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ML-Driven Early Detection of Solar Active Region Emergence for Space-Weather Forecasting

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Improving the ability to predict space weather disturbances – such as solar flares, coronal mass ejections (CMEs), and solar energetic particle (SEP) events – is critical for enabling early detection of solar active regions (ARs), which are primary sources of high-energy release. In this work, we present machine-learning (ML)-driven models designed to predict the location and timing of AR emergence from solar oscillation data several hours before distinct signatures appear in photospheric continuum intensity and magnetograms. The primary idea of our method is that the spectrum of solar oscillations that penetrate deep inside the Sun is affected by emerging active regions before they become visible on the surface. To enable early detection, we track 31° × 31° solar regions in a co-rotating frame for approximately 5 days before and after emergence, generating ensembles of time series that capture the evolution of continuum intensity, magnetic flux, and power of solar oscillations across 4 frequency bands within 3.4° × 3.4° patches. Because AR identification on the solar surface is typically based on continuum intensity signatures, we employ a Long Short-Term Memory (LSTM) architecture to capture pre-emergence decreases in acoustic power associated with increasing magnetic flux and to predict subsequent changes in continuum intensity. The model is trained using observations of 45 active regions and tested on an independent sample of 5 regions, achieving predictive capability within a 12-hour forecast window. Ongoing developments include the public release of an ML-ready dataset (SolARED; https://sun.njit.edu/sarportal/), extension of the framework to predict magnetic flux evolution, and exploration of alternative ML architectures such as Transformers. We also present initial efforts toward transitioning these research developments into operational space-weather forecasting capabilities.