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基于深度网络先验和稀疏性约束的时空核素源项重建方法及其对 2020 年切尔诺贝利野火事件的应用

摘要

放射性核素大气释放源项的精准重建是核事故后果评估与应急响应中的关键科学问题。由于实际放射性事件中源项位置往往未知，相关信息需通过对观测到的核素大气活度浓度数据进行反演获取。源项参数可表征为一个包含经度、纬度、时间、释放高度和颗粒粒径的五维特征张量。然而，该类反演问题具有显著的不适定性，而可用测量数据通常不足，难以支撑对完整张量的可靠估计，因此引入合理的先验信息至关重要。为此，本文首次在该领域提出融合深度图像先验与稀疏性约束的策略，在变分优化框架下，结合卷积神经网络结构与稀疏正则化手段，对源项的时空分布施加有效约束。以 2020 年切尔诺贝利森林野火引发的 137Cs 释放事件为案例验证，本方法在无需初始猜测的前提下，成功获得了紧凑且物理合理的源项时空分布，估算总释放量为 254.938 GBq。在源项位置、释放时序及释放总量方面的重建结果与已有文献报道高度一致，且模拟结果与观测数据表现出良好的吻合度。

关键词

核事故后果评价；时空源项重建；深度图像先验；稀疏正则化；切尔诺贝利野火。

Abstract

Accurate reconstruction of atmospheric release source terms for radionuclides is a critical scientific challenge in nuclear accident consequence assessment and emergency response. In practical radiological events, the source location is typically unknown, and relevant information must be inferred from observed atmospheric activity concentration data. The source term can be represented as a five-dimensional feature tensor comprising longitude, latitude, time, release height, and particle size. However, such inverse problems are inherently ill-posed, and the available measurements are often insufficient to support a reliable estimation of the complete tensor, highlighting the importance of incorporating appropriate prior information. To address this, we propose for the first time in this field a novel strategy that integrates deep image priors with sparsity constraints. Within a variational optimization framework, the method employs convolutional neural networks combined with sparsity regularization to effectively constrain the spatiotemporal characteristics of the source term. Using the 137Cs release event triggered by the 2020 Chernobyl forest fire as a case study, the proposed approach successfully reconstructs a compact and physically plausible spatiotemporal source distribution without requiring an initial guess, with an estimated total release of 254.938 GBq. The reconstructed results, including source location, temporal profile, and total release, show strong agreement with previously reported values, and the simulated concentrations exhibit good consistency with observations.

Keywords

consequence assessment for nuclear accidents; spatiotemporal source term reconstruction; deep image prior; sparsity regularization; Chernobyl wildfire

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