

結合神經網路與全天影像之低緯度即時電漿泡偵測

A Real-Time Plasma Bubble Detection Method Combining Neural Networks and All-Sky Imaging at low-latitude region

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摘要

赤道電漿泡 (EPBs) 是一種大規模的電離層不規則體，對以衛星為基礎的通訊、導航與監測系統構成重大威脅。此種由赤道 F 區於日落後產生的不穩定性所引發的電漿密度空乏現象，會導致穿電離層訊號發生閃爍與衰減。為滿足對此類擾動的即時監測需求，本研究提出一種基於深度學習的方法，利用全天氣輝影像對 EPBs 進行自動化且近乎即時的偵測。我們開發了一套卷積神經網路 (CNN)，並使用由地面全天影像儀 (ASI) 所收集的 630.0 nm 氣輝資料生成的偏差影像對其進行訓練。此網路的設計旨在區分電漿泡結構與背景輻射，從而實現無須人工標記或後期處理的像素級辨識。我們建立了一個包含已標記 EPB 事件的資料集用於訓練與驗證，其中涵蓋了多種夜間條件及地球物理環境，以確保模型的泛化能力。與以往依賴人工特徵、閾值法或離線處理流程的研究不同，我們的方法能直接在處理後的 ASI 資料流上進行高速推論。在低緯度 ASI 觀測站的評估顯示，該模型在偵測 EPBs 方面達到了高精確率與高召回率，且平均推論時間足以滿足即時應用的需求。此系統不僅提供二元偵測結果，更能對 EPB 區域進行空間定位，為未來整合至太空天氣即時預報與警報系統提供了即時增側的工具。

關鍵字：電離層電漿泡，太空天氣

Abstract

Equatorial plasma bubbles (EPBs) are large-scale ionospheric irregularities that pose significant threats to satellite-based communication, navigation, and surveillance systems. These depletions in plasma density, triggered by post-sunset instabilities in the equatorial F-region, lead to trans-ionospheric signal scintillation and degradation. To address the need for real-time monitoring of such disturbances, this study proposes a deep learning-based method for the automatic and near-instantaneous detection of EPBs using all-sky airglow imagery. We develop a convolutional neural network (CNN) trained on deviation images generated from 630.0 nm airglow data collected by a ground-based all-sky imager (ASI). The network is designed to distinguish plasma bubble structures from background emissions, enabling pixel-level identification without manual labeling or post-processing. A dataset of labeled EPB events was constructed for training and validation, incorporating various nighttime conditions and geophysical environments to ensure generalizability. Unlike previous studies that relied on handcrafted features, thresholding, or offline pipelines, our method enables high-speed inference directly on processed ASI data streams. Evaluation at a low-latitude ASI observatory shows that the model achieves high precision and recall in detecting EPBs, with average inference time suitable for real-time applications. The system provides not only binary detection but also spatial localization of EPB regions, offering a valuable tool for integration into future space weather nowcasting and alert systems. This work represents an important advancement toward operational, automated EPB monitoring using

optical remote sensing and deep learning techniques. It also lays the foundation for expanding into multi-instrument integration for improved situational awareness of ionospheric conditions affecting GNSS and communication reliability.

Keywords: plasma bubble, equatorial ionosphere, all-sky imager, convolutional neural network, airglow, real-time detection, GNSS scintillation, space weather

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