Transfer Learning for Specular Meteor Analysis

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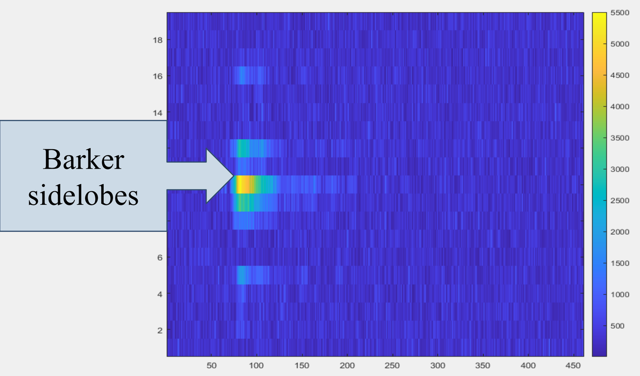
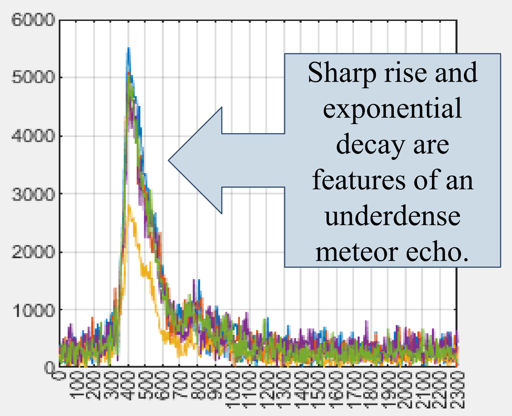
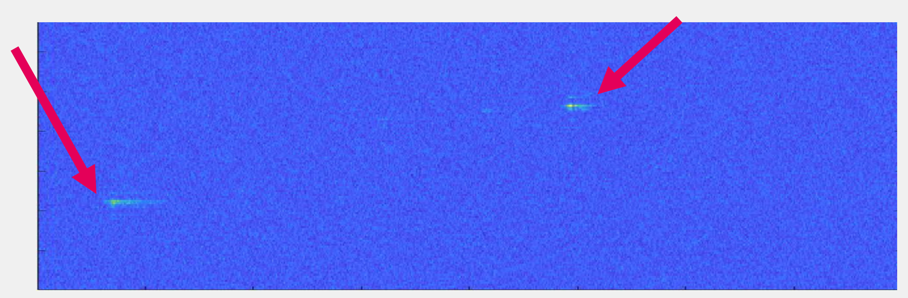
Background

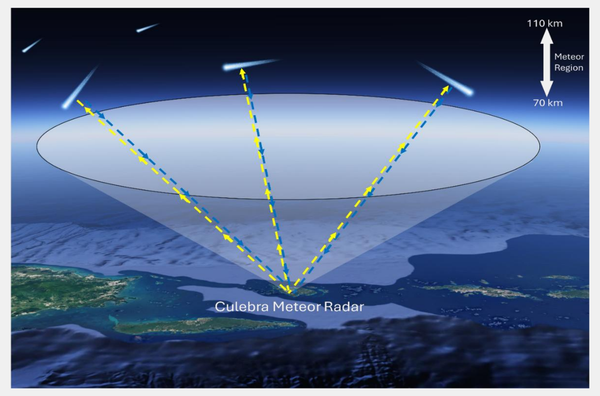




Thousands of meteors all over the world are detected hourly using all-sky meteor radar. These detections are packed with science that can be used to learn about the Earth's atmosphere and space environment. The radar observes trails of ionized gas left behind when meteors burn up as they descend through the atmosphere. This happens in the altitude range of 60 km to 120 km, and by observing the ionized gas scientists can estimate wind velocity, meteor size, metal deposition, and more. All-sky meteor radar is simple and inexpensive and is the best existing method for continuously observing the atmosphere at these altitudes.

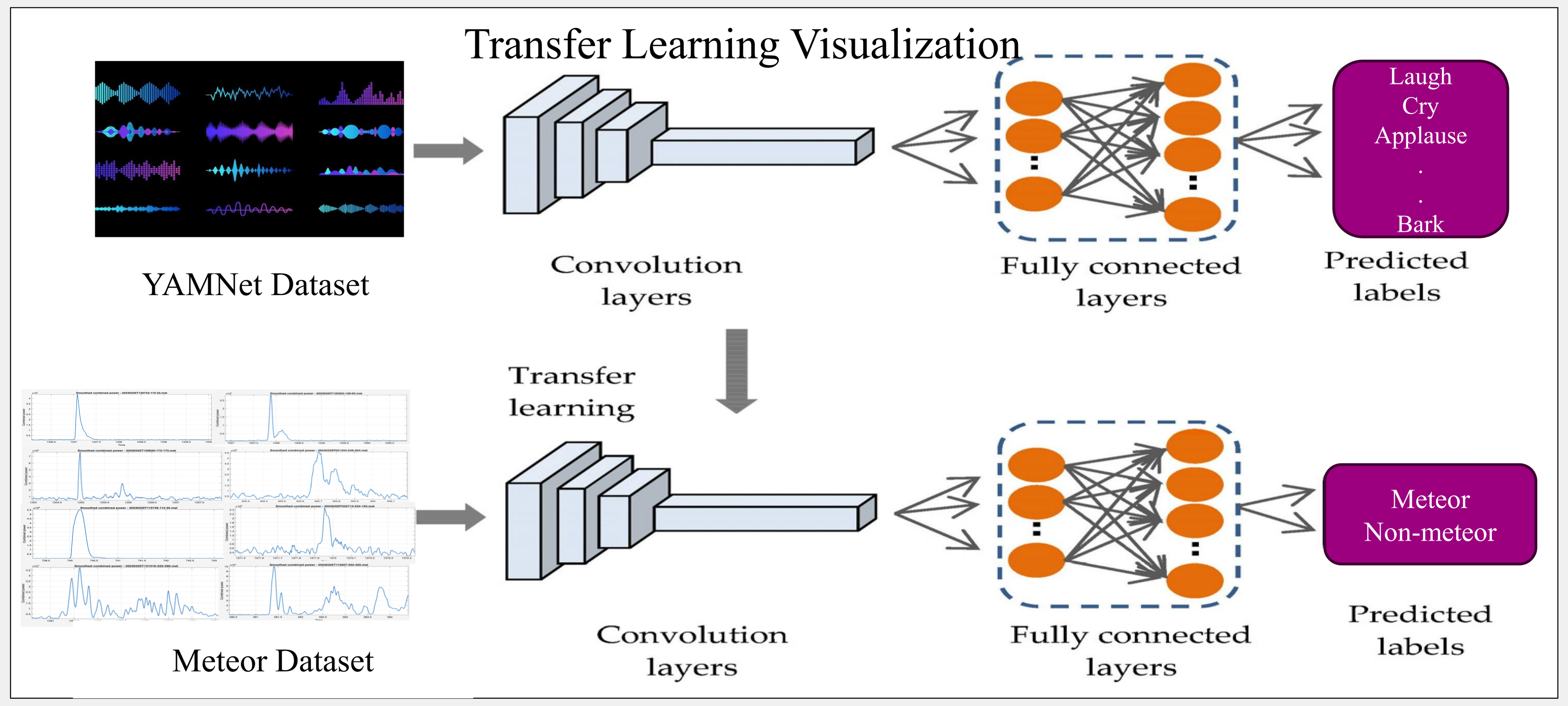


Four seconds of raw radar data. Visible are the signatures of two meteors.

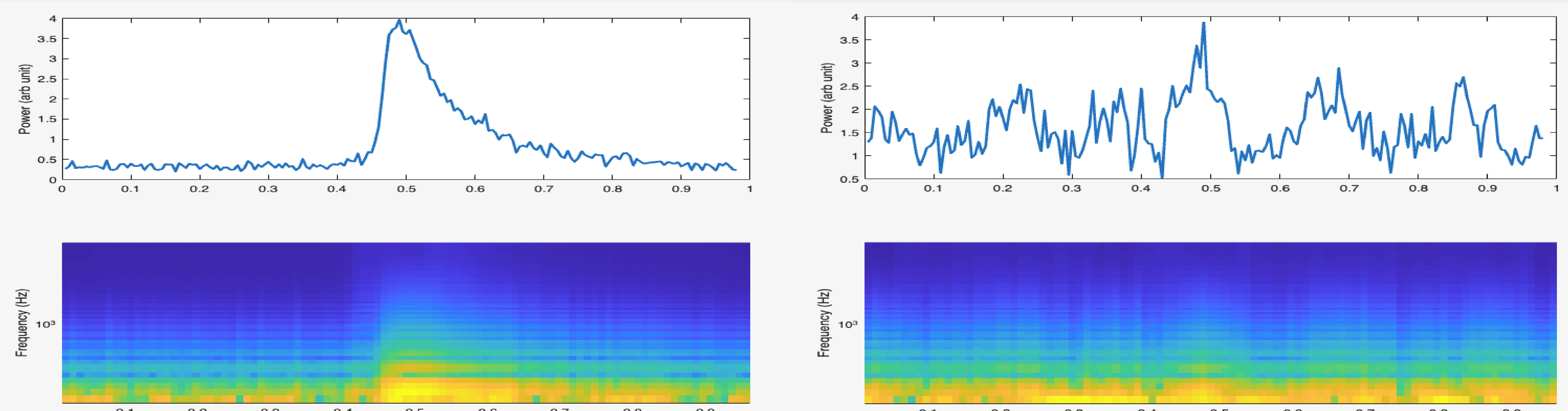


Transfer Learning

Transfer learning is the repurposing of a machine learning model that has already been extensively trained for a particular task by training part of the network on new data. By keeping the early, generalizable, and rigorously trained portions of the network, while re-training a smaller part of it, good performance can be achieved with fewer training data and less computational resources than it would take to train a network from scratch.



YAMNET is a Convolutional Neural Network and operates on 2D data. Time-series radar data needs to be converted. This is especially relevant to interferometric radar data, in which the encoded phase data is important to define meteor parameters.



Underdense Meteor (left) and radio interference (right), with their corresponding spectrograms.

Motivation

Meteors are markers for more than just winds. Because of the value and simplicity of SMR, many have been built around the world. They collectively produce large volumes of data that are typically used to calculate winds, then discarded. This infrastructure can be leveraged to do more observation, monitoring, and science.

There is value in categorizing, collecting, and studying the various signal types observable by SMR.

- Meteor characteristics
- Plasma phenomena
- Space debris

Methodology

Meteor Data Labeling - Automatic
This is pulled straight from the existing data processing system. Automatically labeled according to the error flags raised by the system, which would typically be used to discard the detection. The detection is converted to the frequency domain and fed to the network.

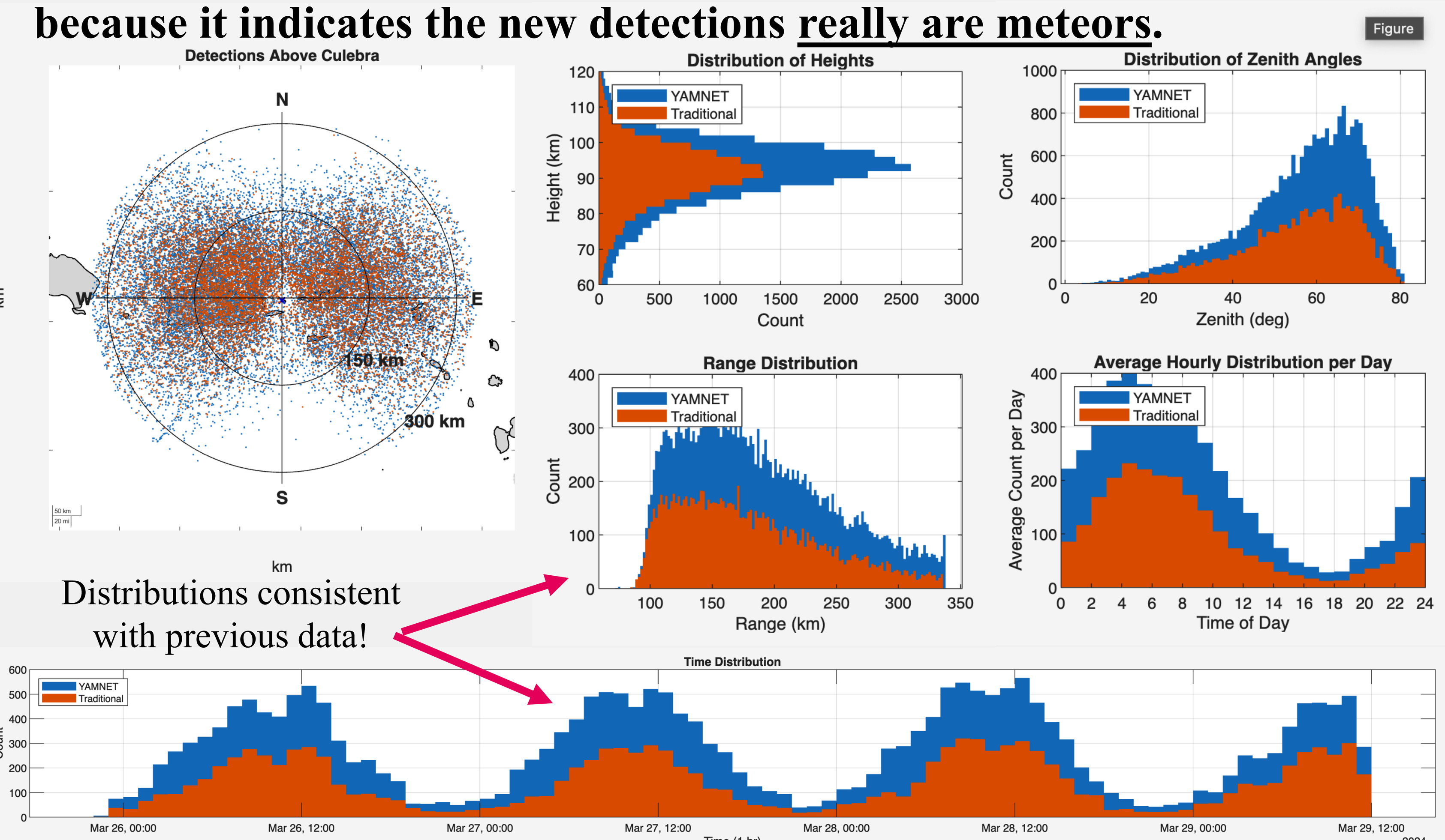
YAMNet Re-Training
The YAMNet learns the fine features of meteors and of noise in the frequency domain, while already being able to recognize larger, more general features. This is fast, computationally light, and does not require as much training data as building a network from scratch.

Detect New Meteors
The trained network is used to analyze new data and detect meteors. Despite the training data being labeled by the original system, it outperforms the original system. It is able to learn the features of meteors robustly even if it was trained with some incorrect samples.

Interferometry and Post Processing
Detections are processed to find their height, latitude and longitude, radial velocity, and more important parameters. They can also be passed on to further analysis steps, which can separate underdense, overdense, specularity-agnostic, and other morphologies.

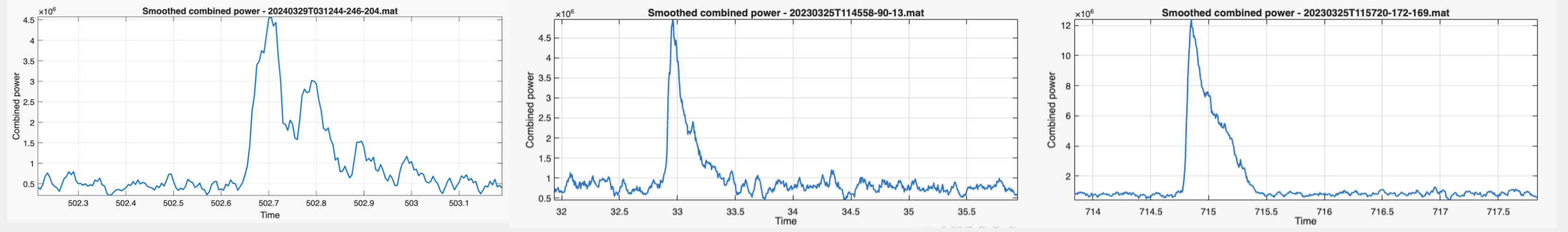
Results: 25% More Meteors Detected!

Distributions are consistent with the original data. This is important because it indicates the new detections <u>really are meteors</u>.



Scientific Question

Can machine learning recover additional meteor detections wile identifying physically meaningful echo morphologies?



Oscillations may indicate single-body meteoroid (i.e. no fragmentation has taken place). This may help infer composition, energy, origin, and more.

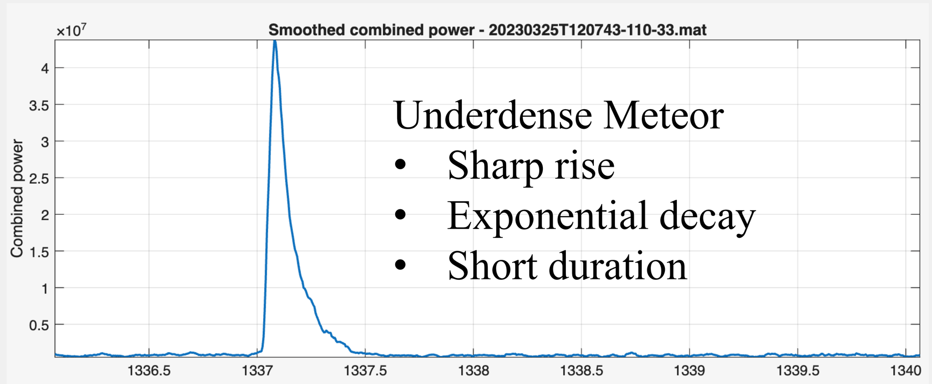
Slight fractures in the decay slope can indicate turbulence, fragmentation, or something else. Alternatively, an undisturbed decay slope likely indicates a steady atmospheric environment.

A change in the decay slope, sometimes called "differential-decay", is a largely unstudied phenomenon. Investigation requires data!

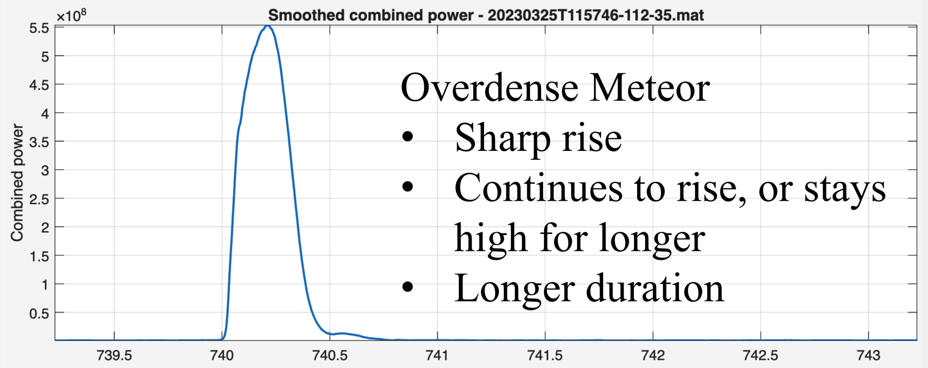
The meteors shown are three underdense detections that have physically meaningful structures. Typically, these meteors would be used only to find winds. The nuance of their structures can tell us information about the atmospheric conditions in which they exist, and about the meteoroid that produced the trail to begin with.

Echo Morphology

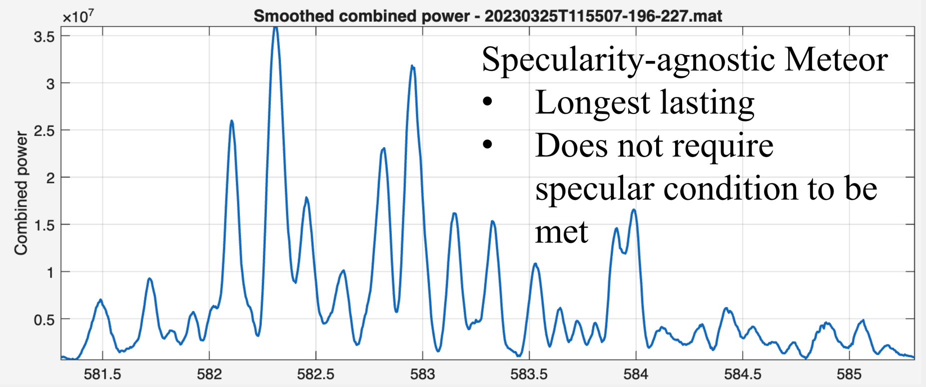
What "shapes" represent meteors in radar data?



Underdense meteors occur when the density of free electrons in the trail is below some threshold, at which radar waves are no longer able to penetrate the meteor trail.



Overdense meteors occur when the electron density is above the threshold, and the trail acts like a metallic cylinder, thus reflecting more radio energy and returning a stronger signal.



Specularity-agnostic meteors are poorly understood. Theories speculate they are the result of dust particles or magnetic field interaction with meteor trails. They can be observed to satisfy the specularity condition occasionally, but often not.

Conclusions

We demonstrate transfer learning to be an effective and practical way to improve SMR systems in their current operational capacity. It can also be used to take advantage of the extensive SMR networks around the world to observe more complex phenomena, such as non-meteor atmospheric plasmas and poorly understood meteor trail dynamics associated with novel or under-studied physical processes.

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