On the Effect of Turbulence on Specular Meteor Echoes

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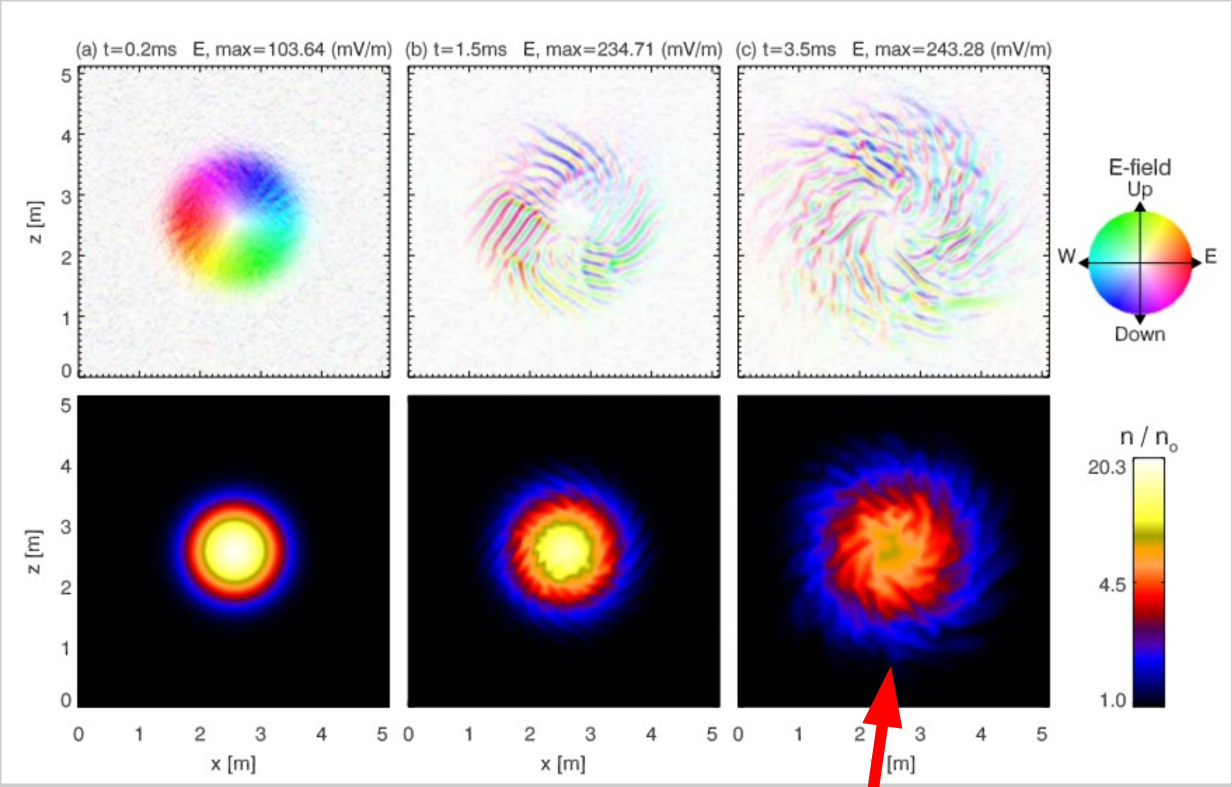
1. Motivation: anomalous diffusion

- The work presented by Dyrud et al, (2001) used plasma simulation of meteor trails to report that anomalous diffusion substantially modifies trail expansion.

- They showed that density gradients at the edges of meteor trails drive gradient-drift instabilities (turbulence)

- The anomalous diffusion depend on the trail altitude, latitude and density gradient.

Vector electric field and density radio of the meteor trail to the background density [extracted from Dyrud et al, 2001].

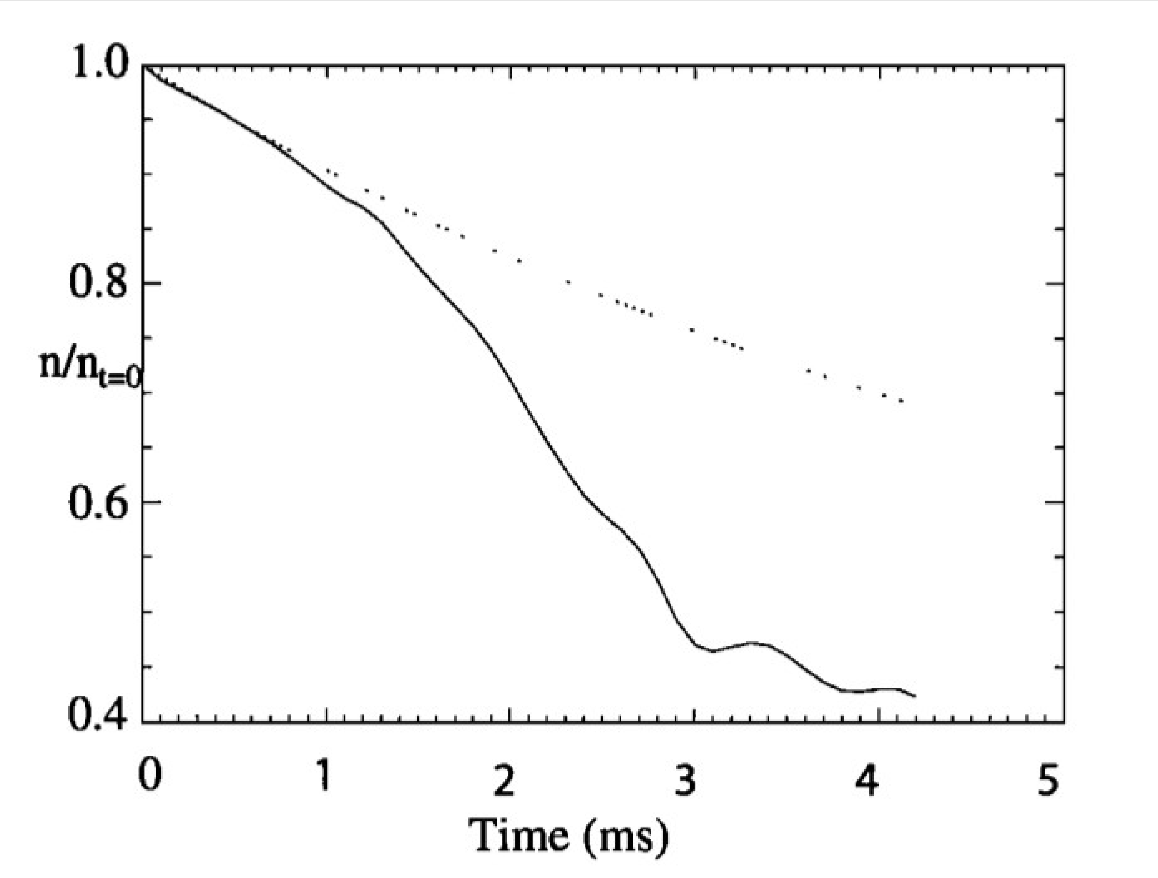


Turbulent wave pattern

1. Motivation: anomalous diffusion

• In other words, the authors showed that the density of meteor trails affected by turbulence, decays faster than the non-turbulent case, i.e. trail diffuses outwards due to anomalous diffusion.

• Understanding anomalous turbulence is important due to its influences the evolution of specular meteor trails, particularly regarding the inference of mesospheric temperatures from trail diffusion rates.



Ratio of trail density to initial density. The dashed and solid lines present the non-turbulent and turbulent expansion [extracted from Dyrud et al, 2001].

2. Numerical model for specular echoes

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Evolution of a meteoroid

Meteor line density

FBGD dispersion relation

Perturbed density

Specular meteor echo

a) Evolution of a meteoroid:

Our approach is constructed by computing the evolution of mass, velocity and temperature of an individual meteoroid during its passage through the atmosphere by using meteor ablation equations:

$$\frac{dv}{ds} = \frac{\Gamma A \rho v}{\delta^{2/3} m^{1/3}}$$

$$\frac{dm}{ds} = \frac{4AK_1 m^{2/3}}{\delta^{2/3} v T^{1/2}} e^{-K_2/T} - \frac{\Lambda_s A \rho m^{2/3} v^2}{2Q\delta^{2/3}}$$

$$\frac{dT}{ds} = \frac{4A\rho v^2}{8C\delta^{2/3} m^{1/3}}(\Lambda - \Lambda_s) - \frac{4A\sigma(T^4 - T_a^4)}{C\delta^{2/3} m^{1/3}} - \frac{4AK_1 Q}{C\delta^{2/3} T^{1/2} m^{1/3} v} e^{-K_2/T}$$

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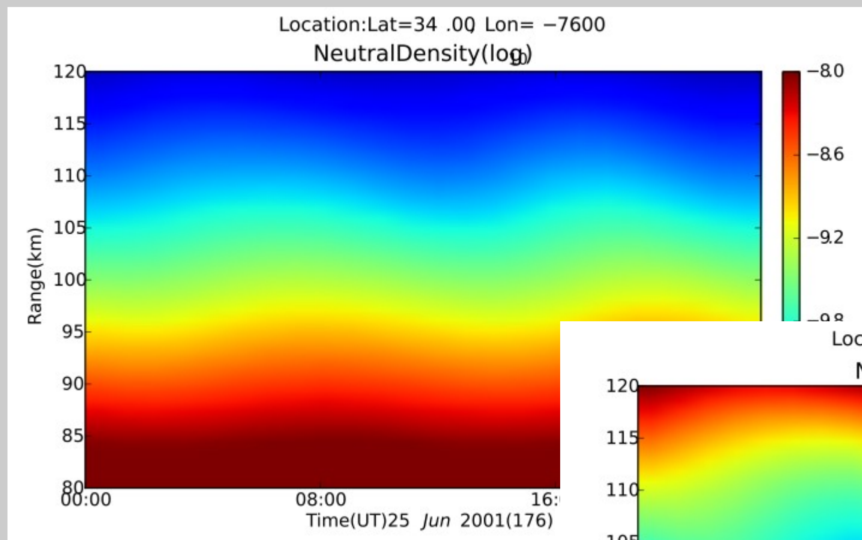
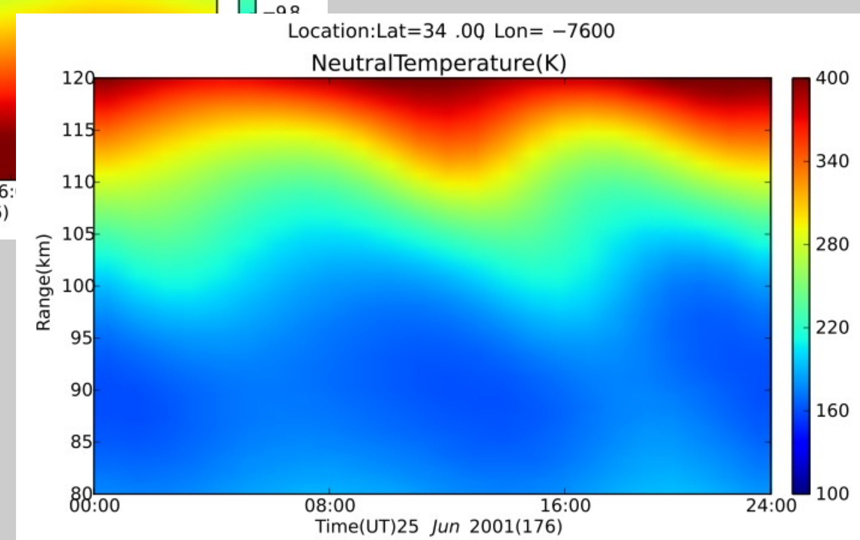
The atmospheric parameters applied in our model are obtained from the empirical models MSISE90 (neutral temperatures and densities model), IRI2007 (international reference ionosphere) and HWM2007 (horizontal wind model)





2. Numerical model for specular echoes

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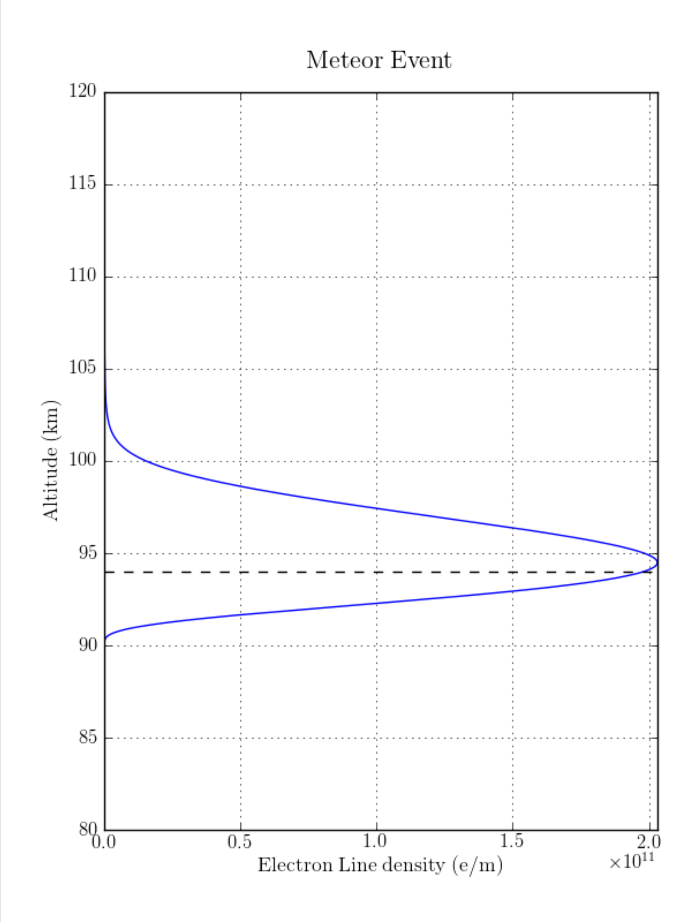
Specular meteor echo

b) Meteor plasma β:

Coefficient of probability that an ablated meteor particle becomes ionized:

$$\beta = k_i (v - v_i^*)^2 v^{0.8}$$



Electron line density computed using the meteor ablation equation and the coefficient of ionization.

2. Numerical model for specular echoes

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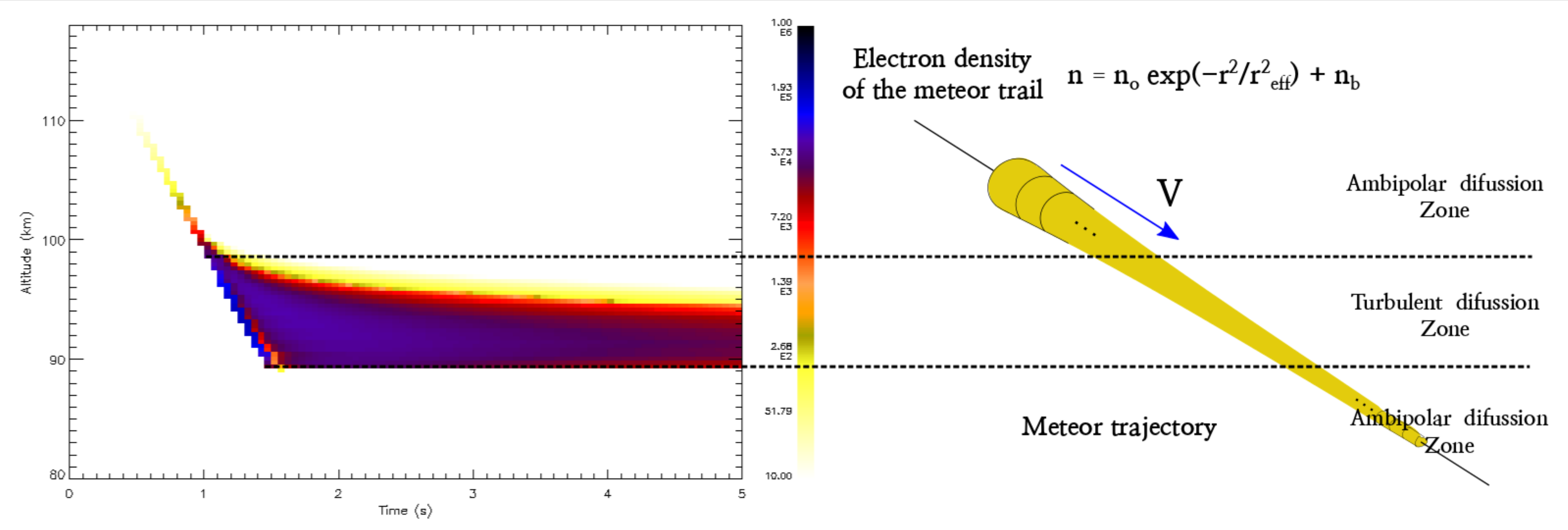
c) Farley-Buneman Gradient Drift (FBGD) dispersion relation:

The FBGD dispersion relation for meteor trails is applied to determine where and when instabilities driven by turbulence occurs

$$\omega - kV_D = \frac{\Psi}{\nu_{in}}[\omega(i\omega - \nu_{in}) - ik^2C_s^2](1 - \frac{i\Omega_e}{\nu_{en}kL_n})$$

2. Numerical model for specular echoes

c) Farley-Buneman Gradient Drift (FBGD) dispersion relation:



Left: A non-specular echo generated by FBGD instabilities. The altitude and time of these instabilities indicates where the electron density is affected by turbulence. Right: Diffusion processes affecting the electron density of a meteor trail.

2. Numerical model for specular echoes

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d) Perturbed density:

Once, the information about where and when turbulence is expected, is known; the electron density is corrected by an amount called the perturbed electron density. This perturbed electron density is computed by using the electron and ion continuity and momentum equations:

$$i(kv_{\text{D}} - w)\widehat{n} + \widehat{v_{ez}}\frac{\partial n_o}{\partial z} + in_o k\widehat{v_{ey}} = 0$$

$$-iw\widehat{n} + in_o k\widehat{v_{iy}} = 0$$

$$\nu_e\widehat{v_{ey}} + \Omega_e\widehat{v_{ez}} = ik\left(e\widehat{\phi}/m_e - u_e^2\widehat{n}/n_o\right)$$

$$\nu_e\widehat{v_{ez}} - \Omega_e\widehat{v_{ey}} = 0$$

$$(-iw + \nu_i)\widehat{v_{iy}} = -ik\left(e\widehat{\phi}/m_i + u_i^2\widehat{n}/n_o\right)$$

2. Numerical model for specular echoes

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Underdense specular meteor echo

we generate our underdense specular meteor echo by combining all the meteor trail information by tracking the meteoroid trajectory and computing the total backscatter signal produced by the electron density generated at different times and affected by either the ambipolar diffusion or anomalous diffusion.

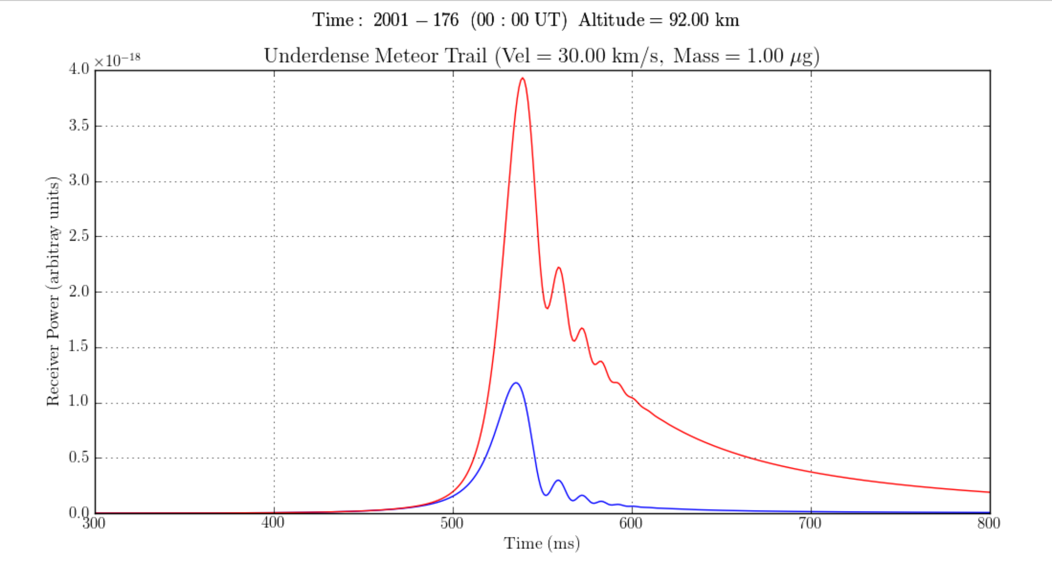
$$P_r = \frac{P_t \lambda^2 \sigma_e}{64\pi^3}[I_c^2 + I_s^2] e^{-\frac{32\pi^2 D_a t}{\lambda^2}} e^{-\frac{-8\pi^2 r_o{}^2}{\lambda^2}}$$

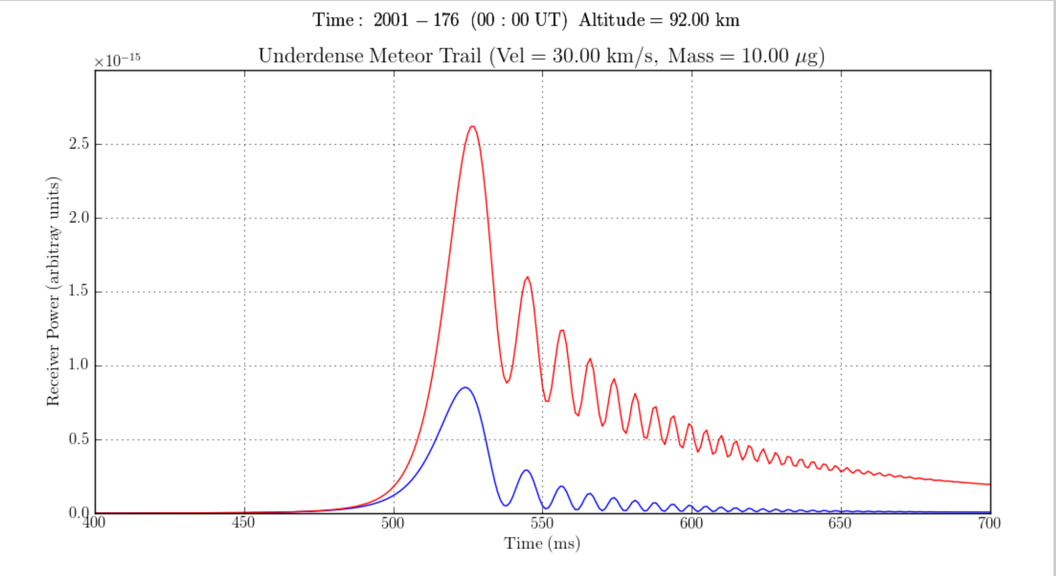
$$I_c = \int_{s_1}^{s} \frac{Gq}{R^2} cos(\frac{4\pi R}{\lambda}) ds$$

$$I_s = \int_{s_1}^{s} \frac{Gq}{R^2} sin(\frac{4\pi R}{\lambda}) ds$$

3. Modeling results

Diffusion perpendicular and parallel to the magnetic field (B)

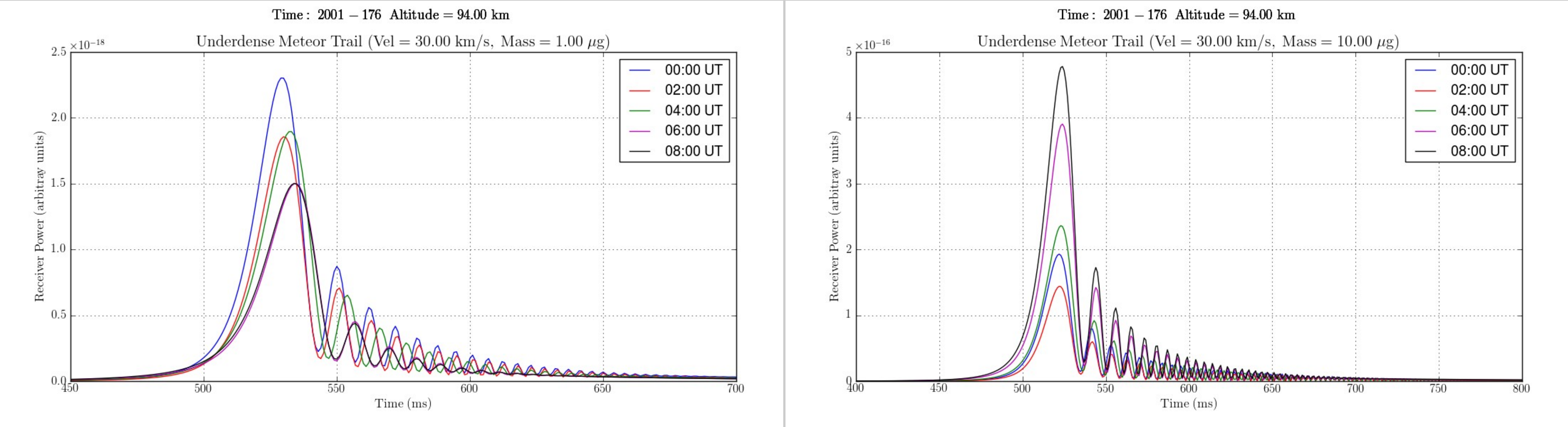




Left: Diffusion perpendicular (red) and parallel (blue) to the magnetic field. This event was produced using a meteoroid of 1 μg mass. Right: similar to left panel but considering a meteoroid of 10 μg mass.

3. Modeling results

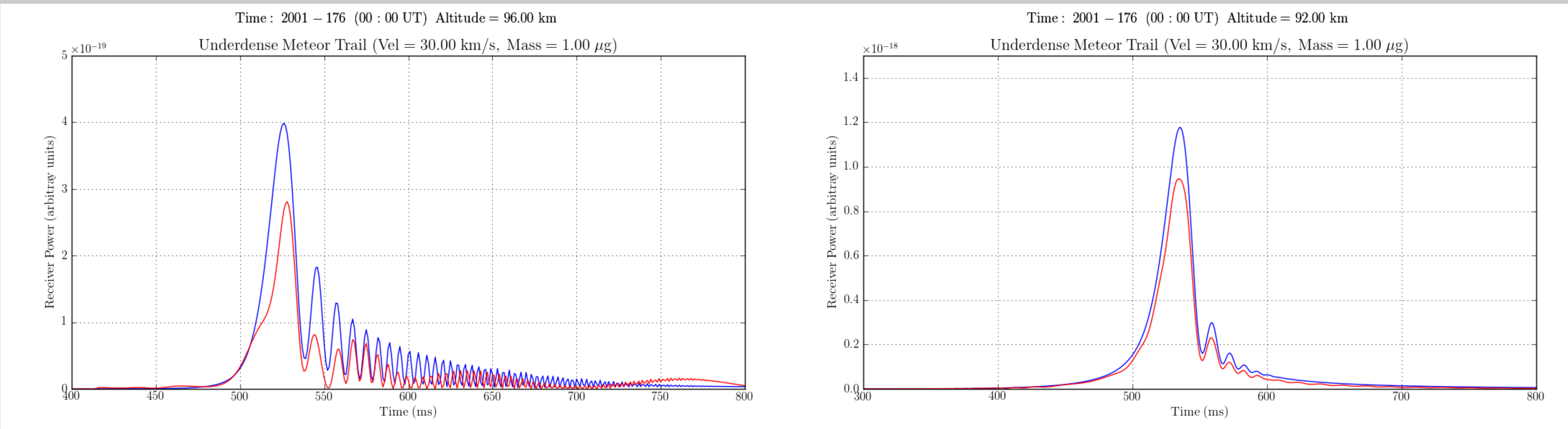
Receiver power variability



Left: Power variability of a specular meteor trail echo under the effect of diffusion parallel to B. This event was produced using a meteoroid of 1 µg. Right: Power variability similar to left panel but for a meteoroid of 10 µg.

3. Modeling results

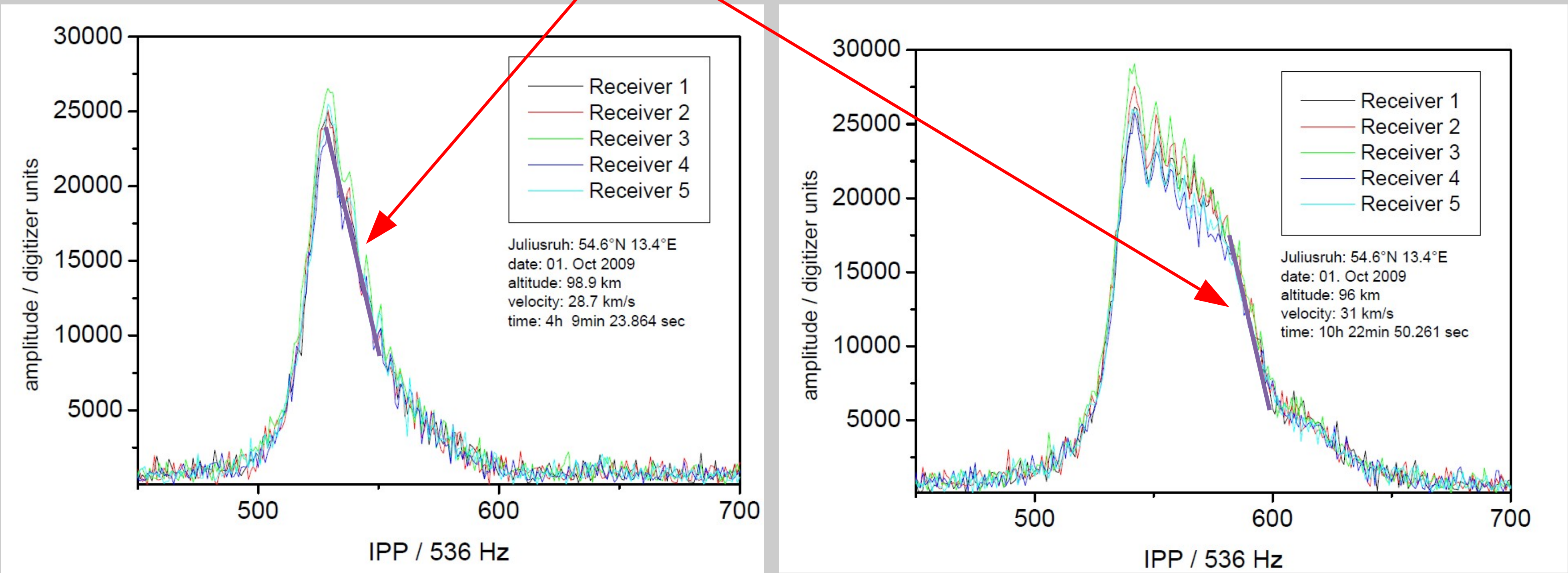
Turbulence on specular meteors



Left: Receiver power of an underdense specular meteor echo under the effect of non-turbulent ambipolar diffusion (blue) and turbulent diffusion (red). This event was produced using a meteoroid of 1 µg mass and considering perpendicularity at 96 km altitude. Right: similar to left panel but considering perpendicularity at 92 km altitude.

4. Experimental examples

Turbulent decay rate



Specular meteor trail echoes detected with Juliusruh meteor radar, located in Kühlungsborn, Germany [Courtesy of G. Stober].

3. Summary & Future Work

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Summary

- We have developed a new approach to study underdense specular meteor returns.
- Our approach allows us to analysis the temporal and spatial variability of the receiver power due to the atmospheric conditions and therefore, investigate possible modulation in the meteor flux measured by different radar systems.
- Our model integrates turbulence effects in the simulator by using FBGD dispersion relation and the electron and ion continuity and momentum equations.
- We expect to understand the role of turbulence during the diffusion and therefore, correctly compute mesospheric temperatures from trail diffusion rates using meteor data.

Future Work

- We will apply this numerical model to the Penn State Meteor Radars (see poster ITIT-12 by Hackett et al).
- Furthermore, we will improve our numerical approach for the estimation of the backscatter signal.

Thanks!