

## Fractal Analysis of Satellite Night-Time Imagery for Environmental and Urban Monitoring

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### Abstract

Satellite remote sensing technologies offer a powerful means for acquiring high-resolution imagery that captures both natural and anthropogenic features across large geographic regions. One particularly valuable application of satellite data is the analysis of night-time lights, which reflect human activity, urban infrastructure and energy consumption. Traditional image processing methods often struggle to describe the irregular and complex geometries inherent to urban environments and natural landscapes. This research proposed the application of fractal analysis as a methodological tool for characterizing such complexity in night-time satellite images. By applying this to satellite images of Ukraine and the city of Kyiv before and after major attacks on energy infrastructure, it demonstrated how reductions in night-time illumination correspond with significant decreases in fractal dimension. Additionally, the method was applied to assess urban expansion in Dubai and Dnipro across multi-decadal periods. Results show a correlation between increased urbanization and changes in fractal characteristics, providing evidence that fractal metrics can serve as proxies for urban morphology and development.

Fractal analysis as an effective method for environmental monitoring, crisis assessment, and urban planning opens pathways for integrating fractal parameters into larger geospatial intelligence systems and provides a foundation for further research on scale-invariant properties of urban and ecological patterns in satellite imagery.

### 1. Introduction

Remote sensing plays an increasingly central role in the observation and analysis of Earth's surface (Honcharov et al., 2024; Santillan et al., 2023; Hordiiuk et al., 2017). Modern satellite systems deliver high-resolution imagery that captures essential data for understanding natural processes and human-induced changes. Among the most dynamic forms of satellite data are night-time images, which offer insights into patterns of illumination associated with electricity usage, urbanization, economic activity, and infrastructure robustness.

The complexity inherent in satellite imagery, especially in urban settings or regions undergoing rapid change, presents analytical challenges. Traditional Euclidean geometry often fails to adequately represent or interpret the irregular, self-similar, or fragmented structures typical of natural landscapes and anthropogenic development. This is particularly true for night-time lights, where the distribution of illumination is non-linear, patchy, and variable in scale. To overcome these limitations, researchers have turned to fractal geometry, a mathematical framework introduced by Benoît Mandelbrot (Mandelbrot, 1982; 1983).

In remote sensing, fractal dimension (D) has been applied to the analysis of texture, terrain modeling, land-use classification, and even vegetation mapping. For night-time satellite imagery, which captures both luminous intensity and spatial distribution of human activity, fractal analysis holds the potential to uncover underlying patterns not easily discernible through conventional techniques.

The work presented aims to leverage fractal geometry to evaluate and interpret night-time satellite imagery from a range of geographic contexts. The primary focus is twofold: first, to assess

how the degradation of energy infrastructure – as evidenced by loss of night-time lighting – affects the fractal characteristics of images; and second, to examine how long-term urban growth influences the fractal morphology of cities.

The method was applied to a series of satellite images from key study areas: Ukraine and Kyiv before and after infrastructure attacks in 2022; Dubai from 1990 to 2022; and Dnipro from 1972 to 2019. The results are interpreted in terms of their relevance to environmental monitoring, resilience assessment, and urban planning.

By highlighting the capability of fractal analysis to extract meaningful information from night-time satellite imagery, this work contributes to the development of new tools and methodologies in geospatial analysis. It advances the understanding of how fractal descriptors can serve as valuable indicators of environmental and urban conditions, particularly in scenarios marked by abrupt change or ongoing development.

### 2. Literature review

Fractal geometry has increasingly become an essential analytical tool in the study of spatial phenomena captured via satellite remote sensing. Since Mandelbrot's seminal works (Mandelbrot, 1982; 1983), which introduced the idea of natural phenomena exhibiting self-similarity and scale invariance, researchers have pursued fractal methods for analyzing the complexity of geographical patterns. In remote sensing, this approach is particularly valuable due to the inherently multiscale nature of satellite imagery.

The fundamental concept of the fractal dimension allows for a quantitative measure of spatial heterogeneity and complexity. Fractal dimension has been widely used to describe texture,

shape, and structural diversity in imagery (Sun et al., 2006). This utility has been demonstrated in land-use classification, vegetation mapping, and geological surveys. In high-resolution remote sensing, the application of fractal-based techniques has proven useful for segmenting and interpreting complex urban structures (Wawrzaszek et al., 2013).

Authors (Zeng et al., 2007) identified distinctive fractal characteristics across different land cover types in very high-resolution satellite imagery. Their study underscores the idea that fractal descriptors can act as reliable indicators for texture classification, especially when traditional methods underperform due to scale variability. Cai (2009) explored both fractal and multifractal characteristics in satellite images, suggesting that such descriptors enhance the analysis of spatial discontinuities and help detect developmental gradients in urban form.

The works (Elvidge et al., 2020; Pishnohraiev et al., 2021) established the VIIRS Day/Night Band as a critical tool for monitoring light emissions from Earth's surface. These studies link night-time illumination to socioeconomic activity and infrastructure resilience. Other research (Ruiz de Miras et al., 2025) introduced rapid methods for computing fractal dimensions on RGB imagery, expanding the scope of fractal analysis into color domains. Tools like VIIRS DNB have been employed to detect fluctuations in electrical supply and urban resilience during wartime (e.g., the Ukraine-Russia war).

Urban form analysis has been enriched by fractal models that explore the scaling behavior of urban expansion. Shen (2002) examined urbanized areas through fractal metrics and identified growth patterns associated with different urban morphologies. Wang et al. (2011) utilized fractal analysis to assess the environmental impacts of urban form, arguing that spatial configuration directly influences air quality and green space availability. These insights were furthered (Lagarias et al., 2021; Wang et al., 2011) and demonstrated fractal and self-similar properties in urban street networks, using these features to infer evolutionary dynamics in city planning.

Yang et al. (2015) proposed a fractal net evolution method based on graph theory to segment remote sensing images, offering improved boundary detection and regional differentiation. Karydas (2020) optimized multi-scale segmentation processes using fractal geometry, improving classification accuracy in satellite image interpretation.

In addition to urban studies, fractal geometry has been applied to environmental monitoring tasks. Del-Pozo-Velázquez et al. (2022) proposed a fractal-dimension-based water detection method, while Altaei and Abdulhassan (2016) applied fractal descriptors to classify rural land use. Both studies exemplify the broader relevance of fractal metrics in assessing natural and human-modified landscapes.

Overall, the literature demonstrates the versatility of fractal analysis in remote sensing applications. Whether analyzing urban growth, infrastructure damage, or ecological heterogeneity, fractal metrics provide meaningful quantitative descriptors that complement spectral and spatial data. This study builds upon these insights by applying a unified fractal analysis framework to night-time satellite images, thereby filling a methodological gap in the integration of temporal and fractal perspectives in crisis and urban dynamics.

This work presents the approach for extracting key fractal features – including fractal dimension, distribution, and

segmentation – from high-resolution satellite images that enable rapid environmental monitoring and urban diagnostics, particularly under conditions of infrastructure disruption.

Thus, the analysis of fractal analysis methods suggests the need for further research focused on adapting existing approaches and developing new techniques for detecting environmental changes based on the fractal characteristics of satellite imagery.

### 3. Materials and Methods

The proposed approach integrates fractal geometry with remote sensing techniques to reveal meaningful spatial patterns related to infrastructure, urban development, and environmental status. It includes the following stages:

1. Acquisition and preprocessing of night-time satellite imagery.
2. Application of fractal analysis algorithms, including global and local estimations.
3. Generation of fractal dimension values, distributions, and segmentation maps.
4. Temporal and spatial comparison of fractal metrics across regions and timeframes.

This tool facilitates high-throughput analysis and allows the user to visually and statistically interpret the results of fractal computations.

A dataset of satellite imagery was analyzed:

- Temporal datasets representing Ukraine and Kyiv before and after major energy infrastructure attacks in 2022. These images were obtained from the VIIRS Day/Night Band (DNB) system and processed for radiometric consistency.
- Urban growth datasets encompassing Dubai (1990 and 2022) and Dnipro (1972 and 2019). High-resolution visible-spectrum imagery was sourced from open-access NASA and Google Earth Engine repositories.

All imagery was converted to grayscale intensity matrices to standardize input across different sensors and resolutions. Brightness normalization was applied to mitigate atmospheric and seasonal effects.

One of the most extensively utilized techniques for quantifying the fractal dimension of urban environments is the box-counting method. This iterative approach involves superimposing a grid of size  $r$  onto a spatial representation of the urban landscape. At each iteration, the number of grid cells  $N(r)$  that intersect with built-up areas is recorded. By systematically varying the grid size, a scale-dependent distribution is obtained, allowing estimation of the scaling relationship  $N(r) = r^{-D}$ , where  $D$  is the fractal dimension. The value of  $D$  is typically derived through log-log linear regression between  $N$  and  $r$ . In addition to box-counting, several alternative methods exist for estimating urban fractal properties, including morphological dilation, correlation dimension, and radius-mass scaling techniques, each offering unique insights into spatial complexity and urban form (Fouroutan et al., 1999). This measure was used as a proxy for overall image complexity. High  $D$ -values suggest rich, diverse spatial structures, while low  $D$ -values indicate uniformity or loss of structural detail (e.g., blackout conditions).

In addition to the global dimension, we computed local fractal dimensions over small sliding windows across each image. This produced a fractal map highlighting regional variations in complexity. The maps were converted into histograms to obtain fractal distributions, which describe the frequency of different local  $D$ -values across the scene. Distributional features such as

modality (number of peaks), skewness, and kurtosis were used to characterize the heterogeneity of illuminated and built-up areas. Based on the local dimension maps, a fractal segmentation algorithm was applied.

Once fractal descriptors were computed, comparative analyses were conducted to evaluate differences:

- Pre- and post-attack imagery (Ukraine, Kyiv): focused on identifying light loss due to infrastructure damage.
- Historical urban growth (Dubai, Dnipro): evaluated how expansion changes complexity and pattern regularity.

To validate the significance of observed fractal variations, statistical tests (t-tests) were applied to  $D$ -values across different scenes. Ground-truthing was supported through auxiliary data, including urban planning maps, population statistics, and official reports on energy disruptions (Elvidge et al., 2009).

Interpretation of results leveraged existing theories of fractal urbanism (Shen, 2002; Zhang et al., 2021), which link changes in spatial self-similarity to economic, infrastructural, and planning phenomena. Night-time lights served as empirical indicators of human presence, enabling inferences about resilience, recovery, and development.

Several methodological limitations must be acknowledged: box-counting may overestimate  $D$  in images with high noise or aliasing; local estimation is sensitive to window size and overlap; night-time imagery is affected by cloud cover, moonlight, and sensor calibration; fractal descriptors are sensitive to resolution differences and must be normalized.

Despite these constraints, the method provides a scalable, interpretable, and reproducible approach to analysing satellite imagery in dynamic environmental and urban contexts.

#### 4. Experiments and Results

The developed method has been tested on classical fractals - Sierpinski triangle and Koch curve, whose theoretical fractal dimension is approximately 1.585 and 1.2618, respectively. The output data agrees well with these theoretical values, which confirms the correctness of the implementation.

It is important to note that the estimated fractal dimension is highly sensitive to the particular fragment of the image being analyzed. While this variability complicates the use of a single global dimension for object characterization, it also suggests anisotropy within the surface structure. As such, a global fractal dimension is insufficient for fully capturing the complexity of fractal objects.

To address this limitation, images were divided into smaller fragments, and local fractal dimensions were computed within each. An empirical distribution of these local dimensions – referred to as the fractal distribution – was then constructed to provide a more detailed representation of the object's structural characteristics.

A sliding window technique was employed to generate the fractal distribution. This method involves calculating the fractal dimension within a moving window of arbitrary size, which is shifted pixel by pixel across the image. At each position, the local fractal dimension within the window is calculated, and the resulting values are used to build a probability distribution function  $W(D) / Wmax(D)$ .

Fractal segmentation is understood here as the partitioning of a digital image into regions with similar or identical fractal dimensions. This enables the identification of objects or textures in the image that exhibit common fractal properties. The developed software module supports such segmentation by assigning colors to regions based on their local fractal dimension. The implemented segmentation algorithm includes the following steps:

- Calculation of local fractal dimensions using sliding window sizes ranging from 5 to 21 pixels.
- Assigning identical colors to regions with matching local fractal dimension values.

The color mapping uses the RGB color spectrum, starting from red (255, 0, 0) corresponding to a fractal dimension of 0, to blue (0, 0, 255) representing a dimension of 2.

#### 4.1 Ukraine: National-Scale Analysis of Infrastructure Impact

To evaluate the impact of large-scale energy infrastructure attacks in 2022, we analyzed VIIRS DNB night-time satellite images of Ukraine from two temporal snapshots: February 6, 2022 (pre-attack) and November 23, 2022 (post-attack) (Figure 1).

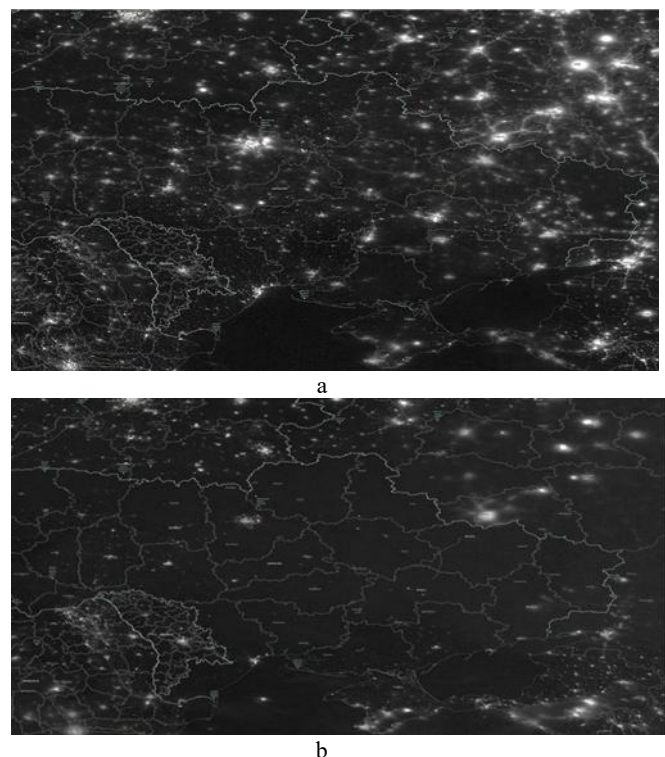


Figure 1. VIIRS DNB night-time satellite images of Ukraine a) February 6, 2022 (pre-attack), b) November 23, 2022 (post-attack)

Figures 2 and 3 show the results of calculating the fractal dimension. The satellite image of Ukraine on 06.02.2022 has a fractal dimension of 1.26, while the satellite image on 23.11.2022 has a fractal dimension of 1.04. This indicates a significant decrease in fractal dimension during the blackout period. Thus, based on the values of the fractal dimensions of satellite images at different points in time, it is possible to assess the state of the country's energy structure and determine the relative damage and state of the energy sector after massive attacks.

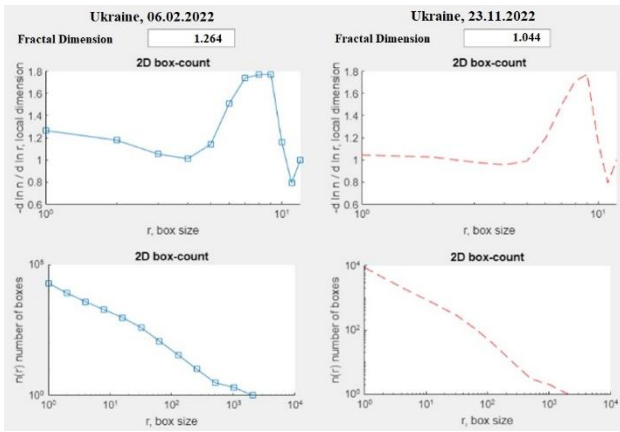


Figure 2. Fractal dimensions of satellite images of Ukraine (image 1 – pre-attack, image 2 – post-attack)

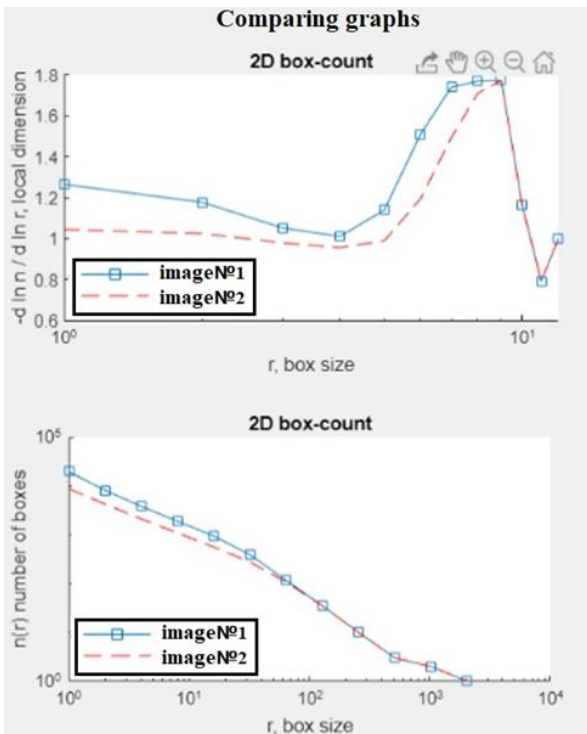
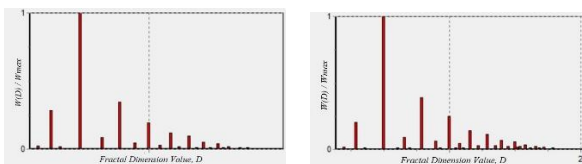


Figure 3. Comparison of fractal dimensions of satellite images of Ukraine

The fractal distributions of the satellite images shown differ in terms of density and intensity (Figure 4). Images with more illumination of territories have a greater number of distribution modes than those with less illumination. This suggests that larger light sources are disappearing, and with them, distribution modes are also disappearing.



November 23, 2022 (post-attack) February 6, 2022 (pre-attack)  
 Figure 4. Fractal distributions of night-time satellite images of Ukraine

The fractal segmentation approach is employed to identify spatially heterogeneous regions based on local fractal metrics (Figure 5).

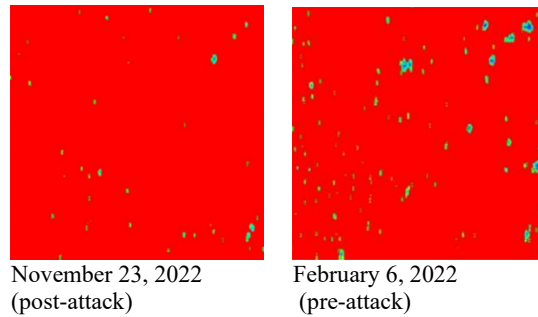


Figure 5. Fractal segmentation of night satellite images of Ukraine

This experiment confirms the sensitivity of fractal metrics to infrastructural degradation and validates their utility in rapid damage assessment using passive satellite observation. The pre-attack image displayed a global fractal dimension of 1.26, reflecting moderate spatial complexity and widespread light distribution. The post-attack image showed a reduced dimension of 1.04, indicating a substantial loss in lighting intensity and spatial coverage. Fractal distribution histograms revealed a collapse of secondary peaks associated with industrial and urban lighting clusters. Fractal segmentation maps displayed a visible contraction of high-complexity regions, particularly in the central and eastern parts of the country.

#### 4.2 Kyiv: Urban-Scale Energy Disruption Monitoring

To complement the national-scale analysis, a focused study on Kyiv was conducted using imagery from January 2022 and November 2022 (Figures 6 -9).

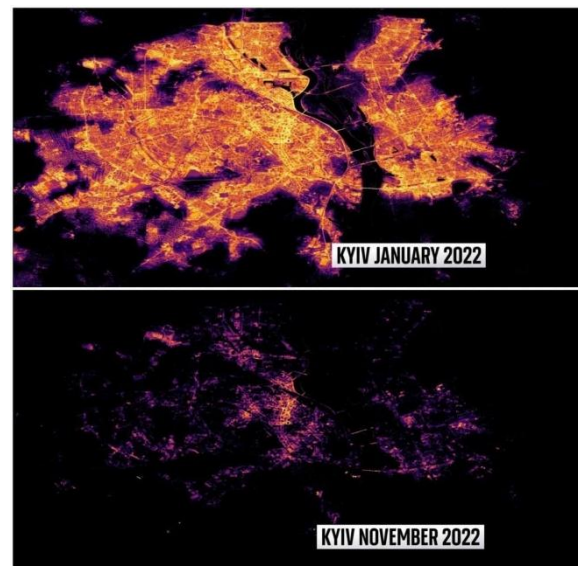


Figure 6. Input night-time satellite images of Kyiv (January 2022 – pre-attack, November 2022 – post-attack)

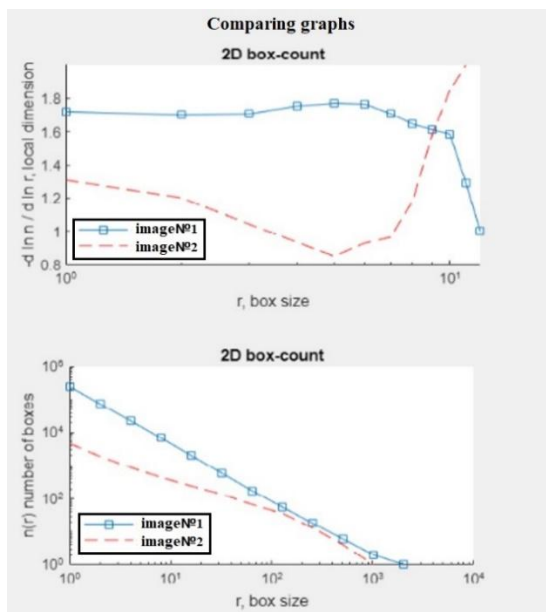
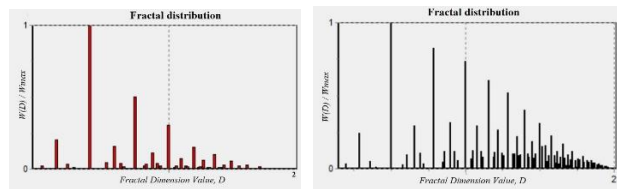
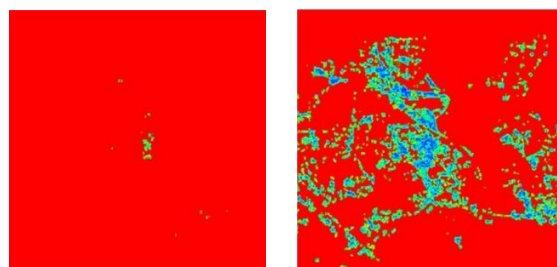


Figure 7. Comparison of fractal dimensions of satellite images of Kyiv (image 1 – pre-attack, image 2 – post-attack)



November 2022 (post-attack)      January 2022 (pre-attack)  
 Figure 8. Fractal distributions of night-time satellite images of Kyiv



November 2022 (post-attack)      January 2022 (pre-attack)  
 Figure 9. Fractal segmentation of night satellite images of Kyiv

The data support the hypothesis that urban complexity, as captured through fractal descriptors, reflects the operational status of energy and civic infrastructure.

The fractal dimension decreased from 1.72 to 1.31 over this period. Fractal segmentation maps showed the fragmentation of the city’s illuminated structure, with outer districts experiencing the most drastic lighting loss. Histogram analyses showed a leftward shift and narrowing of the distribution, indicating homogenization and reduction in bright zones.

### 4.3 Dubai: Fractal Signatures of Rapid Urban Expansion

Urban development patterns were assessed using high-resolution optical images of Dubai from 1990 and 2022 (Figure 10). These years represent the pre- and post-boom phases of urban transformation.

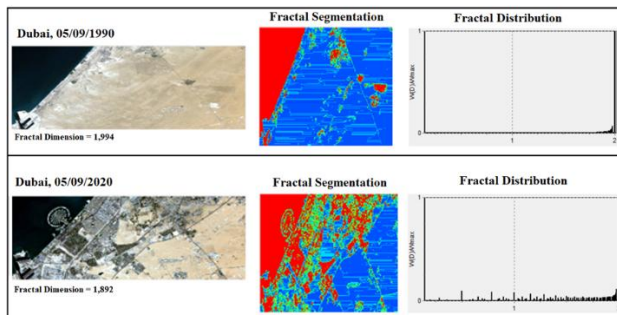


Figure 10. Fractal analysis of satellite images of Dubai (1990 and 2022)

The experiment demonstrates that fractal descriptors capture not only expansion but also morphological diversification in highly dynamic urban landscapes. The fractal dimension slightly decreased from 1.994 to 1.892, suggesting increased geometric regularity due to planned urbanization. Fractal segmentation revealed an increase in low- and mid-complexity regions, consistent with residential and commercial zoning patterns. The fractal distribution became more multimodal, with an increase in small-scale variation due to the diverse spatial textures of new districts.

### 4.4 Dnipro: Long-Term Urban Morphology Tracking

Dnipro's urban evolution was studied using satellite images from 1972 and 2019 (Figure 11, 12). Two districts, Peremoha and Topol, were analyzed for spatial complexity changes.

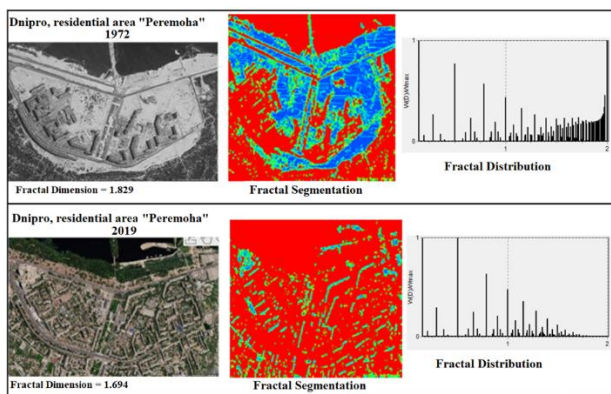


Figure 11. Fractal analysis of satellite images of the city of Dnipro, Ukraine, the Peremoha residential area (1972 and 2019)

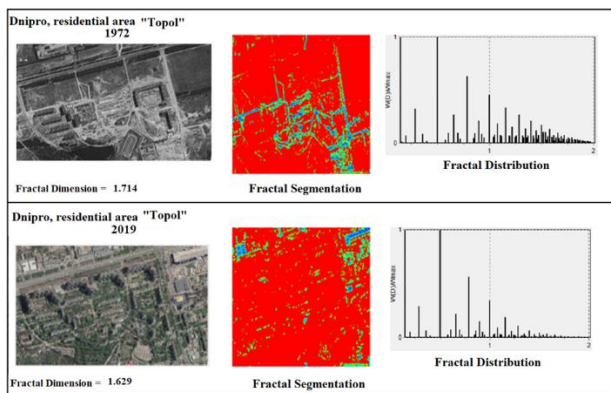


Figure 12. Fractal analysis of satellite images of the city of Dnipro, Ukraine, the Topol residential area (1972 and 2019)

These findings suggest that fractal analysis can serve as a diagnostic tool for urban renewal and the detection of planning-driven morphological shifts.

Both neighborhoods showed a decline in fractal dimension: Peremoha from 1.83 to 1.58 and Topol from 1.88 to 1.61. The segmentation maps indicated increasing spatial regularity and uniformity in new construction zones. Histograms revealed mode shifts and narrowing of distributions, consistent with the replacement of diverse older structures by uniform housing blocks.

## 5. Conclusion

This study has demonstrated the effectiveness of fractal analysis as a methodological approach for interpreting night-time satellite imagery in the context of environmental monitoring, infrastructure assessment, and urban development analysis. Fractal metrics—particularly fractal dimension and fractal segmentation—are capable of capturing subtle yet meaningful spatial variations in illuminated and built environments.

In the cases of Ukraine and Kyiv, we showed that the fractal dimension significantly declines following large-scale disruptions to electrical grids. This finding highlights the utility of fractal metrics for rapid, remote damage assessment during crises such as war, natural disasters, or power outages. In the studies of Dubai and Dnipro, we observed that urban development leads to nuanced shifts in fractal characteristics. While global complexity may decrease due to increased planning regularity, local diversity and segmentation complexity may rise, particularly in mixed-use and transitional zones. By applying a uniform analytical framework to diverse geographic and temporal datasets, we validated the generalizability of fractal descriptors, supporting their integration into broader geospatial intelligence systems for long-term urban and environmental monitoring.

Despite its strengths, this approach faces several limitations. The computed metrics can be sensitive to image quality, as atmospheric conditions, sensor noise, and resolution disparities may introduce variability. Local fractal estimation also depends on the choice of window size, which requires balancing spatial detail against statistical robustness. Moreover, interpreting changes in fractal dimension can be ambiguous, since such variations may stem from economic development, natural phenomena, or data artifacts. These challenges underscore the importance of combining fractal analysis with other remote sensing indicators and ground-truth data, particularly when informing high-stakes decisions.

Looking forward, several promising research directions emerge. Extending the methodology from monofractal to multifractal models would enable a richer characterization of spatial heterogeneity, particularly in complex urban landscapes. Incorporating time-series data could enhance forecasting and trend analysis, allowing fractal descriptors to reveal latent development trajectories or provide early warnings of infrastructural degradation. Another promising avenue lies in integrating fractal metrics into classification, clustering, and anomaly detection models, thereby improving both the accuracy and interpretability of machine learning applications in remote sensing. Further progress may also come from applying the approach to additional sensor modalities, such as radar or thermal imagery, which could expand its applications to vegetation monitoring, surface roughness estimation, and beyond. Finally, the development of user-friendly interfaces and decision-support

systems based on fractal indicators would improve the accessibility of these methods for planners, policymakers, and disaster response teams, ensuring their broader adoption in practice.

## References

- Altaei, Mohammed & Abdulhassan, Aqeel. (2016). Satellite Images Classification in Rural Areas Based on Fractal Dimension. *University of Baghdad Engineering Journal*. 22. 147 - 157. 10.31026/j.eng.2016.04.10.
- Cai, J., 2009. Analysis of fractal and multi-fractal characteristics of satellite images. *Joint Urban Remote Sensing Event*, 1-5.
- Del-Pozo-Velázquez, Javier & Chamorro-Posada, Pedro & Aguiar-Pérez, Javier & Juárez, María Ángeles & Casaseca-de-la-Higuera, Pablo. (2022). Water Detection in Satellite Images Based on Fractal Dimension. *Fractal and Fractional*. 6. 657. 10.3390/fractalfract6110657.
- Elvidge, Christopher & Sutton, Paul & Tuttle, B.T. & Tilottama, Ghosh & Baugh, K.E.. (2009). Global Urban Mapping Based on Nighttime Lights. 129-144. 10.1201/9781420083408-c6.
- Elvidge, C.D., Hsu, F., Zhizhin, M., Ghosh, T., Taneja, J., Bazilian, M., 2020. Indicators of electric power instability from satellite observed nighttime lights. *Remote Sensing*, 12(19), 3194.
- Fouroutan-pour, K., Dutilleul, P., Smith, D.L., 1999. Advances in the implementation of the box-counting method of fractal dimension estimation. *Applied Mathematics and computation*, 105, 195-210
- Honcharov, O., Hnatushenko, Vik., 2024. Land cover mapping with Sentinel-2 imagery using deep learning semantic segmentation models. In *Information Technology and Implementation 2024*, 1-18, [https://ceur-ws.org/Vol-3909/Paper\\_1.pdf](https://ceur-ws.org/Vol-3909/Paper_1.pdf)
- Hordiiuk, D.M., Hnatushenko, V.V., 2017. Neural network and local Laplace filter methods applied to very high resolution remote sensing imagery in urban damage detection. *IEEE International Young Scientists Forum on Applied Physics and Engineering (YSF)*. doi:10.1109/ysf.2017.8126648.
- Karydas, Christos. (2020). Optimization of multi-scale segmentation of satellite imagery using fractal geometry. *International Journal of Remote Sensing*. 41. 2905-2933. 10.1080/01431161.2019.1698071.
- Lagarias, A., Prastacos, P., 2021. Fractal dimension of European Cities: A comparison of the patterns of built-up areas in the urban core and the peri-urban ring. *CyberGeo*. 10.4000/cyberge0.37243.
- Mandelbrot, B.B., 1983. *The Fractal Geometry of Nature*.
- Pyshnograiev, I., Tkachenko, I., Gapon, S., 2021. Possibilities of using data on the brightness of night lights for critical analysis of socio-economic indicators of countries. *Economic Bulletin of the National Technical University of Ukraine 'Kyiv Polytechnic Institute'*. 10.20535/2307-5651.19.2021.240492
- Ruiz de M.J., Li Y., León S. A., Arroyo G., Lopez L., Torres J., Martín D., 2025. Ultra-fast computation of fractal dimension for

RGB images. *Pattern Analysis and Applications*. 28.  
10.1007/s10044-025-01415-y.

Santillan, J. R., Heipke, C., 2023. Using GHSL to Analyze Urbanization and Land-Use Efficiency in the Philippines from 1975-2020: Trends and Implications for Sustainable Development. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 10(1), 413-422.

Shen, G., 2002. Fractal dimension and fractal growth of urbanized areas. *International Journal of Geographical Information Science*, 16(5), 419–437.  
<https://doi.org/10.1080/13658810210137013>

Sun, W., Xu, G., Gong, P., Liang, S., 2006. Fractal analysis of remotely sensed images: A review of methods and applications. *International Journal of Remote Sensing*, 27(22), 4963–4990

Yang, Y. & Li, H. & Han, Y. & Gu, Haiyan. (2015). High resolution remote sensing image segmentation based on graph theory and fractal net evolution approach. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. XL-7/W4. 197-201.  
10.5194/isprsarchives-XL-7-W4-197-2015.

Wawrzaszek, M., Krupiński, S., Aleksandrowicz S., Drzewiecki, W., 2013. Fractal and multifractal characteristics of very high resolution satellite images. *IEEE International Geoscience and Remote Sensing Symposium*, 1501-1504.

Wang, H., Su, X., Wang, C., Dong, R., 2011. Fractal analysis of urban form as a tool for improving environmental quality. *International Journal of Sustainable Development & World Ecology*, 18(6), 548–552

Zhang, H., & Li, Z. (2011). Fractality and Self-Similarity in the Structure of Road Networks. *Annals of the Association of American Geographers*, 102(2), 350–365.  
<https://doi.org/10.1080/00045608.2011.620505>

Zhang, H., Lan, T., & Li, Z. (2021). Fractal evolution of urban street networks in form and structure: a case study of Hong Kong. *International Journal of Geographical Information Science*, 36(6), 1100–1118.  
<https://doi.org/10.1080/13658816.2021.1974451>

Zeng, Y., Zhang, J., Li, H., 2007. Fractal characteristics of very high-resolution satellite imagery. *IEEE International Geoscience and Remote Sensing Symposium*, 389-392.