Simulating Meteor Echoes for Advancing All-Sky Meteor Radar Capabilities

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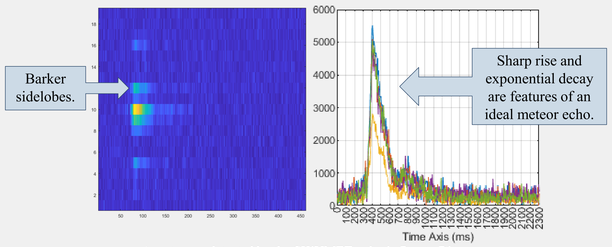
All-Sky Meteor Radar

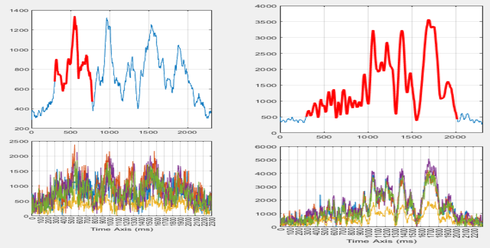
- **Thousands of meteors all over the world are detected hourly using all-sky meteor radar.**
- Meteors burn up and ionize the atmosphere as they travel through it.
- The ionized gas can be detected and used to estimate wind velocity, and meteor counts can be used to estimate the deposition of metals into the atmosphere.
- All-sky radar is simple and inexpensive, and is the best existing method for measuring wind continuously between 60 km and 120km.
- Detections are processed using fitting algorithm and rejection criteria.



A meteor as detected by the SKiYMET radar in Puerto Rico.

System Upgrade – YOLO-X with Synthetic Data

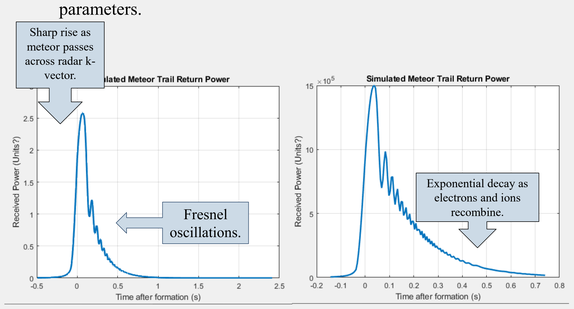
- **Current processing methods are unreliable**: >10% of examined meteors found to be unsuitable for estimating winds.
- **Current detection methods fail to detect many meteors.**
- Using simulated meteors and machine learning to detect and process meteors is much better than a fitting algorithm.
  - Higher counts per hour.
  - Lower error rates.
  - Can expand to other meteor types, not just underdense specular.
    - This feature is a tool for studying the physics of overlooked meteors!



Unreliable meteors selected by original algorithm for winds estimation.

Simulating Meteors

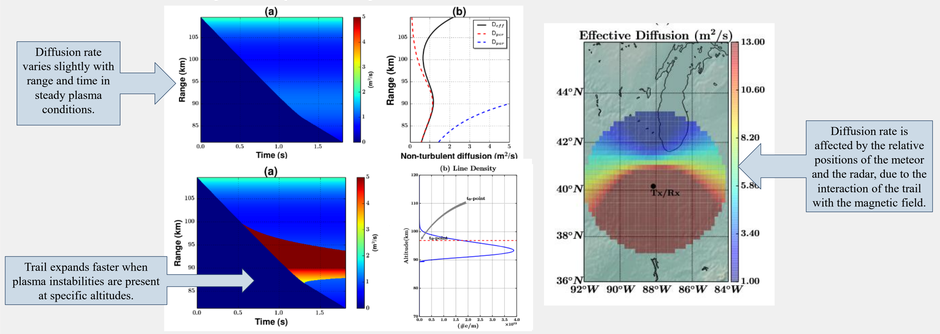
- Calculating received power given a set of parameters.
- Physics-constrained.
- Distributions to match current understanding of meteors.
  - Height, range, zenith.
  - In progress: diffusion coefficient, meteor velocity, correlation of parameters.



Simulated meteor power profile.

Complex Simulation Considerations

- Ambipolar diffusion coefficient and electron line density are dependent on the relative position of the meteor to the radar, and the orientation of the magnetic field.
- This can be further complicated by the assumption of turbulent versus stable trail conditions.



Diffusion rates and electron densities according to simulations by Freddy Galindo.

Synthetic Meteor Parameters

- Radar basics – frequency, gain, power, latitude and longitude.
- Distributions of meteor population – can be tailored for the meteor population of any site.
- Trail radial velocity, SNR, ambipolar diffusion coefficient.

$$P_r = A \cdot B \cdot D \cdot C \cdot P_{\text{fresnel}}$$

$$A = \frac{P_t \lambda^2 \sigma_e}{64\pi^3}$$

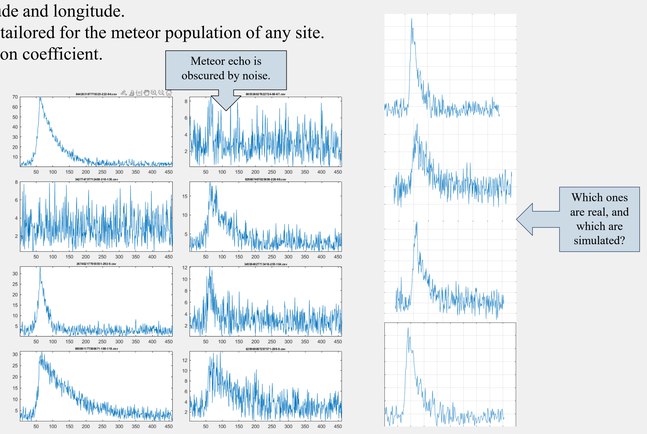
$$B = \left(\int \frac{Gq}{R^2} \cos\left(\frac{4\pi R}{\lambda}\right) ds\right)^2 + \left(\int \frac{Gq}{R^2} \sin\left(\frac{4\pi R}{\lambda}\right) ds\right)^2$$

$$C = \exp\left(-\frac{32\pi^2 D_a t}{\lambda^2}\right)$$

$$D = \exp\left(-\frac{8\pi^2 r_0^2}{\lambda^2}\right)$$

$$P_{\text{fresnel}} = \frac{F_r^2}{\pi^2 s^2}, s < 0$$

$$P_{\text{fresnel}} = 2F_r^2 + \frac{F_r^2}{\pi^2 s^2} + \frac{2\sqrt{2}}{\pi s} F_r^2 \sin\left(\frac{\pi s^2}{2} - \frac{\pi}{4}\right), s \geq 0$$

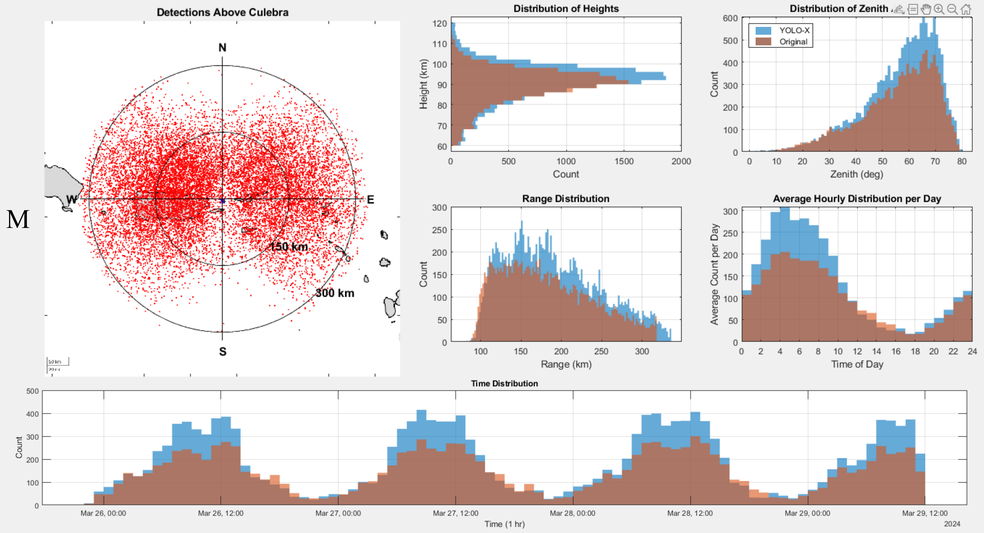


Random sample of simulated underdense meteors.

Two real meteors and two simulated meteors.

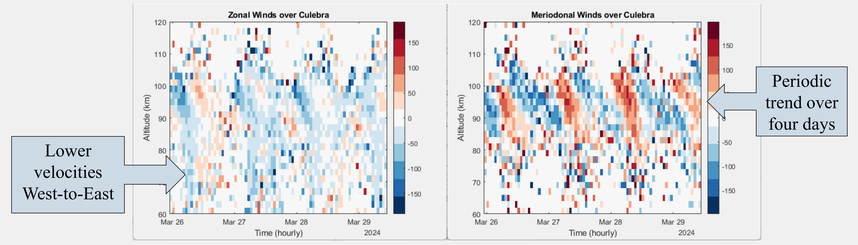
Comparison Between Methods

- The old method: algorithmic, power-threshold, processing using fitting and rejection criteria.
- The new method: YOLO-X applying a bounding box over an RTI. Confidence threshold 0.99.
- Higher counts adhere to existing distributions.

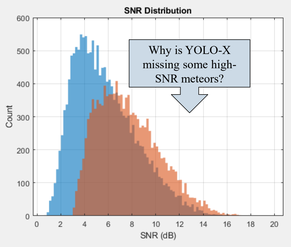


Analysis

- Meteor Counts: 12533 → 16280 – 30% improvement
- Processing time: 363 seconds → 171 seconds – 53% improvement



Wind fields estimated from the meteors detected by the YOLO-X network.

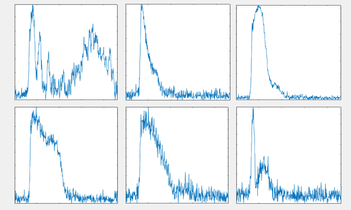


SNR Statistics

- Many more low-SNR meteors.
- YOLO-X is missing many high SNR meteors – why?
  - Training data does not contain overdense traces.
  - Overdense echoes have a distinct ridge that is missing from the training data.
  - Training set focuses on usable low-SNR meteors, but will be expanded.

The Missing Meteors

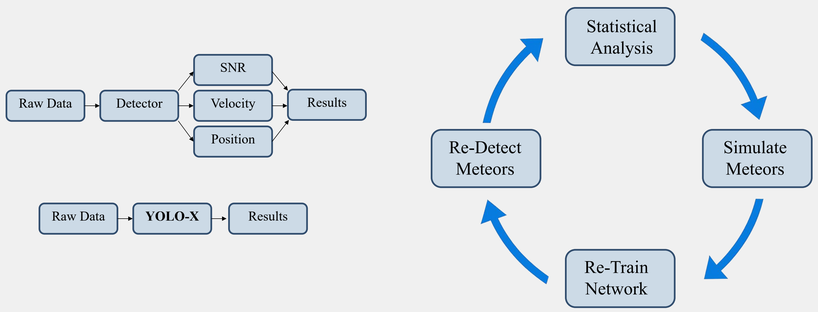
- Meteors not detected by YOLO-X that may still be valuable for wind estimation.
- Overdense, double-decay, turbulent decay…



Meteors detected by the original method that may be missed by YOLO-X

Future Work

- Iterating on simulated meteors, improving their physical constraints, distributions and correlation with other meteor properties.
- One-shot processing, to estimate altitude, location, radial velocity, diffusion coefficient, etc. No additional processing after YOLO-X network.
- Longer training sessions on more diverse datasets on larger networks.
- Cyclical improvement cycle to fine-tune simulated meteor datasets to be as true-to-reality as possible.
- Expand to categorize, simulate, and find different types of echoes.
- Increase confidence in estimations from low SNR meteors.



Synopsis

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