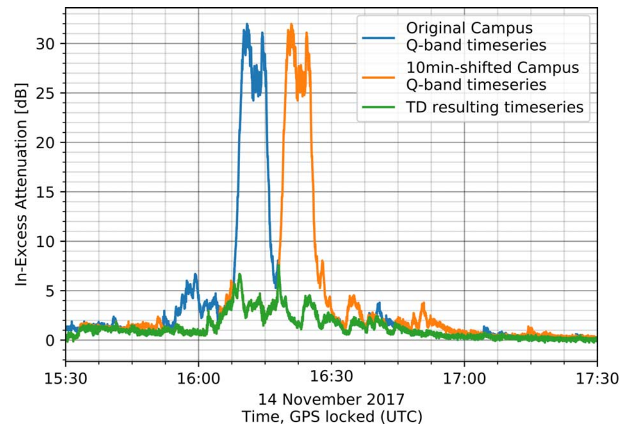

Figure 9. Example of the idealized time-diversity technique for Q band at NTUA campus location on a rainy day using 10 min delay.

time-diversity statistics presented are obtained after harmonizing all the data to 1 s time resolution for TD values of 1 s, 5 s, 10 s, 1 min, 3 min, 5 min, 10 min, 30 min, 1 h, 3 h, 6 h, 12 h, and 18 h.

In Figures 5 and 6 the results of applying this idealized time-diversity technique are presented for the Ka-band receivers at the two locations; Figures 7 and 8 give the results for the Q-band case. It is obvious from the analysis that a relatively short time delay (on the order of a few seconds) offers minimal gain in the long run; nevertheless, the application of a time delay on the order of a few minutes (reasonable for some types of non-real-time applications and services) could yield considerable results. As an example, the use of a 5 min delay can reduce the obtained long-term excess attenuation value from 20 dB to about 13 dB to 14 dB for 0.01% of the total time for the Ka band at both locations. The gain appears to be vast also at the Q band, where for the same fraction of the total time, the attenuation can be minimized from over 32 dB to about 20 dB using a 5 min delay.

The use of longer time delays naturally leads to a higher performance gain, but a long delay would most probably appear similar to an outage from an end user's point of view, since it would also result in (temporal) service disruption.

In Figure 9 an example realization of the time-diversity technique is presented using the NTUA-campus Q-band time series obtained on 14 November 2017.

In Table 1, a brief summary of the diversity gain of the two techniques is presented.

The relation of the performance of time and site diversity has been studied in [13, 14]. Further modeling is a subject of future work.

5. Summary and Discussion

In this article, the first results from one year of the experiment conducted in Attica, Greece, are presented. Both Ka and Q bands appear to suffer from various atmospheric effects for a nonnegligible fraction of the total observation time. It is shown that merely using a conventional fade margin is insufficient, and that other schemes such as FMTs have to be employed to optimize performance and minimize outages. As shown, a site-diversity scheme could greatly enhance system availability even with ground stations relatively close to each other, while a simpler time-diversity technique could improve performance for non-real-time services.

The experimental campaign still continues, and as more results are gathered, they are going to be analyzed and submitted to the relevant international scientific entities, such as the International Telecommunication Union's Radiocommunication Sector. A more rigorous investigation or comparison between the two FMTs (site and time diversity) should follow in a subsequent contribution. Finally, with the aid of time series, the existing channel models for these bands will be verified and possibly improved to match the intricate characteristics of the Mediterranean climate.

Table 1. Summary and comparison of gain (dB) for the two FMTs

	Fraction of time (%)		
FMT	0.1	0.01	0.001
Site diversity, Ka band	3	17.5	25
Time diversity, Ka band	3, using 3 h time delay	17.5, using 12 h time delay	25, using >30 min time delay
Site diversity, Q band	10	21	> dynamic range
Time diversity, Q band	10, using ~2 h time delay	21, using ~1 h time delay	> dynamic range

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