The Alphasat Aldo Paraboni propagation experiment: Measurement campaign at the Italian ground stations

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Summary
Terabit capacity and very high data rates are required for the near-future broadband satellite communication systems, mainly for multimedia services. The increased capacity can be obtained by using the larger bandwidth available at higher frequency bands, like Ka and Q/V. However, severe detrimental atmospheric effects impair radio waves at these bands, which require the extensive use of fade mitigation techniques, such as link power control, site diversity, or on-board adaptive power allocation. The Alphasat Aldo Paraboni propagation experiment was designed and supported by the Italian Space Agency, and implemented by the European Space Agency, to better characterize the atmospheric propagation channel at Ka band and Q band, to support the design of future satellite systems. In Italy, 3 ground stations have been installed and are acquiring the Alphasat beacon signals: the 2 ASI main ground stations in Tito Scalo (Southern Italy) and Spino d’Adda (Northern Italy) and the La Sapienza-FUB station in Roma (Central Italy). The 3 stations cover quite distant locations in Italy, with different climatic characteristics. This paper describes the main features of the experimental setup in the above stations and presents some examples of measurements and results.

KEYWORDS
Alphasat experiment, atmospheric effects, data processing, measurements, microwave propagation

1 | INTRODUCTION

The current high-throughput satellite (HTS) systems operate at Ka band, taking advantage of its already mature technology, of its larger bandwidth, and of its minor congestion. Moreover, the adoption of frequency reuse, enabled by the multispot coverage, assures a total capacity (forward plus return link) of nearly 100 Gbps over a continental coverage, with a single spot capacity of hundreds of Mbps.¹

Even if bandwidth-efficient modulation schemes can be used to achieve larger throughputs,²,³ they require more power, which is a limited resource on board of satellites. On the other hand, higher capacity for the feeder links can also be achieved by using higher bands, like Q/V, where a large part of the spectrum is allocated to fixed satellite services.⁴ Moreover, in this way, the entire Ka spectrum can be allocated to the user link only.

At such high-frequency bands, radio waves are affected by severe atmospheric effects, not only because of rain but also of gases, clouds, and turbulence. As a consequence, absorption, scattering, depolarization, and scintillation have to be carefully studied and modeled not only to calculate the conventional system link budget but also to design fade mitigation techniques (FMTs), such as link power control, site diversity, or on-board adaptive power allocation, needed to properly counteract these effects. In fact, the use of large static link margins is not efficient, because, due to the experienced large attenuation variation, there would be a remarkable waste of system resources in clear sky conditions, as well as an increase of the interspot interference.
In this scenario, in 2006, the Alphasat program of the European Space Agency (ESA) offered a new opportunity to host Technological Demonstration Payloads (TDPs) on board the Alphasat commercial satellite, operated by Inmarsat. The Italian Space Agency (ASI), whose long history in the study of the Ka and Q/V bands started in the 1990s with the Italsat experiment, successfully proposed the TDP#5, after renamed “Aldo Paraboni” Payload, in memory of the late professor of Politecnico di Milano, who greatly contributed to its conception and realization. The objective of the Aldo Paraboni payload is to perform a satellite communication experiment (named COMEX) and a propagation experiment (referred to as SCIEX, scientific experiment), as a part of the wider TRANSPONDERS program that, started in 2004, aimed at demonstrating the effectiveness of the use of some FMTS in the design of new HTS for TLC applications. The propagation experiment, which was supported by ASI and implemented by ESA, allows a better characterization of the atmospheric propagation channel at Ka band and Q band, making use of 2 coherent continuous-wave beacons operating at 19.701 and 39.402 GHz, respectively. The main objective of the experiment is the investigation of first-order and second-order statistics of attenuation, joint depolarization and attenuation measurements, sky noise temperature, and instantaneous frequency scaling.

Alphasat was successfully launched on 25 July 2013, from Kourou (French Guiana). The geosynchronous orbit is inclined on the equatorial plane; the orbit inclination is drifting from 0° to a maximum of 3°, before being reset to 0°. The satellite longitude is 25° East. The in orbit test campaign ended on December 2013, and the experimental campaign started at the end of February 2014.

Three ground stations installed in Italy are currently collecting the Alphasat beacon signals: the 2 ASI main ground stations in Tito Scalo (Southern Italy) and Spino d’Adda (Northern Italy), respectively, and the La Sapienza-FUB station in Roma (Central Italy). The above 3 stations cover quite distant locations, with different climatic characteristics.

This paper describes the main characteristics of the experimental setup in the 3 ground stations and the potentiality of the experiment by presenting some examples of measurements and results. Section 2 describes the experimental setup for the 3 ground stations in Italy. Section 3 outlines the data processing, while Section 4 presents some examples of the obtained results. Finally, Section 5 draws some conclusions.

2 THE ALPHASAT GROUND STATIONS IN ITALY

The Alphasat Italian ground segment for the propagation experiment consists of 3 receiving stations: 2 of them (principal stations) are funded by ASI, and the third one (auxiliary station) has been designed and deployed by a joint effort of Sapienza University of Rome, Fondazione Ugo Bordoni, and Ministero dello Sviluppo Economico (with a partial support from ESA). Figure 1 shows a map with their positions, while Table 1 resumes the main characteristics of the 3 Italian ground stations.

ASI, with the support of Politecnico di Milano as Principal Investigator of the propagation experiment, committed Space Engineering to realize 2 identical propagation ground stations in Italy (the same used for the communication experiment). The first ground station is located in Tito Scalo (near Potenza, south of Italy), while the second one is in Spino d’Adda (near Milan, north of Italy). Being the satellite positioned along an inclined orbit and the beam width of the 4.2-m Cassegrain antenna very narrow (less than 0.3° and 0.15° at Ka and Q band, respectively), both ground stations are equipped with a monopulse auto tracking system, with an accuracy better than 0.01°. Both stations measure copolar beacon signals at 19.701 and 39.402 GHz, with the 4.2-m-diameter antenna at an elevation angle of 42.1° (Tito Scalo) and 35.5° (Spino d’Adda). The cross polar signal at 39.402 GHz is also measured to investigate depolarization. The coherent receiver acquires signal amplitude and phase with 16 Hz sampling rate, allowing a complete characterization of fast fluctuations because of tropospheric turbulence. The principal ground stations’ architecture is fully described in Cornacchini et al.

FIGURE 1 Map with the positions of the 3 Italian Alphasat ground stations installed in Spino d’Adda (Northern Italy), Roma (Central Italy), and Tito Scalo (Southern Italy) [Colour figure can be viewed at wileyonlinelibrary.com]
An Rpg-HATPRO profiler radiometer is installed at each of the 2 sites of the principal Alphasat stations. The profiler is equipped with a heavy-duty dew blower system to prevent formation of dew and accumulation of raindrops on the antenna radome (in combination with a hydrophobic coating). Moreover, the dew blower heater system prevents the formation of liquid water on the radome in foggy conditions (100% relative humidity). The absolute calibration is maintained by exploiting the hot internal black body target (routine calibration) and by using an external cold target (liquid nitrogen; this kind of calibration needed only after transportation of the instrument and every 6 months). The accuracy of the radiometer is anyway regularly monitored by comparison against estimates derived from NWP and radiosounding data (the latter being available only for Spino d’Adda at the Linate airport, which is about 18 km far from the station). Table 2 recalls the main technical characteristics of the radiometer installed at Tito Scalo and Spino d’Adda. A tipping bucket rain gauge and an ancillary meteorological station complete the equipment of both stations. Figure 2 shows the ground station (on the left) and the radiometer, during calibration operations (on the right), installed at Spino d’Adda. The measurement campaign started in November 2014 in both stations.

The Alphasat ground station in Rome has been designed and assembled by refurbishing, after proper laboratory characterization and testing, several microwave and radiofrequency components obtained from previous dismissed satellite missions (eg, Olympus and Italsat).10,11 Figure 3

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Tito Scalo</th>
<th>Spino d’Adda</th>
<th>Roma</th>
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<tbody>
<tr>
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<td>40.60° N 15.7° E alt. 765 m (a.m.s.l.)</td>
<td>45.4° N 9.5° E alt. 84 m (a.m.s.l.)</td>
<td>41.83° N 12.46° E alt. 104 m (a.m.s.l.)</td>
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<td>Frequency (GHz)</td>
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<td>39.402 Linear 45° 26.5</td>
<td>19.701 Linear V 19.5</td>
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<td>Path elevation angle (assuming 0° satellite latitude)</td>
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<td>41°</td>
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<td>Cassegrain 4.2-m diameter</td>
<td>Paraboloid 1.5 m</td>
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<tr>
<td>Data acquisition rate</td>
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<td>30 Hz</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Attenuation type</td>
<td>Excess and total attenuation about 60 dB</td>
<td>Up to 40 dB</td>
<td>About 30 dB</td>
</tr>
<tr>
<td>Radiometer</td>
<td>RPG-HATPRO tropospheric temperature and humidity profiler (7 channels between 22.234 and 31.4 GHz for tropospheric humidity profiling and 7 channels between 51.26 and 58.5 GHz for temperature profiling up to 10 000 m)</td>
<td>X-band research weather radar at 9 km C-band operational weather radar at 70 km</td>
<td></td>
</tr>
<tr>
<td>Rain gauge</td>
<td>SIAP+MICROS t028 TP500R (bucket capacity 0.2 mm)</td>
<td>SIAP+CombiLog (bucket capacity 0.2 mm)</td>
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</tbody>
</table>
shows the current configuration of the overall Alphasat receiving station, installed in Rome and operating both channels using different antennas; their main specifications are summarized in Table 1.

The Ka band station in Rome is characterized by an outdoor unit with a paraboloid having a diameter of 1.5 m (providing an antenna gain of 47 dBi), a low noise amplifier (LNA), and a double-stage frequency conversion. The 19.701 GHz received signal is filtered and runs through an LNA with a 30.5 dB gain. The noise figure of the LNA, including the upstream filter, is 3.3 dB. After amplification, the signal is processed by a 2-stage converter. The local signals for frequency conversions are obtained with high stability local oscillator (LO) followed by a multiplier. The first conversion involves a 94.75 MHz LO and a 200× frequency multiplier. The resulting 18.950 GHz is combined with the 19.701 GHz to obtain the first intermediate frequency (IF) of 751 MHz. In the second conversion stage, we obtain the second IF of 69 MHz mixing the first IF with a generated 820 MHz signal. The first stage is completely realized with microstrip technology, whereas the second one is a printed circuit board (PCB). Both stages provide an overall gain of 55 dB. The output signal, at a frequency of 69 MHz, is sent to the indoor unit where a satellite beacon receiver (SBR) acquires the signal using 1 kHz bandwidth and generates a voltage output proportional to the power of the 69 MHz signal. The received signal power is then collected and monitored by a computer software, specifically engineered. The Ka band receiving station is not equipped with an automatic satellite tracking; however, the antenna elevation can be manually oriented, and the Alphasat orbit oscillation is then removed by postprocessing filters.

The Q band station in Rome, as the Ka band one, consists of an outdoor and an indoor unit. The receiving antenna, front-end, and 2 intermediate frequency conversion chains are part of the main outdoor section, while in the indoor one includes an SBR and an acquisition unit. The Alphasat Q band signal at 39.402 GHz, after LNA amplification, is converted at the first IF 3.406 GHz (IF1), using a 35.996 GHz signal obtained by successive multiplications. A second converter provides the final IF at 70 MHz (IF2). Its local oscillator can be locked on an external frequency reference (ie, cesium-beam frequency standard). The IF2 70 MHz signal is suitably amplified to the level required by the SBR, equipped with a logarithmic detector providing an output voltage signal for data logger acquisition. The selected LNA has a ~50 dB gain and a 3.5 dB noise figure. To maximize the Q band receiver performance, the SBR bandwidth is set at 100 Hz, instead of 1 kHz, to improve the final signal-to-noise ratio of about 10 dB. The Q band station mounts a 40-cm-diameter paraboloid with an efficiency of 0.6 and an overall gain of about 42.7 dBi. The Q band receiving station has been recently equipped in 2017 with an open-loop tracking system, operating both in elevation and in azimuth. It automatically ingests from an online server the satellite nominal ephemerids and calculates the antenna pointing based on the receiver position. The tracking system is able to rotate 200° in azimuth and 180° in elevation with continuity; its maximum speed is of 20° per minute with step-motor position accuracy of ±0.1° and encoders precision of 0.01°.
In the same building of the Alphasat receivers in Rome, the roof hosts a meteorological station, including a temperature sensor, a barometric sensor, an anemometer, and a tipping-bucket rain gauge, acquired every 1 or 5 minutes. In addition to this classical instrumentation, a near-infrared laser disdrometer also collects additional data (to derive raindrop size distribution, particle type, and atmospheric visibility) together with maps obtained from the available weather radar at X band (installed at Sapienza University of Rome about 9 km far part) and at C band (installed at M. Midia near Tagliacozzo, L’Aquila, about 70 km far apart).12,13

3 | DATA PROCESSING

The key product in electromagnetic wave propagation experiments is the tropospheric attenuation that theoretically could be derived from the received beacon levels if the link budget parameters (e.g., path length, frequency, gain of the antennas, ...) could be accurately estimated. Actually, this is not the case for most of them, while some others, like the real-time nominal transmitted power, the gain/attenuation levels in the electronic components (because of aging and/or to temperature variation), pointing errors, are not even known. Therefore, to calibrate the beacon data, the clear sky attenuation is independently estimated by using a colocated microwave radiometer, with the same elevation and azimuth angles as the beacon receiving antenna.

Because of the crucial importance of the radiometric data, they have been carefully inspected and analyzed since the beginning of the experiment, in the Italian ground stations of Tito Scalo and Spino d’Adda. In the initial phase, the instrument, calibrated with liquid nitrogen after deployment (see right side of Figure 2), has collected sky noise measurements along the zenith, while it has been operating along the path to Alphasat since the beacon receivers were switched on. An example of the radiometric measurements is given in Figure 4, which plots the daily time series of brightness temperature \( T_B \) (K) collected on 2 January 2018 for the 2 frequencies 23.84 and 31.4 GHz, more sensitive to water vapor and to suspended liquid water, respectively. The quite stable trend of \( T_B \) at both frequencies indicates a very limited presence of clouds (the signature of light clouds is visible only between 2 and 6 and around 19), with an increased water vapor content in the early morning and in the evening. The \( T_B \) values, calculated using the concurrent radiosonde observations (RAOBS), launched twice a day from the Milano/Linate airport (approximately 18 km far from Spino d’Adda), are also reported in Figure 4; specifically, vertical profiles of pressure, temperature, and relative humidity were used as input to the TKK (Teknilinen KorkeaKoulu) method,14 to detect clouds and quantify the vertical distribution of the liquid water content, and to the Liebe’s MPM93 mass absorption model15 to calculate the brightness temperature at the 2 frequencies. Although the comparison between radiometric measurements and RAOBS-derived estimates must be handled with care because of several uncertainties (distance between Milano/Linate and Spino d’Adda, time required for the radiosonde ascent to cross the whole troposphere, limitations in the mass absorption model, etc.), Figure 4 can at least offer a hint of the correct calibration and operation of the radiometer.

The estimation of the reference attenuation level by using radiometers collocated in Tito Scalo and Spino d’Adda is needed to convert the received power levels (dBm) into total atmospheric attenuation (dB). The slant path atmospheric attenuation \( A_{ref}(f, \vartheta) \) in dB, at frequency \( f \) and slant path elevation angle \( \vartheta \), is calculated during clear-sky periods, from the corresponding slant path brightness temperature, \( T_B \) (K), at the same frequency, as\(^{16-18}\):

\[
A_{ref}(f, \vartheta) = 10 \cdot \log_{10} \left( \frac{T_{mr}(f, \vartheta) - T_C}{T_{mr}(f, \vartheta) - T_B(f, \vartheta)} \right)
\]

where \( T_{mr}(K) \) is the monthly mean radiative temperature, calculated by applying the Liebe’s MPM93 mass absorption model\(^{15}\) to a large dataset of local vertical atmospheric profiles, and \( T_C(K) \) is the cosmic background temperature, typically 2.73 K at microwaves.

The tropospheric attenuation, \( A_{trop}(f, \vartheta) \) (dB), at the beacon frequencies \( f = 19.701 \text{ GHz and } f = 39.402 \text{ GHz, respectively, is estimated, in the absence of rain, as the linear combination of } A_{def}(f, \vartheta), \text{ calculated at the 5 radiometric frequencies of } 23.84, 27.84, 31.40, 51.26, \text{ and } 52.28 \text{ GHz, in}

![FIGURE 4 Brightness temperatures collected by the Spino d’Adda radiometer on 2 January 2018 and values estimated using the TKK method and the Liebe MPM93 mass absorption model (inputs are the RAOBS vertical profiles from Milano Linate airport) [Colour figure can be viewed at wileyonlinelibrary.com](image)
fact, even if 2 channels centered around 20 and 30 GHz (sensitive to water vapor and liquid water extinction, respectively), are typically sufficient to provide \( A_{\text{rad}}(f) \), the 3 available extra channels were used as well to increase the estimation accuracy. Table 3 lists the \( T_{\text{m}}, f, \theta \) monthly values for Tito Scalo and Spino d’Adda, at the selected radiometric frequencies. \( A_{\text{rad}}(f, \theta) \) is thus given by:

\[
A_{\text{rad}}(f, \theta) = a_0 + \sum_{i=1}^{5} a_i A_{\text{ref}}(f, \theta) \tag{2}
\]

where, as for \( T_{\text{m}}, f, \theta \), the coefficients \( a_0 \) and \( a_i \) are calculated by regression of \( A_{\text{ref}}(f, \theta) \) and \( A_{\text{rad}}(f, \theta) \), which are calculated by applying cloud detection and mass absorption models to the local vertical profiles.\(^{16}\) Table 4 lists the coefficients \( a_i (i = 0 \text{ to } 5) \) for Tito Scalo and Spino d’Adda. These coefficients allow a very accurate estimation of \( A_{\text{rad}} \). Considering the whole radio sounding dataset, the root mean square value of the relative error is 0.0035 and 0.0048 dB for 19.701 and 39.402 GHz, respectively, well below the receiver accuracy.

Finally, the beacon power level time series, \( P_{\text{beac}}(\text{dBm}) \), are converted in total attenuation time series, \( A_{\text{tot,beac}}(\text{dB}) \), through:

\[
A_{\text{tot,beac}}(f, \theta) = -P_{\text{beac}}(f, \theta) + P_{\text{beac,cs}}(f, \theta) + A_{\text{rad}}(f, \theta) \tag{3}
\]

where \( P_{\text{beac,cs}} \) (dBm) is the beacon power level during clear sky periods (and linearly interpolated in rainy periods) and concurrent to \( A_{\text{rad}} \). \( P_{\text{beac,cs}} \) and \( A_{\text{rad}} \) are linearly interpolated during rainy periods (between the last sample before the beginning of the rain event and the first sample after the end of the rain event).

Figure 5 shows an example of the beacon calibration procedure by illustrating in detail the steps it consists of. Considering that radiometer is sensitive only to absorption and not to scattering from hydrometeors during precipitation (as well as to scattering from turbulent eddies), \( A_{\text{tot}} \) can be calculated, through Equation (1), only during clear sky periods. For this reason, the procedure presented in Bosio et al.,\(^{15}\) which relies on the brightness temperature at \( f_1 = 23.84 \) and \( f_2 = 31.4 \) GHz, has been applied to preliminarily identify the presence of rain along the path.\(^{16}\) First, the sky status indicator (SSI) is calculated from 1-minute averaged brightness temperature data as:

\[
SSI = \frac{T_B(f_2, \theta) - 10.3}{T_B(f_1, \theta)} \tag{4}
\]

Then, the SSI signal is thresholded by a robust hysteresis method with lower and upper thresholds equal to 0.73 and 0.87, respectively. Rain is present in the time intervals where the SSI signal exceeds the lower threshold and, at the same time, at least 1 SSI sample is above the upper threshold. The above thresholds have been chosen by comparing the cumulative distribution functions of rain rate and SSI at given probability levels. This simple automatic procedure detects almost all rain events. However, it is not able to single out with high accuracy when precipitation begins and ends. Hence, the start and end time of each event have been subsequently adjusted by visual inspection of the rain rate time series derived from the rain gauge and of the received beacon signals. The procedure is clarified in the 4 plots in Figure 5, which reports, for the same day, \( A_{\text{tot}} \) at 39.402 GHz, the rain rate, and the beacon power levels (both bands) (site of Spino d’Adda). In all plots, the yellow line represents the duration of the rain event as identified by visual inspection of all the data. The top left plot shows the result of the preliminary SSI-based method. As expected, \( A_{\text{rad}} \) and \( A_{\text{tot,beac}} \) (bottom right plot) do not overlap during the rain event, because of the limits of (1) to accurately measure rain attenuation.

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**TABLE 3** Monthly mean radiative temperature, \( T_{\text{m}} \), for Tito Scalo and Spino d’Adda, calculated by applying the Liebe’s MPM93 mass absorption model to a large dataset of local vertical atmospheric profiles

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<td>Tito Scalo</td>
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**TABLE 4** Coefficients \( a_i (i = 0 \text{ to } 5) \) for Tito Scalo and Spino d’Adda, to be used in Equation (2) and calculated by regression of \( A_{\text{ref}}(f, \theta) \) and \( A_{\text{rad}}(f, \theta) \), which are calculated by applying cloud detection and mass absorption models to the local vertical profiles

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<th>( f ) (GHz)</th>
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</tr>
<tr>
<td></td>
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<td>-0.2026</td>
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<td>-0.0333</td>
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Data processing procedures at the Rome site is conditioned by the lack of continuous radiometric measurements, useful to set the clear-sky reference. Clear-air attenuation at Ka band is obtained by filtering the time series to remove the satellite orbital oscillations and by selecting clear-air periods on the basis of (i) rain gauge and weather data; (ii) measurements from the available weather radar at X band and C band; (iii) radio-sounding measurements at 12:00 and 24:00 UTC at Pratica di Mare, 20 km away from Rome; and (iv) Meteosat satellite imagery to detect cloud coverage with a spatial resolution of about 3 km every 15 minutes. Once clear-air periods are identified with a time-moving window of 72 hours, the mean received signal is computed and subtracted to the received signal to derive the instantaneous attenuation. By removing the average, the high-rate acquisition at 30 Hz allows the computation of scintillation standard deviation over 1-minute windows in clear (and possibly also cloudy) periods.11 The data processing at Q band is similar, but the removal of the satellite orbital oscillations is not needed as the automatic open-loop tracker avoids these effects, which would be more pronounced at Q band.

4 | PROPAGATION RESULTS

The characteristics of the ASI principal ground stations in Tito Scalo and Spino d’Adda, in terms both of dynamic range and sampling rate, allow a comprehensive investigation of propagation effects. This is confirmed, for example, by beacon signals recorded in Spino d’Adda at 19.701 and 39.402 GHz on 01 December 2014 during a rain attenuation event where the rain rate was up to almost 40 mm/hour, as shown in Figure 6. By observing the 39.402 GHz beacon attenuation (blue curve), it is evident that the receiver dynamic reaches the remarkable value of about 60 dB. The good quality of the recorded data is confirmed by the spectrum of the attenuation time series at 39.402 GHz showed in Figure 7: the theoretical behavior of attenuation and turbulence effects (cyan and black lines, respectively) are confirmed, and the noise floor is still below the received signal spectral components. Though the present technology does not allow such high values of power margin, the performance of the receiving station allows a reliable study of lower value of attenuation and a complete characterization of the tropospheric channel and of its physical modeling.

After the 2 ground stations test and measurements quality check, the data started to be collected quite regularly since October 2014. Unfortunately, in June 2016, the power supply of the antenna motor drive unit in Spino d’Adda was struck by lightning, causing the measurement interruption until November 2016, when it was substituted. In Tito Scalo, the downconverters were out of service in a great part of 2016, preventing measurements on a regular basis. In 2017, there was a problem in that data transfer to the experimental control center in Spino d’Adda (a data backup was recently made available and is under analysis) and a failure of the antenna motor drive unit in Tito Scalo (still under repair in January 2018). For this reason, a good data availability allowing statistical analysis was available, up to now, only in 2015. Figure 8 shows the complementary cumulative distribution function (CCDF) of rain rate for 2015 compared to the long-term one measured during the Italsat experiment (1994-2000) and the prediction by ITU-R P.837-7 maps.20 It is evident that 2015 was slightly drier year; the
agreement with ITU-R model is reasonable. Figure 9 shows the CCDF of total attenuation at 19.701 (black solid line) and 39.402 (blue solid line) GHz measured in Spino d'Adda in 2015 compared with the long-term (1994-2000) CCDFs measured during the Italsat experiment along a 37.7° slant path at 18.7 GHz (black dotted line) and 39.6 GHz (blue dotted line) and the ITU-R P.618-1321 model predictions (back and blueed
dashed lines for 19.701 and 39.402 GHz, respectively); as for ITU-R, the measured rain rate exceeded for 0.01% of the average year (35.6 mm/hour) has been used as input (see Figure 8). The comparison with Italsat CCDFs, considering also the slightly different beacon frequencies (especially at Ka band), confirms that 2015 has been a drier year with respect to the long-term average and that the Alphasat receiver dynamic range permitted to measure higher attenuation values, corresponding to the few very intense rain events. The agreement with the ITU-R model is quite satisfactory especially for time percentages from 100% down to 0.05%, even if it tends to overestimate the measured data in such range.

The receiving station in Rome, despite its design based on a reengineering concept, shows a relatively good performance in sensitivity and dynamics. The quality of the Q band received data stream appears to be better than Ka band, the latter being penalized by the lack of a customized tracking system. The use of an open-loop tracking system at Q band has largely improved the acquisition of data even during rainfall events, even though the overall dynamics of the Q-band receiver is limited by the relatively small antenna. The overall dynamic range of the 2 beacon receivers is about 30 dB. Indeed, this feature of mounting small antennas can be useful to enhance the sensitivity to amplitude scintillation in clear air condition where larger antenna tends to filter out signal fluctuations because of their smaller beam widths.

Figure 10 shows both the Q band and Ka band attenuation time series collected during the rainfall event of the 5 November 2017 in Rome, together with the corresponding rain gauge time series. The partial unavailability of data in the Ka band trace is because of the lack of the satellite tracking system, causing a loss of the beacon signal because of the satellite displacement (which is not evident in the figure as our data postprocessing removes this trend, as mentioned). On the other hand, the Q band channel receiver saturates when the measured rain rate exceeds
about 60 mm/hour, inducing a slant path attenuation larger than the available dynamics of the receiving station at Q band. In the available data time window, there is a good correlation between path attenuation of the 2 Alphasat links, following the variability of the locally measured rain rate. Figure 11 illustrates the amplitude scintillation power spectral density of both channels for the same event. The Q band presents a \(-20\) dB/decade slope at lower frequencies, typical of rain events, and an approximate \(-80/3\) dB/decade typical of scintillation effects at higher frequencies. Spikes above the frequency of 1 Hz are because of the anomalous behavior of 1 of the LO of the conversion stage. However, because of the frequencies of the 2 artifacts, their effects fall in the noise floor frequency band, without affecting the clear air scintillation one. At Ka band, scintillation effects follow the expected \(-80/3\) dB/decade at higher frequency, whereas at lower frequency, the data filtering (necessary to delete unwanted signal oscillation because of the lack of the tracking system at Ka band) makes data unusable.

The distance between the 3 Italian stations (about 500, 700, and 300 km for Spino d’Adda-Roma, Tito Scalo-Spino d’Adda, and Tito Scalo-Roma, respectively) permit the study of the large space correlation of attenuation, quite important to dimension and design smart gateway systems. Figure 12 shows an example of rain attenuation time series recorded in Tito Scalo and Spino d’Adda; it is evident that the decorrelation because of the large distance reduces drastically the simultaneous outage of the 2 stations.

**FIGURE 11**  Power spectral density of Q band and Ka band for the received signals collected on 5 November 2017 rain event in Rome; 1-hour data analysis [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 12**  Example of rain attenuation at 39.402 GHz measured on 15 January 2015 at Spino d’Adda (blue line) and Tito Scalo (red line). The black dashed line represents the case of site diversity configuration [Colour figure can be viewed at wileyonlinelibrary.com]
5 | CONCLUSIONS

The Alphasat Aldo Paraboni propagation experiment aims at gaining a better understanding of the atmospheric propagation channel at Ka band and Q band, taking advantage of the 2 coherent continuous-wave beacons operating at 19.701 and 39.402 GHz aboard the Alphasat satellite. In Italy, 3 ground stations have been installed and are acquiring the beacon signals: the 2 ASI main ground stations in Tito Scalo (Southern Italy) and Spino d’Adda (Northern Italy) and the La Sapienza-FUB station in Roma (Central Italy).

This paper, which illustrates the main characteristics of the 3 Italian stations and describes the procedures for data processing and analysis, is intended to be a reference for all future publications about the statistical results obtained from the whole experiment period (from January 2015 to December 2019). The reported sample results show that the 3 stations offer the opportunity to conduct a careful analysis of the propagation effects on the Italian territory. In fact, besides the very good dynamic of the 2 main Italian stations in Tito Scalo and Spino d’Adda, which permits an accurate characterization of the atmospheric channel as for the attenuation, the depolarization, and the scintillation phenomena, the 3 ground stations cover north, center, and south of Italy, thus enabling the investigation of the spatial correlation of the attenuation at large scale, in particular useful for the design of future smart gateway satellite systems.

Future work will include comprehensive analyses, both on an event basis and a statistical basis, on the whole data set collected during the experiment (several years expected), with a particular focus on attenuation (both first-order and second-order statistics), scintillation, and depolarization effects.

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REFERENCES


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**Augusto Marziani** was born in Italy, in 1987. He get the Bachelor Degree in Electronic Engineering in 2011 and the Master Degree in Electronic Engineering in 2015, both from Sapienza University in Rome (Italy). He is currently a PhD student in Information and Communication Technologies, Applied Electromagnetics curriculum, at DIET (Dipartimento di Ingegneria dell’Informazione, Elettronica e Telecomunicazioni) of Sapienza University. Since 2011, he is part of the Joint Laboratory on Antenna and Propagation, a Sapienza University research program in collaboration with Fondazione Ugo Bordoni and Italian Ministry for Economic Development. He started his research activity with the Satellite to Earth propagation experiment Alphasat Aldo Paraboni, starting from the link budget analysis and, during the years, focusing first on the hardware implementation for this experiment and then on the data acquisition and analysis. Within the Joint Laboratory on Antenna and Propagation, his PhD activity he is mainly involved in tropospheric propagation data analysis, focusing on scintillation effects on the slant path for microwave and millimeter wave signals.

**Fernando Consalvi** He graduated in Industrial Electronics at the ITIS “Morosini” of Ferentino (Italy). In 1985, he won a scholarship for: "Tropospheric radiopropagation for terrestrial and satellite connections at frequencies higher than 10 GHz," issued by the Ugo Bordoni Foundation (FUB). Since 1986, He has been working with the Fondazione Ugo Bordoni (FUB), in the Radiopropagation group, as a senior assistant researcher. His main research experience was to create microwave and millimeter waves devices for the study of the various influences of the Earth’s atmosphere on radio waves for communication and remote sensing techniques. He has been involved in several European scientific programs (COST), in the ITALSAT, OLYMPUS experiments, in the ESA/ENVISAT satellite calibration project, and in the Sardinia Radio Telescope (SRT) project by the Agenzia Spaziale Italiana (ASI). He was a Visiting Scientist at the RESCOM A/S (Technical University of Denmark) research and development center for the study and applications of microwave receivers for Radiometry, working on passive microwave radiometric techniques and on remote sensing observations. He is actually involved in the European satellite AlphaSat TDPS project, in particular for what concerning the project and realization of the satellite receiving stations in the Ka and Q band.
Frank S. Marzano received the Laurea degree (cum laude) in Electrical Engineering (1988) and the PhD degree (1993) in Applied Electromagnetics both from the University of Rome “La Sapienza,” Italy. After being a lecturer at the University of Perugia, Italy, in 1997, he joined the Department of Electrical Engineering, University of L’Aquila, Italy, teaching courses on electromagnetic fields as Assistant Professor. In 1999, he was at Naval Research Laboratory, Monterey, CA, as a visiting scientist. In 2002, co-founded Center of Excellence on Telesensing and Model Prediction of Severe weather (CETEMPS), L’Aquila. In 2005, he finally joined the Dept. of Information engineering, Electronics and Telecommunications, Sapienza Univ. of Rome, Italy, where he presently teaches courses on antennas, propagation and remote sensing. Since 2007, he has been vice-director of CETEMPS of the University of L’Aquila, Italy, where he was nominated director on March 2013. His current research concerns passive and active remote sensing of the atmosphere from ground-based, airborne, and space-borne platforms and electromagnetic propagation studies. Dr Marzano has published more than 140 papers on refereed International Journals, more than 30 contributions to international Book chapters and more than 300 extended abstract on international and national congress proceedings. He was the Editor of 2 books. From January 2004 till June 2014 he has been acting as an Associated Editor of IEEE Geoscience Remote Sensing Letters (GRSL) and since 2014 he is Associated Editor of IEEE Transactions on Geoscience and Remote Sensing (TGRS). Since January 2011, he is Associate Editor of the journal EGU Atmospheric Measurements Techniques. Dr. Marzano is Fellow of RMetS (Royal Meteorological Society) since 2012 and Fellow of IEEE since 2015.