Acoustic-gravity wave propagation characteristics in 3D radiation hydrodynamic simulations of the solar atmosphere

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Motivation

- Goal: Investigate ("benchmark") propagation characteristics and damping of acoustic-gravity waves in various 3D radiative hydrodynamic simulations
  - Bifrost, CO5BOLD, MANCHA3D, MURaM
- Once we have a good understanding and validation of the simulations, we can address science questions such as:
  - Height dependence of energy flux of acoustic-gravity waves
  - Propagation characteristics in the chromosphere
  - Validation of phase diagnostic approach to determine physical parameters such as the acoustic cutoff frequency or radiative damping times in the real Sun (i.e., from observations)
  - Abundance studies

Shortcomings of previous study

- Fleck+: 2021 Phil.Trans.R.Soc. A379: 20200170 (2021RSPTA.37900170F)
- Vastly different setups
  - box size
  - cell size (resolution)
  - cadence
  - duration
  - RT
  - average magnetic field strength

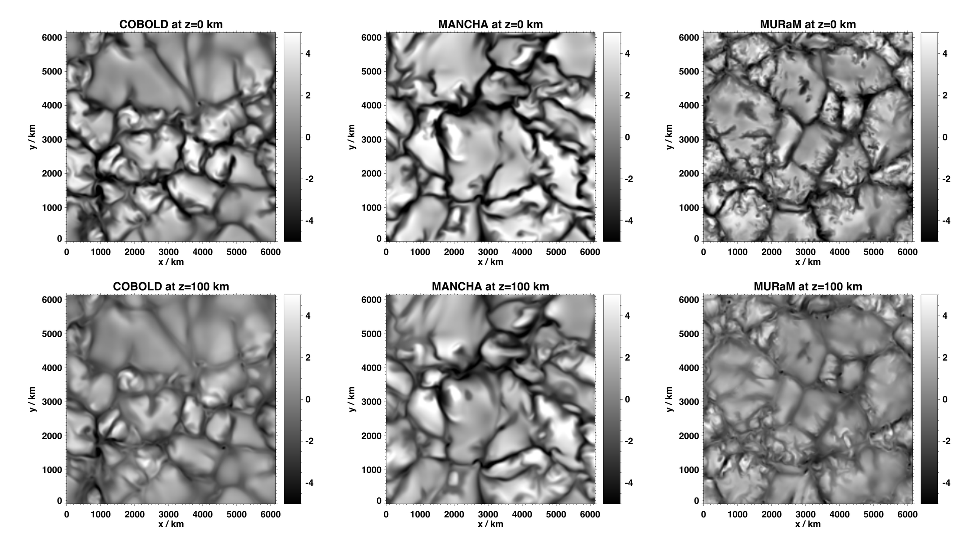
This study: identical setup for all model runs

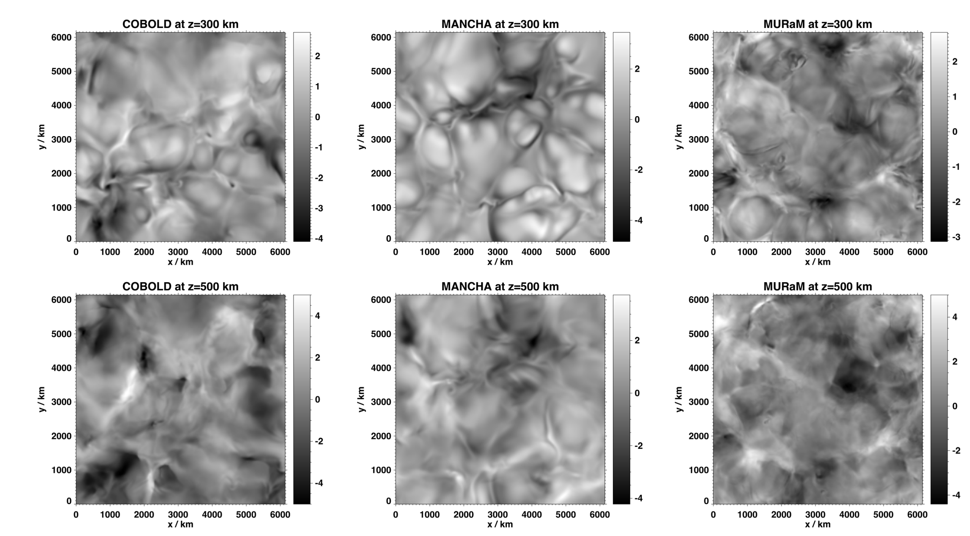
New, common setup

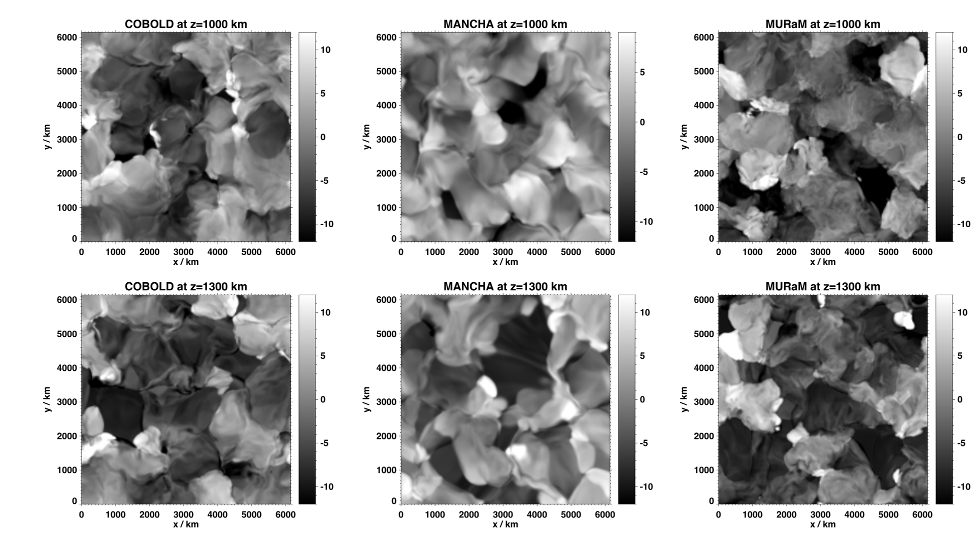
- box size: 6144 km x 6144 km x 4096 km
- cell size: 16 km x 16 km x 16 km, i.e., 384x384x256 cubes
- and half res. runs: 32 km x 32 km x 32 km, i.e. 192x192x128 cubes
- grey RT
- B=0
- closed upper boundary
- lower boundary at -2500 km, upper boundary at 1596 km
- 2-hour runs, with a cadence of Δt=10 s
- 6.3 x 10^7 W/m^2 radiative flux of Sun, i.e. T=5780 K

How do we test various models for their wave propagation characteristics?

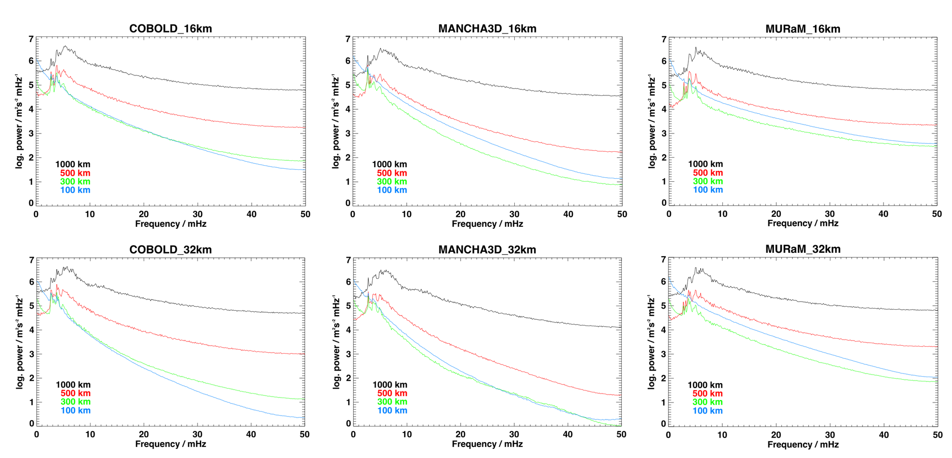
- Measure the dispersion relation of acoustic gravity waves
- Dispersion relation: $k_z = k_z(\omega, k_x, c_s, g, \tau_R)$
- How can we measure it? $v \sim e^{i\,(\omega t - k_z z)}$
- Phase difference: $\Delta\varphi_{21} = k_z(z_2 - z_1)$



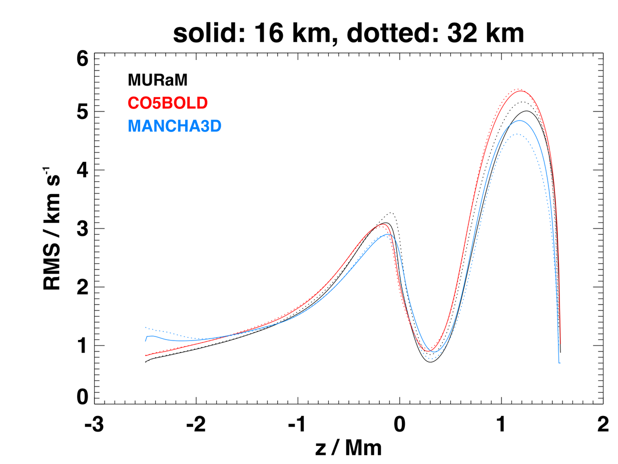




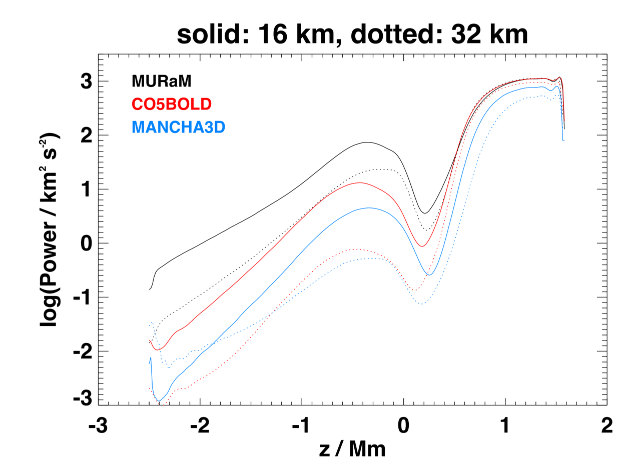
Comparison: Power spectra



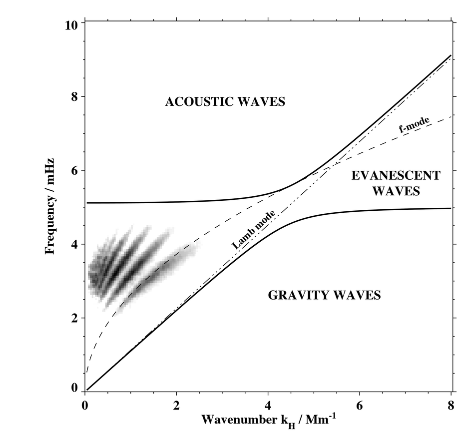
Total RMS vs height



High-frequency power (30-40 mHz) vs height



Diagnostic Diagram



Dispersion relation of acoustic-gravity wa[ves] in an isothermal, stratified atmosphere w[ith] constant radiative damping

$$\omega_{ac} = \frac{\gamma g}{2c_s} = \frac{c_s}{2H} \qquad \omega_{BV}$$

$$k_z = \pm\left[\frac{a}{2} + \frac{\sqrt{a^2+b^2}}{2}\right]^{\frac{1}{2}}$$

$$\kappa = \left(\frac{1}{2H}\right) - \left[\frac{-a}{2} + \frac{\sqrt{a^2+b^2}}{2}\right]^{\frac{1}{2}}$$

$$a = \frac{\omega^2 - \omega_{ac}^2}{c_s^2} + k_x^2\left(\frac{N^2}{\omega^2} - 1\right) - \frac{1}{1+\omega^2\tau_R^2}\frac{N^2}{\omega^2}\left(k_x^2 - \frac{\omega^4}{g^2}\right)$$

$$b = \frac{\omega\tau_R}{1+\omega^2\tau_R^2}\left(\frac{N^2}{\omega^2}\right)\left(k_x^2 - \frac{\omega^4}{g^2}\right).$$

Sou[rce]

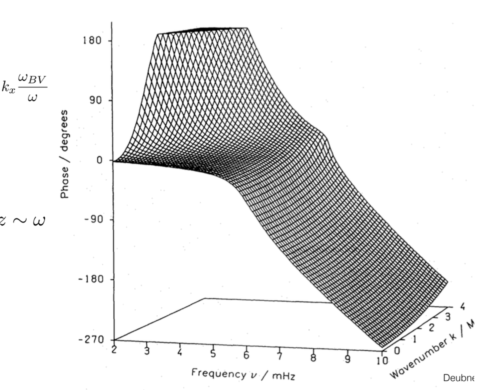
Phase difference spectrum
ϕ(k_x, ω)= $k_z \cdot \Delta z$

For $\omega << \omega_{BV}$

$$k_z \sim \sqrt{k_x^2(\frac{\omega_{BV}^2}{\omega^2} - 1) + 1/4H^2} \approx k_x \frac{\omega_{BV}}{\omega}$$

For $\omega >> \omega_{ac}$

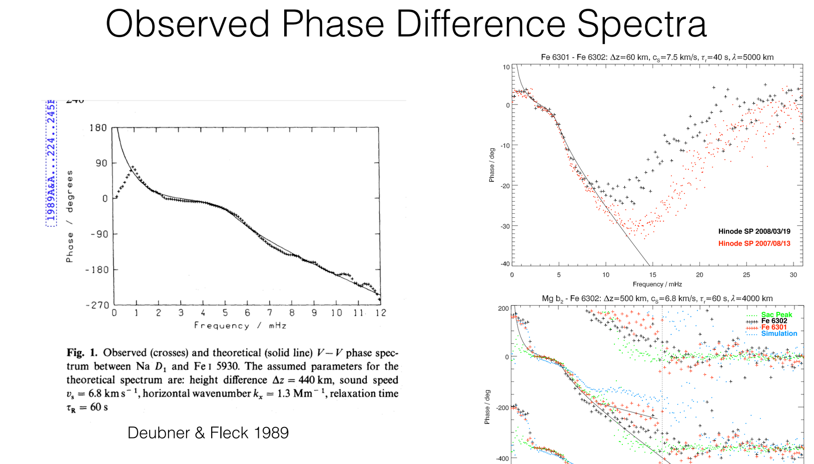
$$\Delta\varphi = k_z \cdot \Delta z \approx \omega/c_s \cdot \Delta z \sim \omega$$



1-D (temporal) phase difference spectra

- 4-D cubes: v(x,y,z,t)
- 4 slices at z=100, 300, 500, 1000 km → 4 3-D cubes v_i(x,y,t)
- pixel by pixel FFT in time and calculate CP(ν) = FFT_{v1}(ν) · FFT_{v2}(ν)*
- average cross power over all pixels in x and y
- calculate phase difference $\Delta\phi$=arctan(IM(CP(ν))/RE(CP(ν))

Observed Phase Difference Spectra

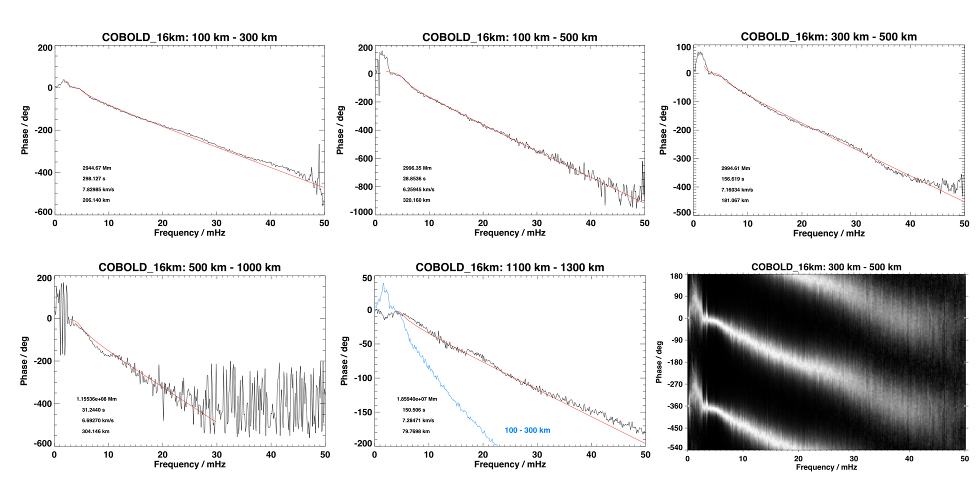


Deubner & Fleck 1989

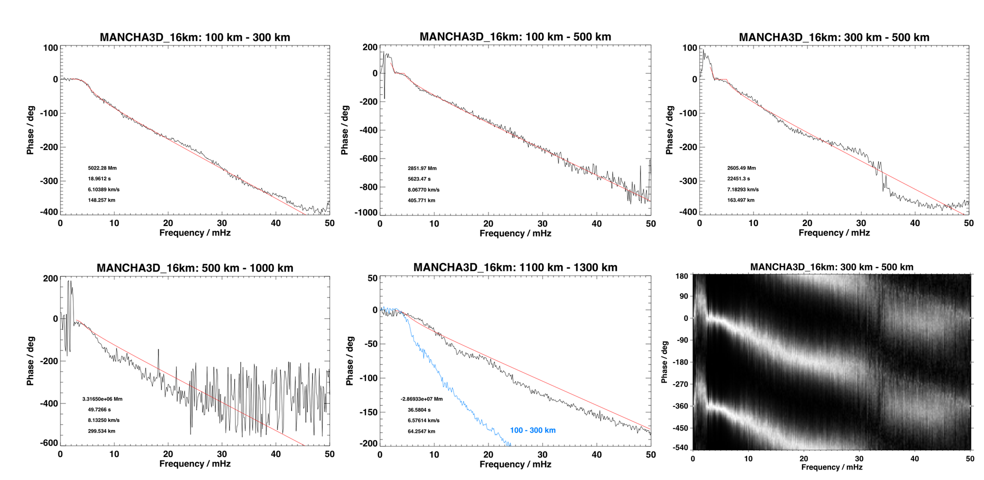
Note: observations limited to ν ≤ 15 mHz (noise limited)

Fleck+ 2008

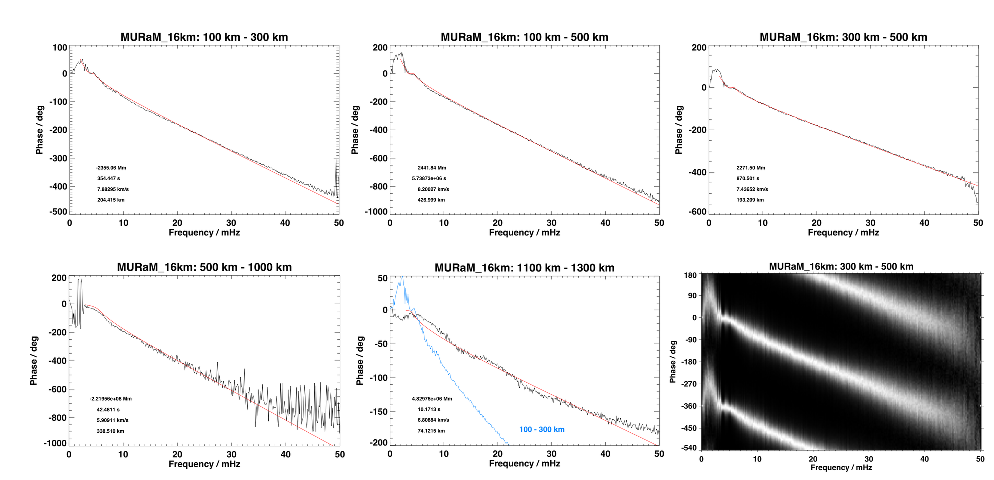
1-D Phase Difference Spectra: COBOLD



1-D Phase Difference Spectra: MANCHA



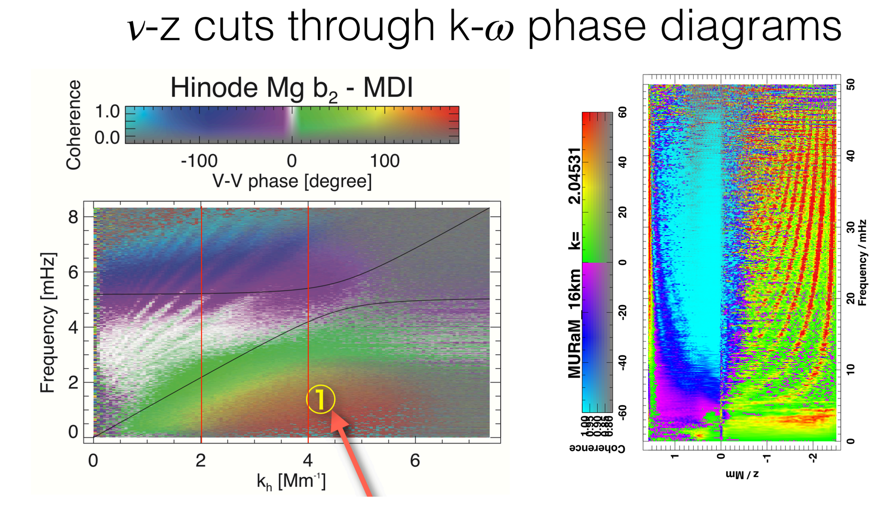
1-D Phase Difference Spectra: MURaM

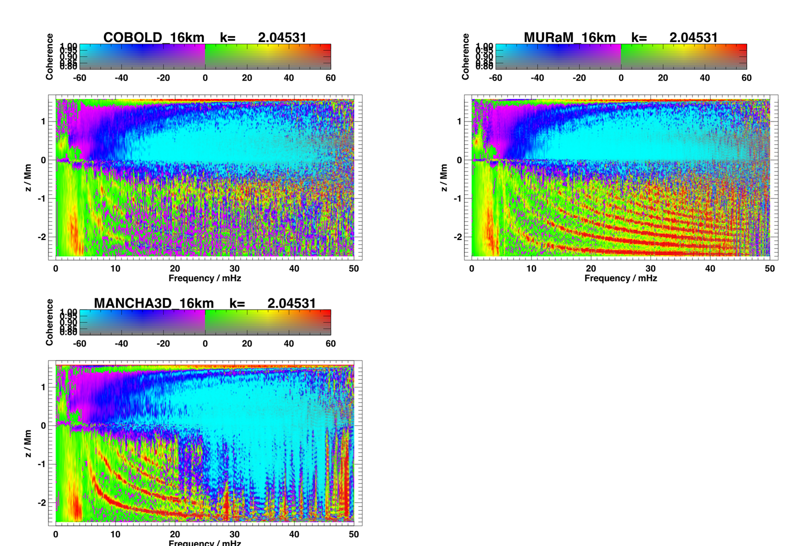


ν-z cuts through k-ω phase diagrams

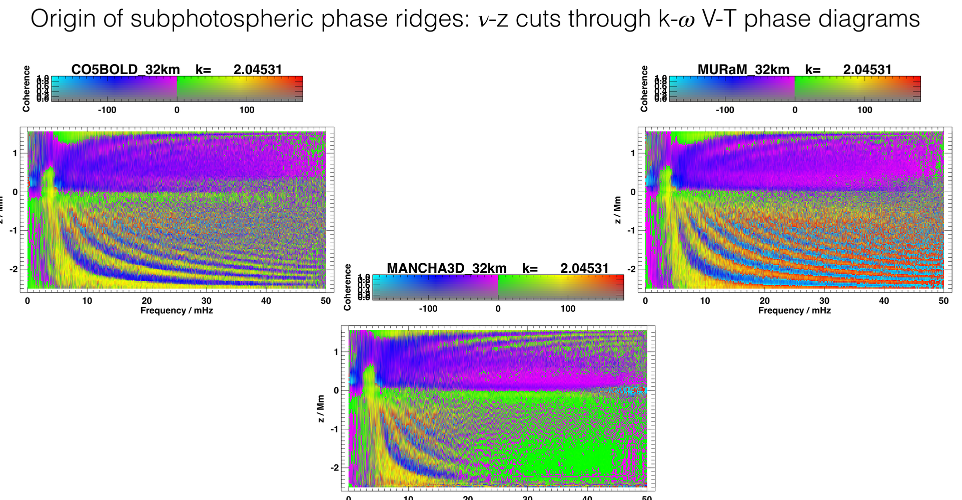
- Instead of selecting particular heights, calculated 3-D FFT for all layers v(x,y,z_i,t) i=1,..,N
- From 3-D Fourier transforms calculate cross power spectra and from those k-ω phase difference spectra between successive layers z_i and z_{i+1}, for all N-1 layer pairs
- make cuts at constant k_x and plot phase difference spectra as function of ν and z
- that provides information how phase propagates from layer to layer

ν-z cuts through k-ω phase diagrams

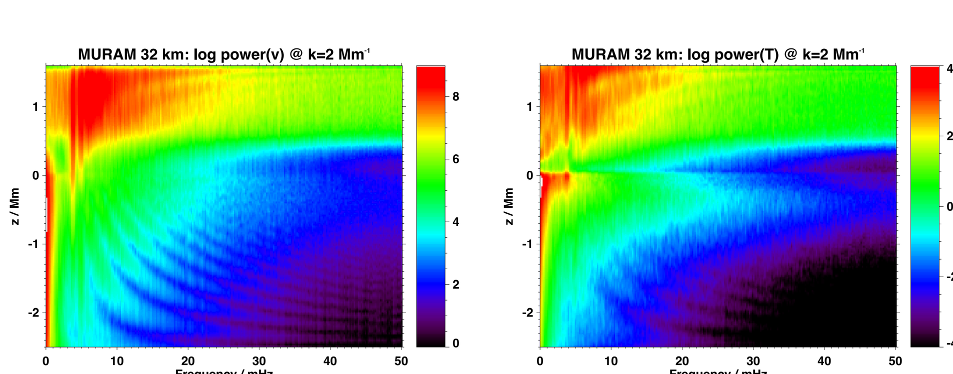




Origin of subphotospheric phase ridges: ν-z cuts through k-ω V-T phase diagrams



Nodes in V and T power



Ridges in V-V and V-T phase diagrams result of standing waves in convection zone, i.e. cavity between lower boundary and reflection/damping at bottom of photosphere

Summary

- Much better agreement between different models than in previous simulations
- Power distributions:
  - Similar now, in particular also total RMS
  - High-frequency power still considerably different, in particular in convection zone, with MURaM being 2 orders of magnitude higher than MANCHA.
  - Doubling the resolution from 32 km to 16 km has little effect on total RMS (and phase spectra), but high-frequency power (in particular in convection zone) increases by almost an order of magnitude
- Phase difference spectra:
  - good agreement with simple Souffrin model in photosphere
  - no obvious phase jumps as in earlier model runs
  - very poor agreement with Souffrin model in chromosphere (but indications of very high phase speeds, as is actually observed)
  - MANCHA run still shows indications of "finger" around z≈300-600 km
- Cause of phase ridges in convection zone identified: standing waves in cavity between lower boundary and bottom of photosphere