A quantitative method for evaluating GNSS signal disruption in sports stadiums

KIM, Mingu, MILLS, Katie, KIM, Bit, PARK, Chulwoo, YOON, Jinsung, PARKINSON, Tom and BILLINGHAM, Johsan

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METHODOLOGY

A quantitative method for evaluating GNSS signal disruption in sports stadiums

Mingu Kim[1] · Katie L. Mills[2,4] · Bit Kim[3] · Chulwoo Park[3] · Jinsung Yoon[3] · Tom Parkinson[2] · Johsan Billingham[2]

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Abstract

This study introduces a quantitative method to evaluate the impact of roof coverage in football stadiums on GNSS (Global Navigation Satellite System) signal quality. GNSS is often used to track the positions of players in outdoor sports. However, stadium roofs or other structural obstacles can degrade the GNSS signal quality, and reduce the overall quality of the data. Given that many players compete across a variety of venues, each with different structural characteristics, this study investigated and analyzed the relationship between the stadium environment and GNSS signal performance. A methodology was developed to quantify the impact of roof coverage on GNSS signal quality. This was followed by hardware experiments that used the proposed method. A strong positive correlation ($r = 0.98$, $p < 0.01$) was found between the GNSS performance attenuation ratio and the GNSS positioning error standard deviation. The results can help coaches and analysts improve the accuracy of player performance evaluations based on positional data in stadium environments.

Keywords EPTS · Stadium roofs · Signal attenuation · GNSS positioning

1 Introduction

GNSS (Global Navigation Satellite Systems) are widely used across football, due to their versatility to be used in both outdoor training and competitive environments. These devices are used to assess the physical exertion and performance of an individual player by tracking metrics such as total distance covered [1], sprint speeds [2], positional information [3], and energy expenditure during a match [4]. This allows coaches to monitor fitness levels, identify signs of fatigue and optimize training programmes while reducing the risk of injury. This data can provide valuable insights into team dynamics, such as relative player positioning, movement patterns or spatial awareness [5].

High signal quality is crucial in football stadiums to ensure accurate tracking of players. Variations or degradation in signal quality across different areas of the pitch can lead to inaccuracies in position and other tracking metrics. The signal quality in these environments can be influenced by several factors.

Firstly, the structural design of the stadium can play a significant role [6] . Modern-day football stadiums often feature large overhangs or dense metal frameworks that can obstruct satellite signals, causing multipath errors [7, 8]. The construction materials of the stadium infrastructure should

✉ Mingu Kim
mingukim@hansung.ac.kr

Katie L. Mills
katie.mills@fifa.org

Bit Kim
bit.kim@fitogether.com

Chulwoo Park
chulwoo.park@fitogether.com

Jinsung Yoon
jinsung.yoon@fitogether.com

Tom Parkinson
tom.parkinson@fifa.org

Johsan Billingham
johsan.billingham@fifa.org

1 Division of Mechanical and Electronics Engineering, Hansung University, Seoul 02876, Republic of Korea

2 Football Technology & Innovation, Federation Internationale de Football Association (FIFA), Zurich 8044, Switzerland

3 Fitogether Inc., Seoul 04378, Republic of Korea

4 Sheffield Hallam University, Sheffield S9 3TU, UK

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also be considered as this can reduce the signal strength. For instance, two roof designs with identical layouts may experience different GNSS performance depending on the materials [9]. A roof made of cloth, may have a lower impact on GNSS signal strength compared to a metal roof that may cause significant signal attenuation or reflection.

Secondly, atmospheric conditions, such as heavy cloud cover or ionospheric disturbance can decrease signal strength and accuracy [10]. Thirdly, the number and geometrical arrangement of the satellites relative to the receiver, can influence the precision of positional data [11]. The GDOP (Geometric Dilution of Precision) quantifies how the positions of the satellites affect the accuracy of calculated GNSS receiver's position. A lower GDOP (typically below 2.0) indicates that the satellites are well-distributed across the sky, as shown in Fig. 1a, leading to higher positional accuracy. While a higher GDOP value (typically above 10) suggests poor satellite geometry, such as clustering as shown in Fig. 1b, that can result in lower accuracy. Each solid circle represents the true distance boundary, each dashed circle represents the pseudorange boundary, and the shaded area represents GDOP in Fig. 1.

Fourthly, interference from electromagnetic electronic equipment such as broadcast systems or nearby urban infrastructure can further disrupt GNSS signal reception. The signal quality is commonly described using metrics such as the Carrier-to-noise density ratio (C/N_0), pseudorange accuracy, and Doppler shift [12].

Many studies have investigated the validity and reliability of GNSS, often carried out in environments with unobstructed views of the sky to ensure optimal signal conditions [13–21]. However, these ideal scenarios, such as testing on an open field or in centrally located positions on a pitch, fail to replicate the complex geometrics and obstructions inherent in stadium structures, which can result in non-uniform errors across a playing field [8]. Analysis of GNSS data collected from 27 professional football players over a season using 10 Hz devices revealed signal quality was poorer for players in wide positions compared to central positions, with proximity to stands exacerbating issues due to multipath effects. On average, approximately 11 min of the match could be affected by poor signal quality, but in extreme cases this could rise to between 66 to 87 min [17]. This compromised data quality can lead to unreliable insights and suboptimal practical implications.

While existing research has confirmed the influence of stadium structure on GNSS accuracy, it has not quantified the effects of specific elements, such as roof coverage. This study aims to address these gaps, by quantifying the relationship between structural environments and GNSS signal quality. This is relevant in professional football, where players compete in a wide range of stadiums throughout the season, each with unique design and levels of roof coverage that can affect the quality and reliability of tracking data used for performance analysis.

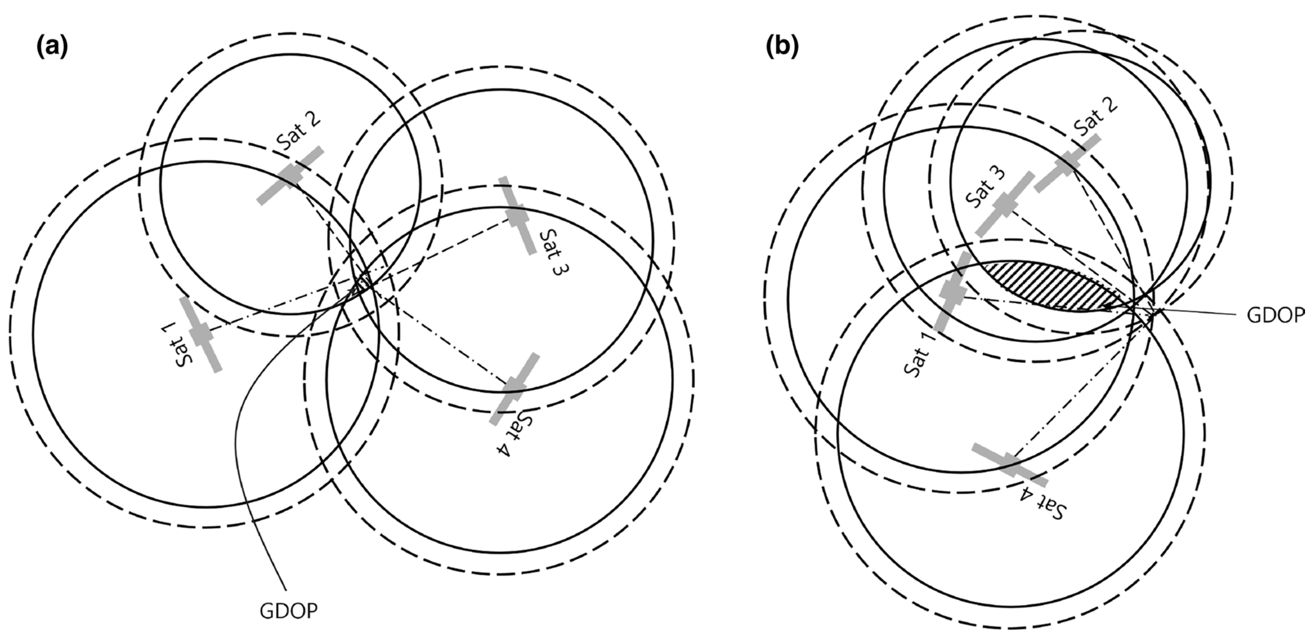

Fig. 1 The relationship between GDOP and satellite geometry: (**a**) good GDOP (left), (**b**) poor GDOP (right)

Fig. 2 The considered wearable EPTS device equipped with a low-cost GNSS receiver

Table 1 Six different stadium environments

Stadium	Country	Capacity	Open/Closed	Cover rate (%)	Roof material
Hyochang Stadium	South Korea	15,194	Open	0	-
Jeju World Cup Stadium	South Korea	35,657	Half-closed	53	Fabric
Daegu DGB Daegu Bank Park	South Korea	12,415	Closed	74	Metal
Ulsan Munsu Football Stadium	South Korea	37,897	Closed	87	Metal
Columbus Historic Crew Stadium	United States	19,968	Open	0	-
Düsseldorf Merkur Spiel-Arena	Germany	54,600	Closed	100	Metal

2 Methods

2.1 Hardware

A low-cost GNSS receiver, u-blox ZED-F9P, was used in a commercial wearable electronic performance and tracking system (EPTS) system, Fitogether Cell Y, for football players, shown in Fig. 2. The horizontal position and velocity accuracies of the GNSS are 1.50 *m* at 24 h static conditions and 0.05 $m \cdot s^{-1}$ at 30 $m \cdot s^{-1}$ for dynamic operation, and the GNSS data (NMEA format) were outputted at 10 *Hz* in open sky environments [22].

2.2 Stadiums

Field tests were performed in six different stadiums: Hyochang Stadium, Jeju World Cup Stadium, Daegu DGB Daegu Bank Park, Ulasn Munsu Football Stadium, Columbus Historic Crew Stadium, and Düsseldorf Merkur Spiel-Arena. Figure 3 provides a visual reference of the six stadiums, and Table 1 summarizes the environment of six stadiums. Hyochang Stadium and Columbus Historic Crew Stadium were categorized as open environments, while Jeju World Cup Stadium was categorized as half-closed environment, and Daegu DGB Daegu Bank Park, Ulsan Munsu Football Stadium, and Düsseldorf Merkur Spiel-Arena were categorized

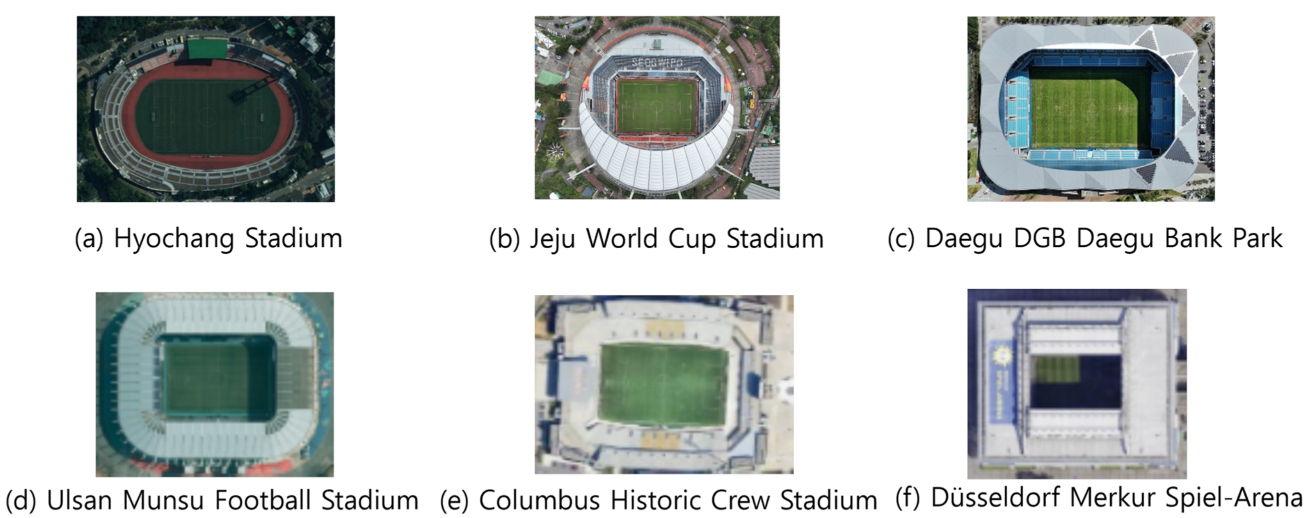

Fig. 3 Test fields: **a** Hyochang Stadium, **b** Jeju World Cup Stadium, **c** Daegu DGB Daegu Bank Park, **d** Ulsan Munsu Football Stadium, (**e**) Columbus Historic Crew Stadium, **f** Düsseldorf Merkur Spiel-Arena

as closed environments. The cover rate refers to the coverage rate for stadium standing, as there are no standardized or unified guidelines for quantifying stadium coverage, the information was obtained from stadium construction brochures [23–25]. The field test at Düsseldorf Merkur Spiel-Arena was conducted under the condition where the roof fully covered the stadium stands, so it was assumed that the coverage rate is 100%.

2.3 A quantitative method to measure the influence of stadium environments on GNSS performance

GDOP (Geometric Dilution of Precision) combines the effects of PDOP (Position Dilution of Precision), that quantifies the three-dimensional positional accuracy, and TDOP (Time Dilution of Precision), that quantifies the influence of satellite geometry on the accuracy of time measurements. The GDOP is calculated as the square root of the sum of the squares of PDOP and TDOP. In terms of positioning, either GDOP or PDOP are used as a criterion for selecting visible satellites. The considered GNSS receivers in this study provided PDOP information directly; therefore, PDOP values were considered.

$$\mathrm{GDOP} = \sqrt{\mathrm{PDOP}^2 + \mathrm{TDOP}^2} \tag{1}$$

New factors based on PDOP and average signal strength were defined to measure the influence of stadium environment in this study. To measure the relative performance from the ideal case, the following concepts based on the relative manner from the open sky were considered. Two average PDOP factors were defined as follows; PDOP_o was defined as the PDOP value measured in the open sky environments, and PDOP_s was defined as the PDOP value measured in the stadium environment. Similarly, two average signal length factors were defined as follows; A_o represented the average GNSS signal strength measured in open sky environments, and A_s represented the average GNSS signal strength measured in stadium environments.

$$\mathrm{A}_o = \frac{\sum_{i=1}^{n} C/N_{0i}}{n} \tag{2}$$

$$\mathrm{A}_s = \frac{\sum_{j=1}^{m} C/N_{0j}}{m} \tag{3}$$

where C/N_{0i} and C/N_{0j} stand for Carrier-to-noise density ratio of the *i*-th and *j*-th GNSS satellite, and *n* and *m* denote the total number of satellites for calculating A_o and A_s, respectively. C/N_0 is expressed in dB-Hz in this study because it is a common practice in field-based GNSS assessments.

A_o is always equal to or greater than A_s. This is because the GNSS signal strength in stadium environments is always lower than that in open sky environments, due to stadium roofs or obstacles. Accordingly, the following equation can be obtained.

$$\mathrm{A}_{o/s} = \frac{\mathrm{A}_o}{\mathrm{A}_s} \tag{4}$$

where $\mathrm{A}_{o/s}$ is the GNSS signal strength ratio of open sky environments to stadium environments.

Based on the defined new factors of PDOP and average GNSS signal strength, the GNSS performance indices were proposed in this study to measure the impact on stadium environments. The proposed GNSS performance indices were considered to be proportional to GNSS signal strength and inversely proportional to PDOP. A higher GNSS performance index is an indication of better GNSS positioning performance.

$$\mathrm{P}_o = \frac{\mathrm{A}_o}{\mathrm{PDOP}_o} \tag{5}$$

$$\mathrm{P}_s = \frac{\mathrm{A}_s}{\mathrm{PDOP}_s} \tag{6}$$

In this study, the relative GNSS performance attenuation ratio R was used to compare different stadium environments. A large performance attenuation ratio implies that the stadium environment negatively affects valid GNSS signal strength to a lower degree. In other words, a stadium with a smaller value of R is better suited to accurately collect players' performance data than those with larger values of R.

$$\mathrm{R} = \frac{\mathrm{P}_o}{\mathrm{P}_s} = \frac{\frac{\mathrm{A}_o}{\mathrm{PDOP}_o}}{\frac{\mathrm{A}_s}{\mathrm{PDOP}_s}} \tag{7}$$

The factor R was heuristically chosen as a metric for evaluating GNSS signal quality because it can be directly computed from standard GNSS receiver outputs without requiring additional processing or proprietary data access. Moreover, since C/N_0 has been widely used to assess GNSS signal quality [26], R is particularly useful for practical field studies and large-scale deployments.

2.4 Stadium data collection

To collect the data required for the calculations carried out in the previous section, seven GNSS receivers were placed

Fig. 4 The location distribution of GNSS receivers to reflect stadium geometry

at the corners, centre point and centre line to reflect the stadiums geometry, as shown in Fig. 4. The devices then collected the PDOP, position data, and signal strength for at least one hour. During the collection each device remained stationary to isolate the errors caused by GNSS signal performance rather than movement.

Despite the devices remaining stationary, GNSS errors cause slight positional variations, referred to as position deviation error. This deviation is proportional to GNSS performance, with smaller deviations indicating better accuracy. To evaluate the impact of the stadium environment, the standard deviation of the positional errors recorded in the stadium, σ_s, was compared to those obtained under open sky conditions, such as near a stadium (e.g parking lots or open sky environment training fields) but not inside a stadium, σ_o. Five GNSS receivers were used to collect data under open-sky conditions to obtain σ_o and seven GNSS receivers were used to collect data inside the stadium to obtain σ_s. The standard deviation measures the spread of the data around the mean, which means any consistent bias, shift, or absolute position error in the receiver location does not affect the computed value of S. A large position bias can still strongly affect the effectiveness of GNSS measurements and should be taken into account when interpreting the results. The ratio of the standard deviations, S, was calculated as follows.

$$\mathrm{S} = \frac{\sigma_s}{\sigma_o} \tag{8}$$

where σ_o and σ_s are the position error standard deviations in open sky environments and stadium environments, respectively.

A large standard deviation ratio, S, corresponds to a minimal difference in positioning performance between open-sky and stadium environments. Accordingly, a large performance attenuation ratio reflects increased degradation of GNSS positioning performance in stadium environments. For this study, 3 was selected as a threshold, above which GNSS-based positioning should be treated with caution due to potential instability. The value of S exceeding 10 could be interpreted as indicating environments where GNSS receivers may not operate reliably. The linear correlation coefficient, *r*, and significance, *p*, were used to analyze the relationship between R and S.

Table 2 Open sky PDOP, stadium PDOP, and the mean value of the logarithm of GNSS performance attenuation ratio, R, in six stadiums

Stadium	Cover rate (%)	PDOP_o	PDOP_s	mean R
Hyochang Stadium	0	0.950	1.000	1.083
Jeju World Cup Stadium	53	0.940	1.020	1.122
Daegu DGB Daegu Bank Park	74	0.980	1.170	1.355
Ulsan Munsu Football Stadium	87	1.010	1.170	1.261
Columbus Historic Crew Stadium	0	0.910	0.980	1.077
Düsseldorf Merkur Spiel-Arena	100	0.910	1.550	2.031

3 Results

For each of the R and S, 252,000 values were collected over one hour across seven different locations within each stadium (36,000 samples per receiver). The mean value of R was smaller for stadiums with lower roof coverage as shown by the results in Table 2. For example, the Columbus Historic Crew Stadium, with 0% coverage demonstrated a mean value that was approximately 1.89 times smaller compared to the Düsseldorf Mekur-Spiel Arena, with a coverage of 100%.

Figure 5 shows a histogram of the R with the probability density, showing that stadiums with lower roof coverage are concentrated at the lower end of the scale.

The mean value of S for stadiums with greater roof coverage was higher than those with lower coverages, as show in Table 3. Columbus Historic Crew Stadium and Hyochang Stadium, categorized as open environments, had mean values of S that were approximately 9.65 and 16.08

Fig. 5 R histogram with density

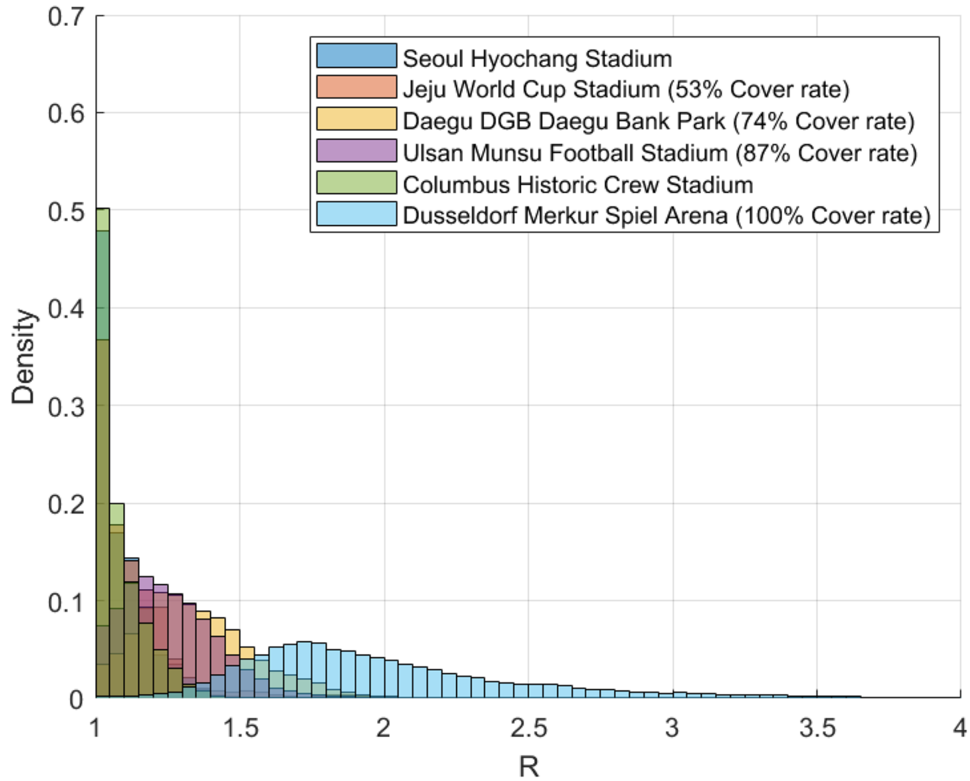

Table 3 The mean value of GNSS positioning error standard deviation in open sky environments and stadium environments, the mean value of the logarithm of GNSS positioning error standard deviation ratio, S, and the mean value of the logarithm of GNSS performance attenuation ratio, R, in six stadiums

Stadium	Cover rate (%)	σ_o	σ_s	mean(S)	mean(R)
Hyochang Stadium	0	0.540	0.709	1.312	1.083
Jeju World Cup Stadium	53	0.294	0.721	2.454	1.122
Daegu DGB Daegu Bank Park	74	1.220	4.621	3.788	1.355
Ulsan Munsu Football Stadium	87	0.366	1.872	5.114	1.261
Columbus Historic Crew Stadium	0	0.215	0.470	2.186	1.077
Düsseldorf Merkur Spiel-Arena	100	0.690	14.554	21.093	2.031

times smaller, respectively, compared to Düsseldorf Merkur Spiel-Arena, categorized as closed environments.

A strong positive relationship was found between R and S ($r = 0.98, p < 0.01$). The relationship between the mean value of S and mean value of R, is presented in Eq.(9), this was defined using the following linear equation and is shown by the solid red line in Fig. 6.

$$\text{mean(S)} = 20.231\ \text{mean(R)} - 20.744 \tag{9}$$

4 Discussions

This investigation observed differences in attenuation and positioning error between open and roofed stadium environments, with important implications for the use of GNSS technology in sports analytics. The R and S values were consistently lower in open stadium environments compared to roofed stadiums, which highlights the significant influence of roof coverage on GNSS signal quality. This suggests that enclosed or partially covered stadiums are more likely to introduce signal degradation.

These findings are notable given the trend towards increasingly architecturally distinctive and enclosed modern stadium designs, that prioritize aesthetics and spectator experience but may inadvertently degrade GNSS signal performance. For example, degraded tracking performance is often observed in winger players who typically play on the sides of the field, and this may be linked to the signal degradation due to the roof coverage [17]. This would have implications for performance analysis such as player monitoring or longitudinal studies conducted across different match environments as it is important to recognize that data collected in roof stadiums may be less reliable or comparable to data captured from open environments.

The proposed method provides a systematic framework to quantify the impact of such designs on GNSS signal quality, and this study bridges a gap in sports analytics and infrastructure design. The results have implications for coaches

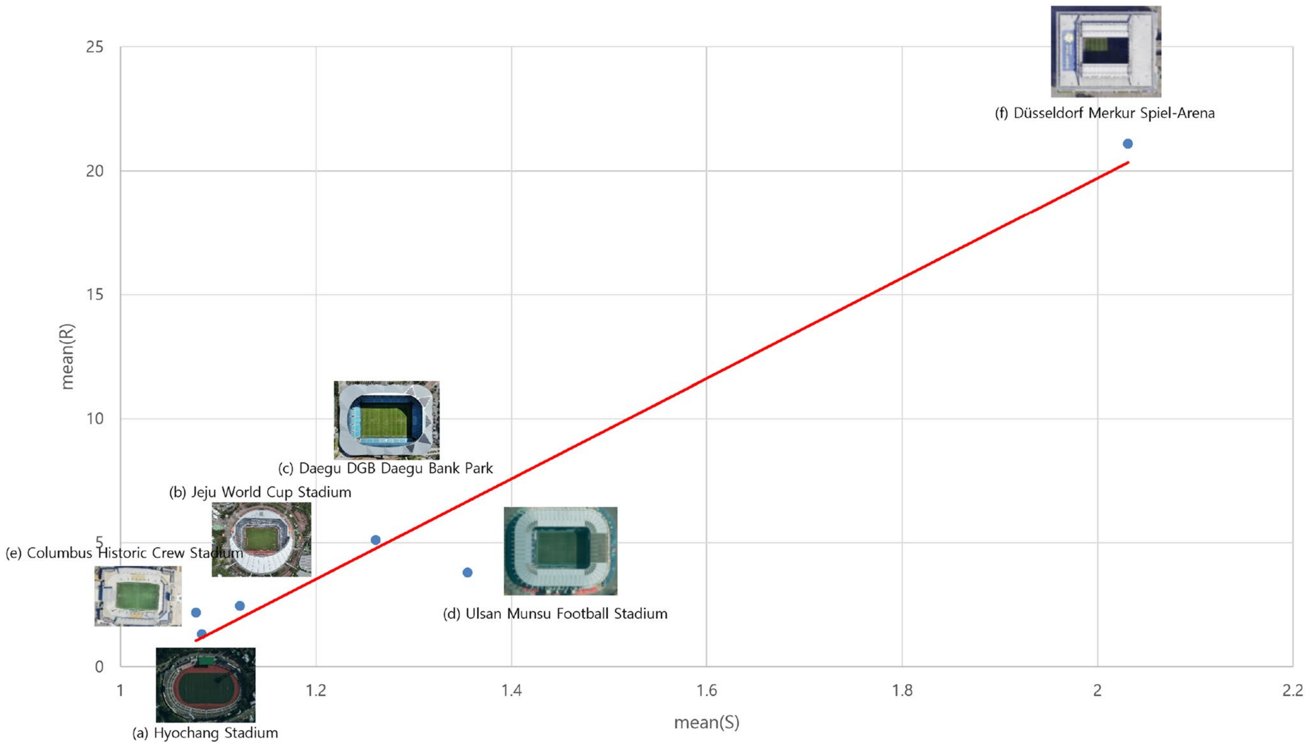

Fig. 6 The relationship between the performance attenuation ratio and the position error standard deviation ratio

and sports analysts, offering reliable information to improve player performance evaluation more accurately, develop data-driven strategies, and enhance decision-making processes. While precise GNSS devices (i.e., RTK(Real-Time Kinematics)-GNSS devices) or GNSS/IMU(Inertial Measurement Unit) fusion systems can be an alternative option for coaches and sports analysts operating in stadiums with higher roof coverage to overcome the limitations of standalone GNSS receivers, these devices often require more resources and can be costly in comparison.

This study provides the first quantitative framework for assessing the influence of coverage on GNSS signal quality in football stadiums. Whilst this study focused used R and S, the use of alternative metrics, such as WDOP (Weighted Dilution of Precision) to evaluate GNSS signal quality, could be explored in comparative study. Second, averaging C/N_0 in linear units could be considered to enhance the analysis. In this study, averaging C/N_0 in dB-Hz units was adopted because it is a common practice in field-based GNSS assessments and the focus was on relative differences in GNSS performance across stadium environments rather than absolute values. Nevertheless, averaging C/N_0 in linear units could provide a more rigorous analysis, since the variance of individual GNSS observations (i.e., pseudoranges) is linearly related to C/N_0 expressed in linear units.

Third, using a single model of GNSS device ensured a controlled approach for measurement but limited the generalizability across different technologies and hardware. Further research should explore device-specific performance variations to broaden these findings. Fourth, the hardware experiments were conducted once in each stadium environment in this study. Conducting repeated experiments under similar and varying conditions could further validate the consistency and reliability of the results and should be considered in future work.

Fifth, while the study categorized stadium by roof coverage, it did not consider the diversity of roof materials and the associated properties within these categories. Properties such as material composition, thickness and reflectivity are known to influence GNSS signal quality, further detailed classification could guide future stadium design requirements. Finally, expanding the scope to include stadiums with a wider array of architectural features and structural designs would enhance the robustness and applicability of the conclusions. Nonetheless, this study lays a strong foundation for these future investigations, offering a methodology that can be refined and adapted to better understand GNSS performance in complex stadium environments.

5 Conclusion

This study investigated how stadium environments affect GNSS signal quality, which is important for accurately tracking football players' performance. Roofs and other obstacles in stadiums can reduce GNSS signal quality, potentially influencing the consistency of performance data across different stadiums. To examine this, a methodology was developed to measure the effect of roof coverage on GNSS signals. Experiments using this approach showed that GNSS performance decreased in more enclosed stadiums and that this decrease was linked to higher positional errors. The method provides a quantitative way to assess GNSS performance in complex stadium environments. It also lays the groundwork for future studies, which could include a more detailed analysis of roof materials and a wider variety of stadium designs to improve the general applicability of these findings.

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Author contributions MK conducted methodology, formal analysis, software, manuscript writing, and manuscript review. KM, TP, and JB conducted formal analysis, manuscript writing, and manuscript review. BK and CP conducted methodology, formal analysis, data curation, resources, and manuscript review. JY conducted resources, investigation and funding acquisition. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest Mr Johsan Billingham is a guest editor for the topical collection on football research and was blinded from the peer-review process.

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