

Enhanced Alphasat Aldo Paraboni Q/V Band Test-bed Configurations for Additional Experiments (CALIBRATE)

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Abstract

Future Q/V-band satellite communication systems will rely on adaptive techniques such as Smart Gateway Diversity (SGD), Adaptive Coding and Modulation (ACM), and Uplink Power Control (ULPC) to mitigate severe atmospheric propagation impairments that became critical as carrier frequencies increase. The evaluation of their performance requires realistic propagation datasets and representative system-level simulation environments. This paper presents the methodology developed within the ESA CALIBRATE project to construct a measurement-driven Q/V-band satellite communication Test-Bed for the assessment of adaptive control algorithms. More than ten years of heterogeneous propagation

measurements from the Alphasat Aldo Paraboni, Astra 3B, and Ka-Sat experiments are harmonized into a unified propagation database and used to construct representative Gateway and User Earth Station configurations. Synthetic attenuation time series generated from ERA5-driven channel models complement the measurements to extend the temporal coverage and support a larger Reference System. The resulting framework enables realistic system-level simulations and performance scaling from the experimental Test-Bed to an operational Very High Throughput Satellite (VHTS) system.

1. Introduction

The continued growth in broadband satellite communications is driving the development of High Throughput Satellite (HTS) and Very High Throughput Satellite (VHTS) systems capable of delivering ever-increasing network capacity [1]-[4]. One of the principal approaches for achieving this objective is the migration of feeder links from the conventional Ka band to the Q/V bands, where substantially larger bandwidths are available [1], [2]. By moving the feeder segment to higher frequencies, additional Ka-band spectrum can be reserved for user links, enabling higher overall system throughput and more efficient spectrum utilization [1]-[4].

The principal challenge associated with Q/V-band operation is the increased sensitivity of the propagation channel to atmospheric impairments. Rain attenuation, clouds, atmospheric gases, and water vapour introduce severe attenuation with significant temporal and spatial variability, making the performance of the communication system strongly dependent on both the local propagation conditions and the geographical distribution of the gateway network [1], [5]. Consequently, future Q/V-band systems are expected to rely on a combination of different adaptive techniques such as Adaptive Coding and Modulation (ACM), Uplink Power Control (ULPC), and Smart Gateway Diversity (SGD) to maintain high availability and maximize system capacity [2]-[4], [6].

The evaluation of these adaptive techniques requires realistic propagation data that simultaneously capture the temporal evolution of atmospheric attenuation and its spatial correlation across multiple sites [7], [8] over the large (typically continental) coverage area of the Fixed Satellite Service. Although several long-term propagation measurement campaigns have been conducted throughout Europe, including the Alphasat Aldo Paraboni Scientific experiment [6], [9]-[18] and complementary Ka- and Q-band experiments [8], these datasets were primarily developed for propagation studies rather than system-level satellite simulations. They measured data differ in observation period, operating frequency, sampling interval, geographical coverage, data availability and quality, making their direct use within a common satellite communication simulator particularly challenging.

To address these limitations, the European Space Agency (ESA) CALIBRATE project developed a measurement-driven Q/V-band satellite communication Test-Bed representative of a future operational system and proposes a new methodology to scale the performance of continental adaptive systems from smaller initial deployments (defined as test-bed) to the final large scale operational network (defined in the following the 'reference' system). This methodology could be used by operators of VHTS systems to assess the actual system performance (e.g. in terms of throughput) VS the expected ones (defined by the initial design) as the operational system is gradually deployed, taking into account the effect of stochastic variability in space and time of the Q/V band atmospheric radio channel. In this way the initial cost and risk of the system can be controlled and eventually adapted to changing market requirements. The framework combines long-term experimental propagation measurements with statistically consistent synthetic attenuation time series to support the evaluation of adaptive satellite communication techniques under realistic atmospheric conditions [7], [14]. A reduced-scale Test-Bed (TB), driven by measured propagation data, is coupled with a larger Reference System (RS) using identical simulation logics, enabling the performance observed on the experimental network to be extrapolated to an operational VHTS configuration.

This paper presents the methodology adopted to construct the CALIBRATE TB and its associated propagation database. Starting from more than ten years of heterogeneous propagation measurements collected across Europe, a representative network of Gateway Earth Stations (GESs) and User Earth Stations (UESs) is identified through a systematic selection process based on data availability, geographical distribution, and network topology. The resulting experimental datasets are complemented by long-term synthetic propagation time series to provide realistic simulation inputs for both the TB and the RS. Finally, the paper describes the simulation framework developed to evaluate adaptive Q/V-band satellite communication techniques using these datasets.

The remainder of this paper is organized as follows. Section II presents the CALIBRATE TB architecture and the corresponding RS. Section III describes the propagation measurement database and the associated data processing chain. Section IV presents the methodology used to construct the TB from

the available measurements. Section V describes the synthetic propagation datasets and the overall simulation framework. Finally, Section VI summarizes the main contributions of the work.

2. Reference System and Test-Bed Architectures

The CALIBRATE framework was developed to evaluate the performance of a stations system for Q/V-band Fixed Satellite Services using adaptive control techniques using propagation measurements. In this way the actual effect of the stochastic variability in space and time of the atmospheric radio channel over a continental region can be evaluated to produce a realistic statistical distribution of station system performance. The problem is addressed by using the existing network of terminals for propagation experiments as representative of the initial deployment of the stations system (i.e an operational test-bed operating for a certain period of time, TB) which will be gradually expanded towards the final system configuration (the reference system, RS) providing FSS to a large number of terminals over a continental coverage region (e.g. Europe). As it will be inherently complex and costly to perform propagation representative of the RS, the performance of the RS are evaluated using a performance scaling method, produced using the ESA LASCAMOD atmospheric channel model (derived using a large dataset of propagation experimental data). In this way the statistical variability of TB performance, determined using experimental propagation data, can be scaled to the size of the RS using a coherent approach based on actual data (i.e. ESA LASCAMOD model and CALIBRATE data).

The RS considers a hybrid Ka/Q/V-band GEO satellite communication network employing a star topology, illustrated in Figure 1. User links operate in the Ka band, whereas feeder links use the Q/V bands to exploit the larger spectrum available at higher frequencies [1], [2]. The adopted architecture is representative of current concepts for future Q/V-band feeder-link satellite systems employing geographically distributed gateways and adaptive fade mitigation techniques [1]-[4]. The reference configuration consists of 10 Ground large Earth Stations (GESs), implementing an 8+2 Smart Gateway Diversity (SGD) architecture [3], [4], together with 206 small User Earth Stations (UESs) distributed across Europe. The simulated system includes a 50 GHz forward feeder uplink, a 20 GHz forward user downlink, a 30 GHz return user uplink, and a 40 GHz return feeder downlink.

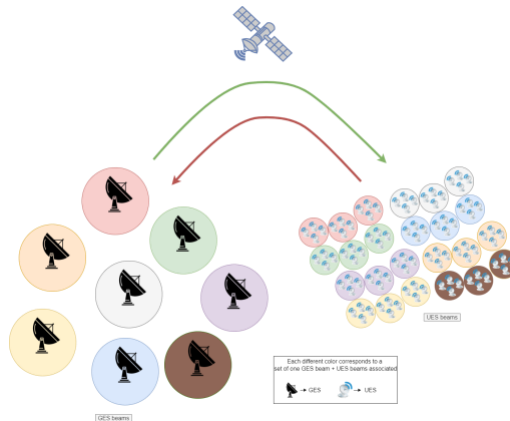


Figure 1: Reference satellite communication architecture considered in the CALIBRATE study, with Q/V-band feeder links and Ka-band user links.

The principal characteristics of the TB and the RS are summarized in Table 1. The TB preserves the same communication architecture and control logic while reducing the number of GES and UES to match the available experimental infrastructure. Importantly, every GES included in the TB is also present within the RS, ensuring a consistent relationship between the two configurations and enabling subsequent scaling of the distributions of station system performance.

Table 1: Input types and scale of the TB and RS simulations

Feature	Test-Bed (TB)	Reference System (RS)
Purpose	Experimental Evaluation	Operational-scale reference
Network Size	Reduced-scale	Commercial-scale
GES	4	10 (8+2 SGD)
UES	7-9	~200
Propagation data	Measured and synthetic	Synthetic
Main Application	Experimental validation	Performance benchmarking

Two complementary TB configurations are considered throughout this work. The first configuration, denoted TB1, is derived from propagation measurements collected before 2024 (the start of ESA Calibrate campaign) [6], [9]-[11], [14]-[18] (defined as historical). TB1 was defined to maximize the availability of concurrent measurements across the ground segment and to provide an alternative dataset in case of insufficient data availability or measurement outages during the CALIBRATE campaign. It comprises four GESs and nine UESs distributed across Europe. The second configuration, TB2, corresponds to the experimental network of propagation terminals deployed during the execution of the CALIBRATE project (from July 2024 to June 2025) and represents the operational measurement configuration used throughout the campaign. TB2 comprises four GESs and seven UESs and therefore provides the primary experimental dataset used to reproduce the propagation conditions experienced by the CALIBRATE measurement network. Figure 2 illustrates the geographical distribution of the TB stations together with the corresponding RS gateways.

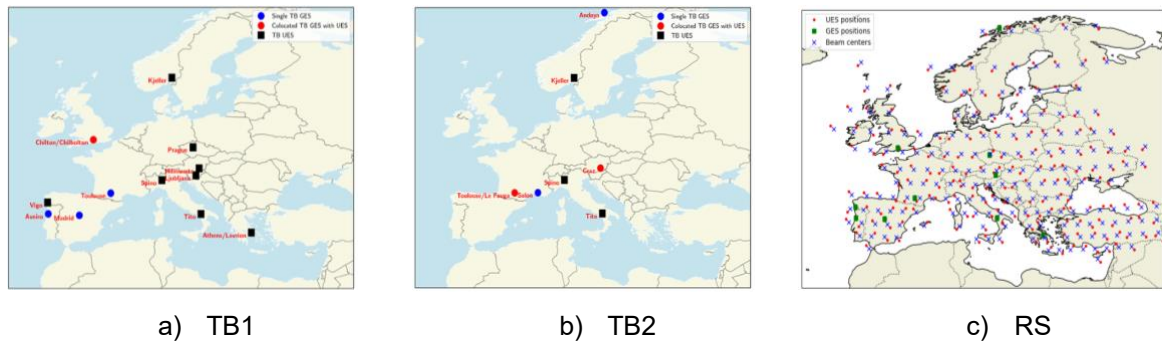


Figure 2: Position of the GES and US in the Test-Bed 1 and Test-Bed 2 (a and b) and in the reference system c). Figure c indicates also the positions of the satellite antenna beams.

Both the TB and the RS are simulated using the same space segment. The simulator implements the complete forward-link processing chain, including link-budget calculations, ACM, ULPC, and SGD [12]. Consequently, the only differences between the two systems arise from the ground segment (UES/GES), the number of gateway and user stations, and the propagation data used to drive the simulations. This computational framework enables the direct comparison of TB and RS performance under identical operating assumptions.

3. Propagation Measurement Database

The assessment of the communication performance of TB1 and TB2 depends strongly on the data quality, availability, accuracy and statistical representativity of the propagation data used to drive the system simulator developed during Calibrate (obtained as an update of BiLiDget (Bidirectional Link budget, developed by ONERA in the framework of the ESA LASCAMOD project [12]). Consequently, the first step in the CALIBRATE methodology was the construction of a coherent set of propagation data from multiple long-term satellite propagation campaigns conducted across Europe by various organisations during different projects, collaborating in the framework of the ASI/ESA ASAPE group [13].

The main and most relevant source of propagation data is the Alphasat (TDP5) Aldo Paraboni scientific experiment (SCIEX), which provides long-term attenuation measurements (since 2014) at Ka- and Q-band frequencies from a distributed network of beacon receivers [6], [9]-[11], [14]-[18]. To extend both the temporal coverage and geographical diversity of the database, these measurements are complemented by historical campaigns performed using the Astra 3B and Ka-Sat satellites [17], [18]. Together, these datasets provide more than ten years of propagation measurements, spanning the period from January 2015 to June 2025 and covering approximately twenty terminals distributed across a wide range of European climatic regions.

Although extensive, the resulting database is inherently heterogeneous. The individual propagation campaigns were performed independently by different organisations in the framework of different projects (e.g. national, ESA or internal R&D activities) established independently and therefore differ in operating frequency, sampling interval, observation period, attenuation products, and data availability [6], [9]-[11], [14]-[18]. Beacon measurements are primarily available around 19.7 GHz and 39.4 GHz, with additional observations acquired at nearby frequencies depending on the experimental campaign. Likewise, sampling intervals range between 0.1 s and 1 s, while some stations provide total

atmospheric attenuation measurements (i.e. derived using a co-located microwave radiometer, MWR)) and others only excess attenuation (intended as representative of attenuation due to atmospheric precipitation). These differences prevent the direct use of the exhaustive measurement archive within a common satellite communication simulator.

To produce a consistent set of propagation inputs, all available measurements are harmonized through a common processing chain aimed at producing a coherent set of input data for the system simulator, as illustrated in Figure 3. Raw beacon measurements first underwent quality control to identify invalid samples, receiver outages, loss-of-lock events, and hardware anomalies [22]. Measurement timelines are subsequently synchronized, and all the total atmospheric attenuation measurements are processed to derive excess attenuation (the remaining components, *i.e.*, gas and cloud attenuation, are added successively to all data, to ensure a consistent estimate for both the original total and excess attenuation data [15], [16]. The measured data are validated by comparing distributions with predictions obtained using the method of ITU-R Recommendation P.618-14. Finally, the frequency-scaling procedure, based on ITU-R Recommendation P.618-14 is applied whenever necessary to map the measured attenuation to the operating frequencies adopted by the satellite system simulator [5], [19]-[24]. Additional atmospheric attenuation contributions due to clouds and atmospheric gases were generated using atmospheric data from concurrent ECMWF ERA5 meteorological reanalysis together with the ITU-R P.676 and P.840 models [26]-[28]. The output of this processing chain is a unified propagation database comprising calibrated, synchronized, and simulator-ready total attenuation time series for all available measurement stations.

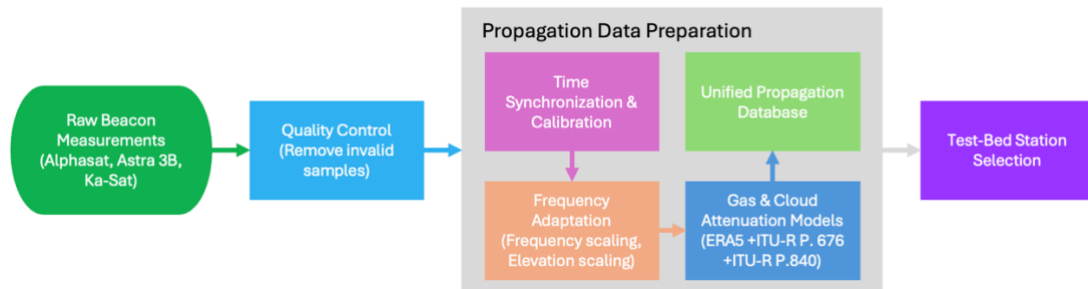


Figure 3: Propagation data preparation workflow used to generate the unified propagation database.

Despite the consistency of the database provided by the harmonization process, data from various terminals were collected from different propagation campaigns at different time. Moreover, even in a campaign conducted within a specific project (e.g. the ESA ASALASCA [29] each terminal can have different operational periods and valid data availability. These facts prevent us to directly use the dataset in a single TB configuration. Consequently, an additional selection methodology was developed to identify representative subsets of propagation terminals selected to represent GES and UES, capable of supporting the generation of statistically representative system-level simulations. This methodology is presented in the following section.

4. Test-Bed Construction Methodology

The unified propagation database described in the previous section contains more than ten years of measurements collected from twenty European terminals, representing both GESs and UESs. Individual stations differ in observation period and data availability making the construction of a representative Test-Bed a constrained selection problem. The overall Test-Bed construction methodology is summarized in Figure 4.

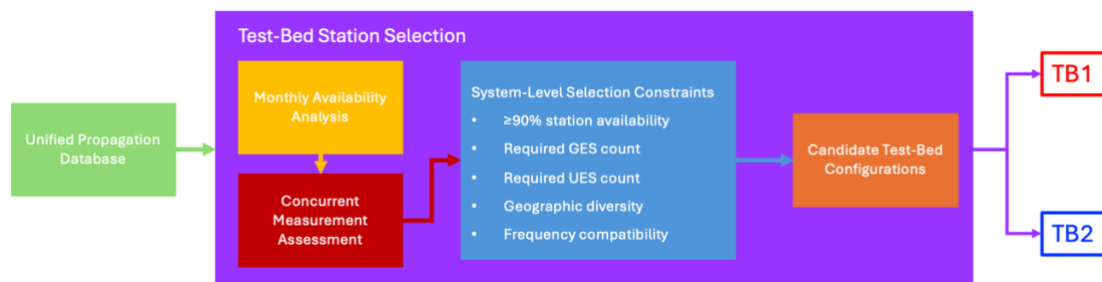


Figure 4: Methodology adopted for the construction of the Test-Bed.

As shown in Figure 4, the selection procedure begins with the analysis of every candidate station aimed at maximising the monthly data availability. For each station, the percentage of valid attenuation samples was evaluated for each month throughout the complete measurement archive to identify periods of reliable operation. This information was subsequently combined through the assessment of concurrent data among different terminals to determine intervals during which complete ground segment configurations could be formed. Unlike conventional propagation studies, which primarily focus on the statistical characterization of individual or paired propagation paths [8], system-level satellite simulations require simultaneous observations from multiple GESs and UESs over common time periods. Consequently, the station selection process must satisfy both concurrent measurement availability and network architecture requirements (e.g., at least 4 GES to perform meaningful SGD), which selects combinations of Earth stations.

Candidate configurations have then evaluated against a series of system-level constraints. These included a minimum station availability of approximately 90% (high enough to possibly produce to a reasonable concurrent availability and corresponding to the annual data availability target set by ITU-R Study Group 3 for data submission), sufficient numbers of operational GESs (at least 4) and a maximum of UES to support SGD simulations, broad geographical coverage representative of different European climatic regions, and compatibility with the propagation adaptation procedures described in Section III.

The selection process resulted in two complementary TB configurations:

1. TB1 based on historical propagation measurements acquired between July 2017 and June 2018 and was selected to maximize concurrent data availability prior to the CALIBRATE measurement campaign. This configuration provides four GESs together with seven UESs for measured-data simulations while maintaining high concurrent availability.
2. TB2 derived from measurements collected during the CALIBRATE campaign between August 2024 and July 2025. It represents the operational measurement network established within the project and serves as the primary experimental dataset for validating the proposed simulation framework. The configuration comprises four GES and up to four concurrently available UES, reflecting the measurement availability achieved during the campaign. Although the number of operational UESs is lower than for TB1, TB2 provides a realistic representation of the deployed experimental infrastructure.

Together, TB1 and TB2 provide complementary propagation datasets for system-level simulations. TB1 on one hand is an extensive historical dataset with high concurrent availability generated with different satellites, while TB2 focuses on the use of Alphasat (TDP5) Ka/Q band SCIEX in the recent period leveraging on consolidated measurement methods and procedures.

5. Simulation Framework and Validation

a. Generation of synthetic time series using an atmospheric radio channel model

Although the TB is driven primarily by experimental propagation measurements, the available datasets are insufficient to support long-term statistical analyses or to directly represent the larger RS. Consequently, synthetic attenuation time series has been generated to extend the temporal coverage of the measurements while preserving the statistical characteristics of the local propagation environment [7], [14].

The synthetic propagation database was generated using the ESA/LASCAMOD channel model [25] driven by ERA5 meteorological reanalysis data [26]. Five independent meteorological years (2015–2019) were combined with ten stochastic realizations per year, resulting in an equivalent observation period of fifty years for every simulated ground segment of the TB while five years of data have been generated for the RS. This approach captures both the natural variability of meteorological conditions and the stochastic evolution of rain events, providing statistically robust propagation inputs for system-level simulations.

b. General description of Simulation Activities

The propagation datasets developed throughout this work support three complementary simulation activities, illustrated in Figure 5. Together, these activities provide a complete framework for training the performance scaling methodology, applying it to measured propagation data, and validating the representativeness of the synthetic attenuation model. The simulator used in ESA CALIBRATE, is an updated version of the original BiLiDget simulator, developed initially by ONERA in the framework of the ESA LASCAMOD project [12]. In this version BiLiDget implements parallel computing using Python

modules to simulate both the forward and return link using propagation data (either synthetic or measured). More details on the system simulator are provided in another paper of this conference [REF ONERA PAPER].

The simulation activity is based on 3 separate experiments (see Figure 5).

The first activity (EXP1) employs the same synthetic attenuation time series, generated using the channel model of ESA/LASCAMOD project) to simulate simultaneous operations of the TB and the RS systems. This equivalent to simulate the two systems as operating in the same period and coverage area. Since the stations of TB1 (and TB2) are a subset of RS, this configuration provides fully correlated system parameters of TB1 (or TB2) and RS. Then the statistical results of these paired simulations can be used to identify the performance scaling method.

The second activity (EXP2) applies the performance scaling methodology derived in EXP1 to the results of TB simulations driven by measured propagation data collected during the historical (TB1) and CALIBRATE (TB2) campaigns. In this way the corresponding RS performance are estimated starting from actual atmospheric conditions (as originally measured by the propagation terminals) and scaled with a coherent method (i.e. by using the channel model of ESA/LASCAMOD project, also based on experimental data).

The third activity (EXP3) aims at assessing the statistical fluctuation due to interannual fluctuations over a long period and the accuracy of the channel model for synthetic time-series, by comparing the results obtained those obtained with measured attenuation statistics (exp 3a which is equivalent to the output of EXP2) with those obtained a large number of synthetic timeseries (exp 3b 50 years TBC, also generated with the channel model of ESA/LASCAMOD project) Long-term attenuation distributions and performance parameters can then be analysed to quantify the uncertainty introduced by both the channel model and long-term interannual variations. In this way the uncertainty associated with the results to a real operational testbed executed for a limited period (e.g. 6 months or 1 year) can be estimated.

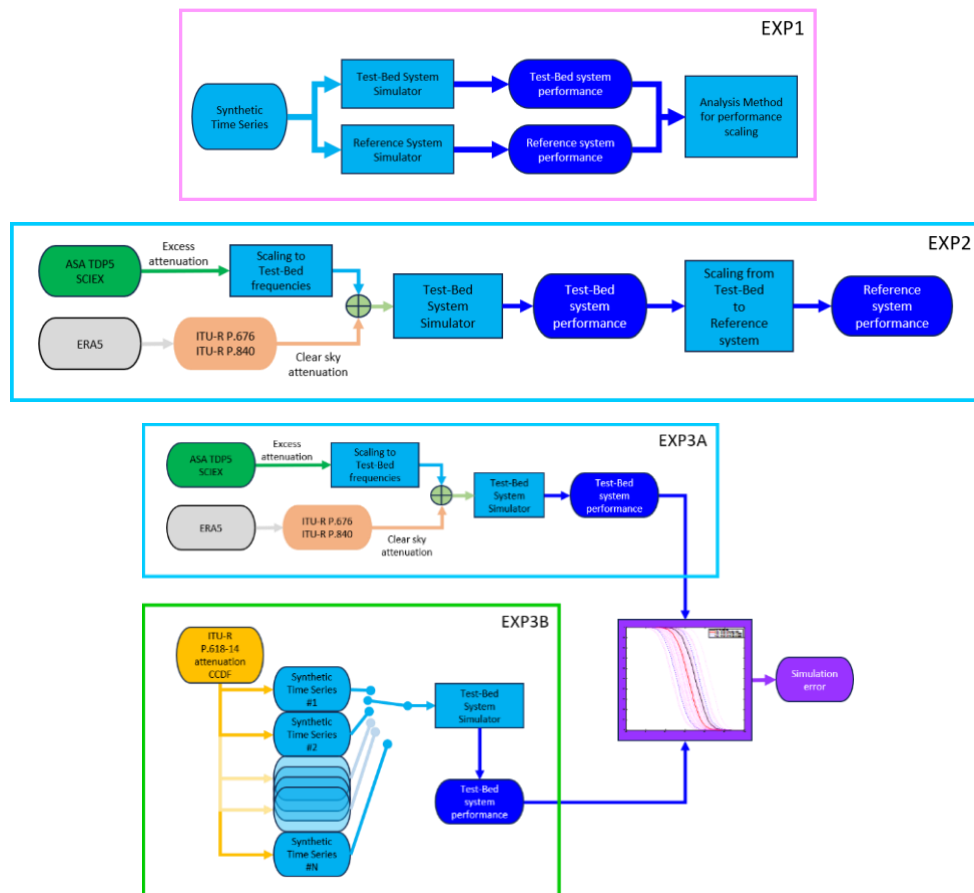


Figure 5: Simulation framework adopted within the CALIBRATE methodology

6. Conclusions

This paper has presented the methodology adopted within the ESA CALIBRATE project to construct a measurement-driven TB for the evaluation of adaptive Q/V-band satellite communication systems. By combining more than ten years of propagation measurements from multiple European satellite experiments with statistically consistent synthetic attenuation time series, a unified propagation database was developed to support realistic system-level simulations.

A systematic TB construction methodology was introduced to identify representative ground segment configurations based on measurement availability, network topology, and geographical diversity. The resulting historical (TB1) and operational (TB2) TB configurations provide complementary datasets for the evaluation of adaptive techniques such as SGD, ACM, and ULPC.

Finally, a simulation framework combining synthetic propagation generation, measured-data simulations, and system-level performance scaling was presented, enabling the behaviour of a reduced experimental TB to be extrapolated to a larger RS representative of a future operational Q/V-band satellite network.

The proposed methodology establishes a flexible framework for evaluating advanced satellite communication techniques using realistic propagation measurements while providing a practical bridge between experimental test facilities and operational VHTS systems.

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