Preliminary Statistics from the NASA Alphasat Beacon Receiver in Milan, Italy

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***Abstract*— NASA Glenn Research Center (GRC) and the Politecnico di Milano (POLIMI) have initiated a joint propagation campaign within the framework of the Alphasat propagation experiment to characterize rain attenuation, scintillation, and gaseous absorption effects of the atmosphere in the 40 GHz band. NASA GRC has developed and installed a K/Q-band (20/40 GHz) beacon receiver at the POLIMI campus in Milan, Italy, which receives the 20/40 GHz signals broadcast from the Alphasat Aldo Paraboni TDP#5 beacon payload. The primary goal of these measurements is to develop a physical model to improve predictions of communications systems performance within the Q-band. Herein, we provide an overview of the design and data calibration procedure, and present 6 months of preliminary statistics of the NASA propagation terminal, which has been installed and operating in Milan since May 2014. The Q-band receiver has demonstrated a dynamic range of 40 dB at an 8-Hz sampling rate. A weather station with an optical disdrometer is also installed to characterize rain drop size distribution for correlation with physical based models.**

***Index Terms*—Alphasat, propagation, Q-band, measurement.**

I. Introduction

Though the primary focus of NASA's future space communications architecture is in the exploitation of Ka and optical frequencies, NASA is also investigating the potential use of spectrum in the Ka/Q-bands (37-42 GHz) and V/W-bands (74-84 GHz) as a downlink option in the next generation of relay satellites expected to replace the existing Tracking and Data Relay Satellite (TDRS) system in the 2025 timeframe. As such, NASA Glenn Research Center is spearheading a collaborative effort to characterize atmospheric propagation effects at these millimeter wave frequencies. A major part of this campaign includes the use of the Alphasat Aldo Paraboni TDP#5 20/40 GHz beacon in Europe. The primary goal of these measurements is to develop a physical model to improve predictions of atmospheric attenuation within the desired spectrum. Herein, we provide an overview of the design, calibration procedure, and preliminary statistics of the 20/40 GHz beacon receiver built in-house by NASA Glenn Research Center, and which has been recording data at the Politecnico di Milano (POLIMI) campus since May 2014. The receiver is based upon the validated FFT digital design approach utilized in other operational GRC propagation terminals [1-2]. The new design incorporates upgrades and modifications to coherently track and measure the amplitude of the 20/40 GHz beacon signals with improved dynamic range. It is believed that these measurements, combined with thorough characterization of local meteorological conditions, will provide the necessary basis for improved models to assess the performance of communications systems employing frequencies in the Q-band.

II. Experimental Setup

The receivers were installed atop the roof of the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) building on the POLIMI campus in April 2014 and is shown in the photograph of Fig. 1. The nominal elevation angle of observation is approximately 35 deg. During initial operations, several anomalies were addressed and operational status was achieved on June 1, 2014. To supplement the beacon receivers, a suite of weather sensors are utilized to obtain surface temperature, pressure, humidity, wind speed/ direction, and rain rate. A disdrometer has also been installed at the POLIMI site to obtain drop size distribution, fall velocity, and high resolution rain rate measurements.

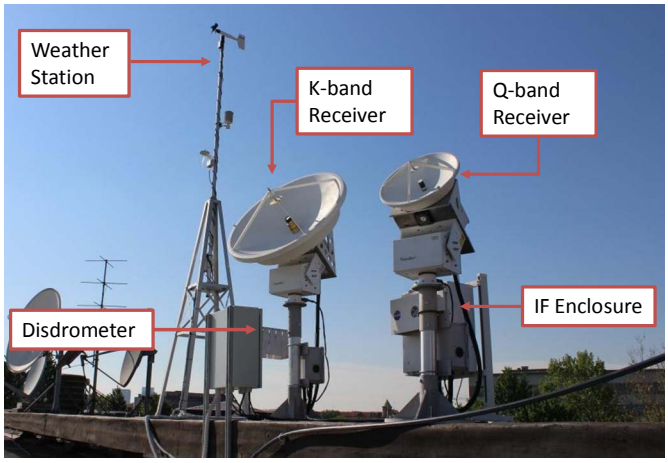


Fig. 1. Photograph of K/Q-band beacon receiver and weather instruments installed at POLIMI campus.

III. GRC K\Q-band Beacon Receiver Design

A. Receiver Hardware

The Alphasat beacon receiver developed at NASA GRC consists of a 1.2m K-band and a 0.6m Q-band Cassegrain reflector with equivalent antenna beamwidths of 0.9 deg. The receivers employ independent open-loop tracking systems for each antenna to track the inclined orbit of the Alphasat

satellite. A block diagram of the front ends and common Intermediate Frequency (IF) downconversion cards (labeled K-DACS and Q-DACS) of the system are provided in Fig. 2 and Fig. 3, respectively. Primary downconversion to a common IF of 70 MHz is performed within the temperature controlled RF boxes mounted directly behind the antennas. Independent temperature control of the LNA and the plate upon which the RF electronics are mounted maintain a temperature stability of +/- 0.01 deg C. From the RF boxes, the signal is routed to a secondary temperature controlled IF box where final downconversion stages take place to the common 455 kHz IF with a final IF passband of 10 kHz. Temperature stability of the IF box is maintained to within +/- 0.25 deg C. All downconversion stages are referenced to a common ultra-stable 10 MHz reference oscillator housed within the IF box.

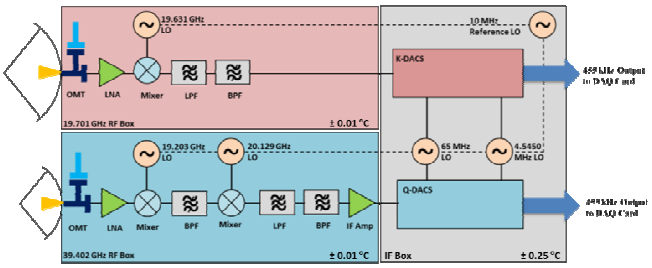


Fig. 2. Block diagram of coherent K/Q-band beacon receiver

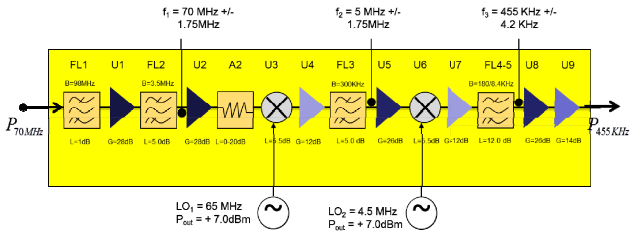


Fig. 3. Block diagram of 70 MHz to 455 kHz downconversion card (labeled K-DACS and Q-DACS in Figure 1).

From there, the signals are routed via coaxial cable to the control and data acquisition computer. The 455 kHz IF signal is Nyquist sampled by a 12-bit National Instruments 5124 data acquisition (DAQ) card at a sampling frequency (fs) of 1.111MHz. At an 8 Hz data measurement rate, 2^{17} samples are collected for a final fs/N resolution of 8.47Hz. The 8 Hz power measurements are averaged each second to derive 1 Hz data and both data sets are recorded to file. Frequency estimation and power measurement of the beacon signal employs a modified Quinn-Fernandes frequency estimation routine, as described in [3] and discussed in more detail in the next section. During deep rain fades, i.e., fades greater than 30dB, the beacon receiver utilizes the K-band signal for frequency tracking to maintain lock on the Q-band signal. Based on this approach, the measurement range of the Q-band receiver is improved down to a 3 dB bin signal to noise ratio (SNR) and is capable of reestablishing lock once the signal emerges from the noise. This implementation provides a measurement dynamic range of approximately 40 dB for the 8 Hz sampling rate, and 45 dB for the 1 Hz samples. Further, by employing a frequency estimation routine, we are also able to derive Doppler parameters for estimates of relative spacecraft position and calibration of gain variation across the passband of our receiver.

B. *Digital Receiver*

For a digital FFT receiver in the absence of a phase-locked loop (PLL), the beacon frequency can drift and must be identified such that a power measurement can be performed. As the frequency drifts from the center of an FFT bin, the signal power will spill over into adjacent bins and, if measuring the peak bin power, will decrease by as much as 3 dB at the bin edges. This effect can be reduced by summing over multiple FFT bins, but this has the negative effect of reducing the system dynamic range due to the integration of the noise power over a wider bandwidth. One method to alleviate this problem is to employ a frequency estimator to more accurately identify the signal frequency within the peak bin and measure the signal power at baseband.

Fig. 4 shows the simulated performance of various frequency estimators as compared to the single bin power estimation technique for an SNR of -10 dB [3]. As the simulated frequency is swept between adjacent FFT bins, we observe that any of the identified frequency estimator routines sufficiently track the frequency and provide an accurate power measurement, as compared to the peak FFT approach, where the scalloping effect is readily observable.

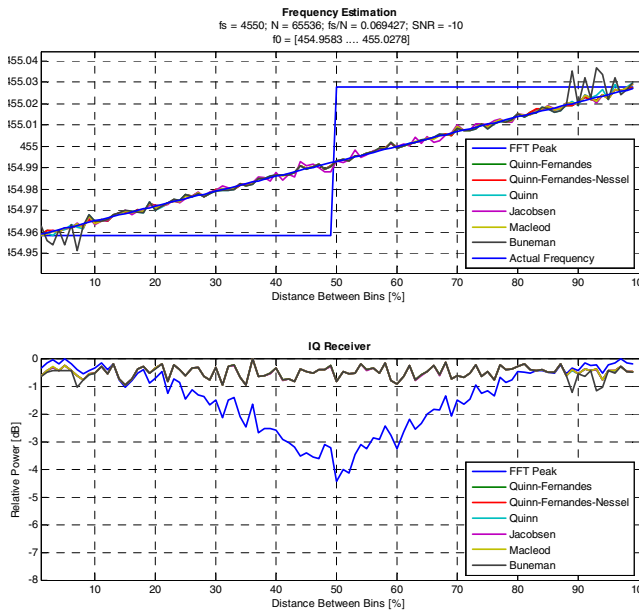


Fig. 4. Frequency estimate of various estimation routines (top) and the corresponding power (bottom) for a simulated -10dB SNR.

For our receiver design, we employ the Quinn-Fernandes frequency estimation technique [4]. The Quinn-Fernandes technique attempts to find the local maximum of a smoothed periodogram nearest some initial frequency estimate by optimizing the parameters α and β in the filtered spectrum as,

$$y_t - \beta y_{t-1} + y_{t-2} = \varepsilon_t - \alpha\varepsilon_{t-1} + \varepsilon_{t-2} \quad (1)$$

Utilizing this approach, it is possible to derive the frequency estimate within typically 2-3 iterations, provided a good initial estimate is supplied. As we deal with relatively high SNR, this is easily realized. In situations where deep fades occur on the Q-band signal, a modified form of the Quinn-Fernandes technique is employed in which the initial frequency estimate is supplied by the K-band reference. To determine the Q-band frequency, a band-limited Quinn-Fernandes algorithm accurately identifies the beacon frequency over a reduced spectral range. In Fig. 5, it can be observed that, during a rain event, the frequency estimator is able to track the signal as it approaches the noise floor, and recover it immediately once it returns.

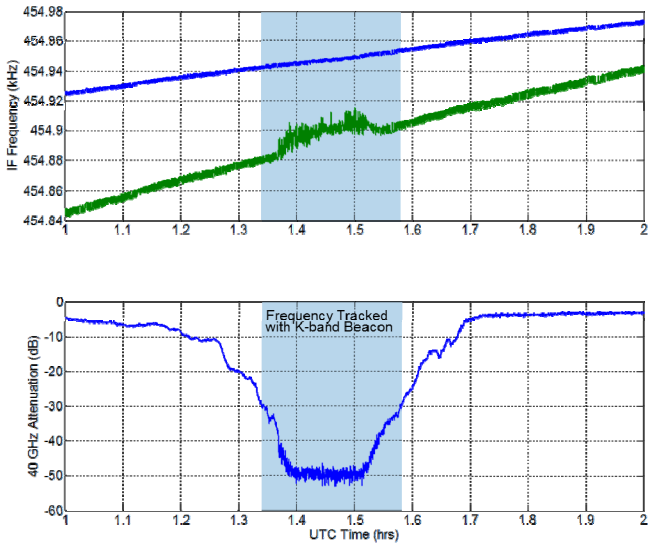


Fig. 5. A deep rain fade event where the Q-band receiver entered frequency track mode utilizing the K-band beacon reference. Note that lock was maintained down to approximately -40 dB of attenuation.

IV. Receiver Calibration

A. Passband Calibration

During the system checkout phase, it was observed that a diurnal drift of the signal power was evident in the measured data. Further investigation of this phenomenon resulted in the discovery that the filter passband of the IF cards exhibited some significant variation across the band. In previous campaigns, this effect was not noticeable, but does require calibration for the Alphasat experiment due to the non-trivial frequency variation induced by the Doppler shift of Alphasat's inclined orbit. To calibrate the passband variation of the receivers, the antennas are pointed to zenith on a clear evening and a decimated version of the passband spectrum is recorded to file every second for two hours. The spectrum is subsequently averaged and an 8th order polynomial is fit to the curvature of the passband, as shown in Fig. 6.

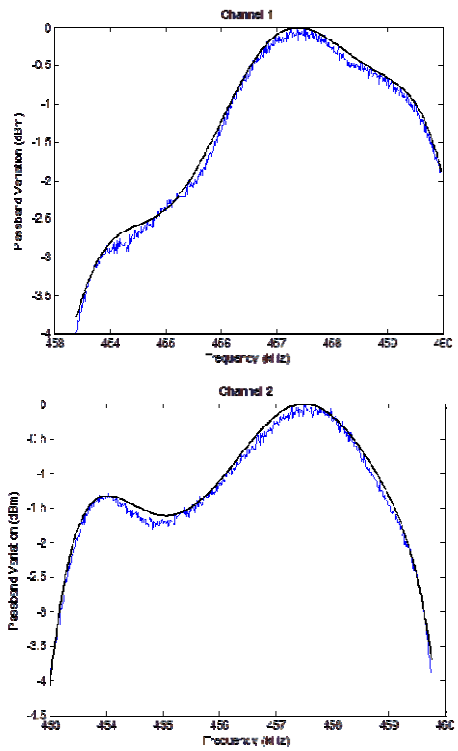


Fig. 6. Measurement and fitting of an 8th order polynomial of the passband spectrum indicating a non-trivial gain variation for (top) the K-DACS and (bottom) the Q-DACS.

B. Clear Sky Reference Calibration

Typically, a radiometer is used to calibrate the receive power level to set the reference attenuation to clear sky. When a radiometer is not available, as is presently the case for the experiment at POLIMI, the same reference attenuation levels can be estimated by means of well-known mass absorption models such as those proposed by Liebe et al. [5] and Rosenkranz [6]. To this aim, this kind of models needs, as inputs, vertical profiles of pressure (P), temperature (T) and relative humidity (RH), in turn obtainable from RAdiosonde OBServations (RAOBS) or Numerical Weather Prediction (NWP) products (e.g. forecasts data made available by the ECMWF every 6 hours on a regular latitude/longitude grid with 0.125°×0.125° spatial resolution).

As a preliminary step, automatic procedures (triggered every week) have been set up to retrieve RAOBS data collected at Milano Linate airport (launches at 0 and 6 UTC), 5 km far from the NASA station, as well as ECMWF vertical profiles for the pixel where the NASA station site falls (data available at 0, 6, 12 and 18 UTC). An example of the vertical profiles extracted from RAOBS and ECWMF data is reported in Fig. 7. Fig. 8 summarizes the workflow for the calibration of beacon data that is presently being implemented. Fig. 9 shows the result of the total calibration for the nonlinear passband and the clear sky reference level.

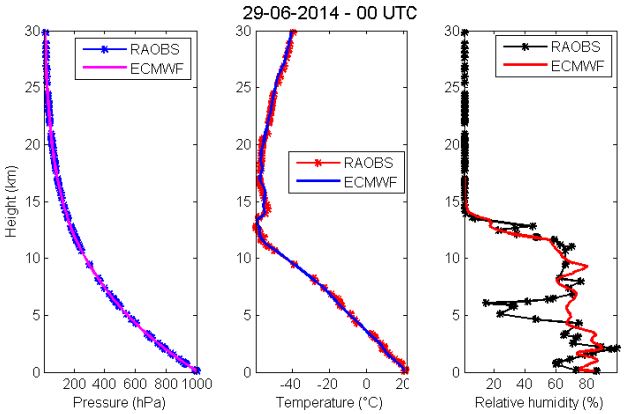


Fig. 7. Example of the vertical profiles of pressure, temperature and relative humidity extracted from RAOBS (launched at Milano Linate Airport) and from ECWMF (29th June, 2014).

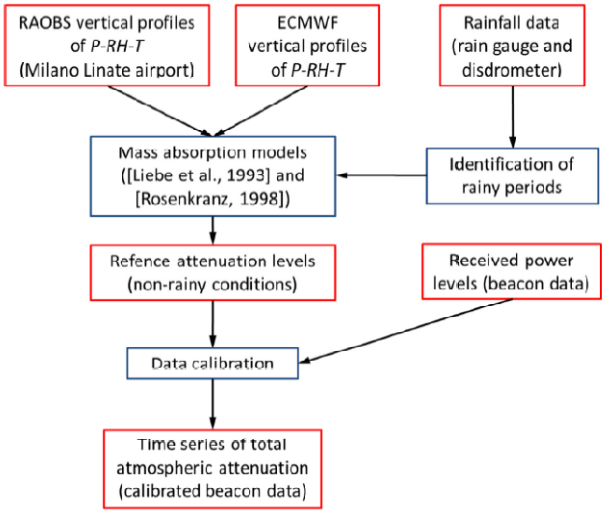


Fig. 8. Detailed workflow for the calibration of beacon data.

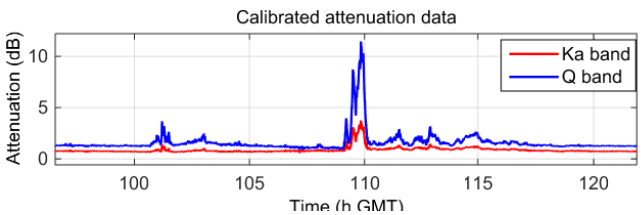
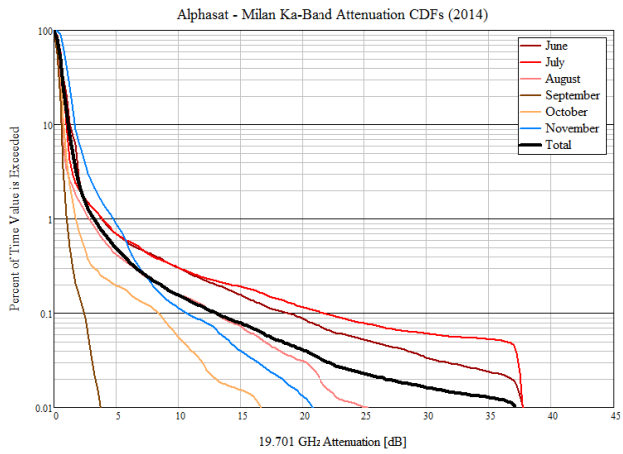


Fig. 9. Resultant example calibrated attenuation time series following the prescribed procedure.

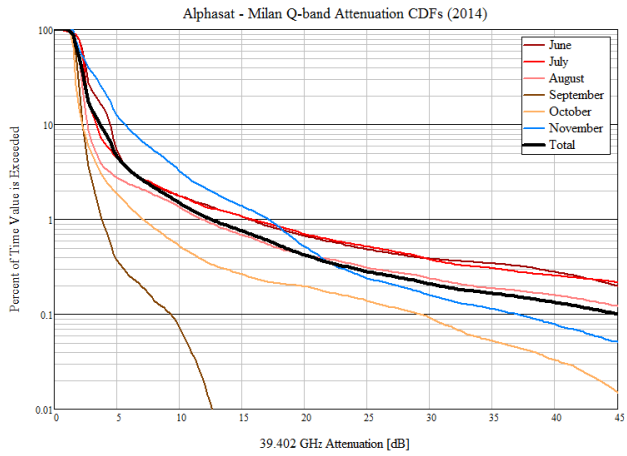
V. Preliminary Statistics and Model Comparison

To date, 6 months of data have been collected and processed at the POLIMI site in Milan, Italy. Fig. 10 shows the monthly and average total attenuation complementary cumulative distribution function (ccdf) curves for the the K- and Q-band signals derived from the calibration procedure described in the previous section. From the ccdf curves we can validate the receiver performance as possessing a dynamic range of approximately 37 dB for the K-band receiver and 45 dB for the Q-band receiver at the 1-Hz sampling rate. The improved Q-band receiver performance is due to the coherent tracking of the K-band signal during deep rain fades.

Fig. 11 provides the measured rain rate statistics over the first 6 months of operation, comparing the tipping bucket results with the optical disdrometer. The statistics derived for these curves are concurrent with the attenuation measurements. The tipping bucket and disdrometer data indicate good agreement with each other. From the plot, the rain rate statistics indicate a plateau near the 0.01% rain rate value of between 70 and 90 mm/hr. Utilizing these minimum and maximum rain rate values and implementing them into the ITU-R 618-11 model to derive total attenuation (gaseous, cloud, and rain components), we observe very good agreement between the measured data over this 6-month interval and the model bounds for the concurrent rain rate statistics, as shown in Fig. 12 [7]. There still appears to exist slightly higher measured attenuation at the higher availability levels as compared to the model, but this can be explained by several observed rain events that were present on the path but not detected by the rain rate sensors, as well as the lack of a complete year of data measurements.



(a)



(b)

Fig. 10. CCDF of monthly and average total attenuation for (a) 19.701 GHz and (b) 39.402 GHz frequencies.

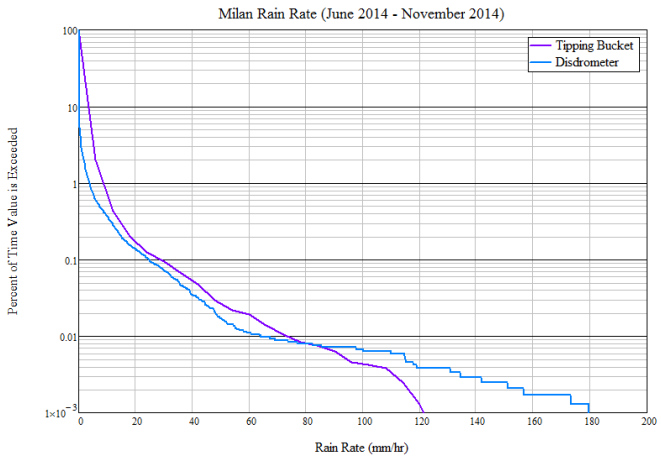


Fig. 11. CCDF of concurrent rain rate from the tipping bucket and optical disdrometer for 6 months in Milan, Italy.

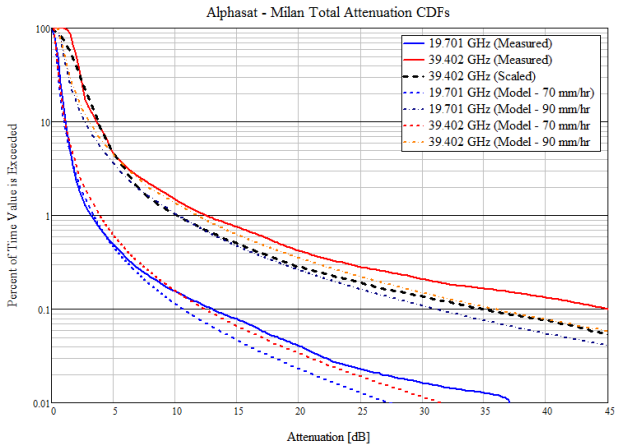


Fig. 12. CCDF of attenuation of K-band and Q-band signals for 6 months in Milan, Italy, compared with ITU-R P.618 attenuation model.

Also shown in Fig. 12 is the resulting ccdf curve derived from frequency scaling of the measured long-term K-band attenuation statistics, following ITU-R Recommendation P.618 [7]. Again, we see very close agreement with the measured data at 39.402 GHz and the frequency scaling model.

In addition, the scintillation statistics for the K-band and Q-band signals were analyzed. Scintillation events were isolated from the 8-Hz attenuation time series utilizing a high pass filter of sufficient cut-off frequency to capture the full scintillation spectrum component of the signal. An attenuation threshold was identified to effectively remove rain events and the resulting time series was used to derive the 5-min standard deviation of scintillation. The ccdf curves for the K-band and Q-band signals are shown in Fig. 13. A frequency scaling ratio of approximately 1.6 is plotted in Fig. 13, as well, to scale the K-band scintillation statistics to the Q-band frequency. As is evidenced by the two curves, very good agreement is obtained, and the frequency scaling ratio is in close agreement to the expected value of 1.53, indicating the validity of the measurement and analytical approach.

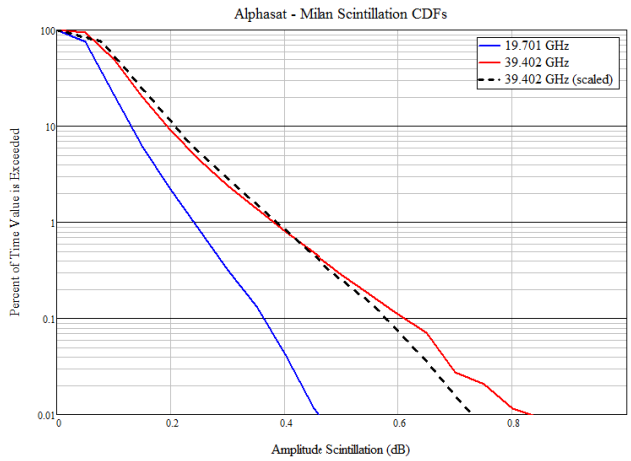


Fig. 13. CCDF of amplitude scintillation of K-band and Q-band signals for 6 months in Milan, Italy, compared with ITU-R P.618 scintillation scaling model.

VI. Conclusions

Herein, we present the preliminary statistics from the first 6 months of data collection in Milan, Italy utilizing the Alphasat Aldo Paraboni TDP#5 beacon. Data collection has been ongoing since May 2014 and reliable data collection has been maintained since June 2014. Preliminary analysis and results indicate proper operation and performance of the beacon receiver system. Statistics for the rain attenuation at K-band and Q-band for the first 6 months of data collection indicate a 99.9% attenuation level of 13 dB and 45 dB, respectively. This is primarily influenced by the rainy season in Milan during which data collection has principally taken place. Analysis of the scintillation statistics at K- and Q-band shows good agreement between measurement and theory. The measurement campaign is expected to continue for a minimum of 3 years. Future plans include the installation of a water vapor radiometer at the site in early calendar year 2015 to enhance the measurement campaign.

References

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