GNSS Positioning Environment Assessment in Urban Rivers for Autonomous Boats Using Polarimetric SAR data

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Abstract: *The growing need for autonomous boat navigation on urban rivers has revealed a major challenge: the substantial reduction in Global Navigation Satellite System (GNSS) accuracy caused by surrounding high-rise buildings and bridges. To Ensuring safe autonomous navigation requires, identifying non-GNSS areas by assessing the positioning environment over a wide area, However, conventional methods lack efficiency and spatial coverage. This study proposes a novel methodology that uses full-polarimetric synthetic aperture radar (SAR) data to estimate the GNSS positioning environment over a large area. We validated the effectiveness using in situ data from a waterborne mobile mapping system (MMS). Using ALOS-2/PALSAR-2 data, we applied Pauli decomposition to classify microwave scattering mechanisms as surface, double-bounce, or volume scattering. We hypothesized that surface scattering would correspond to favorable GNSS conditions, whereas double-bounce and volume scattering would indicate poor environments prone to multipath and signal blockage. To validate the estimation, we conducted a qualitative analysis by comparing the Pauli decomposition results with three data sources: 1) 3-D point clouds acquired by the waterborne MMS, 2) a 3-D city model (Project PLATEAU), and 3) the measured GNSS positioning solutions (RTK-FIX/FLOAT). The analysis revealed a strong correlation between the SAR-derived scattering map and the actual GNSS performance. Specifically, open sky areas such as the Shiomi Canal exhibited surface scattering and stable RTK-FIX solutions. By contrast, the sections of the Nihonbashi River under the expressway were dominated by double-bounce and volume scattering. This resulted in unstable RTK-FLOAT solutions. This study demonstrates that Pauli decomposition of polarimetric SAR data can effectively evaluate the GNSS positioning environment across an entire area. These results can be applied to optimize navigation routes and generate positioning environment maps to enable seamless switching between GNSS and non-GNSS positioning.*

Keywords: ALOS, RTK-GNSS, SAR, waterborne MMS

Introduction

In recent years, significant efforts have been devoted to visualizing urban spaces in three dimensions and constructing digital twins around the world. In Japan, the Ministry of Land, Infrastructure, Transport and Tourism is promoting the PLATEAU project, which aims to develop high-precision 3-D city models, with expected applications across a wide range of fields, including urban planning, disaster prevention, transportation, and environmental monitoring. Similarly, the introduction of autonomous boats for urban river navigation has attracted considerable attention. The operation of these boats requires high-precision positioning, typically achieved using satellite-based technologies such as RTK-GNSS.

However, urban river environments are often surrounded by high-rise buildings and bridges, which block GNSS signals and cause multipath propagation. This leads to substantial positioning accuracy degradation. Prior to these challenges, previous studies have primarily relied on collecting in situ measurement data to evaluate GNSS positioning environments to address these challenges. Examples include field tests using mobile platforms equipped with RTK-GNSS receivers and long-term monitoring at fixed stations. Although these methods provide highly reliable data, they are constrained by several limitations. These limitations include limited spatial coverage, time-consuming and costly procedures, and challenges in reproducibility and comprehensiveness. Moreover, critical factors affecting positioning accuracy, such as signal blockage and multipath propagation, cannot always be fully captured by visual inspection or 2-D maps. This underscores the necessity of evaluation methodologies that explicitly consider 3-D structural configurations. Consequently, there is a strong demand for wide-area, periodic spatial analysis techniques that use satellite remote sensing as an alternative to conventional approaches. In this study, we propose a methodology for estimating the GNSS positioning environment in urban rivers using spaceborne synthetic aperture radar (SAR), specifically full-polarimetric SAR data acquired by ALOS-2/PALSAR-2. Our approach focuses on the correlation between SAR scattering mechanisms, such as surface scattering, double-bounce scattering, and volume scattering, and GNSS positioning performance. We use Pauli decomposition as the analytical framework. We verify the validity of the proposed methodology through comparative analysis of RTK-GNSS positioning data, point clouds obtained by a waterborne MMS, and a 3-D city model (PLATEAU). This study provides fundamental insights into the geospatial characterization of GNSS positioning availability. These insights offer foundational support for autonomous navigation, route optimization, and seamless switching between GNSS and non-GNSS positioning techniques in urban river environments.

Literature Review

a. Physical Factors Causing GNSS Accuracy Degradation in Urban Areas

Urban environments present numerous challenges for GNSS signal reception. Without specific countermeasures, the performance of GNSS positioning is significantly degraded. These urban-specific challenges pose major obstacles to the practical deployment of autonomous boats, urban mobility systems, surveying, and other applications. Zhu et al. (2018) state that these issues are primarily caused by physical phenomena, such as signal blockage, multipath interference, and non-line-of-sight (NLOS) reception. Signal blockage occurs when obstacles such as high-rise buildings physically obstruct the line-of-sight (LOS) to satellites. This reduces the number of visible satellites and degrades their geometry, which worsens the dilution of precision (DOP) and directly impacts positioning accuracy. More severe errors arise from multipath and NLOS reception. Multipath occurs when direct and reflected signals from surrounding structures are received simultaneously. This interference distorts the receiver's correlation function, leading to ranging errors. By contrast, NLOS reception occurs when the direct signal is completely blocked and only reflected signals are received. Because the propagation path of reflected signals is longer than the true range, range measurements based on NLOS reception consistently have a large positive bias error. Zhu et al. (2018) emphasize the importance of distinguishing between these two phenomena, because they introduce different types of ranging errors. Performance degradation may also result from interference with other radio signals or from attenuation caused by vegetation.

b. Conventional GNSS Positioning Environment Evaluation Methods

GNSS positioning in urban environments is known to be significantly degraded by building obstructions and multipath effects. Numerous studies have been conducted to evaluate and predict positioning environments in advance. These approaches can be broadly classified as either empirical measurement or simulation. Empirical measurement is the most direct methodology and involves operating vehicles or boats equipped with GNSS receivers to collect and analyze log data. This methodology effectively obtains highly reliable data reflecting the complex effects of the actual radio wave propagation environment. However, surveys are limited to linear information along a route. Conducting a comprehensive evaluation across an area requires significant time and resources, which makes it inefficient, especially for large-scale applications. By contrast, simulation methodologies use 3-D urban models to simulate GNSS signal propagation geometrically or physically. Early research relied on building models to determine LOS and predict reductions in the number of visible satellites as well as deterioration of DOP. Since then, efforts have been made to use ray tracing technology to estimate the propagation paths and delay quantities of NLOS signals. For example, Kbayer et al. (2018) proposed a methodology for predicting NLOS bias using 3-D urban models and GNSS simulators. They incorporated this methodology into positioning calculations for correction. A new direction is emerging that involves actively utilizing NLOS signals, which were previously excluded as error factors. However, simulation-based methodologies depend on the accuracy and detail of the 3-D urban model, and ray tracing requires significant computing power, which limits its applicability for large areas and real-time applications. Furthermore, considering dynamic elements, such as vehicles and pedestrians, remains difficult. Thus, conventional field surveys are limited in terms of comprehensiveness, and simulations have limitations in terms of computational cost and model dependency. An efficient and regular methodology for evaluating the GNSS positioning environment across the entire urban area has yet to be established. This study focuses on using SAR remote sensing as a new approach due to a research gap in this area. Building on previous studies that found SAR image scattering characteristics reflect urban structure, this study applies these findings. Furthermore, this study establishes a framework that links the physical relationship between urban structure and GNSS positioning quality. It also proposes an interdisciplinary methodology for evaluating the GNSS positioning environment using SAR.

Methodology

This study aims to develop a methodology for spatially estimating the GNSS positioning environment of urban rivers using the scattering characteristics of full-polarimetric SAR. The quality of GNSS positioning heavily depends on the presence and configuration of urban structures, such as buildings and bridges. This study takes a fundamental approach to defining the relationship between SAR scattering mechanisms and GNSS positioning quality and visualizing this relationship through image processing. Figure 1 shows the flow of the proposed methodology. After converting the full-polarimetric SAR data into backscatter coefficients, Pauli decomposition was applied. This technique decomposes the complex scattering matrix into three fundamental scattering mechanisms that can be physically interpreted as follows:

a. Surface Scattering

This phenomenon is primarily observed in areas where specular reflection occurs, such as on water surfaces and smooth ground. In the context of GNSS positioning, favorable environments with unobstructed sky visibility are required.

b. Double-Bounce Scattering:

This phenomenon occurs when signals undergo two reflections, typically at right angles formed by buildings and the ground. It indicates the presence of artificial structures such as buildings and bridge piers and is associated with unstable environments where multipath effects are likely to occur.

c. Volume Scattering

This phenomenon occurs when a microwave is scattered by random multiple reflections within complex objects, such as vegetation or complex building structures. It is hypothesized to represent poor environments where GNSS signals are frequently obstructed. In this study, the three types of scattering phenomenon were computed and mapped to red (double-bounce scattering), green (volume scattering), and blue (surface scattering) in an RGB composite image. This visualization intuitively represents the GNSS positioning environment.

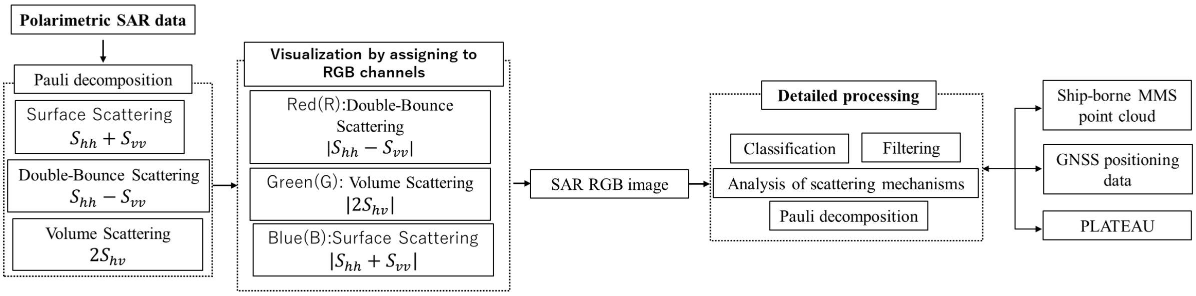

Figure 1: Methodology.

Experiment

a. SAR Data

This study used full-polarimetric observation data from the Phased Array type L-band Synthetic Aperture Radar-2 (PALSAR-2), which is aboard the Advanced Land Observing Satellite-2 (ALOS-2), and is operated by the Japan Aerospace Exploration Agency (JAXA). PALSAR-2 uses L-band microwaves, which can penetrate clouds and smoke. This enables stable observations regardless of the conditions or time of day. For this analysis, quad polarization mode data were used. This mode provides full-polarimetric information (HH, HV, VH, and VV channels), which is essential for detailed scattering analyses, such as Pauli decomposition. The SAR data acquisitions were scheduled to be as close as possible to the GNSS measurement campaign dates in late 2022 to ensure temporal consistency with ground-based positioning data.

b. Conversion to Backscattering Coefficient

SAR images record radar backscatter intensity as pixel values, or digital numbers (DN). For quantitative analysis, these values were converted into the backscattering coefficient (σ^0) using equation 1:

$$\sigma^0 = 10\log_{10}(DN^2) + CF, \qquad (1)$$

where DN is the pixel value (digital number), CF is the calibration factor (−83.0 dB), and σ^0 is the backscattering coefficient in decibels.

Subsequently, Pauli decomposition was then applied to the calibrated SAR data, enabling the extraction of three scattering mechanisms: surface scattering, double-bounce scattering, and volume scattering. These components were mapped into an RGB composite, with red representing double-bounce, green representing volume, and blue representing surface.

c. A Waterborne Mobile Mapping System

To validate the SAR-based estimation, ground-truth data were obtained using a real-time kinematic global navigation satellite system (RTK-GNSS) receiver mounted on *Raichou I*, a battery-powered boat. The boat was equipped with a waterborne MMS, which continuously recorded high-precision positioning logs. In addition, point clouds were also acquired using the MMS to support the validation of the SAR-based estimation. The GNSS solutions were classified as follows:

RTK-FIX

The carrier-phase integer ambiguity has been successfully resolved, resulting in centimeter-level accuracy. This state was defined as a good GNSS positioning environment in our experiment.

RTK-FLOAT

The ambiguity could not be resolved, resulting in degraded accuracy ranging from several decimeters to several meters. Together with single-point solutions and loss of solution, this was defined as a poor GNSS positioning environment in our experiment.

We mapped these solutions along the boat trajectory to enable a direct spatial comparison with the SAR-derived estimation results.

d. 3-D City Model (PLATEAU)

3-D geometric information on urban structures was obtained from the PLATEAU 3-D City Model, published by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in Japan. This dataset provides 3-D geometries and building heights, as well as high-precision geospatial information for major structures, such as buildings, roads, and bridges. In this study, the PLATEAU model served as a 3-D basemap to identify the physical structures that obstruct GNSS signals and influence SAR scattering.

Results

a. Spatial Estimation of the Positioning Environment using SAR Analysis

Figures 2 and 3 show the results of applying the Pauli decomposition methodology to the ALOS-2/PALSAR-2 data over the target area, as detailed in the analytical procedure of this study. In these images, each color pixel represents a dominant microwave scattering mechanism: red corresponds to double-bounce scattering, green to volume scattering, and blue to surface scattering. Our central hypothesis is that there is a correlation between these physical scattering mechanisms and the quality of the GNSS positioning environment. Moreover, a fundamental characteristic of SAR is that smooth water surfaces cause specular reflection. This results in extremely low backscatter coefficients, causing these bodies of water to appear as dark areas in the image. Exploiting this property enables us to clearly identify features such as rivers and canals in SAR data. In the subsequent sections, we compare these SAR-based estimation results with in situ GNSS measurements to validate our hypothesis.

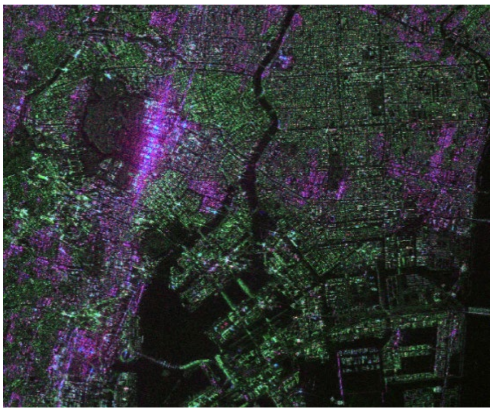

Figure 2: Pauli Decomposition Result (September 2, 2022).

Figure 3: Pauli Decomposition Result (October 15, 2022).

b. Mapping of Positioning Quality using In Situ GNSS Data

To validate the SAR-based analysis, we evaluated the positioning quality of the target rivers using RTK-GNSS data acquired by the waterborne MMS. We classified the positioning quality of the solution at each epoch. High-precision RTK-FIX solutions were classified as “good” and plotted in blue. All other solutions, including RTK-FLOAT and single-point positioning, were classified as “poor” and plotted in red. We mapped these results along the boat's trajectory to visualize the spatial distribution of positioning quality, as detailed in the following three case studies.

c. Nihonbashi River: Non-GNSS Positioning Environment

The Nihonbashi River, located under the Metropolitan Expressway, is a non-GNSS positioning environment. Figure 4 shows the GNSS positioning quality mapping for this section. As shown, the trajectory is predominantly plotted in red, indicating “poor” positioning quality across nearly the entire area. In the corresponding SAR image, the underside of the elevated expressway appears as a region of low backscatter, or a dark area, similar to the surface of water. This makes it difficult to distinguish between the two features. This finding demonstrates that the SAR-based detection of such large-scale, elevated structures is particularly challenging.

d. Shiomi Canal: GNSS Positioning Environment

The Shiomi Canal is a wide waterway surrounded by a few high-rise buildings, providing an open space and a GNSS positioning environment. Figure 5 shows the GNSS positioning quality mapping for this section. Most of the trajectory is plotted in blue, indicating stable and “good” positioning quality. However, immediately after passing under multiple bridges, localized “poor” quality, or red plots, were observed. In the SAR imagery, the water surface was clearly delineated as a dark area, and the bridges were identifiable due to their scattering characteristics, which were distinct from those of the water. The spatial correspondence between the bridge locations and the local degradation of GNSS accuracy confirms stable performance in open water sections and temporary instability directly beneath and in the vicinity of bridges.

e. Kanda River: A Mixed Environment

RTK-FIX solutions were obtained along most of the Kanda River trajectory, indicating a favorable positioning environment overall. Figure 6 shows the GNSS positioning quality mapping for this section. However, RTK-FLOAT solutions were found directly under and around the bridges, which resulted in significant localized degradation of positioning accuracy. These results suggest that bridges primarily contribute to the deterioration of the positioning environment in urban rivers. In the SAR Pauli decomposition images, the river surface appeared dark due to low backscatter, whereas the bridges exhibited distinct scattering characteristics. This contrast demonstrates the potential for using SAR imagery to detect bridges over rivers and identify, localized factors responsible for GNSS performance degradation.

Figure 4: CLAS Positioning Mapping Result (the Nihonbashi River).

Figure 5: CLAS Positioning Mapping Result (the Shiomi Canal).

Figure 6: CLAS Positioning Mapping Result (the Kanda River).

f. 3-D Verification of the Physical Environment

To investigate the physical factors underlying the correlation between the SAR analysis and the GNSS measurements, we examined the 3-D structure of the study area using both point clouds acquired by the waterborne MMS and the PLATEAU 3D City Model. Figure 7 shows the point clouds obtained by the waterborne MMS along the Nihonbashi River. This dataset accurately captures the detailed geometry of river structures, such as bridges, revetments, and the Metropolitan Expressway slab. By contrast, the surrounding high-rise buildings were not fully captured because the LOS of the laser scanner was obstructed by the river structures. To supplement the waterborne MMS data and improve understanding of the broader urban structure, the PLATEAU 3D City Model was used. Figures 8 and 9 show the PLATEAU models of the Nihonbashi River and Shiomi Canal areas, respectively. The models confirm that the Nihonbashi River is surrounded by dense high-rise buildings, whereas the Shiomi area is a relatively open space with a wide river and fewer tall structures. These data provide an objective, 3-D representation of the physical enclosure of each area.

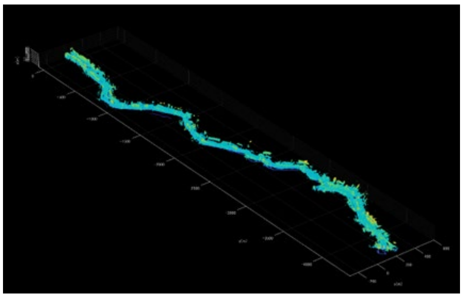

Figure 7: Point Clouds Obtained by the Waterborne MMS on the Nihonbashi River.

Figure 8: PLATEAU model of the Nihonbashi River.

Figure 9: PLATEAU model of the Shiomi Canal.

Discussion

a. Correlation Between SAR Scattering Characteristics and GNSS Positioning Quality

The results of this study demonstrate a clear correlation between the SAR-derived scattering characteristics, as expressed through Pauli decomposition, and the in situ GNSS positioning quality. The nature of this correlation depends on the physical environment. In the open environment of the Shiomi area, the water surface was uniformly depicted as a region of low backscatter, and bridges were represented with a distinct contrast. The spatial distribution of these bridges coincided with locations where temporary GNSS quality degradation (RTK-FLOAT) was observed. This confirms that local degradation factors, such as bridges, can be identified from SAR images. Conversely, in the enclosed environment of the Nihonbashi River, the underside of the elevated expressway also produced low backscatter, appearing similar to the water surface and making discrimination between the two features difficult with SAR alone. While the GNSS quality in this section was nearly always poor (RTK-FLOAT), the difficulty in identifying the overhead structure from SAR indicates that additional information is necessary for more accurate spatial estimation. In the mixed environment of the Kanda River, the locations of the bridges appeared as distinct features in the SAR images, separate from the water surface. This corresponded with the intermittent GNSS quality degradation observed near the bridges. In summary, SAR can effectively identify local GNSS degradation factors when bridges are distinguishable from the water surface (as in the Shiomi and Kanda Rivers). However, SAR alone is insufficient for an unambiguous estimation when both the water and large overhead structures appear as low-backscatter regions (e.g., the Nihonbashi River).

b. Physical Basis for the Correlation

The observed correlation is explained by a common physical basis. The same 3-D urban structures that give rise to specific microwave scattering mechanisms for SAR are also the root cause of GNSS signal degradation. In SAR imagery, calm water surfaces cause specular reflection, resulting in extremely low-backscatter regions (dark areas). By contrast, the complex 3-D structures of bridges, such as piers and girders, produce a variety of strong returns, including double-bounce and volume scattering. Consequently, bridges appear with a distinct contrast against the dark background of the water surfaces. This principle explains why areas of degraded GNSS quality align with the locations of bridges detected in the SAR image of the Kanda and Shiomi Rivers. Furthermore, mixed colors in the Pauli decomposition carry additional significance. Magenta, for instance, indicates a combination of surface and double-bounce scattering, often associated with dense artificial structures. Cyan, reflecting a mixture of surface and volume scattering, suggests moderately unstable environments with features such as vegetation or complex rooftop structures. Thus, while SAR scattering patterns do not directly measure GNSS positioning quality, they indirectly capture the structural characteristics of the urban environment that influence GNSS performance.

c. Effectiveness and Significance of the Proposed Method

Based on these findings, we conclude that applying Pauli decomposition to full-polarimetric SAR data is an effective approach for mapping GNSS positioning environments in urban rivers. Traditionally, wide-area evaluations required either costly and time-intensive field surveys or computationally demanding simulations dependent on high-fidelity 3-D city models. By contrast, the proposed method offers the significant advantage of enabling wide-area mapping using a single source of satellite SAR data, independent of weather conditions or time of day. Beyond autonomous navigation, this approach has broader significance, with potential applications in disaster prevention planning and urban infrastructure management. In particular, the methodology allows for the creation of hazard maps showing expected degradation by extracting bridge masks from SAR images and designating surrounding zones as potential GNSS risk areas. This information can support critical operational decisions, such as route planning and sensor-switching strategies between GNSS and non-GNSS technologies (e.g., IMU, LiDAR SLAM).

d. Limitations and Future Prospects

This study demonstrated the effectiveness of SAR data for this application. However, several limitations remain. First, the observation dates of the SAR and GNSS datasets did not perfectly coincide. Although we assumed static urban structures, seasonal vegetation changes, water level fluctuations, and temporary constructions could alter the positioning environment in practice. Second, estimations that rely solely on Pauli decomposition have inherent constraints. For example, in the case of the Nihonbashi River, the bridge deck and water surface were indistinguishable. Third, interpreting mixed colors such as magenta and cyan is not straightforward and requires more detailed physical analysis and data integration. Future research should therefore focus on multimodal data fusion, integrating SAR-derived polarization parameters with height information from 3-D urban models and applying machine learning to achieve more robust classification. Moreover, this methodology is not limited to data-rich cities like Tokyo but can also be applied to overseas cities and ports with limited map information. In such environments with limited data, SAR-based estimation methodologies are expected to play a vital role in supporting autonomous navigation.

Conclusion

In this study, we estimated the GNSS positioning environment in urban rivers using Pauli decomposition of multipolarization SAR data, and we verified its effectiveness by comparing the result with actual measurement data. Our results showed that in environments such as the Shiomi Canal and Kanda River, where the water surface and bridges exhibit distinct scattering properties, the positions of the bridges identified in the SAR data aligned with a localized reduction in GNSS positioning quality. This finding suggests the potential application of using SAR images for identifying areas of positioning risk. By contrast, in sections covered by the Metropolitan Expressway, such as the Nihonbashi River, both the water surface and the elevated structures were depicted as having low scattering. Because it is difficult to distinguish between the two using SAR alone, the limitations of the estimation were also clarified. Furthermore, 3-D verification using MMS point clouds and PLATEAU models confirmed that the relationship between SAR scattering patterns and GNSS quality stems from the same urban structure. This finding substantiates the physical basis for the correlation. Thus, although SAR does not directly measure GNSS, it can indirectly estimate positioning quality by analyzing the 3-D characteristics of the urban environments. This methodology has several advantages over conventional methodologies. It can evaluate a wide range of positioning environment at once, regardless of weather or time of day. It is expected to be applied to autonomous navigation support and urban management. However, issues remain regarding observation timing differences, limitations of Pauli decomposition, and the difficulty of interpreting mixed colors. Further development through diverse data fusion and machine learning will be necessary in the future. The results of this study are being considered for application in navigation route optimization and map generation for GNSS/non-GNSS seamless positioning.

Acknowledgements

This research is part of a public joint research project utilizing data from JAXA's Advanced Land Observing Satellite (ALOS-2).

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