Multipath and Interference Modelling in Complex GNSS Scenarios

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Abstract — **This present paper describes the techniques and methodologies adopted by IDS in modelling complex GNSS scenarios such as airport sites, where local/ground augmentation system siting problems need an evaluation of the positioning signal degradation caused by multipath effects and interfering emissions. An overview is given of the main results achieved during a validation campaign, starting from basic laboratory tests, up to comparison with data measured in actual airport environments.**

I. INTRODUCTION

The improved performance of GNSS systems, achievable with the support of *wide-area augmentation systems* (e.g., the US WAAS and the European EGNOS) and *local-area augmentation systems* (DGPS or LAAS systems also referred to as GBAS, *Ground-Based Augmentation System*), has triggered a modernization process in aeronautical navigation, such as the use of GNSS systems in landing or precision approach procedures, [1] and [2].

In this context ICAO and RTCA have provided a large set of requirements to characterize GNSS performance in airport areas, [3]-[6], specifying the *minimal operational performance* in terms of service availability, signal integrity, level of interference and multipath, position accuracy, etc.

On the basis of these international standards, many *Air-Navigation Service Providers* (ANSPs), such as ENAV in Italy, are intensively investigating GNSS performance in airport areas, promoting measurement campaigns and funding studies to assess the degradation impact generated by complex environments (such as airport sites) on signal reception and positioning accuracy performed by state-of-art GNSS receivers.

These studies have led to the design and implementation of efficient and reliable predictive tools focused on the estimation of pseudorange accuracy degradation due to:

- multipath introduced by scattering phenomena in the presence of terrain and man-made obstacles;
- interfering emissions in the L1 bandwidth introduced by broadcast communication systems (e.g., TV, radio-aids, FM radio, etc.), near radionavigation aids or other communications services.

At the same time the promoted measurement campaigns have encouraged the setting up of a GNSS measurement system, in order to assess the actual GNSS performance furnished by GPS-Only, GPS/EGNOS and GBAS systems in many Italian airports which feature different orography, specific EM environments, air-traffic, etc.

Finally, specific electromagnetic measurements carried out in each site have enabled comparison with results generated by the aforementioned prediction software, in order to tune and validate the implemented algorithms.

The paper is basically arranged in three main sections:

- Sect. II: description of the modelling guidelines used to simulate a complex GNSS scenario.
- Sect. III: description of the measurement equipment used to acquire GNSS signals in Italian airport sites.
- Sect. IV: comparison between measurements and simulations.

II. MODELLING TECHNIQUES

The siting of a GNSS receiving station for a safety critical application such as aircraft instrumental approaches, requires the evaluation of multipath and interference impact on positioning measurements performed by the receiving station.

A quantitative and qualitative analysis of this impact is possible through a suitable mix of existing techniques tailored to the GNSS context.

Starting from its previous experience in antenna siting optimization based on CAD-based electromagnetic prediction tools, IDS has extended its modelling capabilities to GNSS scenarios. The different frames of modelling are presented in the following sections.

A. Surrounding Environment

The conformation of the ground and the main man-made obstacles in the neighbourhood of the GNSS receiving station is responsible for:

- possible obstruction of free-space signal propagation necessary for the evaluation of the satellite signal and interfering emissions really received;
- multipath effects due to reflection/diffraction phenomena between the sources (satellites) and the receiver.

For these reasons two different obstacle representation formats are involved for interference and multipath analysis respectively:

- a digital terrain model representing the terrain elevation for each point of a regular grid in the x-y plane (as shown in Fig. 1);
- an electromagnetic surface model (as shown in Fig. 2), which also accounts for constitutive equations of materials for a better estimation of reflection and diffraction coefficients. In addition, it includes a mesh fitting of the zone near the antenna to apply far field considerations with respect to the receiving antenna.

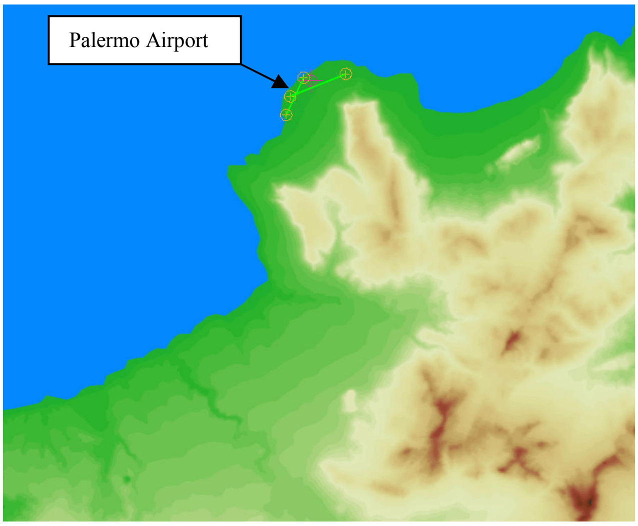

Fig. 1: Digital Terrain Model in the area surrounding Palermo Airport.

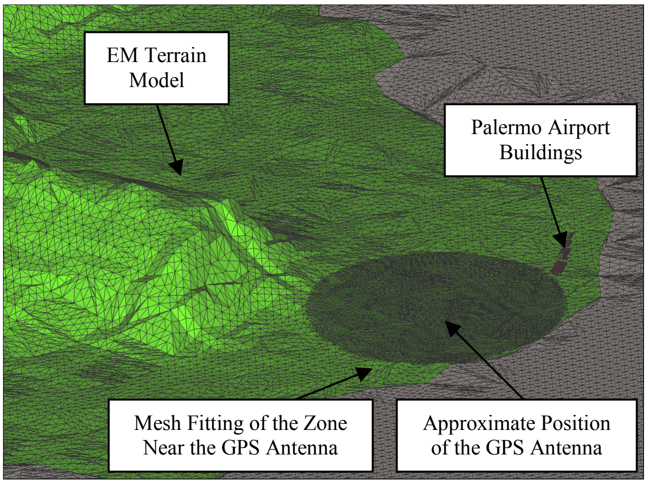

Fig. 2: EM Surface Model in the area surrounding Palermo Airport.

B. Antenna

Multipath analysis requires a faithful representation of the conversion from electromagnetic waves reaching the antenna itself into electrical signals. In particular the conversion must depend on polarisation and direction of arrival of the waves, as well as antenna phase and amplitude behaviour. For these reasons, accurate synthesis tools are available in order to model the most common antenna structures such as aperture, patch spiral or choke-ring antennas. Fig. 3 compares the vertical pattern of the NovAtel GPS-533 choke-ring antenna (extracted from data-sheet) and its representation obtained through patch modelling.

This antenna model can be simplified for interference assessment based on the estimation of interference power levels at the antenna port through a link-budget evaluation between interfering emitters and the receiving antenna. The L-band interfering emitters are collected in an electronic archive and are characterized by geographical coordinates, antenna pointing and transmitted channels. Power, horizontal and vertical patterns, modulation type and measured spurious emission are defined for each channel frequency. In this context only antenna gain elevation pattern (ground station antennas are typically omni-directional) and out-of-band selectivity is relevant for the receiving antenna modelling.

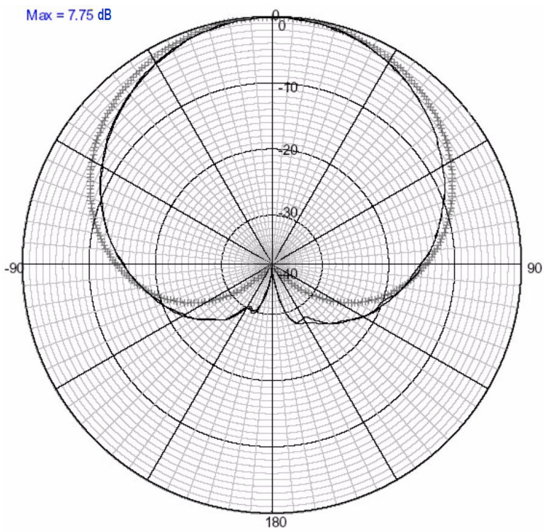

Fig. 3: Comparison between vertical pattern of the NovAtel GPS-533 choke-ring antenna (solid line) and its equivalent EM model (gray line).

C. EM Propagation

Starting from the EM propagation methods known in literature, IDS indentified GTD [7] (Geometrical Theory of Diffraction) and PO/PTD [8] (Physical Optics/Physical Theory of Diffraction) asymptotic approximations as the best solutions to treat the electromagnetic propagation of L-band signals such as those for GNSS. Nevertheless, a tailoring of the IDS proprietary EM solver was required in order to manage complex site models, whose faithful representation requires more than one million elements (such as the one shown in Fig. 2), each one responsible for a distinct propagation path. In particular, the PO/PTD approximation was re-examined to obtain a field representation in the time domain where the propagation paths appear as replies of the line-of-sight signal. In order to avoid the time domain representation of the antenna, which is complex and not useful in narrowband analysis, an optimised frequency domain method was used in place of the TDPO analytical representation proposed by Sun and Rush in [9]. In order to make the frequency domain efficient, an Inverse Fast Fourier Transform of an accelerated impulse-response analysis was applied. In fact, in the case of far field and narrow band conditions, a band-limited frequency domain response can be obtained through an analytical correction of the PO field at L1 frequency.

When a detailed analysis of the reflection/diffraction propagation paths is required, the IDS-UTD method becomes the suggested solution because it outputs a ray-based EM field representation.

The above mentioned propagation methodologies are typically involved during a multipath analysis. A simplified propagation model based on link budget consideration is applied in an interference analysis.

D. Receiver

GNSS receiver modelling is focused on the evaluation of the code-phase tracking error at the Delay Locked-Loop stage of a receiver's channel [11].

The multipath effect prediction is based on the simulation of the DLL (Delay Locked Loop) architecture. Starting from the *N*+1 propagation paths identified between a satellite and the receiving antenna (*N* multipath rays and the LOS signal), the time domain form of the received signal can be represented by

$$R(t) = \sum_{i=0}^{N} \alpha_i \, p(t - \delta_i) \cos(\omega_0 t + \theta_i)$$

where α_i, δ_i and θ_i are respectively amplitude, delay and phase of the *i*-th propagation path and $p(t)$ represents the PRN code. The received signal is correlated with the locally generated PRN replies to obtain the discrimination curve or "S-curve" (deformed in presence of multipath rays) related to the selected DLL type. The zero-crossing of the multipath deformed discrimination curve represents the code-phase tracking error as shown in Fig. 4.

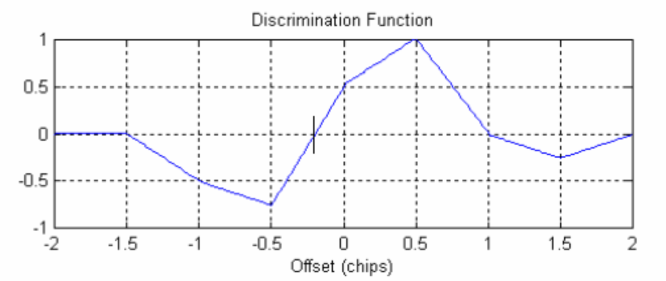

Fig. 4: Example of multipath deformed discrimination curve, resulting from a single out-of-phase half-power multipath ray delayed by half chip-period (α_1=0.5, δ_1=0.5T_c, θ_1=180°).

Various algorithms such as standard correlators, up to specific mitigation techniques such as Narrow Correlator [12], NovAtel's Pulse Aperture Correlator [13] and Septentrio's A-Posteriori Multipath Estimator [14] are available. The performance of the various emulated techniques is compared in Fig. 5.

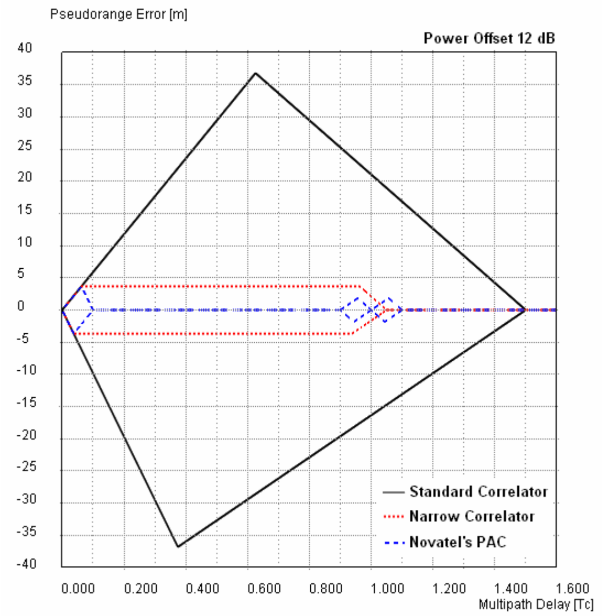

Fig. 5: Comparison of pseudorange error envelopes obtained with the modelled correlator types.

The code-phase tracking error due to interference effects is based on the accuracy estimation of common discriminators such as Coherent, Early-Minus-Late Power, Dot-Product [11]. The code tracking error variance of a non-coherent discriminators (in terms of code chips) is

$$\sigma^2 = \frac{B_L d}{2 C/N}\left[1 + \frac{2}{C/N \, T(2-d)}\right]$$

for an Early-Minus-Late Power discriminator, or

$$\sigma^2 = \frac{B_L d}{2 C/N}\left[1 + \frac{1}{C/N \, T}\right]$$

for a Dot-Product discriminator, where B_L is the code tracking loop bandwidth in Hz, *d* is the early-late correlator spacing normalized with respect to one code chip, *T* is the predetection integration interval in seconds and *C/N* is the carrier to noise ratio in Hz.

The interference effect is included in noise power density using the following equations:

$$N[dBW/Hz] = N_T[dBW/Hz] + N_I[dBW/Hz]$$

$$N_T[dBW/Hz] = K[J/K] T_E[K]$$

$$N_I[dBW/Hz] = I[dBW] + 10\log(T_c[\sec]) + L_{PG}[dB]$$

where N_T is the thermal noise power density, N_I is the interference power density, *K* is Boltzmann's constant, T_E is the effective noise temperature, T_c is the chip time, L_{PG} is the processing gain (typically this varies from 0 dB for wide band interfering signals up to 10 dB or higher for CW) and *I* is the interference power level at the receiver input. When this level is negligible, the above mentioned equations represent the code-phase tracking error variance due to noise effect only.

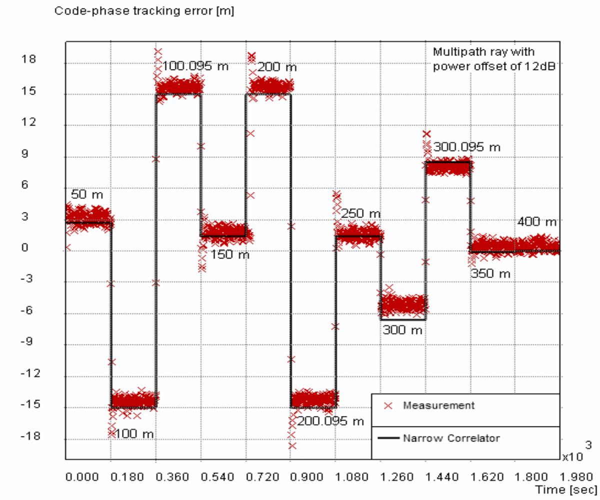

Fig. 6: Comparison between estimated pseudorange error and measured CmC when a 12 dB power offset multipath ray is applied with different delays.

The receiver channel modelling effectiveness was verified by a laboratory campaign using commercial GNSS receivers, such as the Septentrio's PolaRx2, the Spirent GNSS signal generator and the Agilent interfering signal generator.

Fig. 6 compares the code-phase tracking error estimated with a modelling of the PolaRx2's DLL (no mitigations) and the Code-minus-Carrier measured when multipath signal is injected with a 12 dB power offset and a delay variable every 180 seconds.

In addition, the theoretical code tracking errors root mean square is compared with the mean residuals measured for different interfering levels in Fig. 7.

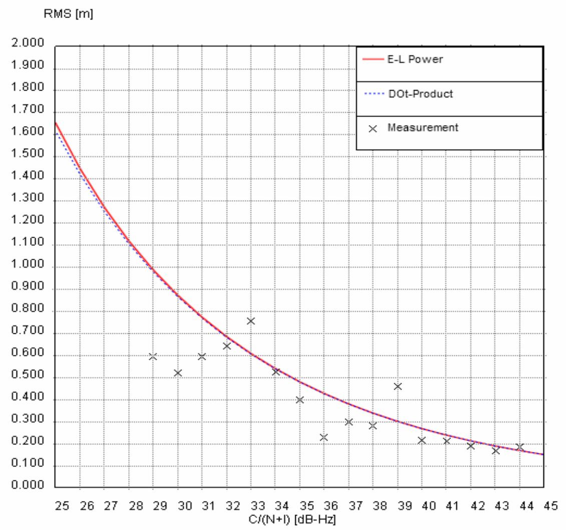

Fig. 7: Estimated pseudorange errors as function of carrier to noise plus interference ratio compared with measured pseudorange residuals when different interference levels are applied (thermal noise and carrier power levels are constant during measurement).

III. GNSS Monitoring Station (GMS)

Characterizing the GNSS scenario in aeronautical applications is a mandatory step, when evaluating in-site GNSS performance. Therefore, in compliance with the well known international standards [3]-[6], IDS built a GNSS Monitoring Station (GMS) [10].

The final goal for the construction of this station was the measurement of the GNSS performance in site survey applications (e.g., to select the best location for a GBAS installation) and to monitor them continuously. Therefore, the subsequent post-processing is a necessary step to evaluate the achieved on-site performance, in terms of accuracy, integrity, service availability, signal level, multipath, interferences, and so on ([3]-[6]).

The GMS is able to monitor positioning signals in range, navigation, and frequency domains, and to do this, the station consists of the following devices:

- 3 GNSS receivers to acquire and track GPS/SBAS signals in range and navigation domains. The availability of different receivers permit a simultaneous acquisition in single (L1) and dual-frequency (L1 and L2) modes. All receivers are connected together (by an amplified splitter) to a GNSS dual-frequency (L1/L2) choke-ring antenna.
- A spectrum analyzer is connected to the same antenna to detect interfering emissions.

The overall architecture is depicted in Fig. 8. The picture shows the presence of the PC that carries out data storage and system control operations. A wireless connection guarantees the remote control of the station during measurement activities.

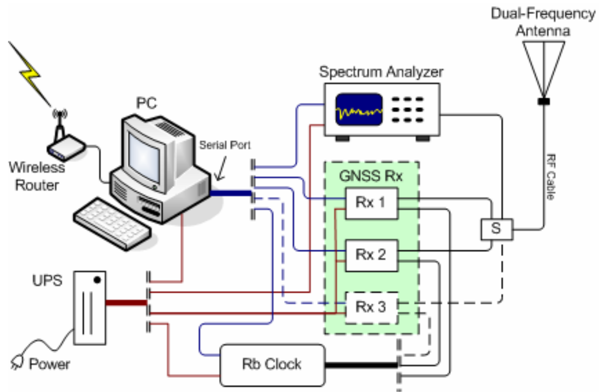

Fig. 8: Overall architecture of the GMS.

This station has been intensively used in some Italian airports (including Parma, Perugia, Taranto, Palermo, and Bologna) to characterize the GNSS related scenario. A picture of the station in operational contexts is shown in Fig. 9.

IV. Validation Campaigns

The multipath and interference prediction tools have been tailored and verified through extensive comparisons with raw data measured in different Italian regional airports, paying attention to minimal recommended operational performance. The following figure presents some significant results. For example, high terrain reliefs close to Palermo airport site make the multipath assessment of the installed GBAS station particularly important. A statistical characterization of the code-phase tracking accuracy obtained for different elevation angles is shown in Fig. 10. Prediction and measurement give results in close agreement: the multipath effect localized between 20° and 40° elevation angles is not compliant with the relevant accuracy designator.

Fig. 9: GMS in some operational scenarios

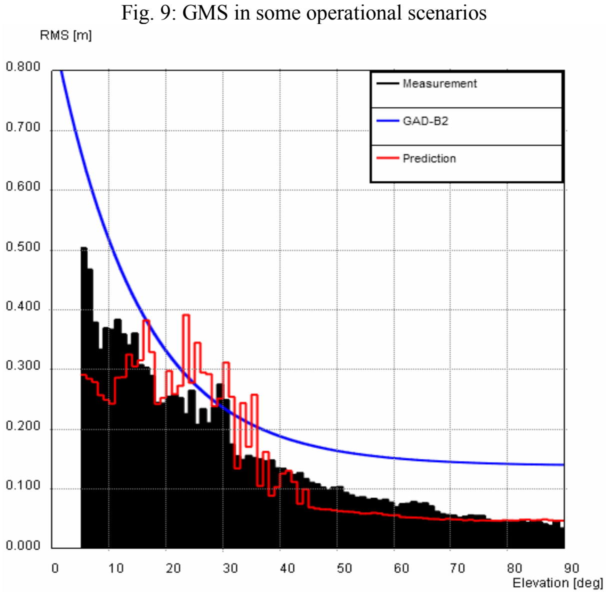

Fig. 10: Code-phase tracking accuracy due to multipath and thermal noise at different elevation angles. A ground station accuracy designator is shown for a class B GBAS station with 2 receivers [6].

V. Conclusions

The accurate modelling of complex GNSS scenarios to predict multipath and interfering effects has been accomplished through implementation of a numerical model and suitable software able to represent the site surrounding environment in terms of orography, obstacles, transmitters, etc., to simulate the EM propagation and related scattering effects, to reproduce the antenna features, and finally to run the main GNSS receiver algorithms. All of these aspects have been taken into account in the design of a complex framework used to predict GNSS performance in Italian airports.

Additional effort has been dedicated to the validation and tuning phases, which are necessary steps to gain confidence in prediction results. For this reason, a GNSS Monitoring Station (GMS) has been set up and intensively used in Italian airports to measure the GNSS performance on-site. In this context, the ICAO guidelines provide a set of useful discriminators (such as the interference mask and the GAD curve) to evaluate the quality of each site and resolve the antenna siting problems.

A good match between real measurements and simulated results has been achieved in different operational scenarios, encouraging further effort to improve the modelling and the efficiency of the implemented algorithms.

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