NASA’s Alphasat Propagation Terminals: Milan, Italy and Edinburgh, Scotland

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Since May of 2014, NASA's Glenn Research Center has operated measurement campaigns for the Alphasat Aldo Paraboni Propagation Experiment alongside the European community of propagation experimenters. Presently, three NASA stations have been deployed to distinct climatological regions across Europe. NASA's participation in the campaign began in 2014 through a collaborative effort with the Politecnico di Milano (POLIMI) to jointly operate a 20/40 GHz ground terminal at the POLIMI campus in Milan, Italy. Subsequently, a single-channel 40 GHz terminal was deployed to Edinburgh, Scotland in March 2016 in collaboration with Heriot-Watt University (HWU). A third terminal was deployed to NASA’s Madrid Deep Space Communications Complex (MDSCC) in March 2017 with NASA’s Jet Propulsion Laboratory (JPL), also observing the 40 GHz beacon. In addition, a fourth station is planned for deployment to Andoya, Norway by early 2019 in collaboration with the Norwegian Defence Research Establishment (FFI). This paper will detail the design and results of the two most established terminals, Milan and Edinburgh, which together comprise 11 station years of propagation measurements.

Keywords
Alphasat experiment, atmospheric effects, measurements, microwave propagation, propagation losses
1 | INTRODUCTION

As the finite spectrum available for satellite communications continues to grow congested, there is commensurate demand for higher frequency capabilities. This demand is simultaneously driven by the appeal of link capacities that are much higher than presently achievable within lower frequency allocations. However, one significant impediment to the implementation of higher frequency systems is the increased sensitivity of the link to atmospheric effects. A considerable increase in attenuation due to rain, clouds, and gases necessitates the use of intelligent system design through mitigation techniques such as adaptive power control and site diversity, while increased phase distortion presents a substantial challenge in the implementation of microwave uplink arrays [1]. Thus, a thorough understanding of atmospheric propagation at these frequencies of interest and within the pertinent climatological zones is required to effectively implement satellite communications links at Ka-band and above.

To this end, the Inmarsat communications satellite Alphasat was launched in July 2013 with the hosted Aldo Paraboni Technology Demonstration Payload (TDP) #5[2]. The Aldo Paraboni experiment was developed by the Italian Space Agency (ASI) and European Space Agency (ESA) and, in addition to a Q/V-band communications experiment, features coherent continuous-wave (CW) Ka- and Q-band beacons for the purpose of assessing atmospheric effects (rain attenuation, scintillation, depolarization, etc.) on links operating in these frequencies. In addition, the experiment will assist in refining physical models for predictions of atmospheric attenuation within the Q-band.[3, 4].

NASA’s vision for the agency’s future space communication architecture turns primarily to Ka-band and optical communications in pursuit of higher bandwidth and link security. Such an architecture must utilize extensive cognitive networking and fade mitigation techniques to circumvent weather-related impairments and ensure efficient management of network resources. In addition, the next generation successor to the Tracking and Data Relay Satellite System (TDRSS) will require significantly higher bandwidths than available in the current Ku-band allocation, and the agency is thusly investigating the use of available allocations in the Q-band (37-42 GHz) and V/W-bands (74-84 GHz) as downlink options to meet these requirements[5].

![Fig 1](image.jpg)

**FIGURE 1** NASA’s current and planned Alphasat propagation terminals: Milan, Italy, installed in 2014 at Politecnico di Milano; Edinburgh, Scotland, installed in 2016 at Heriot-Watt University; and Robledo de Chavela, Spain, installed in 2017 at NASA’s Madrid Deep Space Communications Complex. A fourth terminal is planned for Andøya, Norway with the Norwegian Defence Research Establishment.
As depicted in Figure 1, NASA presently maintains three Alphasat propagation terminals. The first of these was installed in April 2014 at the Politecnico di Milano campus in Milan, Italy and observes both the Ka- and Q-band beacons [6, 7, 8]. This station was also recently updated in September 2017, which is further detailed in Section 2.1. After two years of operation in Milan, in March 2016, a second Q-band receiver was installed at Heriot-Watt University (HWU) in Edinburgh, Scotland. Given the high latitude (55.9123° N), this installation presently yields the lowest elevation angle (21°) measurements within the framework of the Alphasat experiment. In 2018, HWU updated the terminal with Ka-band measurement capability. Most recently, another Q-band receiver was deployed to the NASA Madrid Deep Space Communications Complex (MDSCC) in Robledo de Chavela, Spain to provide atmospheric characterization for links near 40 GHz through the Deep Space Network (DSN). Lastly, plans are underway for a fourth terminal in Andoya Norway in collaboration with the Norwegian Defence Research Establishment (FFI). This station is intended to yield co- and cross-polarization measurements at both Ka- and Q-band and would provide unique low-elevation angle data in a coastal environment above the arctic circle. While the aforementioned receivers share much in terms of their design and data processing techniques, Section 2 will elaborate on the unique details of the design and operation of the two sites covered in this paper, Milan (2.1) and Edinburgh (2.2).

2 | EXPERIMENT DESIGN

2.1 | Milan, Italy

The Milan receivers were installed at the POLIMI campus in April 2014 atop the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) building (Figure 2). In addition to the Ka-band and Q-band beacon receivers, a suite of collocated weather instrumentation includes an R. M. Young weather station providing measurements of temperature, pressure, humidity, wind speed, wind direction, rain accumulation by means of a tipping bucket, as well as a Thies Clima laser disdrometer which yields droplet size and velocity distributions. Previous work has taken advantage these additional measurements to investigate frequency scaling from 20 to 40 GHz using the drop size distribution (DSD) [9, 10], as well as the impact of the scattering model on the specific attenuation as derived from the DSD [11]. Additionally, a Radiometer Physics GmbH (RPG) water vapor radiometer was installed in November 2016, providing radiometric measurements that will be used to validate the digital radiometric measurement recently added to the receivers.

![Figure 2](image-url) The Ka/Q-band Alphasat receivers at Politecnico di Milano in Milan, Italy. On the left, a photo of the receivers and the associated weather monitoring equipment including weather station, laser disdrometer, and tipping bucket. On the right, an overhead view of the receiver location atop the roof of the Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB) building.
FIGURE 3  A block diagram of the Milan Ka- and Q-band beacon receivers, which share a common intermediate frequency (IF) downconversion stage. The station was updated in September 2017 to adapt the final IF from 455 kHz to 5 MHz and to widen the IF bandwidth to accommodate a digital noise power measurement.

The Milan beacon receivers, like all of NASA’s Alphat seat terminals, were designed and developed at NASA GRC. As originally deployed, the Milan receivers downconverted each beacon to a final frequency of 455 kHz; this design was selected to utilize legacy hardware that was readily available for this configuration. As subsequent receivers were designed for Edinburgh and Madrid, a novel digital radiometric measurement was implemented which led to the downconversion stages for the receivers being designed for a final IF of 5 MHz. To accommodate the new measurement, a higher IF was desirable to widen the bandwidth of the system and allow for integration of the noise power over a wider final output band. To add this functionality in Milan, the IF was thusly reconfigured in September 2017 – Figure 3 shows the block diagram of the receivers in their present and upgraded configuration. The system consists of 1.2 m (Ka) and 0.6 m (Q) Cassegrain reflector antennas, each with beamwidths of 0.9° and with gains of 45.6 dBi. This narrow beamwidth, in conjunction the inclined orbit of Alphat (0° - 3°), necessitates active tracking of the beacons which is accomplished through the use of electronic pan/tilt positioners that update the pointing of the antennas once every 60 seconds with a pointing accuracy of 0.01°. The first downconversion of the beacon occurs directly at the feed of each antenna. The Ka-band channel is downconverted from 19.701 GHz to 70 MHz in one stage, while the Q-band is downconverted in two stages from 39.402 GHz to 20.199 GHz and then to 70 MHz. All local oscillators (LOs) are referenced to a common ultra-stable 10 MHz citrine oscillator. The RF electronics are mounted to a temperature-controlled cold plate that is stabilized within ± 0.01°C through thermoelectric cooling (TEC) tiles. The low-noise amplifier (LNA), which is mounted to the waveguide output of the antenna rather than the cold plate, is maintained to ± 0.1 °C through its own TEC tile. The air temperature within the enclosures is not controlled directly but remains stable within ± 2 °C as a
byproduct of the plate and LNA control. After downconversion to 70 MHz, both channels continue to a second, common IF stage < 2 meters from the antennas which is also temperature controlled to within ± 1 °C. In this stage, the final downconversion to 5 MHz occurs, followed by additional filtering and amplification prior to transmission of the signal to the digitizer over coaxial cabling. Discussion of the digital signal processing beyond this point is discussed in Section 3.

2.2 | Edinburgh, Scotland

The Edinburgh beacon receiver was installed at the HWU campus in March 2016 on the roof of the Earl Mountbatten building (Figure 4) and observes Alphasat at an elevation of 21°, presently the lowest elevation angle measurements within the Alphasat campaign. A nearby Campbell Scientific weather station is located approximately 70 m to the south of the receiver and 42° west of the path to Alphasat, again providing the standard meteorological measurements of temperature, pressure, humidity, wind speed, wind direction, and rain accumulation via a tipping bucket. The design of the HWU receiver is largely derived from the Q-band channel of the Milan terminal with a few incremental improvements such as the elimination of the secondary IF enclosure and the addition of the noise power measurement.

FIGURE 4 The Q-band Alphasat receiver at Heriot-Watt University in Edinburgh, Scotland, UK. On the left, a photo of the Q-band beacon receiver with tracking system, and on the right, an overhead view of the receiver location atop the roof of the Earl Mountbatten building.

FIGURE 5 A block diagram of the Edinburgh Q-band beacon receiver, which downconverts from 39.402 GHz to 5 MHz in three stages within the outdoor, temperature-controlled enclosure. A 1 MHz bandwidth is used to accommodate noise power measurement.
As in Milan, the Scotland beacon receiver utilizes a 0.6 m Cassegrain reflector with a 0.9° beamwidth, 45.6 dBi gain, and mechanical tracking with a resolution of 0.01°. At all NASA Alphasat stations, the positioning system employs open-loop tracking utilizing Orbital Ephemeris Message (OEM) data which is updated weekly. Temperature stability for the RF electronics is achieved in the same manner with control of the cold plate to the same tolerances, although the LNA does not have independent temperature control in this system. Another change as compared to Milan is that the downconversion is implemented entirely within the enclosure at the antenna feed (from 39.402 GHz to 20.199 GHz to 70 MHz to 5 MHz). The LNA used in the Edinburgh system also has a slightly higher noise figure as compared to the Milan receiver (3.4 dB vs. 2.7 dB at POLIMI), resulting in a slight reduction of dynamic range (35 dB vs. 40 dB at POLIMI).

3 | DIGITAL SIGNAL PROCESSING

3.1 | Frequency Tracking & Windowing

In both Milan and Edinburgh, the downconverted 5 MHz beacon signals are digitized using a National Instruments PCI-5124 oscilloscope card. Measurement of the signal power is accomplished through a novel frequency estimation technique[12, 13] using a variant of the Quinn-Fernandes (QNF) frequency estimator[14, 15], which interpolates the Fast Fourier Transform (FFT). Measurements are recorded at a rate of 10 Hz and are also averaged in real time to 1 Hz. This allows for characterization of atmospheric scintillation with the 10 Hz data while the 1 Hz data remains available for characterization of attenuation and other long timescale phenomena without affecting the computational load. The sampling frequency and number of points acquired by the digitizer for each measurement are adjustable and are primarily set to maintain a measurement bandwidth near to 10 Hz within the processing capabilities of the digitizer and workstation (e.g. a sampling frequency of $f_s = 3.07$ MHz and $N = 2^{18}$ for a measurement bandwidth of $f_s/N = 11.7$ Hz).

Several digital processing techniques are also applied to maximize the dynamic range of the receivers by improving their performance in low signal-to-noise ratio environments: the simplest of these is the use of an a priori frequency window to limit the measurement to a small frequency range known to contain the beacon. Because the QNF algorithm begins with a simple peak search, it is susceptible to favoring spurious noise peaks over the true signal when the SNR is low. This can be reduced by restricting the bandwidth of the peak search as signal power decreases. While the

![Figure 6](image-url)  
**Figure 6** Timeseries examples of heavy attenuation events in in Milan (left, 2017-09-01), and in Edinburgh (right, 2017-11-16), demonstrating the full dynamic range of the receivers and the frequency tracking algorithms.
beacon frequency does drift gradually due to Doppler shift, it does not change significantly over the duration of extreme fades. This windowing procedure is implemented by maintaining an 2-minute average of the most recent frequency observations as long as the beacon is above a predefined high-power threshold. As the power approaches the noise floor and falls below this threshold, the peak search of the QNF algorithm is restricted to a small bandwidth around the mean of the previously observed frequency. The size of the window must be larger than the maximum expected doppler drift over the duration of any event that fully exceeds the system dynamic range, such that the beacon is immediately reacquired as it reappears above the noise.

A second technique is also employed in Milan, where both the Ka- and Q-band channels are being observed. With measurements of both channels available, the Ka-band signal can be used to track the Q-band beacon during moderate fades due to the coherency of the two beacons. In moderate attenuation events where the Q-band channel is near the noise floor but the Ka-band channel is still clearly visible, the frequency of the Q-band beacon can be predicted from an accurate measurement of the Ka-band beacon frequency. In this case, a similar a priori window is applied as described above, but here the center of the band is defined by the prediction calculated from the observed Ka-band frequency. This results in a modest increase in dynamic range by eliminating erroneous estimates caused by spurious peaks in the initial peak search of the QNF algorithm.

Figure 6 presents timeseries examples of heavy attenuation events for each receiver, Milan (left) and Edinburgh (right). In both examples, the total attenuation (top) exceeds the full dynamic range of the receivers, and the effect of the aforementioned tracking algorithms can be observed in the recorded IF frequency of the beacons (bottom). In Milan, the Q-band receiver fades below the noise floor for over 10 minutes, but the receiver is able to utilize the Ka-band signal to continue tracking the anticipated frequency of the Q-band beacon. While this does not impact performance for periods where the signal level is completely below the noise floor, it is able to slightly improve dynamic range at the fringes of the event by reducing the effect of noise on the frequency estimation algorithm. It is only as the Ka-band signal also loses lock for approximately 2 minutes that the algorithm is unable to accurately predict the location of either beacon. In the Edinburgh example, the Q-band signal is tracked through use of past frequency measurements. As the power fades below the noise floor, the past frequency observations are used to restrict the frequency estimate to a narrow band around the expected beacon location. This approach is also implemented in Milan for conditions when the Ka band beacon is unavailable, although it as not as readily visible in this example due to use of a wider bandwidth window.

3.2 Filtering, Decimation & Digital Radiometric Measurement

While the 5 MHz output of each beacon receiver would require a sampling rate of ≥10 MHz to meet the Nyquist sampling requirement, the extremely narrow-band nature of the CW signals allows for several alternative approaches.

![Figure 7](image-url)  
**Figure 7** Example noise power measurement of a moderate attenuation event in Edinburgh, 2018-01-23.
In Milan, the signals are bandpass sampled; the channels are bandpass filtered, and the sampling rate is set below the Nyquist rate such that the image of the high-frequency components is observed at baseband. This reduces the computational load as opposed to sampling at a much higher rate, which requires the processing of orders of magnitude more data that is not required to characterize very narrowband beacon signals. Beginning in Edinburgh, a process of filtering and decimation was designed to similarly expedite processing time while also enabling a digital radiometric measurement. In the Edinburgh implementation, the spectrum is fully Nyquist sampled (fs = 11.11 MHz) and a digital bandpass filter (50 kHz, 10th order Type 2 Chebyshev) is applied to isolate the beacon signal. The frequency tracking of the signal, detailed in Section 3.1, is also used here to center the passband of the Chebyshev filter at the current tracked frequency. The resulting filtered spectrum is then digitally decimated by a factor of 32 to reduce processing time (given the processing requirement of 0.1 seconds mandated by the 10 Hz measurement rate). In parallel with the beacon power measurement, the original, fully sampled spectrum is also filtered with a notch filter centered at the beacon frequency to eliminate the beacon. Here, a 10th order Type II Chebyshev bandstop filter with a 250 kHz bandwidth is applied. This is done to null the beacon signal and allow for an integrated noise power measurement over the full IF bandwidth of 1 MHz. With the beacon signal removed, the noise power within the final 1 MHz bandwidth is integrated and recorded at 10 Hz and averaged over a 1 sec integration time, resulting in an estimated radiometric resolution of:

\[
\Delta T = \frac{T_{sys}}{B + \tau} = \frac{908K}{\sqrt{10^6 \text{Hz} \times 1 \text{sec}}} = 0.908K
\]

A 1 MHz bandwidth is still very narrow for a radiometer measurement, but previous analysis [16] has demonstrated it to have utility alongside the beacon measurements, particularly given the very limited cost and overhead required to implement it. Calibration of the digital radiometer measurement is also detailed in previous work [16]. Figure 7 presents an example timeseries measurement of the integrated noise power along with the received Q-band beacon power during a moderate attenuation event in Edinburgh, demonstrating the expected inverse correlation between two.

### 3.3 Data Calibration

Measured signal attenuation is calibrated using vertical profiles of pressure, humidity and temperature from the European Centre for Medium-Range Weather Forecast (ECMWF) and the MPM93 Mass Absorption Model[17] to calculate reference clear-sky attenuation levels. This reference level is compared to clear-sky conditions at the receivers (identified using the on-site rain gauges) and a calibration offset is calculated on a monthly basis. In the event that a single calibration is not valid for a full month (e.g. due to changes in operation such as the 2017 receiver modifications), the offset is calculated for shorter periods as necessary. In addition, erroneous data (power outages, loss of satellite tracking) are removed from the data by manual inspection.

### 4 RESULTS

#### 4.1 Milan, Italy

After calibrating the datasets as described in Section 3.3, the total attenuation from each site was statistically analyzed for characterization of the attenuation statistics over the presently available data. Milan was characterized from May 2014 through June 2018 for a total of four years and one month. The annual attenuation statistics for Milan are shown in Figure 8a (Ka) and 8b (Q) in the form of complementary cumulative distribution functions (CCDFs). Each curve
FIGURE 8  Complementary Cumulative Distribution Functions (CCDFs) of total attenuation in Milan at Ka- (19.701 GHz) and Q-band (39.402 GHz), by year (top) and averaged by month (bottom).

represents the noted calendar year, with the exception of 2014 and 2018, which are a partial years at the beginning and end of the dataset (from May 2014 forward, and from June 2018 backward). The total CCDF over the entire dataset is also shown, as well as a comparison with the ITU-R model[18, 19, 20], which shows very good agreement. For 99% availability, the associated link margin was 2.56 dB (Ka) and 6.73 dB (Q).

In addition, in Figure 8c and 8d, a seasonal analysis is presented in the form of monthly average CCDFs. These curves represent the average of each calendar month for all data in the data set – e.g., the curve for ‘May’ (dark green) is the average of all data collected during the month of May from 2014 to 2018. Again, the ITU model shows good agreement with the total curve, with the wetter summer months (June, July, August) experiencing a statistically higher attenuation than the average model, and the drier winter months experiencing less (December, January, February). This is true of both the Ka- and Q-band channels, although there is a more marked variability between the wet/dry seasons at Q-band due to the significantly higher impact of rain attenuation in the 40 GHz band. The highest average attenuation, observed in June, corresponded to a 99% availability margin of 3.87 dB (Ka) and 9.54 dB (Q). The lowest attenuation, observed in December, corresponded to 1.22 dB (Ka) and 1.95 dB (Q) at 99% availability.

Figure 9 also presents plots of the power spectral density (PSD) during strong, characteristic events of rain atten-
4.2 Edinburgh, Scotland

The Edinburgh dataset was characterized from April 2016 through May 2018 for a total of two years and one month. The annual attenuation statistics at Q-band are shown in Figure 10a. As in Figure 8b, each curve represents the noted calendar year, with the exception of those at the beginning and end of the dataset (2016 and 2018) which are partial years. The total CCDF over the entire dataset is also shown, as well as a comparison with the ITU-R model. Here,
agreement with the ITU-R model is not as good as in Milan, and it is postulated that this is due to an overprediction of rain rate within the model. While rain in Edinburgh is extremely common, it tends to rain frequently at low rain rates (< 20 mm/hr) and more rarely at higher rain rates, which may be the cause of the discrepancy between the model and the collected data. The model curve plotted in 8b was generated by interpolation of the ITU-R P.837-7 rain maps[19], yielding an 0.01% rain rate of $R_{0.01} = 49.0$ mm/hr. Data analyzed from the HWU tipping bucket suggests a much lower $R_{0.01} = 19.5$ mm/hr. When this lower rate is incorporated, agreement is better, although there is still a noticeable overprediction. 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.

In addition, in Figure 8c and 8d, the monthly averages are presented for Edinburgh. As in Figure 8d, these curves again represent the average of each calendar month for all data in the data set. Here, it can be observed that the ITU model shows better 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 highest average attenuation, 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 attenuation, observed in December, corresponded to 2.86 dB, 4.42 dB, and 9.11 dB at 95%, 99%, and 99.9% availabilities.

5 CONCLUSIONS

NASA’s participation in the Alphasat propagation experiment has thus far yielded 11 station years of propagation data between the Ka- and Q-band measurements in Milan, Italy, and Edinburgh, Scotland. The data collection campaigns are expected to continue for a minimum of five years at each location, and may be extended contingent upon hardware lifespan and beacon payload availability. Herein we have presented the design, operation, and first several years of statistics of the propagation data collected at POLIMI and HWU. In addition, a third Q-band receiver was recently deployed to NASA’s Madrid Deep Space Communications Complex, and a fourth Alphasat terminal is planned for installation in Andaya Norway by 2019, which is expected to supersede Edinburgh as the highest latitude Alphasat installation with an elevation of approximately 11°. These low elevation angle polar measurements will also complement the ongoing ESA/NASA Ka-band measurement campaign in Svalbard [22]. Future publications will explore second-order propagation statistics such as rain fade duration and fade slope, as well as further statistical characterization of scintillation.

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REFERENCES


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JAMES NESSEL received the B.S. and M.S. degrees in electrical engineering from Arizona State University (ASU) in 2002 and 2004, respectively, and received his Ph.D. in 2014 from the University of Akron in the area of active phase compensation of widely distributed antenna arrays. At ASU, he specialized in semiconductor device theory where his research involved the development of models for predicting the effects of gamma radiation on semiconductor microelectromechanical systems (MEMS) devices with Los Alamos National Laboratories. Since 2004, he has been an Electronics Engineer with the Advanced High Frequency Branch of the National Aeronautics and Space Administration Glenn Research Center in Cleveland, OH, USA. He is presently co-investigator of NASA’s Atmospheric Propagation Studies project, and his research interests include Ka-band propagation, microwave remote sensing, and active phase correction for transmit arraying of microwave signals.

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**Lorenzo Luini** was born in Italy, in 1979. He received the Laurea Degree in Telecommunication Engineering in 2004 and the PhD in Information Technology in 2009 both from Politecnico di Milano, Italy. He is currently an assistant professor at DEIB (Dipartimento di Elettronica, Informazione e Bioingegneria). Since 2004, his research activities have been relative to E.M. wave propagation through the atmosphere, both at radio and optical frequencies: physical modeling and synthesis of the meteorological environment (atmospheric gases, clouds and precipitation); development and implementation of models for the remote sensing of atmospheric constituents using radiometric data; physical and statistical modeling for E.M. propagation applications (rain intensity, gaseous absorption, attenuation due to rain/ice particles, wave depolarization, scintillations, attenuation dynamics, attenuation due to clouds, expected performance of SatCom and terrestrial wireless links, radio interference, spatial correlation of phenomena); analysis and dimensioning of wireless terrestrial and SatCom (GEO, MEO, LEO) systems operating in the 1 to 100 GHz range; design and simulation of systems implementing Fade Mitigation Techniques (site/time diversity, reconfigurable systems, power control); assessment of the impact of the atmosphere on Free Space Optics Earth-space (to satellite or deep space probes) systems; assessment of the impact of atmospheric constituents on Ka-band Synthetic Aperture Radars (SAR); analysis of the performance of space-borne GNSS receivers. He has been involved in several European COST projects, in the European Satellite Network of Excellence (SatNEx), and in several projects commissioned to the research group by the European Space Agency (ESA) and the USA Air Force Laboratory. Lorenzo Luini also worked as a System Engineer in the Industrial Unit—Global Navigation Satellite System (GNSS) Department—at Thales Alenia Space Italia S.p.A.

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