Review of GNSS Scintillation Detection Methods with Emphasis on Low-Latitude and Indian Region Challenges

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Abstract

Satellite-based navigation systems are often affected by ionospheric disturbances, especially in low-latitude regions like India. Signal fading, positioning errors, and tracking issues caused by scintillation and rapid TEC changes are still difficult to manage in real time. Over the years, researchers have used indicators like the S4 index and phase scintillation (σϕ) to detect such events, but most of these methods rely on fixed thresholds and do not adapt well to changing conditions. In recent studies, machine learning models like SVMs and decision trees have been introduced to improve detection. These approaches show better accuracy, especially when using frequency-domain features from GNSS signal intensity. However, many of these models are still focused on classifying past events rather than predicting them ahead of time. Also, a large portion of this research is based on data from polar and mid-latitude regions, with limited work targeting India's unique ionospheric environment. This paper presents a detailed review of existing detection methods, recent advancements using machine learning, and the current challenges in applying these models to low-latitude conditions. The survey also highlights gaps in the literature, such as the lack of predictive modeling and limited use of region-specific data. These observations help shape the direction for future work aimed at developing more accurate, adaptive, and real-time solutions for GNSS signal integrity monitoring.

Keywords: GNSS Scintillation; Ionospheric Disturbances; Machine Learning in GNSS; Low-Latitude Ionosphere; Signal Integrity Monitoring.

Introduction

GNSS systems are important in areas like transportation, agriculture, and safety. However, these systems can be affected by disturbances in the ionosphere, leading to issues like signal fading and positioning errors. Ionospheric scintillation is a major issue, especially in low-latitude regions like India. It happens when changes in the ionosphere cause GNSS signals to fluctuate, making them unreliable, particularly during geomagnetic storms and equinox periods. To detect scintillation, researchers often use the S4 index and phase scintillation index ($\sigma\phi$) [1]. These tools are useful but have limitations. They are sensitive to the settings of the receiver, may not work well in noisy environments, and cannot predict future events. In recent years, machine learning (ML) techniques, like support vector machines (SVMs) and decision trees, have been explored to improve detection. These methods are more flexible than traditional ones, but most studies still focus on identifying past events, not predicting future scintillation. Prediction is important for mitigation and planning. Much of the research so far has focused on high-latitude areas, while India remains underexplored. This gap in research needs to be addressed. This paper reviews current methods for detecting ionospheric scintillation and GNSS signal issues [2]. It covers both traditional and machine learning-based techniques, highlighting strengths and limitations, and identifying areas for future research.

Background and Preliminaries

GNSS signals often get disturbed while passing through the ionosphere (60–1000 km), which is filled with charged particles. These effects are stronger in low-latitude regions like India, especially during evenings or geomagnetic storms [3]. Scintillation weakens signals, causing accuracy loss or even failure, while Total Electron Content (TEC) variations also add errors. Indices like S4 and $\sigma\phi$ are commonly used to study these issues but can be unreliable in noisy conditions [4–5]. Although many global studies exist, research focused on India's highly dynamic ionosphere is still limited, showing the need for region-specific work.

Classification of Existing Work

Many studies have examined ionospheric disturbances and their impact on GNSS signals. These studies can be categorized by the methods used, data types, regions studied, and research goals. Figure 1 below summarizes the classification of existing research by technique, data, region, and objective. This Figure 1 helps visualize the scope and limitations of earlier works in a structured way.

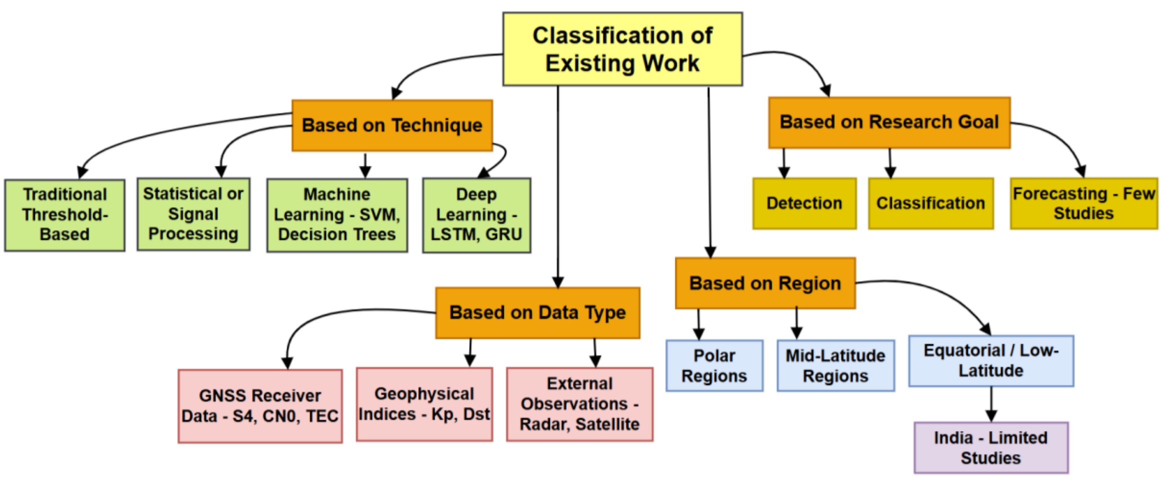

Figure 1: Classification of existing studies on ionospheric scintillation detection and prediction based on technique, data type, region, and research goal

Based on Technique Used

- Traditional Methods: These methods use fixed thresholds, such as an S4 index greater than 0.6, to detect scintillation. While simple, they are not always reliable, especially under rapidly changing conditions or in noisy environments [2].
- Signal Processing Methods: Techniques like wavelet transforms and spectral analysis have been used to detect scintillation, but they require expert knowledge and often depend on statistical assumptions [6].
- Machine Learning: Recent studies have applied machine learning methods like SVM, decision trees, and random forests for better detection. These models can adapt to different signal patterns but mostly focus on classifying past events rather than predicting future ones.

Based on Data Type

- GNSS Data: Most studies use GNSS data such as signal-to-noise ratio (C/N_0), S4 index, and TEC. High-rate receivers provide more detailed data for studying fast changes.
- Geophysical Data: Some studies combine GNSS data with geomagnetic indices like Kp and Dst to study how space weather affects signal quality.
- External Data: A few studies use data from ionosondes, radars, and satellite sensors to study ionospheric conditions along with GNSS data.

Based on Region

- Polar and Mid-Latitude Regions: Many early studies focused on high-latitude areas where ionospheric activity is more frequent.
- Low-Latitude Regions: Studies in the equatorial and low-latitude regions, including India, are fewer. These regions experience strong scintillation, but there is limited research on predictive modeling.

Based on Research Goal

- Detection: Most studies have focused on detecting when scintillation affects GNSS signals.
- Classification: Some studies classify the type or severity of scintillation using machine learning models.
- Forecasting and Early Warning: Few studies aim to predict when scintillation will occur, especially in low-latitude regions like India. This is an area that requires more attention.

Detailed Literature Review

Traditional methods often use fixed thresholds (like $S4 > 0.6$) to detect scintillation, which are simple but unreliable in noisy or rapidly changing conditions. Signal processing approaches such as wavelets and MF-DFA perform better for short-term variations, yet they struggle under strong equatorial disturbances or weak signals. Machine learning models, including SVM, decision trees, and random forests, offer improved detection but mainly classify past events and have difficulty generalizing across regions. Forecasting efforts remain limited; while some studies use indices like Kp and Dst, the results are still not dependable. Deep learning models such as LSTM show promise for time-series prediction but are rarely applied to India's low-latitude ionosphere.

TABLE I

SUMMARY OF KEY LITERATURE ON SCINTILLATION DETECTION AND CLASSIFICATION

Author(s), Year	Method	Region / Focus
Danilchuk et al., 2025 [6]	ROTI, GIM, PPP	Global – Storm impact
González-Casado et al., 2025 [7]	Detrending	Spain/Global – Monitoring
Kuruva et al., 2024 [8]	LSTM vs Holt-Winters	India (Hyd, GAGAN) – Forecasting
Tiwari et al., 2024 [9]	GNSS Signal Analysis	Equatorial – Impact
Nandakumar et al., 2024 [10]	GNSS + solar/geomagnetic	India (Varanasi) – Scintillation occurrence

Paul et al., 2024 [11]	Multi-GNSS + VHF	India (EIA) – Characterization
Chakraborty et al., 2024 [12]	Spectral analysis	India (Indore, Hyd) – Irregularity tracking
Ram Kumar et al., 2024 [13]	Multi-GNSS + ML	India (Hyd, Blr) – Detection
Sivakrishna et al., 2024 [14]	SVR Regression	India (Hyd, Blr) – TEC prediction
Kumar et al., 2023 [15]	ML with Kp & Dst	Global – Early detection
Sharma et al., 2022 [16]	S4 Threshold	India (Low-lat) – Detection
Lavin et al., 2021 [17]	Random Forest	Brazil (Low-lat) – Detection
Miriyala et al., 2018 [18]	MF-DFA	India (Hyd) – Detection
Jiao et al., 2017 [19]	SVM	Equatorial – Detection

While many detection approaches have evolved, forecasting-based models remain relatively rare. Figure 2 highlights the shift from traditional signal processing methods to machine learning and forecasting-based approaches over time, based on the studies summarized in Table I [6–19]. However, there are still significant gaps in the current literature, particularly in the application of these techniques in low-latitude regions like India. In the following section, we will critically analyze these gaps and identify the areas where future research should be focused.

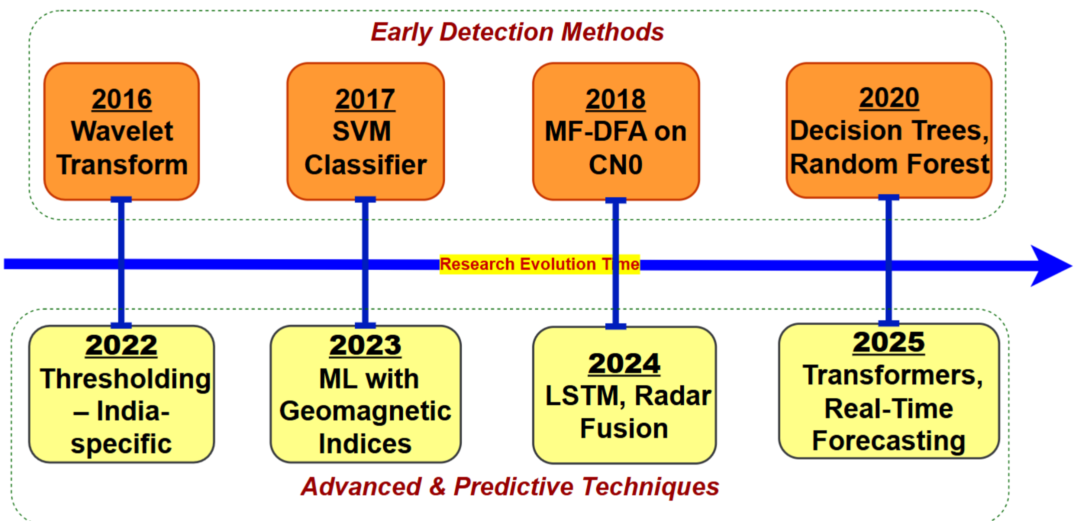

Figure 2: Timeline showing the evolution of GNSS scintillation detection techniques from 2016 to 2025

Critical Analysis and Knowledge Gaps

Most studies emphasize detection rather than forecasting, which limits their use in preventing disruptions, and the few predictive attempts often lack accuracy in fast-changing ionospheric conditions [8]. Deep learning models like LSTM, GRU, and Transformers—well-suited for time-series forecasting—are still underused, particularly in low-latitude regions such as India [12]. Moreover, much of the work relies on mid-latitude data, while India-focused studies remain scarce and often limited to small observational datasets, highlighting the need for region-specific predictive modeling [15].

Future Research Directions

Future studies should move from just detection to actual forecasting so that signal problems can be anticipated in advance, which is important for aviation, defense, and space [6]. Deep learning models like LSTM, BiLSTM, and GRU can be used for predicting short-term changes in TEC or S4 values and need more attention. Models should also be trained on Indian GNSS data since the ionosphere here is different from mid-latitude regions [18]. Using geophysical indices like Kp and Dst along with GNSS data could improve accuracy [16]. There is also a need to build real-time dashboards and risk maps for early alerts, especially in aviation [2]. Finally, data sharing and standardization across Indian institutions will help in faster progress and better comparisons [15].

Conclusion

This review has summarized key advancements in detecting GNSS signal disturbances caused by ionospheric scintillation, especially in low-latitude regions like India. A wide range of methods, from statistical approaches to recent machine learning models, have been explored in the literature, yet forecasting remains underdeveloped. While global studies dominate, India-specific research is still limited, particularly in the area of real-time prediction. Addressing the identified knowledge gaps through region-specific, adaptive, and predictive modeling can significantly enhance the reliability of GNSS applications in space weather–sensitive domains such as aviation, defense, and disaster management.

Author Contributions

P. Sirish Kumar conceptualized the study, carried out the literature review, and prepared the manuscript. Saikiran Oruganti contributed to analysis, provided feedback, and assisted in revising the paper. Both authors approved the final version.

References

1. P. M. Kintner, B. M. Ledvina, and E. R. de Paula, "GPS and ionospheric scintillations," Space Weather, vol. 5, no. 9, pp. 1–8, 2007.
2. J. T. Curran, N. Linty, P. Closas, F. Dovis, and J. Vilà-Valls, "Survey on signal processing for GNSS under ionospheric scintillation: Detection, monitoring, and mitigation," NAVIGATION, vol. 67, no. 3, pp. 511–536, 2020.
3. P. M. Kintner and B. M. Ledvina, "The ionosphere, radio navigation, and global navigation satellite systems," Advances in Space Research, vol. 35, no. 5, pp. 788–811, 2005.
4. B. Roy, "Impact of space weather events on satellite-based navigation," Space Weather, vol. 11, no. 11, pp. 680–686, 2013.
5. Y. Lou and X. Zhang, "Assessing 1-Second ROTI for Ionospheric Perturbation Monitoring Using GNSS," Space Weather, vol. 23, no. 1, pp. 1–9, 2025.
6. Y. Danilchuk et al., "Amplitude scintillation detection with geodetic GNSS receivers," Satellite Navigation, vol. 5, no. 1, p. 36, 2025.
7. G. González-Casado et al., "Feasibility of Scintillation Monitoring with Low-cost GNSS Receivers Using Geodetic Detrending," Chinese Journal of Aeronautics, vol. 38, pp. 1–10, 2025.
8. S. Kuruva et al., "Amplitude scintillation detection with geodetic GNSS receivers," Satellite Navigation, vol. 4, no. 1, p. 36, 2024.
9. R. Tiwari et al., "Modeling the Effects of Ionospheric Scintillation on GPS Carrier Phase Measurements," Proceedings of the Institute of Navigation, vol. 81, pp. 1–9, 2024.
10. R. Nandakumar, S. Suresh, and P. Arora, "Impact of solar and geomagnetic activity on GNSS scintillation in low-latitude India," Journal of Geophysical Research: Space Physics, vol. 129, no. 3, pp. 1–12, 2024.
11. A. Paul et al., "Low-latitude ionospheric responses and positioning errors during scintillation events," Frontiers in Astronomy and Space Sciences, vol. 11, p. 1431611, 2024.
12. S. Chakraborty et al., "Impact of the May 2024 Extreme Geomagnetic Storm on the Ionosphere," Remote Sensing, vol. 17, no. 9, p. 1492, 2024.
13. V. Ram Kumar et al., "Global Ionospheric Scintillation Estimation Based on Phase Screen Model," Space Weather, vol. 22, no. 3, pp. 1–10, 2024.
14. P. Sivakrishna et al., "Time-Lagged Effects of Ionospheric Response to Severe Geomagnetic Storms," Space Weather, vol. 22, no. 2, pp. 1–7, 2024.

15. S. Kumar et al., "An Improved Stochastic Model for the Geodetic GNSS Receivers Under Ionospheric Scintillation," Space Weather, vol. 21, no. 12, pp. 1–8, 2023.
16. R. Sharma et al., "Analysis of global ionospheric scintillation and GPS positioning errors," Advances in Space Research, vol. 70, no. 3, p. 5441, 2022.
17. A. Lavin, R. E. de Paula, and D. S. Rosa, "Random Forest-based classification of ionospheric scintillation using GNSS and TEC data in low-latitude Brazil," Advances in Space Research, vol. 67, no. 2, pp. 489–498, 2021.
18. S. Miriyala et al., "Detection of amplitude scintillation from C/N_0 data using MF-DFA," Journal of Atmospheric and Solar-Terrestrial Physics, vol. 165, pp. 122–130, 2018.
19. Y. Jiao et al., "Automatic equatorial GPS amplitude scintillation detection using machine learning," IEEE Transactions on Aerospace and Electronic Systems, vol. 53, no. 1, pp. 405–418, 2017.