TWO YEARS OF ATMOSPHERIC MEASUREMENTS IN EDINBURGH, SCOTLAND

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Abstract

Since March of 2016, NASA Glenn Research Center (GRC) and Heriot Watt University (HWU) have jointly operated an atmospheric propagation terminal to measure and characterize propagation phenomena near 40 GHz at the HWU campus in Edinburgh, Scotland within the framework of the Alphasat experiment. The system was also recently upgraded in June 2018 to take simultaneous measurements near 20 GHz. The Q-band system utilizes a novel design which combines a beacon receiver and digital radiometer into the same RF front-end and observes the 39.402 GHz beacon of the European Space Agency's Alphasat Aldo Paraboni TDP#5 experiment. Atmospheric measurements can thusly be assessed to characterize link performance. The objective in orchestrating these types of measurements is to improve statistical understanding of the atmosphere at these frequencies of interest, as well as to contribute to the development and improvement of International Telecommunications Union (ITU) models for prediction of communications systems performance within the Q-band. Herein, we provide an overview of the system design, as well as an analysis of the first two years of data collected in Edinburgh, including attenuation, fade duration, and fade slope.

1. Introduction

As the limited spectrum available for satellite communications continues to grow congested, there is an increased demand for higher frequency capabilities. This demand is also driven by the fact that higher frequencies offer link capacities much higher than presently achievable at lower frequency allocations. However, these links are also increasingly susceptible to atmospheric effects. Because of this, the study of atmospheric propagation at frequencies of interest is paramount to the effective implementation of space-to-ground satellite communication links at higher microwave frequencies.

For this purpose, the Alphasat satellite was launched with a hosted communications and propagation experiment in July 2013. The Aldo Paraboni Technology Demonstration Payload (TDP) #5 was developed by the Italian Space Agency (ASI) and European Space Agency (ESA) [1, 2] and, in addition to a Q/V-band communications experiment, also features coherent, continuous-wave Ka- and Q-band beacons for use in a propagation experiment campaign to assess atmospheric effects such as attenuation, depolarization, and scintillation on SATCOM links at 20 and 40 GHz across Europe.

NASA's roadmap for its space communication architectures focuses primarily on Ka-band and optical communications [3], and such an architecture will require cognitive networking and fade mitigation techniques to account for weather impairments, relying on a thorough understanding of atmospheric statistics. In addition, NASA's next generation successors to the Tracking and Data Relay Satellite System (TDRSS) are anticipated to require significantly higher bandwidths than are presently available in the current Ku-band allocations, and the agency is therefore studying the viability of allocations in the Q-band and V/W-bands as downlink options.

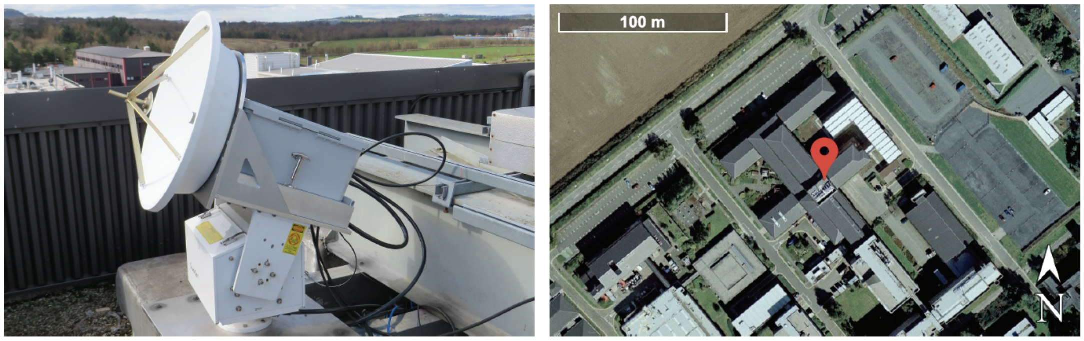

Figure 1. *The Q-band beacon receiver hardware at Heriot-Watt University in Edinburgh, Scotland (left) and an overhead view of its location atop the roof of the Earl Mountbatten building (right).*

2. Experiment

The Alphasat receiver in Edinburgh, Scotland was installed in March 2016 at the Heriot-Watt University atop the roof of the Earl Mountbatten building. Figure 1 shows the Q-band beacon receiver and pan-tilt positioner on the left, while an overhead view of the receiver location is shown on the right. Given the high latitude of 55.9° N, the Edinburgh site presently yields the lowest elevation angle measurements available from Alphasat, 21° above the horizon. In June 2018, Heriot-Watt also updated the terminal with Ka-band measurement capability, although these results will not be covered in this paper due to the small amount of data collected thus far. The station has much in common with previous NASA receivers [4, 5] in terms of RF design and data processing, with several generational improvements as detailed in Section 3. A HWU weather station of Campbell Scientific instruments is also located approximately 70 meters south of the receiver location and 42° to the west of the receiver's path toward Alphasat (147° from true north). The instrumentation suite provides the standard meteorological measurements of temperature, humidity, pressure, wind speed, wind direction, and rain accumulation through use of a tipping bucket at 60 second intervals. In addition, the solar-powered station also provides a measurement of solar radiation which is intended as an indicator of battery charging efficiency, but which may have utility in deriving cloud coverage.

Table 1. Edinburgh System Installation & Performance Specifications

Installation Date	March 2016	***Beacon Frequency***	39.402 GHz
Latitude	55.9123° N	***Tracking Resolution***	0.01°
Longitude	3.3223° E	***LNA Gain***	35 dB
Altitude	130 m	***LNA Noise Figure***	3.4 dB
Nominal Azimuth	147°	***Final IF***	5 MHz
Nominal Elevation	21°	***Measurement Rate***	10 Hz / 1 Hz
Antenna Diameter	0.6 m	***Dynamic Range***	35 dB
Antenna Gain	45.6 dBi	***Temperature Control***	0.01 °C / 1 °C
Antenna Beamwidth	0.9°	***Digital Radiometer BW***	1 MHz

3. System Design

The Edinburgh receiver was designed and developed at NASA Glenn Research Center and is based on the FFT-based frequency estimator design demonstrated in previous terminals [6 – 8]. During the design process, a novel digital radiometric measurement was also conceived which led to the downconversion stages for the receivers being re-designed for a final IF of 5 MHz as opposed to the 455 kHz that has been employed in previous terminals. This change was introduced because a higher IF was needed to widen the bandwidth of the system and thus enable integration of the noise power over a wider final output band. This gives more fidelity to the measurement, although the receiver's bandwidth still remains much lower than that of a true radiometer.

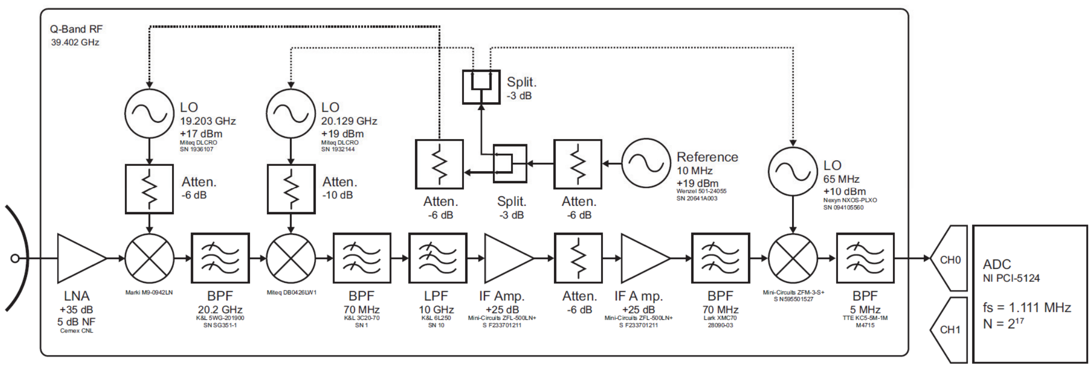

Figure 2. *The block diagram of the Edinburgh beacon receiver, which downconverts from 39.402 GHz to 5 MHz in three stages within a temperature-controlled enclosure at the feed of the antenna.*

Figure 2 shows the block diagram of the Q-band receiver. The receiver uses a 0.6 m Cassegrain reflector with a beamwidth of 0.9° and a gain of 45.6 dBi. The narrow beamwidth and highly inclined orbit of the Alphasat satellite necessitates tracking of the satellite's motion, which is accomplished using a mechanical pan/tilt positioner with a resolution of 0.01° and which is updated with the current position once every 60 seconds through open-loop tracking of Orbital Ephemeris Message (OEM) data.

Downconversion from 39.402 GHz to 5 MHz occurs directly at the feed in 3 stages (39.402 GHz to 20.199 GHz to 70 MHz to 5 MHz) within a temperature controlled enclosure. All oscillators are referenced to a common, ultra-stable 10 MHz reference, and the RF electronics are mounted to a temperature controlled cold-plate that is stable within ±0.01°C. One exception is the LNA, which is mounted at the antenna feed. While previous systems have implemented a secondary temperature control system for the LNA, this was omitted in this terminal to reduce cost. However, the air temperature within the enclosure is stable to within ±2°C as a byproduct of the plate thermal control, which does maintain a reasonable LNA temperature stability. Another difference relative to other NASA receivers is a slightly increased noise figure resulting in a reduction of dynamic range to 35 dB. From the receiver, the downconverted 5 MHz signal is transmitted over coaxial line to the digitizer.

The downconverted 5 MHz signal is digitized through a National Instruments PCI-5124 oscilloscope card. Measurement of the signal power is accomplished using an FFT-based frequency estimation technique that employs a variant of the Quinn-Fernandes (QNF) frequency estimator [7, 8]. Measurements are recorded at a rate of 10 Hz and are also averaged in real time to 1 Hz. Several digital signal processing (DSP) techniques are also applied to improve performance in low signal-to-noise ratio (SNR) environments. For example, the initial peak search of the QNF algorithm is limited to a relatively narrow bandwidth known to contain the beacon, and this bandwidth is dynamically adjusted using past frequency estimates in clear conditions to continue tracking the beacon through fade events close to the noise floor. This adds some resiliance to the QNF peak search which is otherwise susceptible to locking on to spurious noise peaks during low SNR conditions.

Another unique feature of the Edinburgh terminal is the addition of the digital radiometric measurement mentioned earlier. To achieve this measurement, the spectrum is fully oversampled (fs = 11.11 MHz) and a digital bandpass filter (Type II Chebyshev, 10th order, 50 kHz bandwidth) is applied to isolate the beacon signal. The resulting, filtered spectrum is then decimated (by a factor of 32) to reduce processing time before the QNF algorithm is applied. In parallel, the original spectrum is also notch filtered with a notch centered at the beacon frequency to fully eliminate the beacon so that the noise power may be integrated. Here, a 10th order Type II Chebyshev with a 250 Hz bandwidth is applied. With the beacon signal removed, the noise power is integrated over the full 1 MHz band. While a 1 MHz bandwidth is still extremely narrow for a radiometric measurement, previous analysis [9] has demonstrated its utility, particularly given the very minimal overhead associated with its implementation.

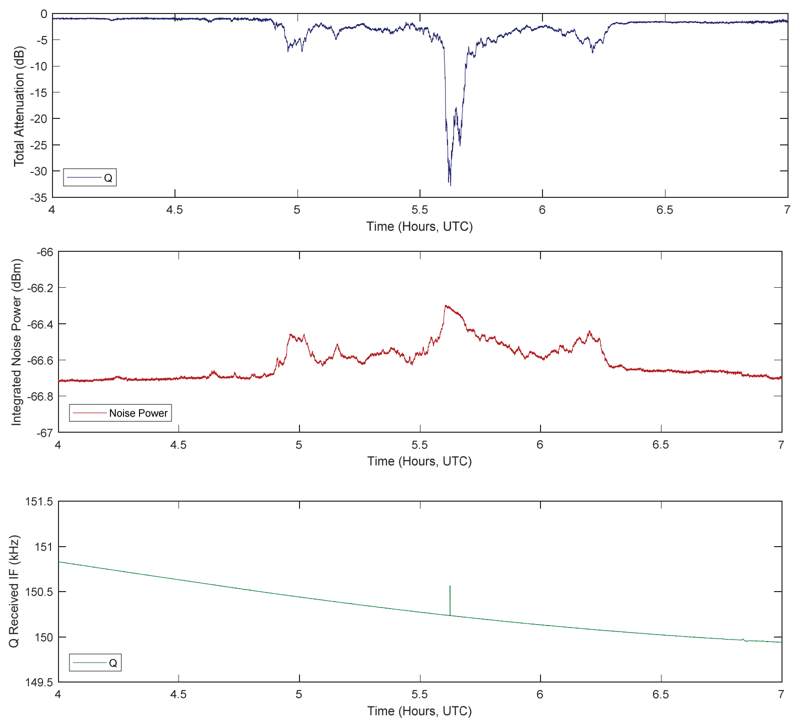

Figure 3. *Timeseries example of a heavy attenuation event in Edinburgh on 2017-11-16, demonstrating the full dynamic range of the receiver, the noise power measurement and its inverse correlation with the beacon power, and the brief loss of lock on the beacon during the deepest portion of the fade.*

Figure 3 presents a timeseries example of a heavy attenuation event in Edinburgh on 2017-11-16, demonstrating the full dynamic range of the receiver, the noise power measurement and its expected inverse correlation with the beacon power, and also a brief loss of lock on the beacon during the deepest portion of the fade.

4. Results

The Edinburgh data was statistically characterized from April 2016 through May 2018 for a total of two years and one month. The measured total attenuation is calibrated using vertical profiles of temperature, humidity, and pressure from the European Centre for Medium-Range Weather Forecast (ECMWF) in conjunction with the MPM93 Mass Absorption Model [10] to calculate a reference clear-sky attenuation level; this level is then compared to clear-sky conditions at the receiver and a calibration offset is calculated on a monthly basis. Periods of erroneous data such as from loss of tracking or power outages are removed from the data by manual inspection.

The annual attenuation statistics at Q-band are presented in Figure 4 in the form of Complementary Cumulative Distribution Functions (CCDFs). On the left, the CCDFs are shown by year, with each curve representing the noted calendar year -- 2016 and 2018 are the partial calendar years which begin and end at the limits of the dataset. On the right, the average CCDF is shown for each month through the dataset (e.g. the curve for May is the average of May 2016, May 2017 and May 2018). The total CCDF

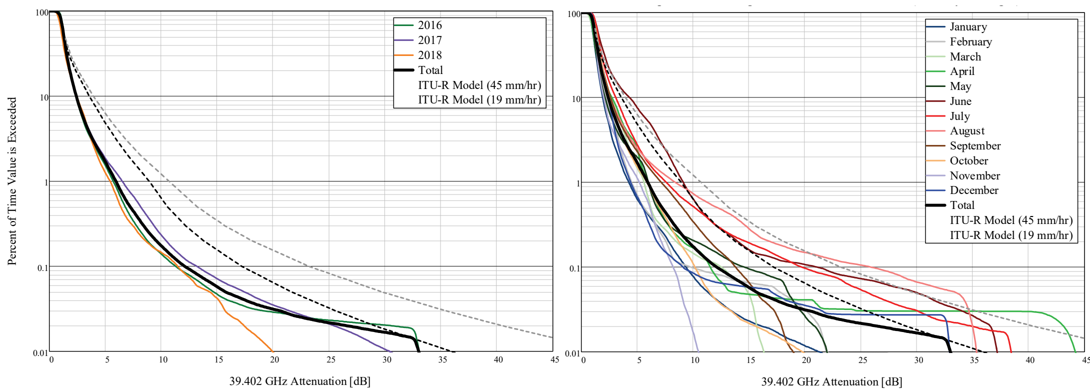

Figure 4. *CCDFs of total attenuation in Edinburgh at 39.402 GHz by year (left) and averaged by month (right).*

over the entire dataset is also shown in both figures, as well as a comparison with two instances of the ITU-R model [11 - 13]. As can be seen, the ITU-R model seems to overpredict as compared to the data, and it is postulated that this is due to an overprediction of rain rate within the model. While Edinburgh experiences precipitation very frequently, it tends to be rain of very low rain rates (< 20 mm/hr) and higher rain rates are much more rarely observed. The two model curves plotted in Figure 4 represent two different $R_{0.01}$ rain rates: 45 mm/hr and 19 mm/hr. When the ITU-R P.837-7 rain maps are interpolated for Edinburgh, a 0.01% rain rate of $R_{0.01}$ = 45.0 mm/hr is calculated. Meanwhile, data analyzed from the HWU tipping bucket suggests a much lower $R_{0.01}$ of 19 mm/hr due to a lack of high rain rate observations. When this lower rate is incorporated, agreement between the model and data is better, although there is still a notable overprediction. On the monthly plots, it can be observed that the model shows reasonable agreement with the rainier months (June, July, August, September), but still tends to overpredict as compared to the average and particularly as to the drier months (November, December, January, February). The observed margins over the dataset from 2016 to 2018 were 3.19 dB, 5.96 dB, and 12.12 dB for 95%, 99% and 99.9% availability, respectively. The highest average attenuation by month, observed in August, corresponded to a 95%, 99%, and 99.9% availability margin of 3.61 dB, 8.39 dB, and 25.90 dB, respectively. The lowest monthly attenuation, observed in December, corresponded to 2.86 dB, 4.42 dB, and 9.11 dB at 95%, 99%, and 99.9% availabilities.

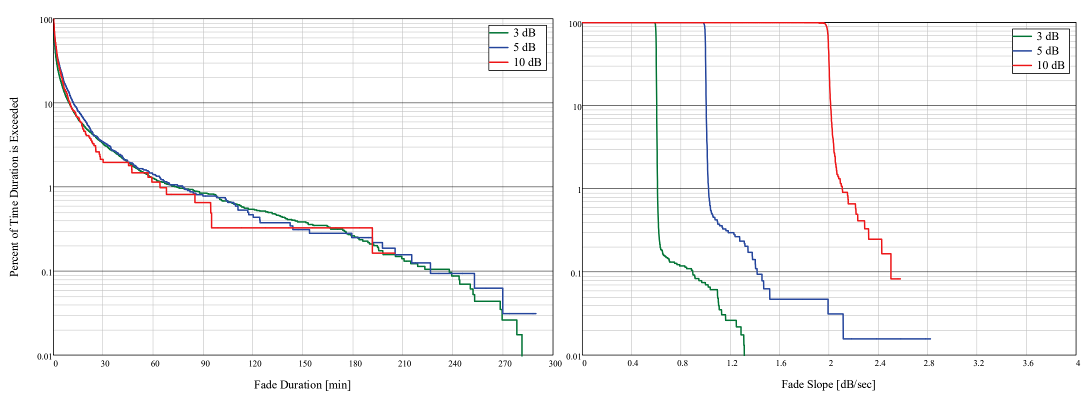

Figure 5. *CCDFs of second-order attenuation statistics: fade duration (left) and fade slope (right) in Edinburgh at Q-band (39.402 GHz).*

In Figure 5, the CCDFs of fade duration (left) and fade slope (right) are presented for fade thresholds of 3 dB, 5 dB, and 10 dB. The fade duration for this analysis was defined as the period of time that the attenuation exceeds the cited threshold. Before calculating fade duration, a 30 second moving average is applied to the calibrated attenuation timeseries to reduce noise. As shown, 99% of all fades at the 3, 5, and 10 dB thresholds were less than 78 minutes in duration. Fade slope was calculated by locating the points at which the attenuation crosses the cited threshold and calculating the difference between the attenuation 5 seconds before the crossing and 5 seconds after the crossing, then dividing by 10 seconds to yield fade slope in dB/sec. As with fade duration, a 30 second moving average is applied to low-pass filter the data. As shown in Figure 5 (right), the fade slope for a 3 dB fade was observed to be at least 0.58 dB/sec, while the fade slopes for 5 dB and 10 dB fades were at least 0.98 and 1.9 dB/sec, respectively. The highest observed fade slopes were approximately 2.5 – 2.9 dB/sec, which were observed less than 0.1% of the time for 5 and 10 dB fades. These statistics are referenced to the total number of fades observed at each threshold -- for example, in 99% of all 10 dB fades, a fade slope less than 2.1 dB/sec was observed.

5. Conclusions

NASA's Q-band Alphasat beacon receiver in Edinburgh has been operational at Heriot-Watt University since April of 2016 without issue and has performed above expectations. The noise power integration measurement that was first demonstrated with this receiver has been shown to yield a reasonable approximation of a radiometric measurement. Though it does offer less fidelity than a true, wide bandwidth radiometer measurement, the cost and effort associated with implementing it into an FFT-based beacon receiver is negligible. Overall, NASA's participation in the Alphasat framework has so far yielded 11 station years of valuable propagation data, including the 2 years of Q-band measurements in Edinburgh as detailed above. The campaign is expected to continue for a minimum of five years or for the duration of the beacon payload availability. Herein we have presented the design, operation, and first two years of attenuation, fade duration, and fade slope statistics of the propagation data collected at HWU. Future work will further investigate the performance of the ITU-R model relative to the observed statistics, as well as a statistical characterization of scintillation at Q-band as observed in Edinburgh.

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