# Aerodynamic oscillations during GOCE de-orbit

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Delft University of Technology, Belstead Research Limited
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1 March 2018

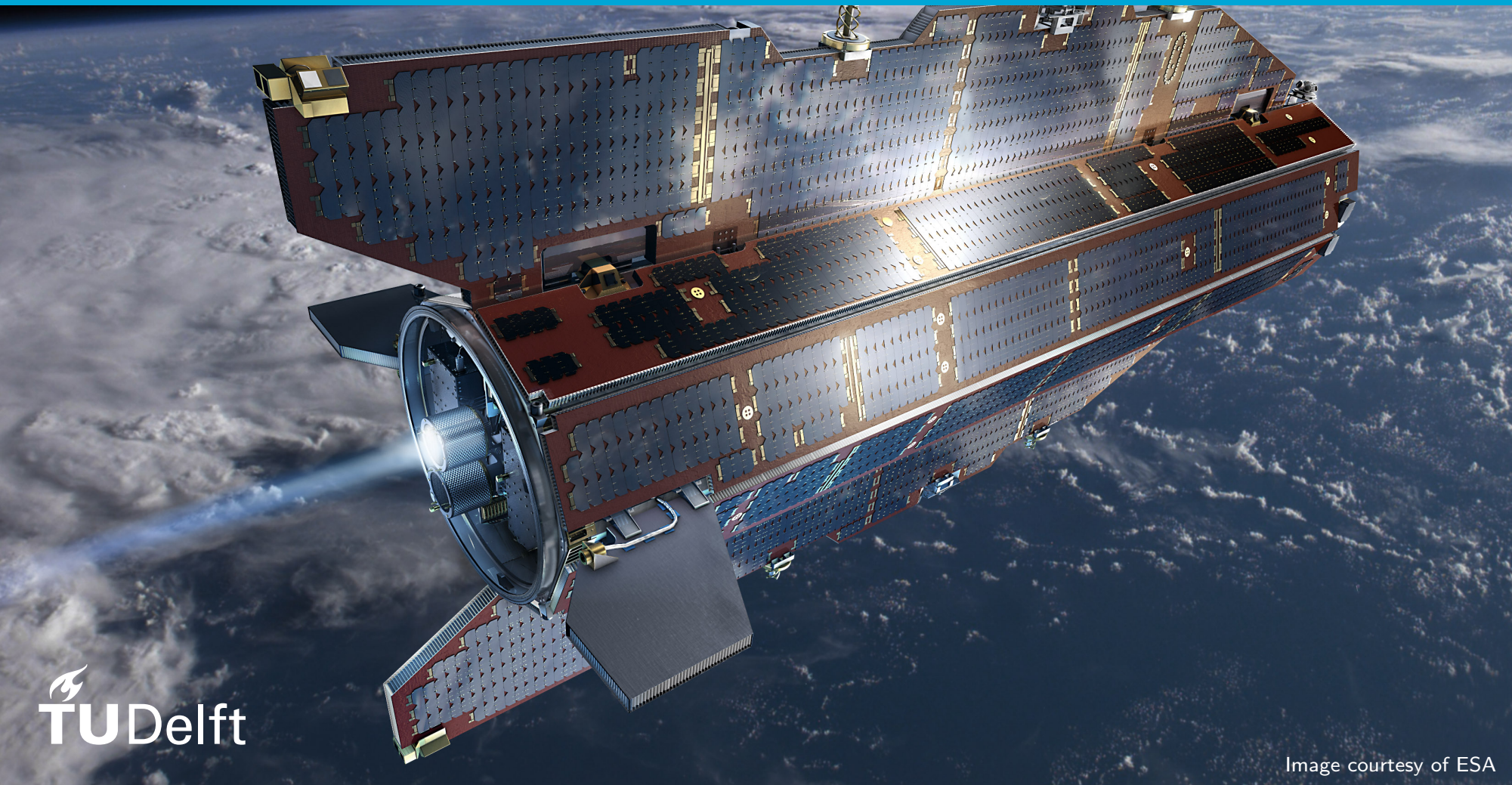

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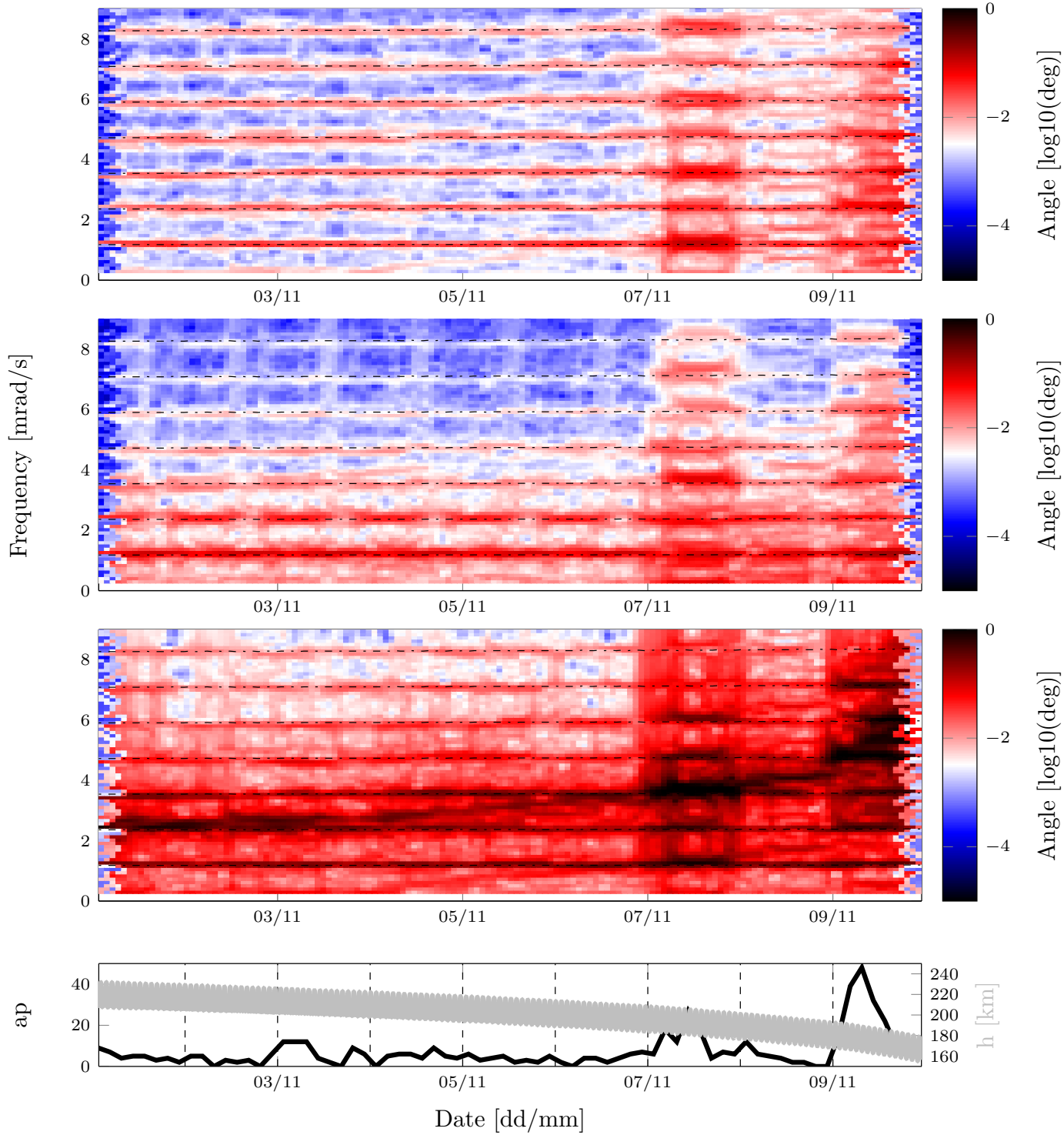
Image courtesy of ESA

# Euler angles: Will it tumble?

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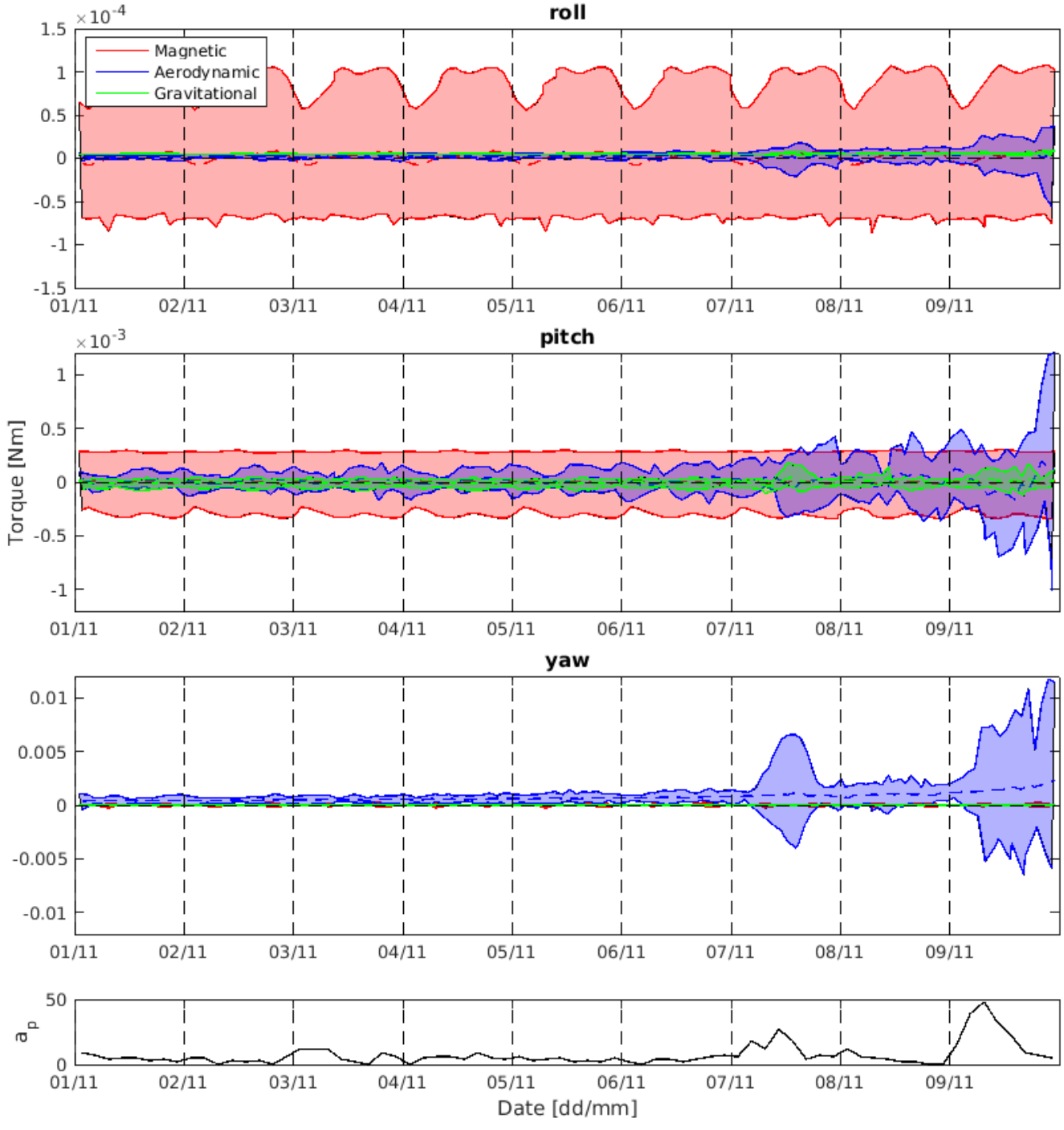
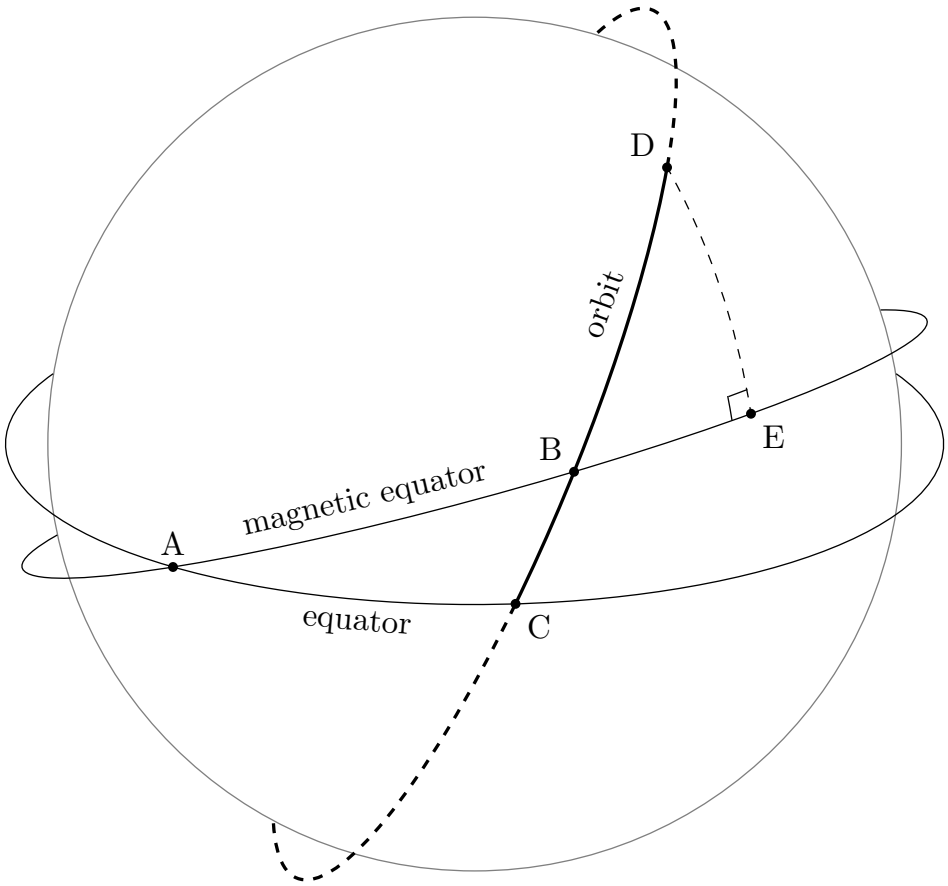
# Torques during de-orbit



# Simplified Earth model




Geomagnetic field:

$$B_N = B_0 \left(\frac{R_E}{R}\right)^3 \cos\delta_M$$

$$B_E = 0$$

$$B_D = 2B_0 \left(\frac{R_E}{R}\right)^3 \sin\delta_M$$

Atmospheric co-rotation:

$$\beta = -\frac{\dot{\tau} R}{V} \sin i \cos(\chi_0 + nt)$$

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# Linearized attitude model

| | $\ddot{\varphi}$ | $\ddot{\theta}$ | $\ddot{\psi}$ |
|---|---|---|---|
| $\varphi$ | **n** $T_M$ $T_G$ | $T_A$ $T_M$ | $T_M$ |
| $\theta$ | $T_A$ $T_M$ | $T_A$ $T_M$ $T_G$ | $T_M$ |
| $\psi$ | $T_M$ | $T_M$ | $T_A$ $T_M$ |
| $\dot{\varphi}$ | | | **n** |
| $\dot{\theta}$ | | | |
| $\dot{\psi}$ | **n** | | |
| forcing | $T_M$ | $T_M$ | $T_A$ $T_M$ |

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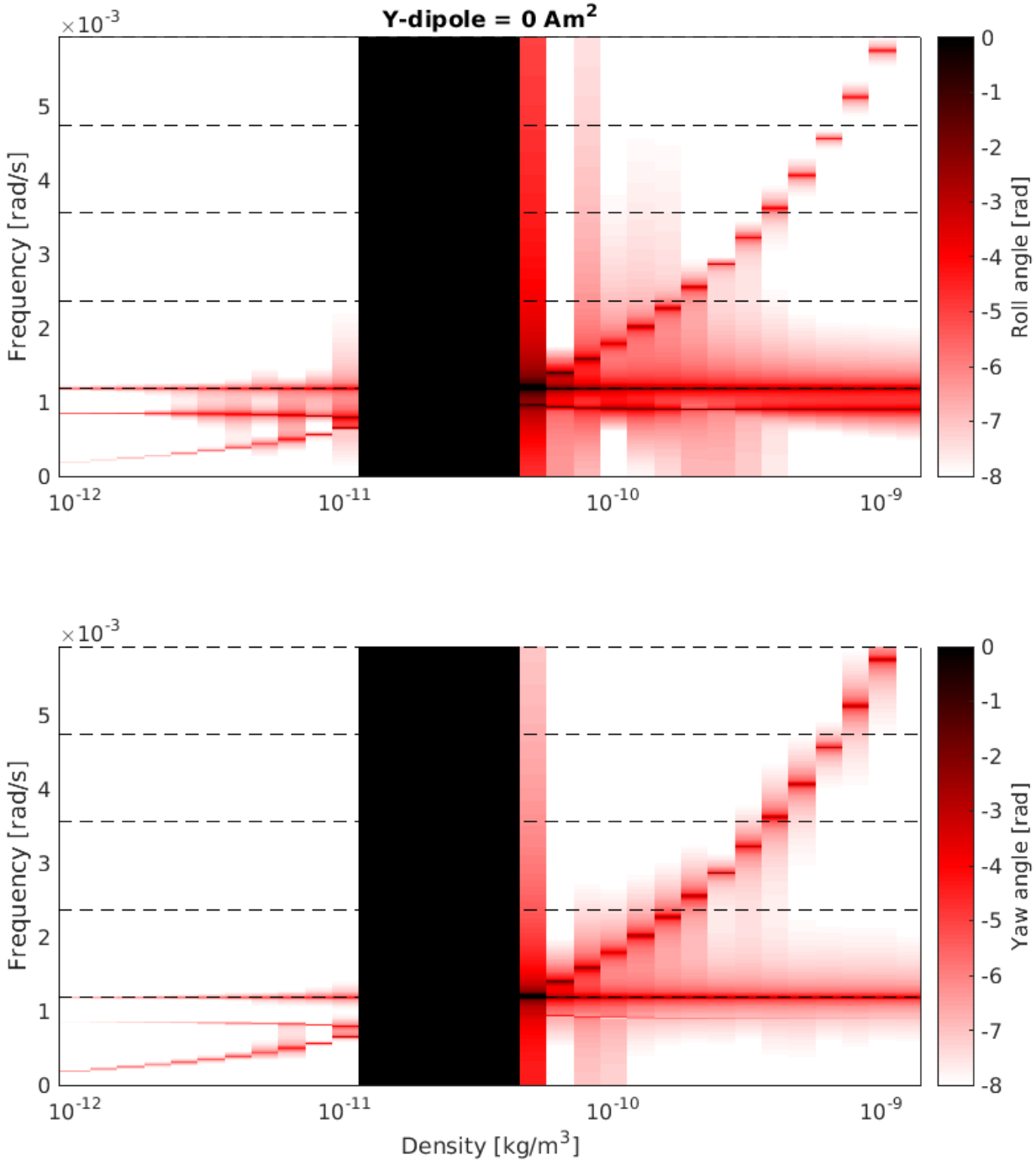
# Density

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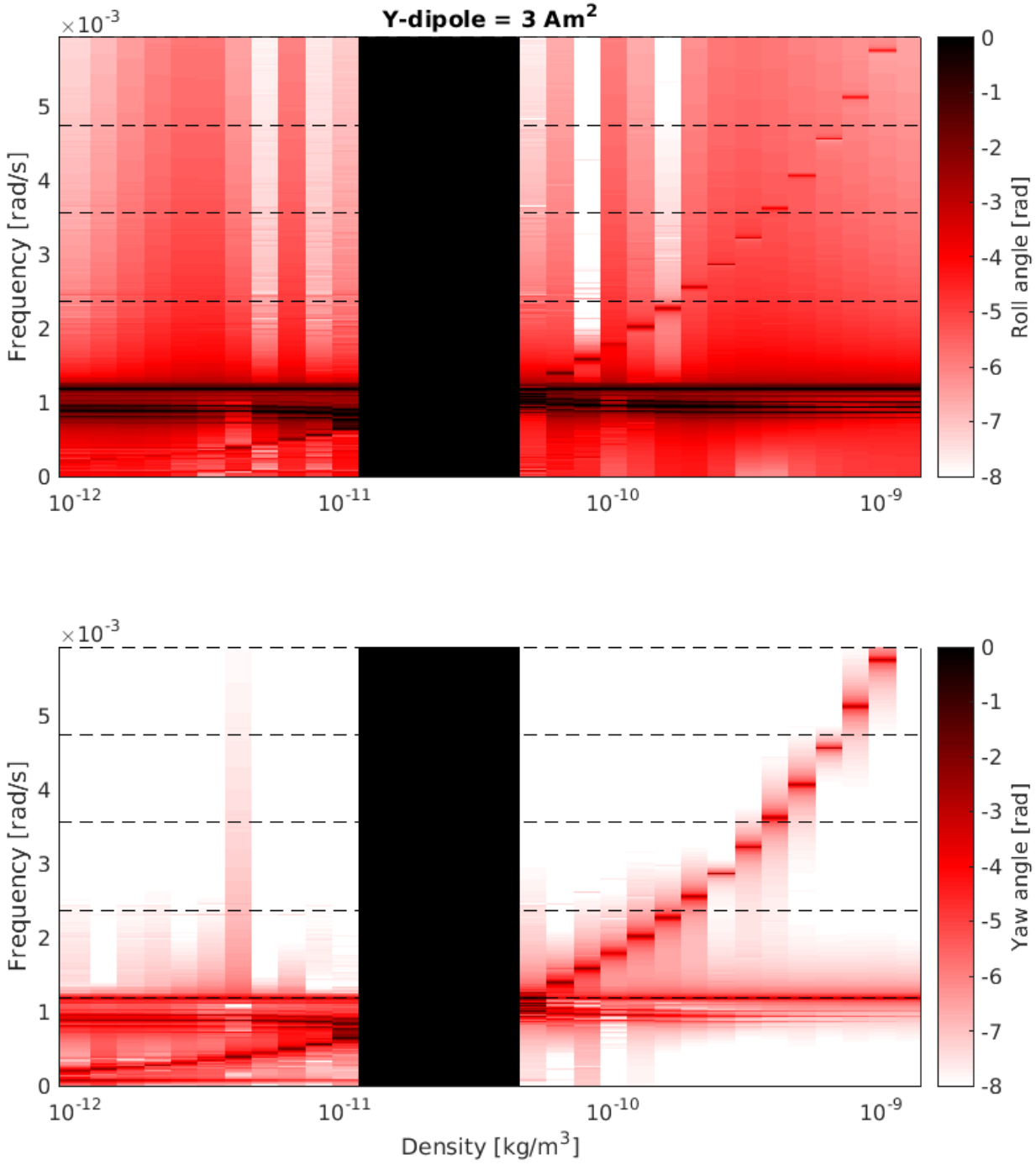
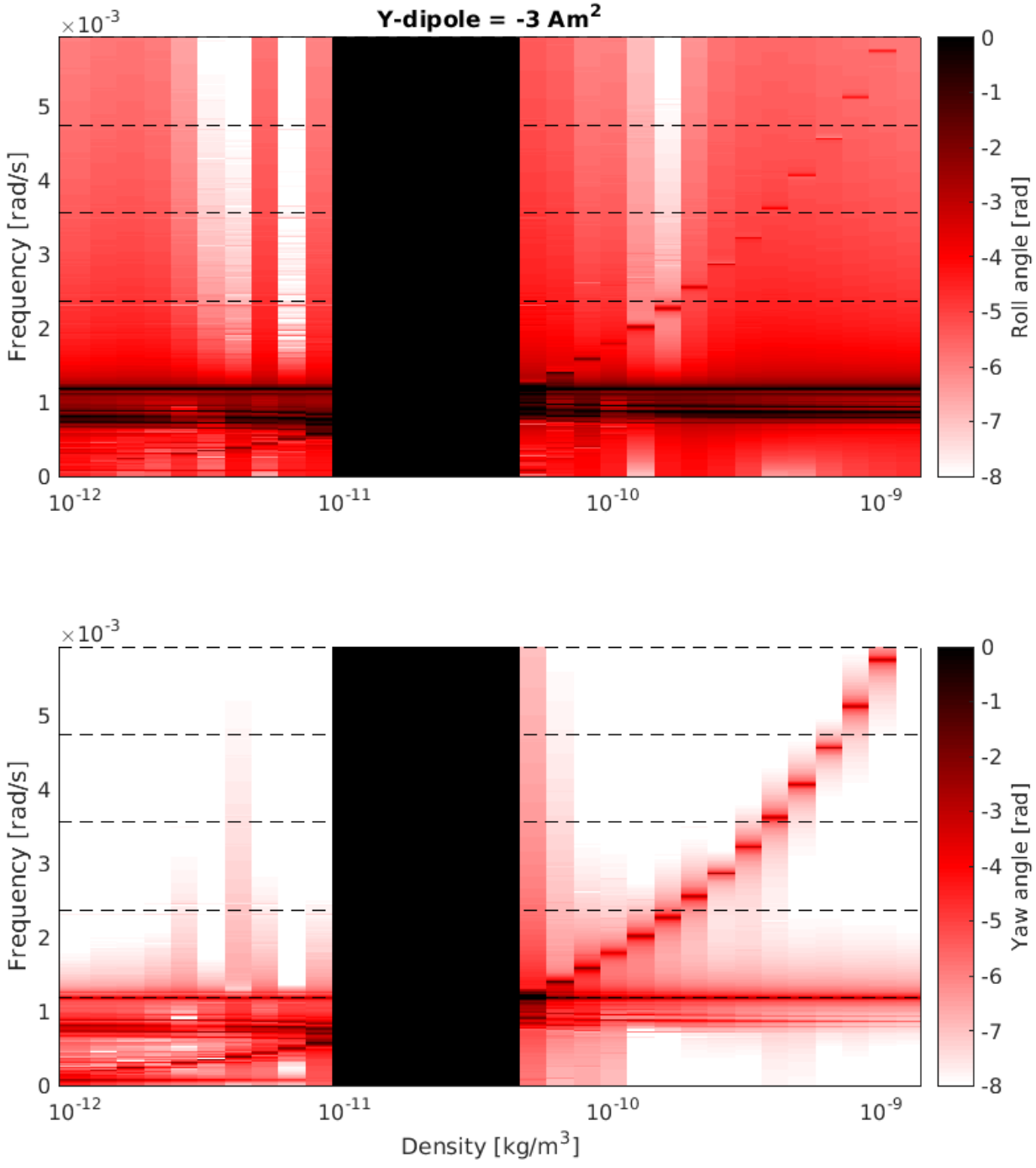
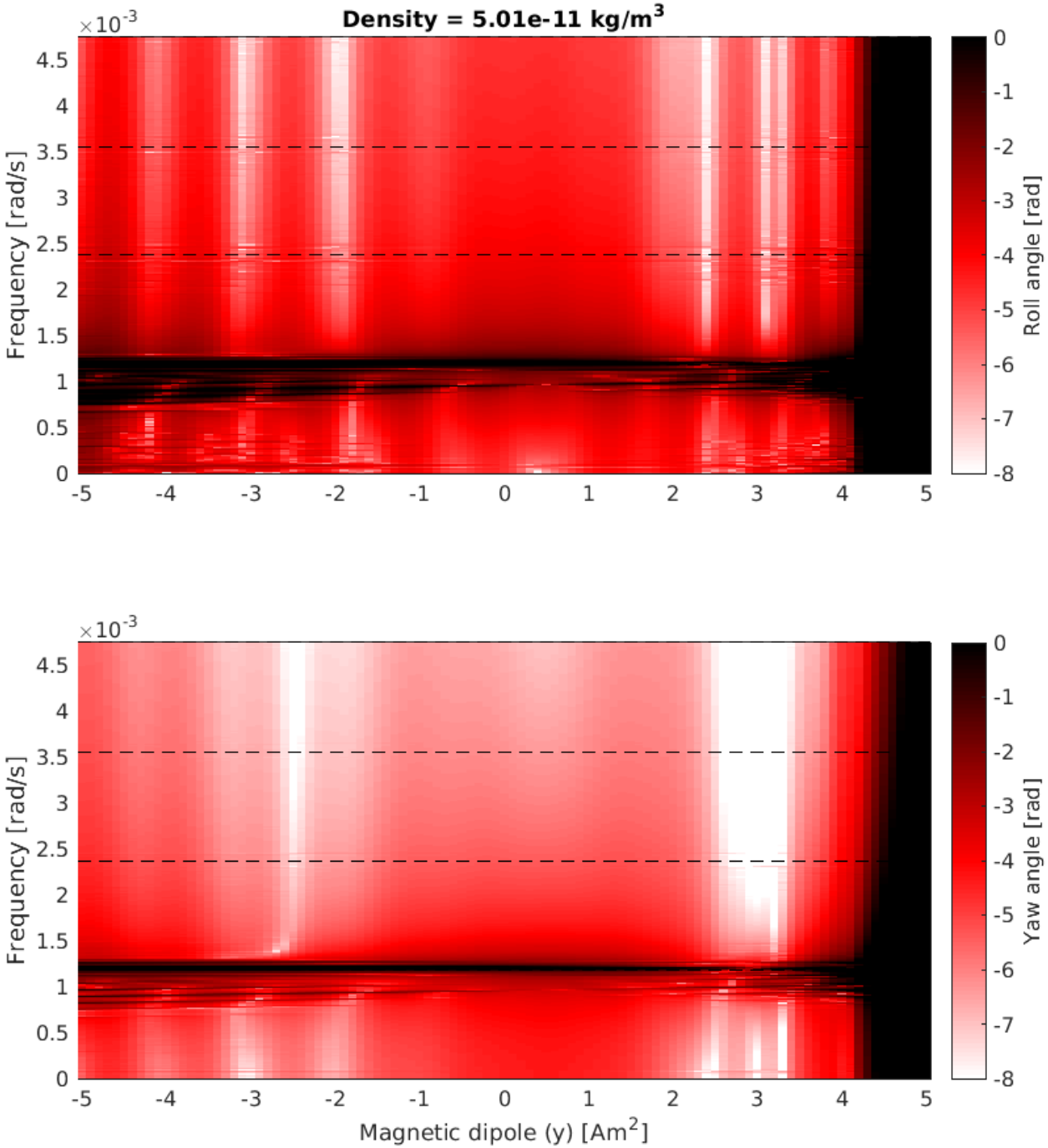
# Density


Y-dipole = 3 Am$^2$
$\times 10^{-3}$
Frequency [rad/s]
Roll angle [rad]
Yaw angle [rad]
Density [kg/m$^3$]
$10^{-12}$
$10^{-11}$
$10^{-10}$
$10^{-9}$

# Density


Y-dipole = -3 Am$^2$
$\times 10^{-3}$
Frequency [rad/s]
Roll angle [rad]
Yaw angle [rad]
Density [kg/m$^3$]
$10^{-12}$
$10^{-11}$
$10^{-10}$
$10^{-9}$

# Magnetic dipole

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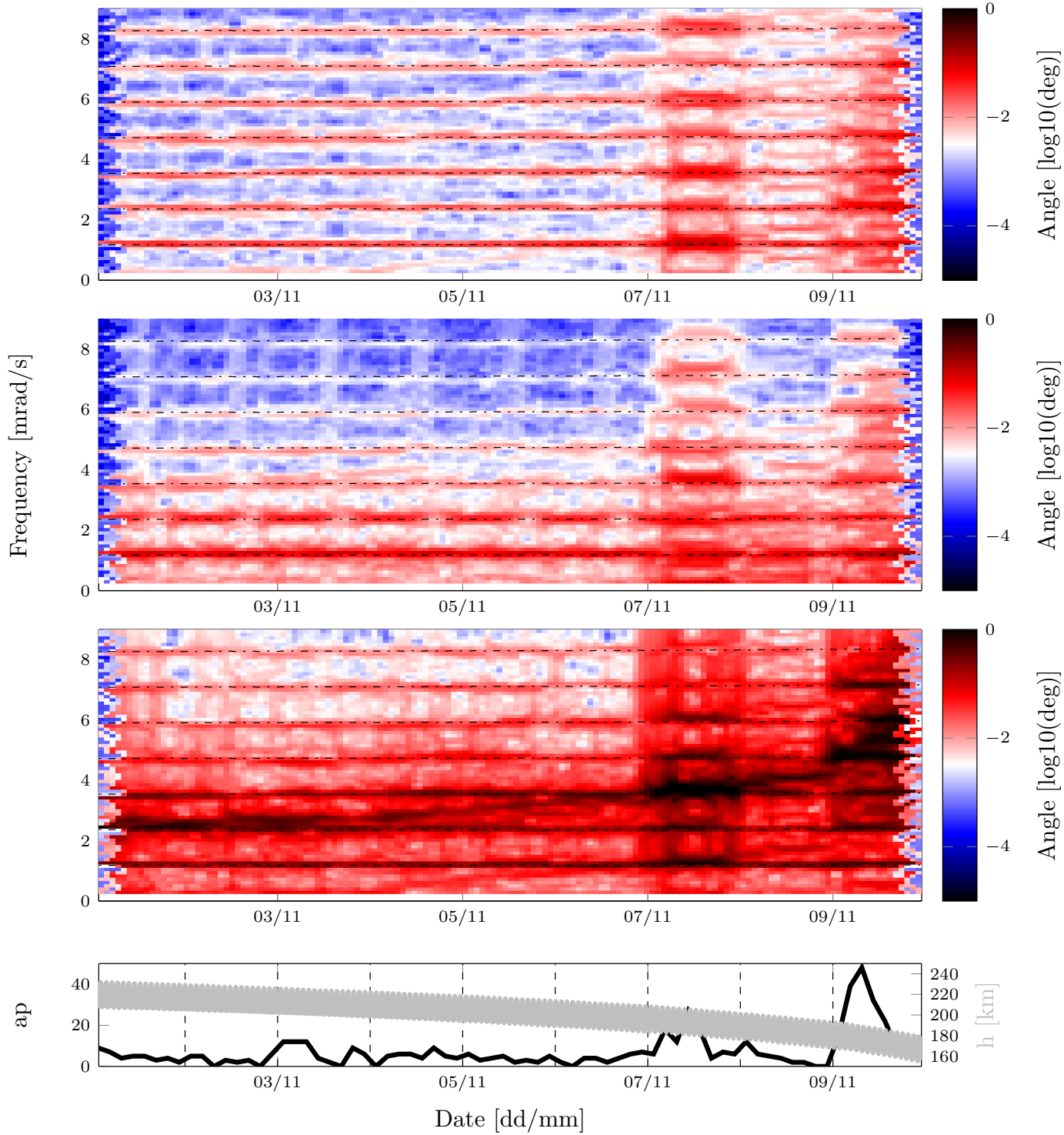
# Back to reality

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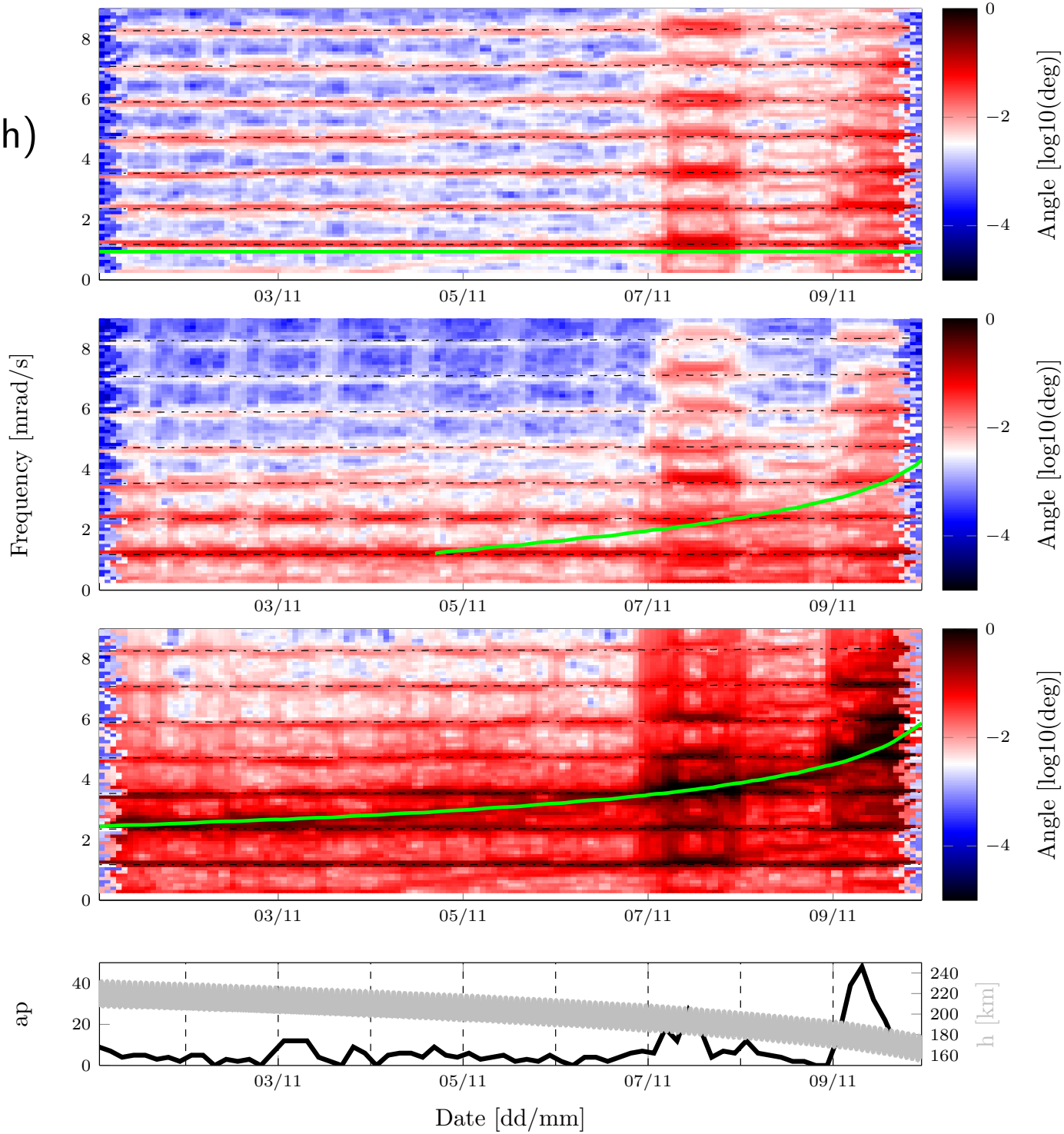
## Back to reality

- NRLMSISE-00
- SPARTA (G.March)

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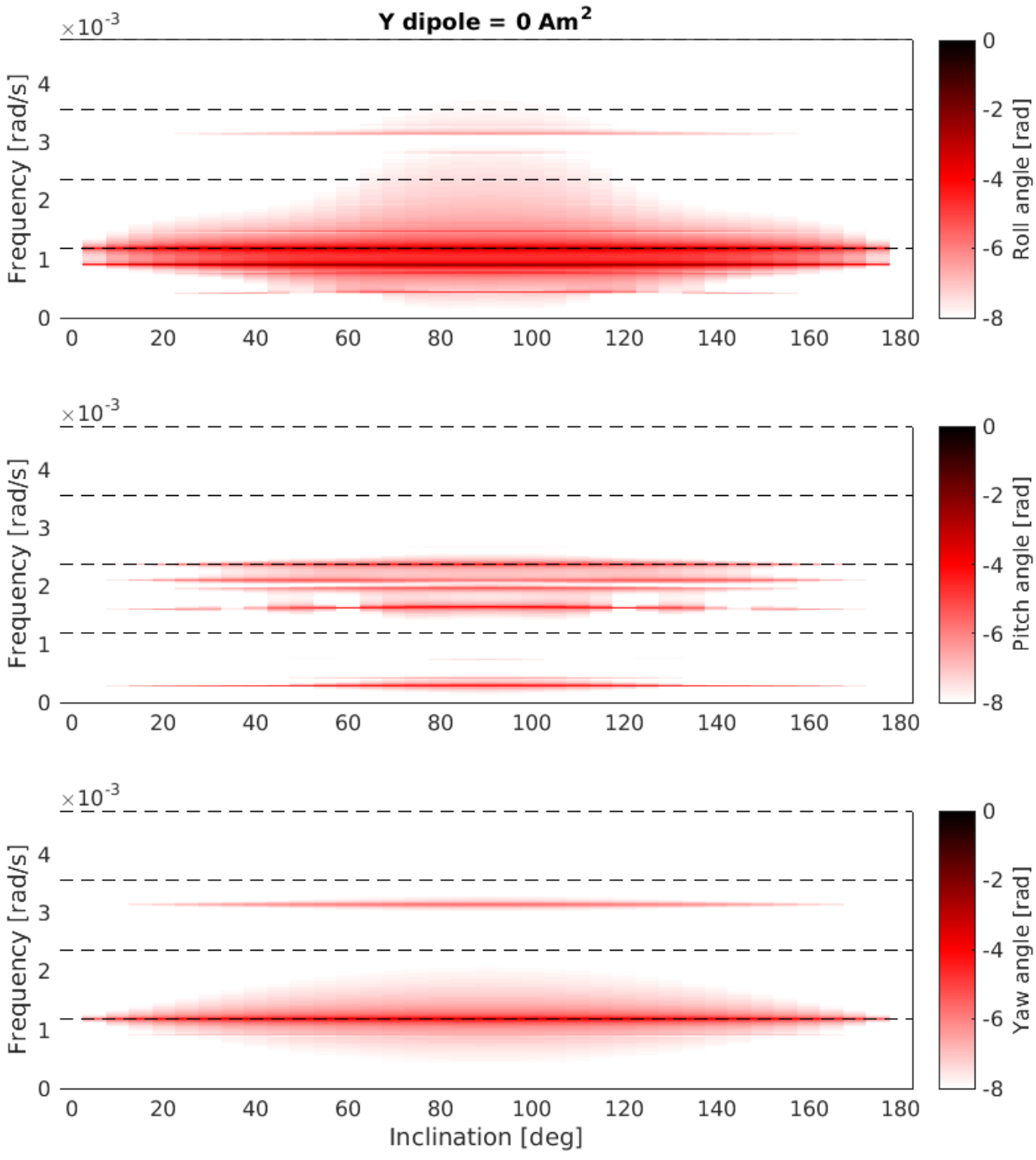
## Inclination

$3 \times 10^{-10} \mathrm{kg/m^3}$

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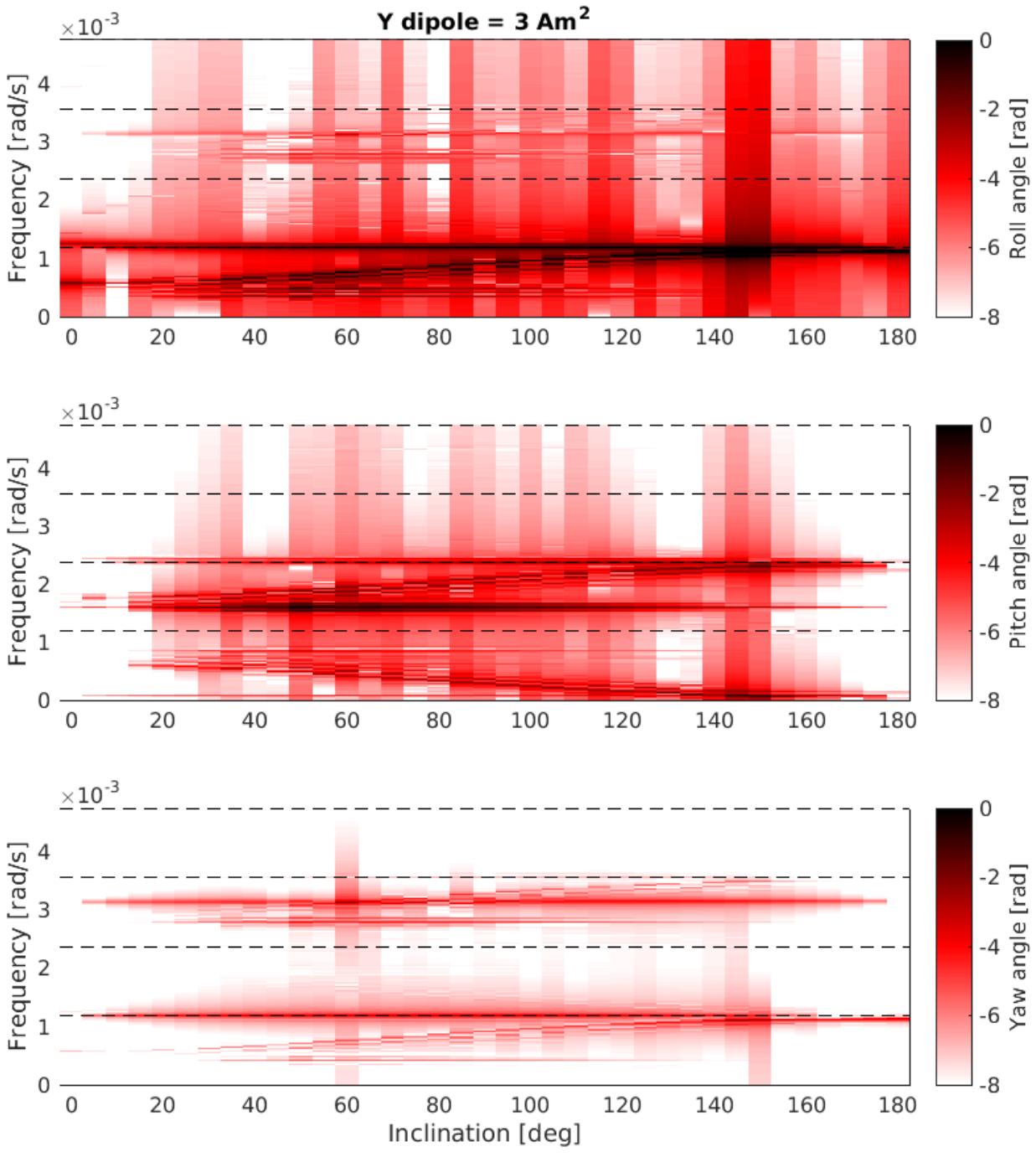


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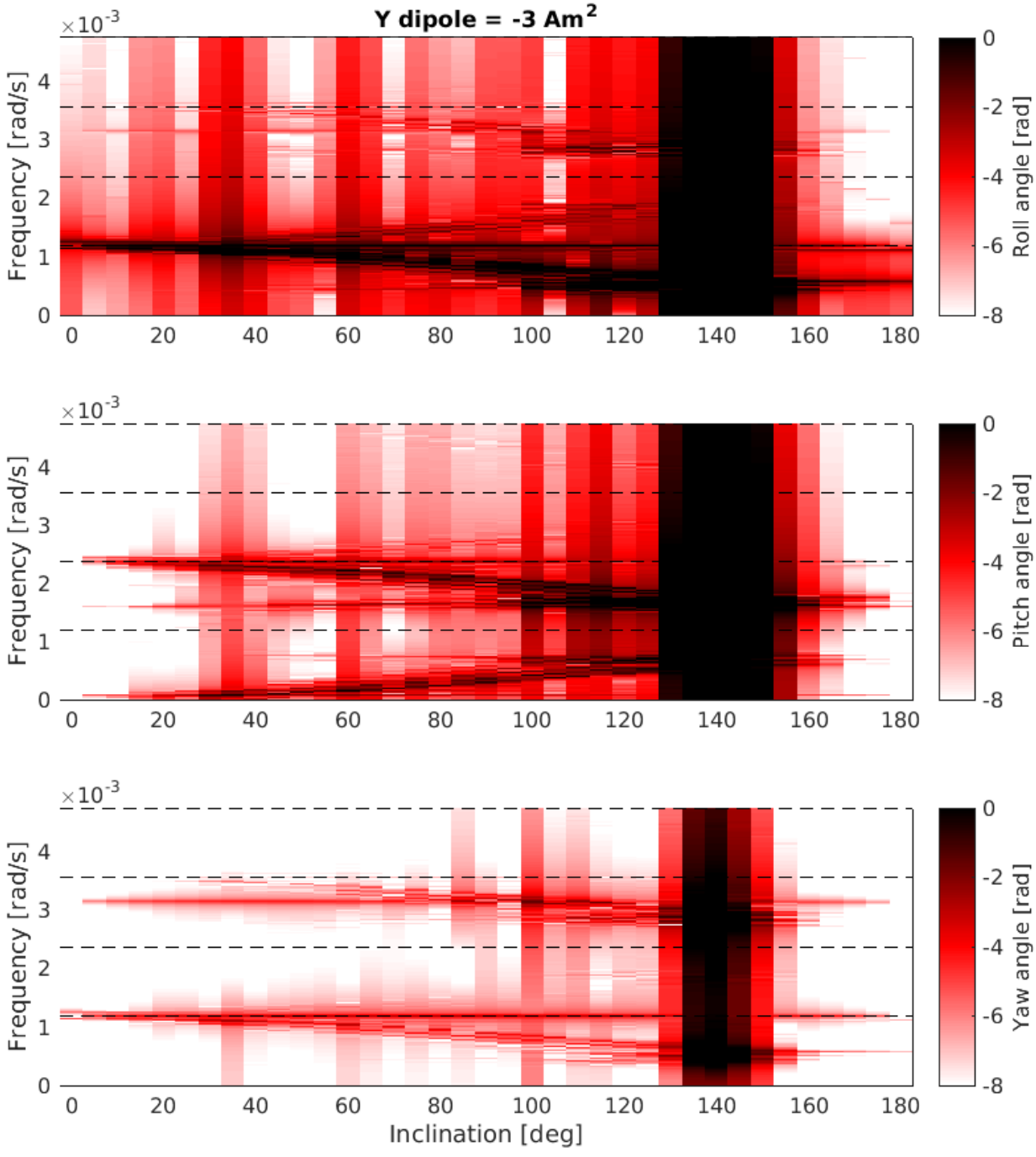


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## Conclusions

- Significant magnetic torques during de-orbit;
- High density required for pitch stability;
- Resonance destabilizes attitude.

## Recommendations

- Include $C_{l_{\alpha,\beta}}$ (roll aerodynamics);
- Analytic expressions for aerodynamic coefficients (B. Fritsche);
- Verification using simulations.

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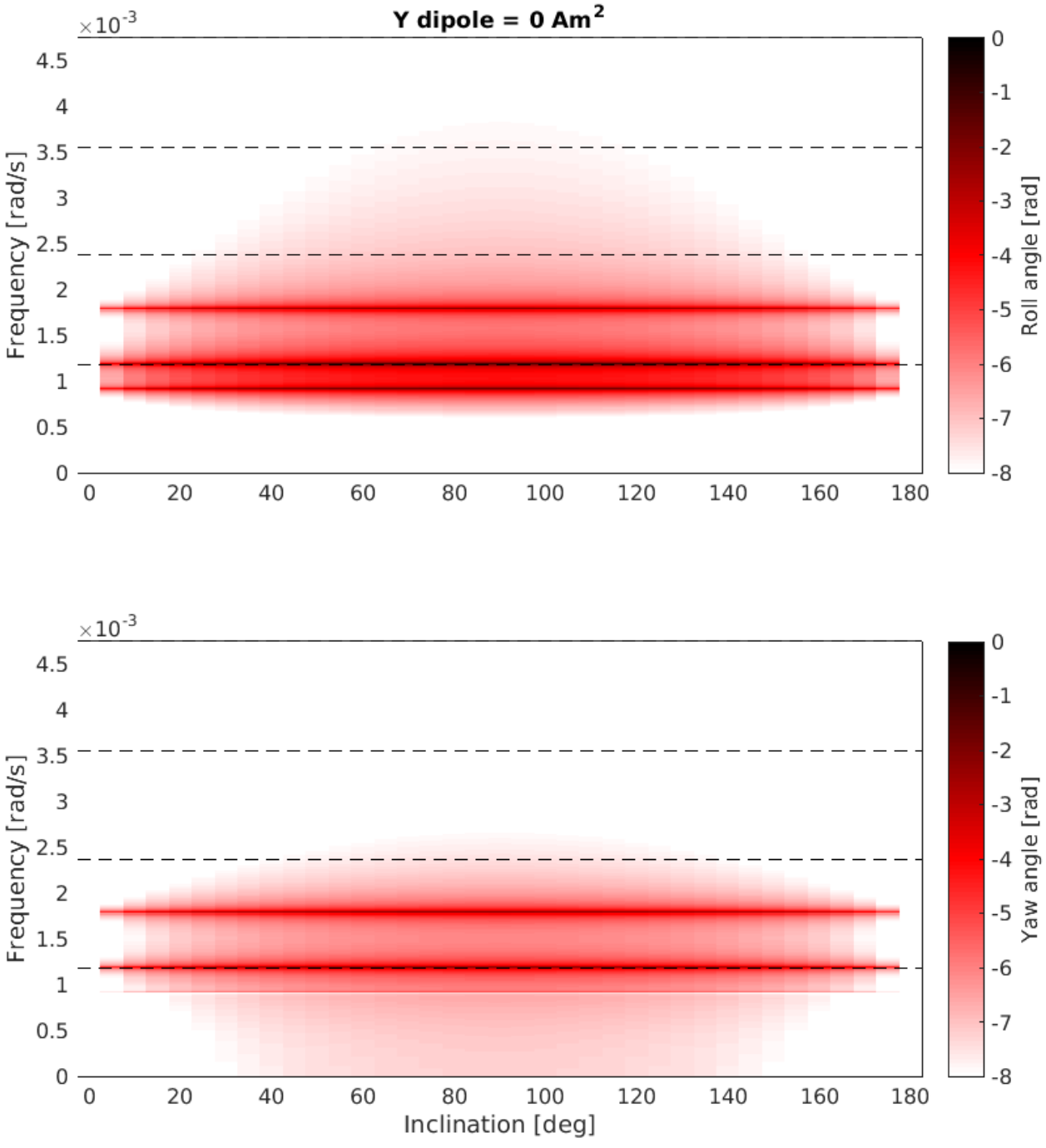
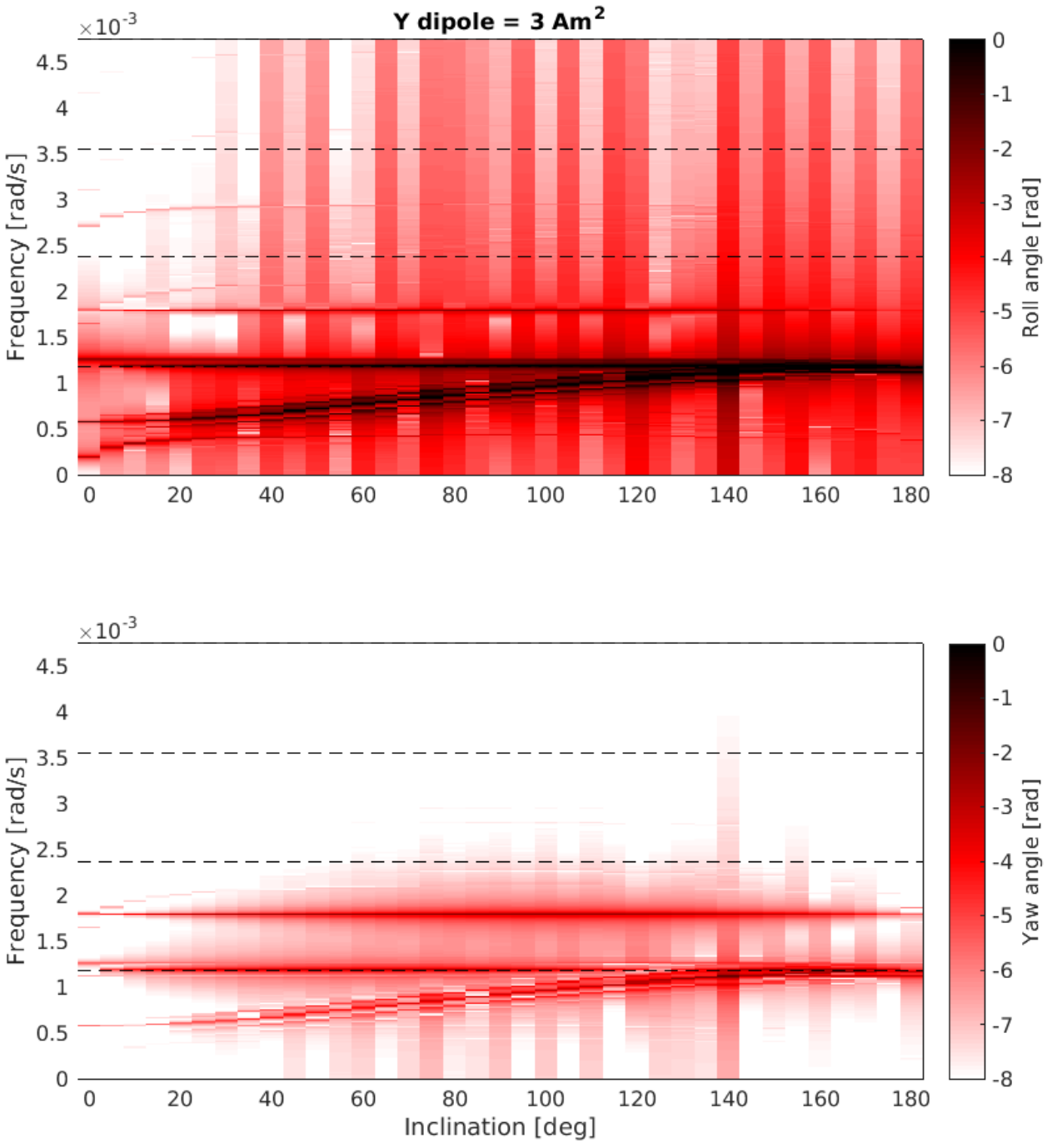
# EXTRA SLIDES

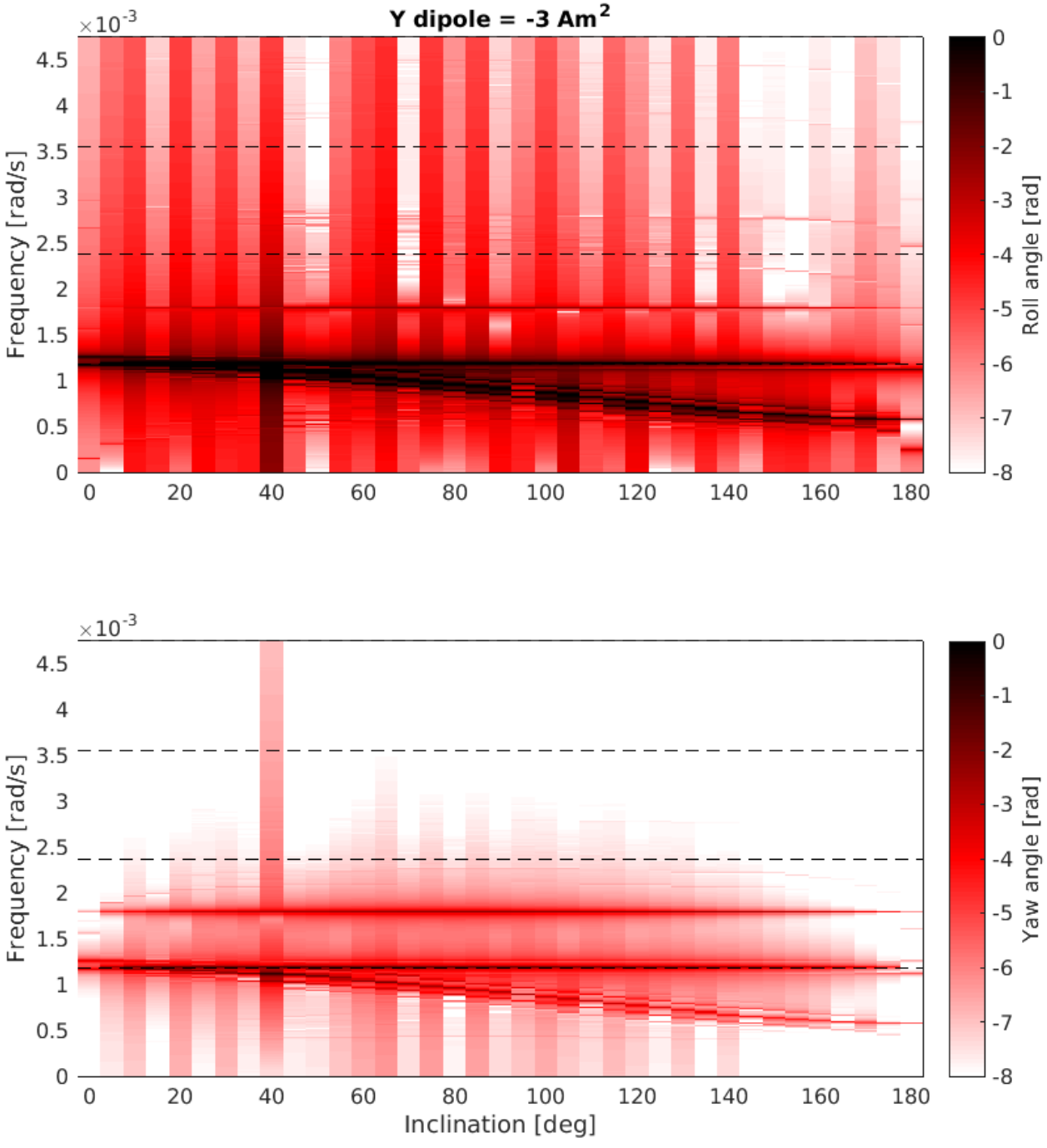
# Inclination



# Inclination



# Inclination



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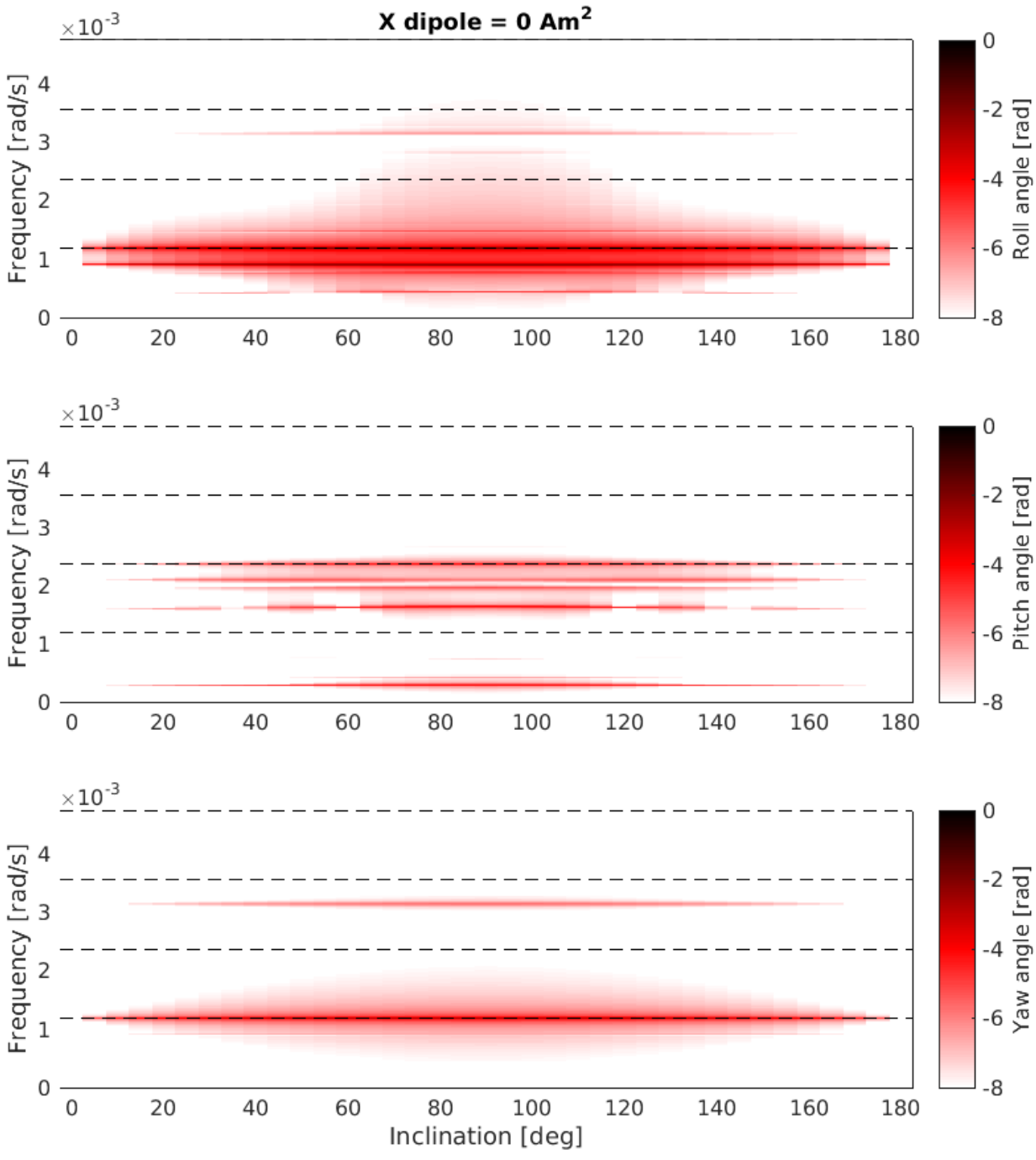


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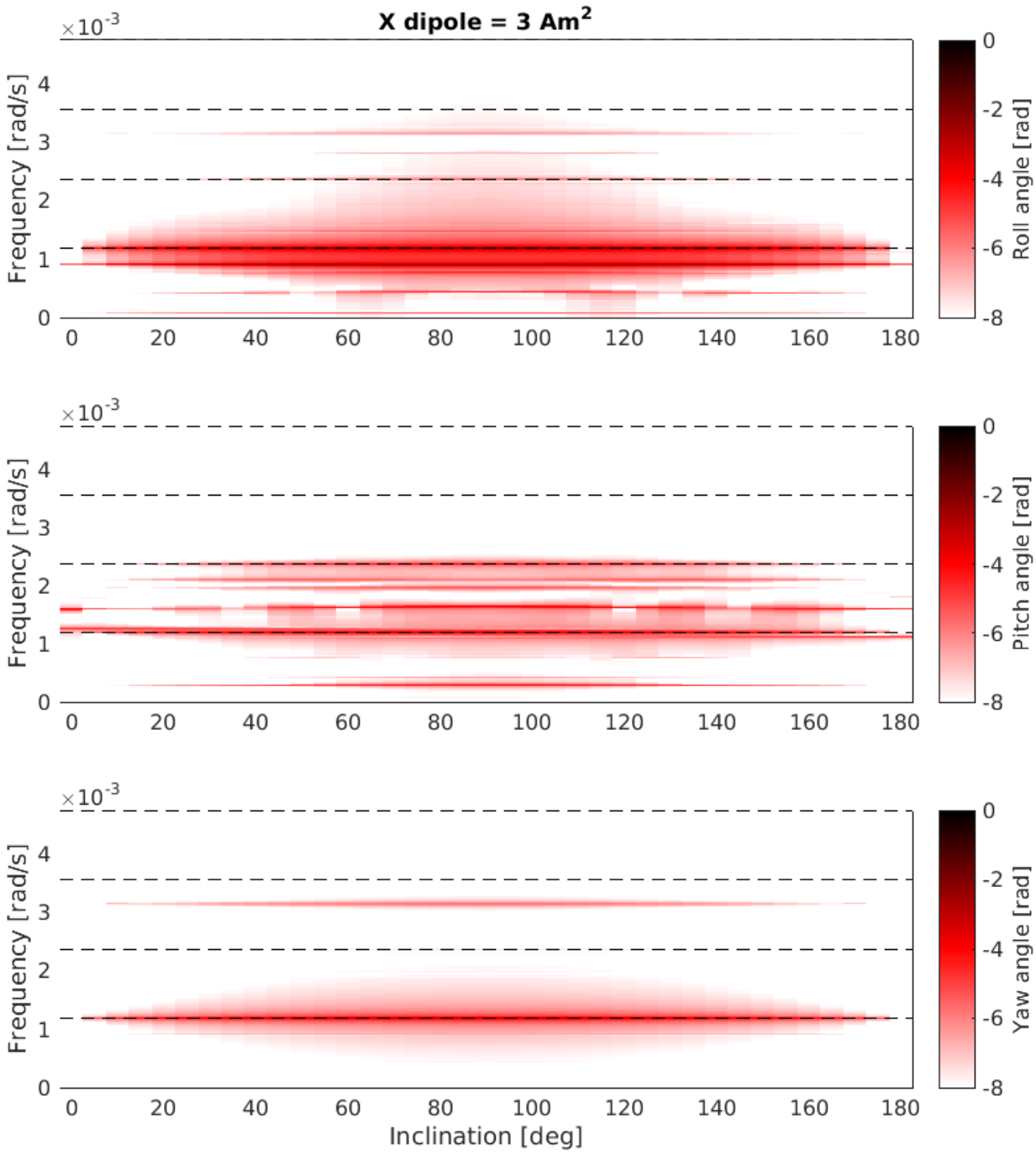


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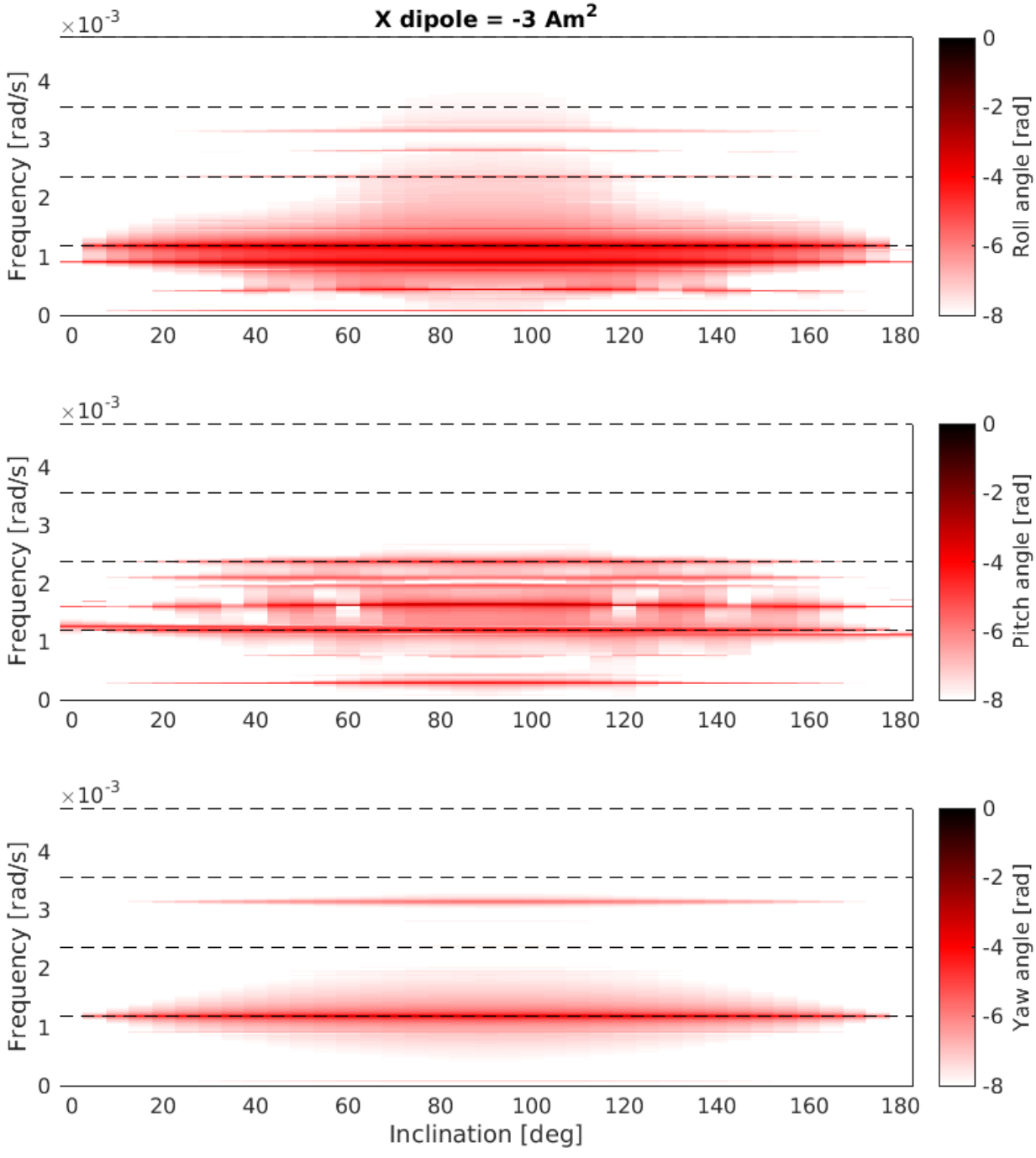


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# Control dipole

$\mu_x = -\mu_c \cos(2nt)$