Atmospheric normal modes of the Earth

Theory and observations

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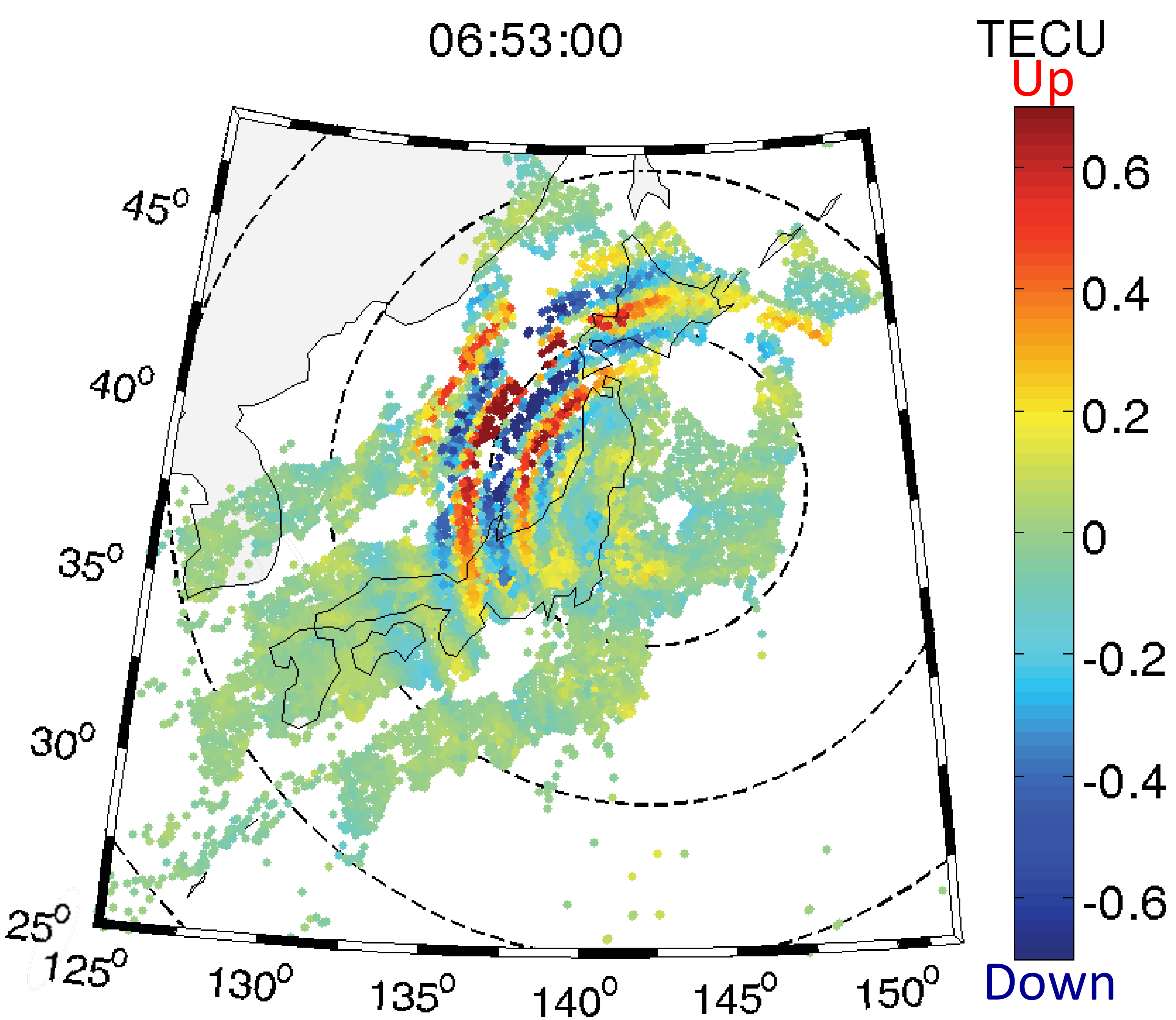
IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

Normal modes excited by a very large earthquake - Observations

(Tohoku 2011, Mw=9.2)



TEC data filtered from 1 to 10 mHz

Rolland et al. (2011)

Solid Earth / neutral atmosphere coupling: normal modes modeling

- Compute the modes of a full Earth model
  - Interior, including mantle and core
  - Ocean
  - Atmosphere and Ionosphere

- Compute waves by computing the excitation of these modes and summing the modes

- Compare to observations

<u>Anelasticity equation</u>

$$\frac{\partial^2 \mathbf{u}}{\partial t^2} = \frac{1}{\rho}(\nabla \cdot (\mathbf{T} - \mathbf{u}\nabla\mathbf{T_0})) - div(\rho\mathbf{u})\mathbf{g} - \rho\nabla\Phi_{E_1}) = -\mathbf{A}(\mathbf{u})$$

Solid Earth / neutral atmosphere coupling: normal modes modeling

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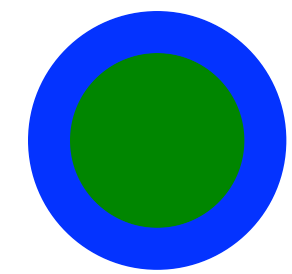
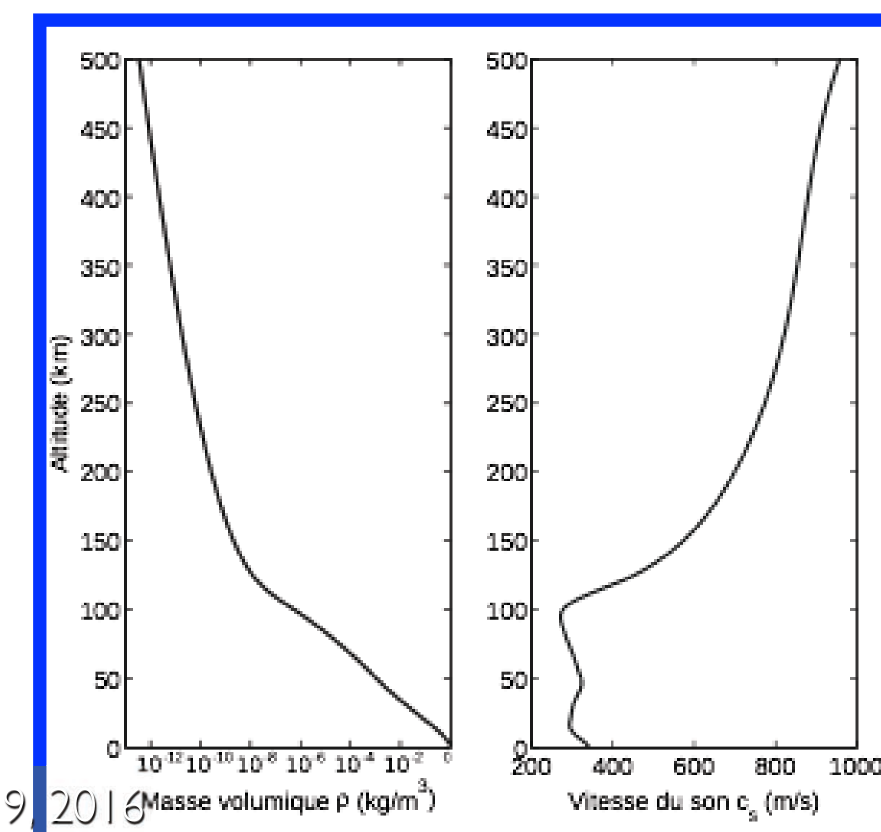
1D Earth model

Spherical symmetry
Solid Earth + **atmosphere**



PREM : Average seismic model of the solid Earth (density, Vp ,Vs)



- Compute the modes of a full Earth model
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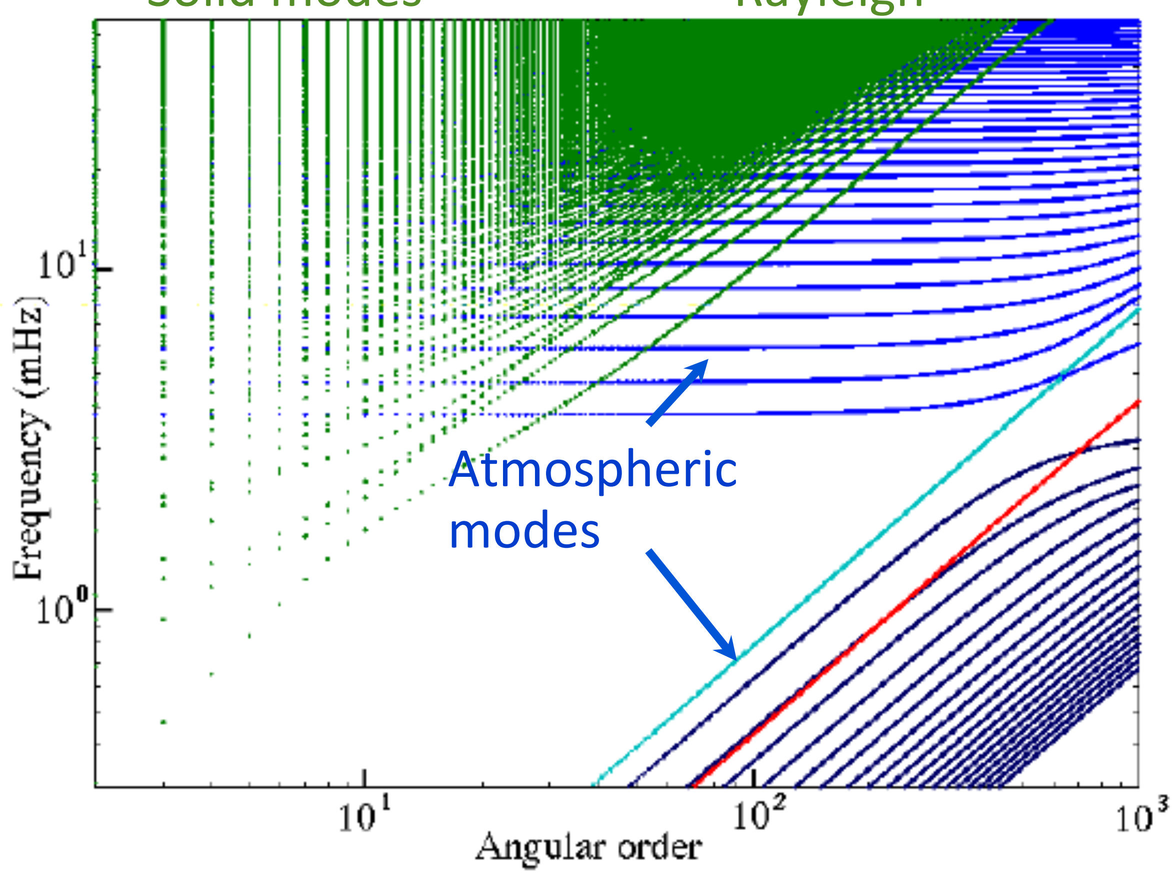
Solid Earth / neutral atmosphere coupling: normal modes modeling

The Normal modes are eigen-solutions

- of the elastodynamic wave equation

$\sigma^2 \vec{u} = \vec{A}(\vec{u})$ everywhere

- verifying all boundary conditions at discontinuities



+ **radiative condition**

(Lognonné & Clévédé,1998)

viscosity

(Artru & Lognonné, 2001)

Solid Earth / neutral atmosphere coupling: normal modes modeling

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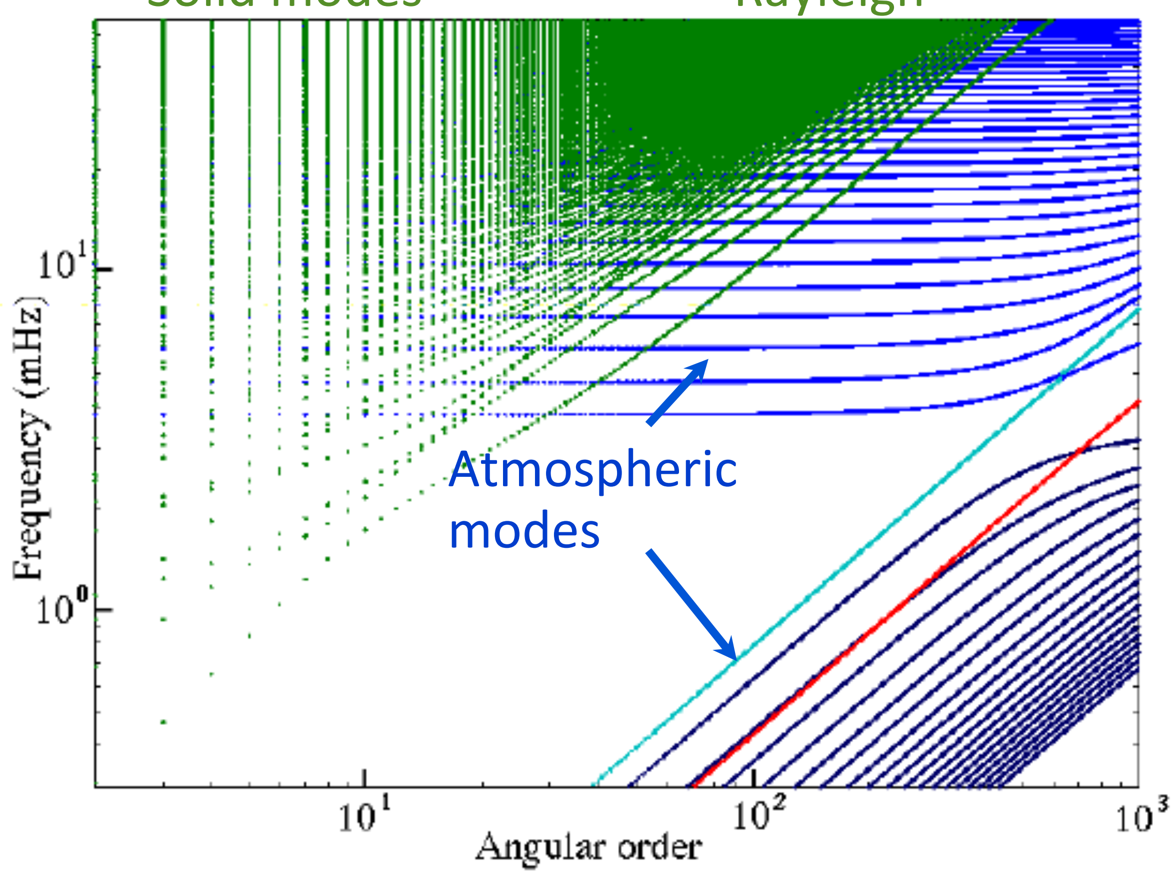

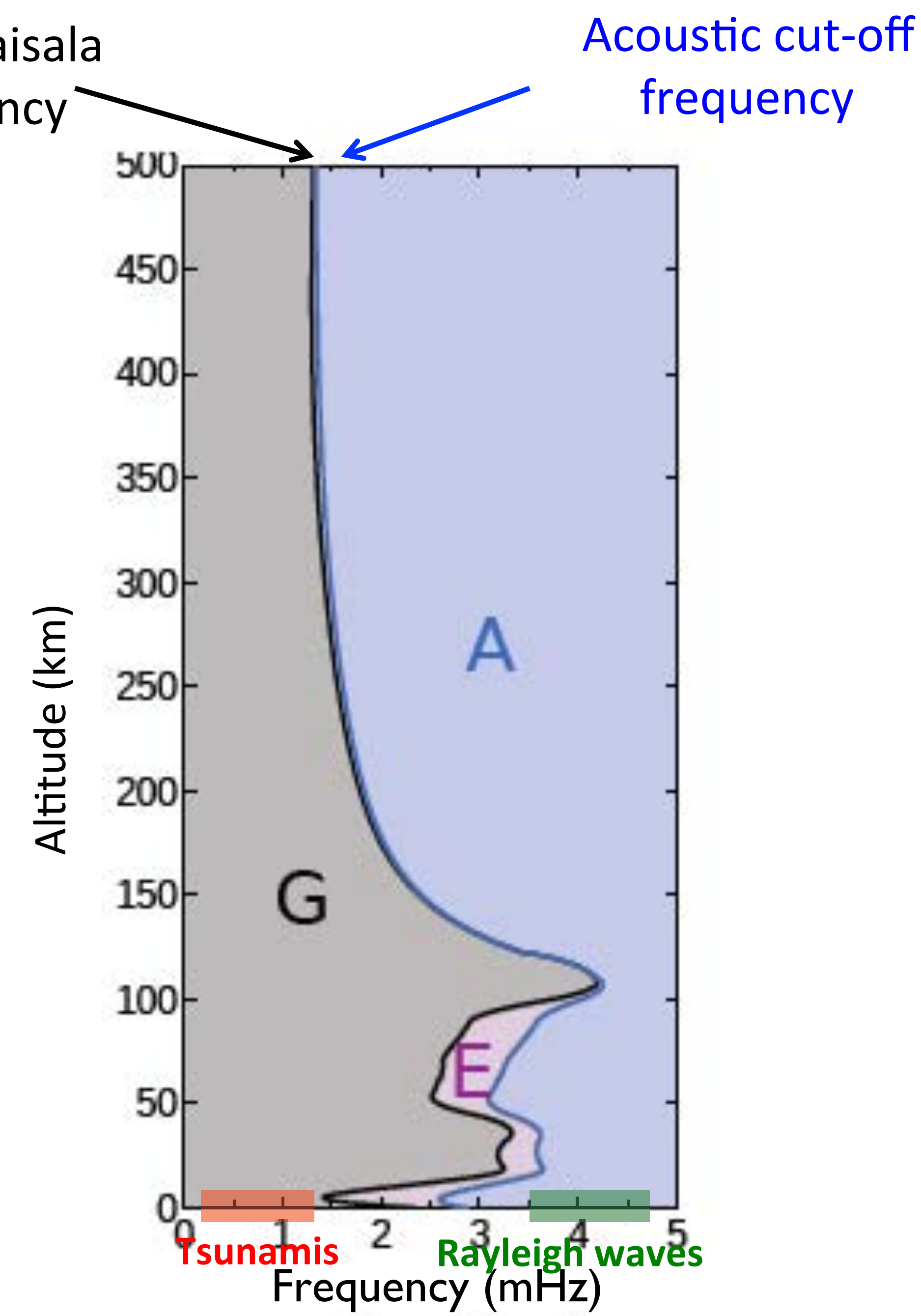

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(Lognonné & Clévédé,1998)

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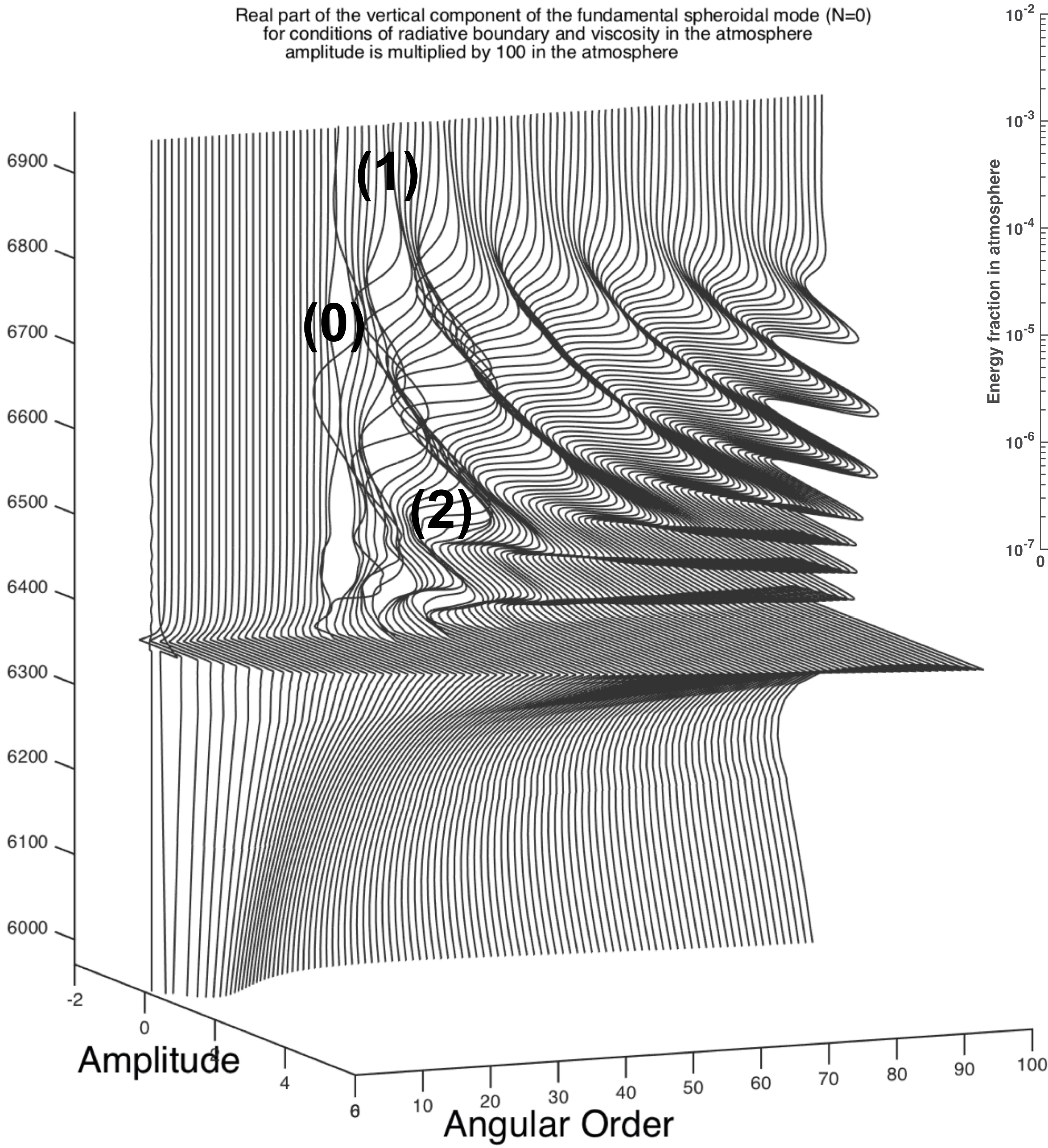
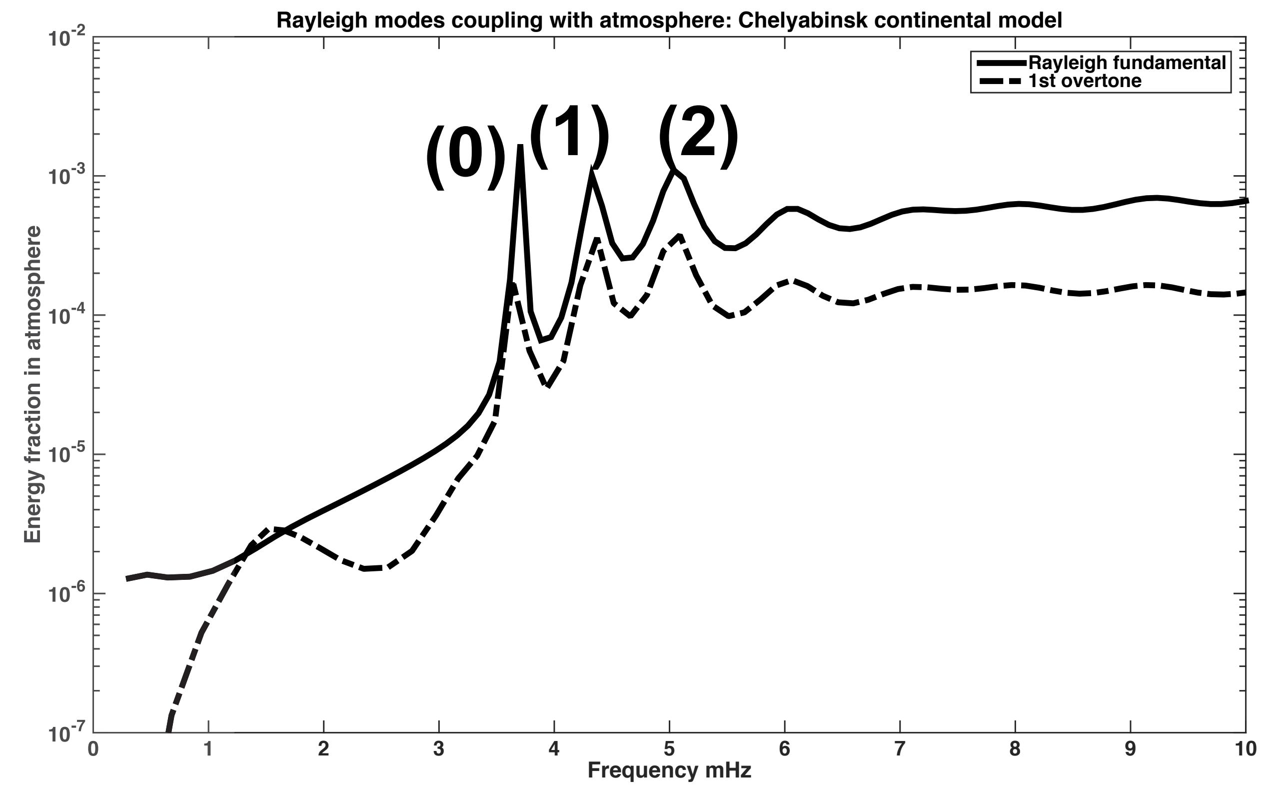
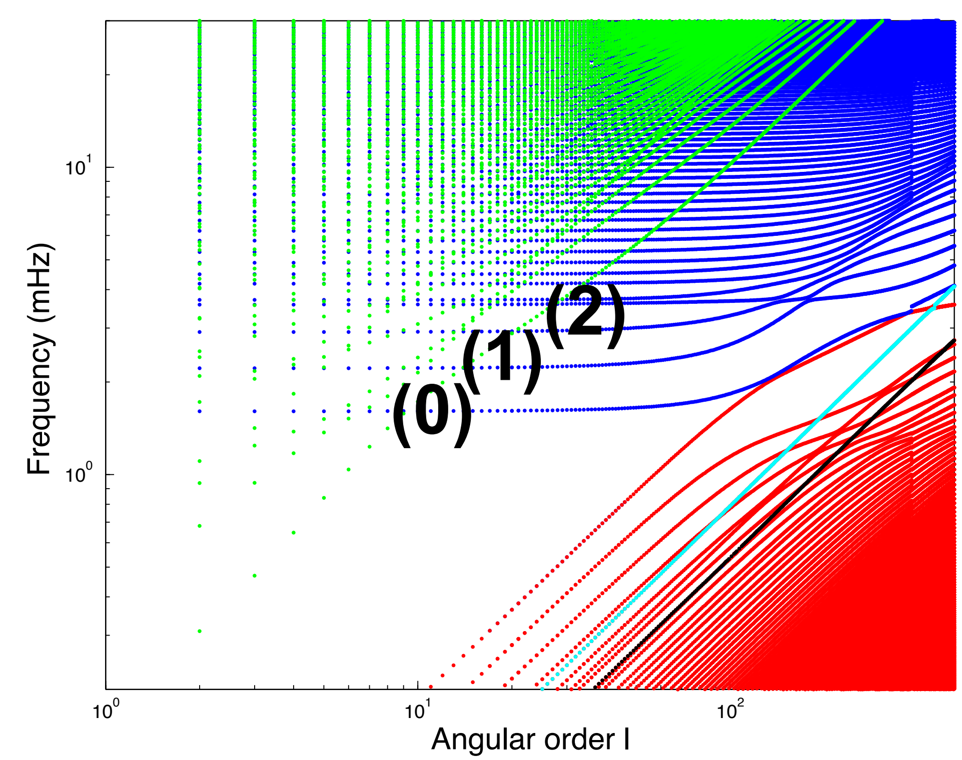
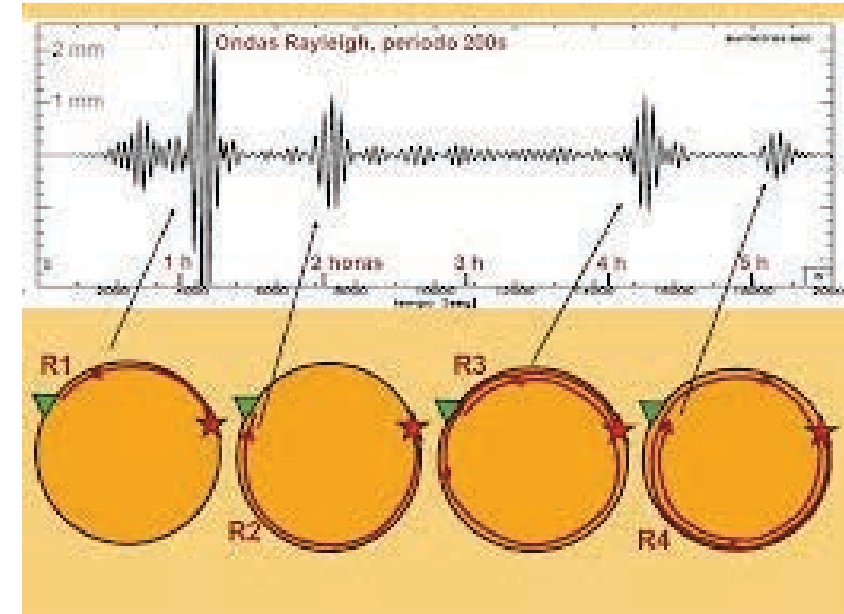
Rayleigh waves

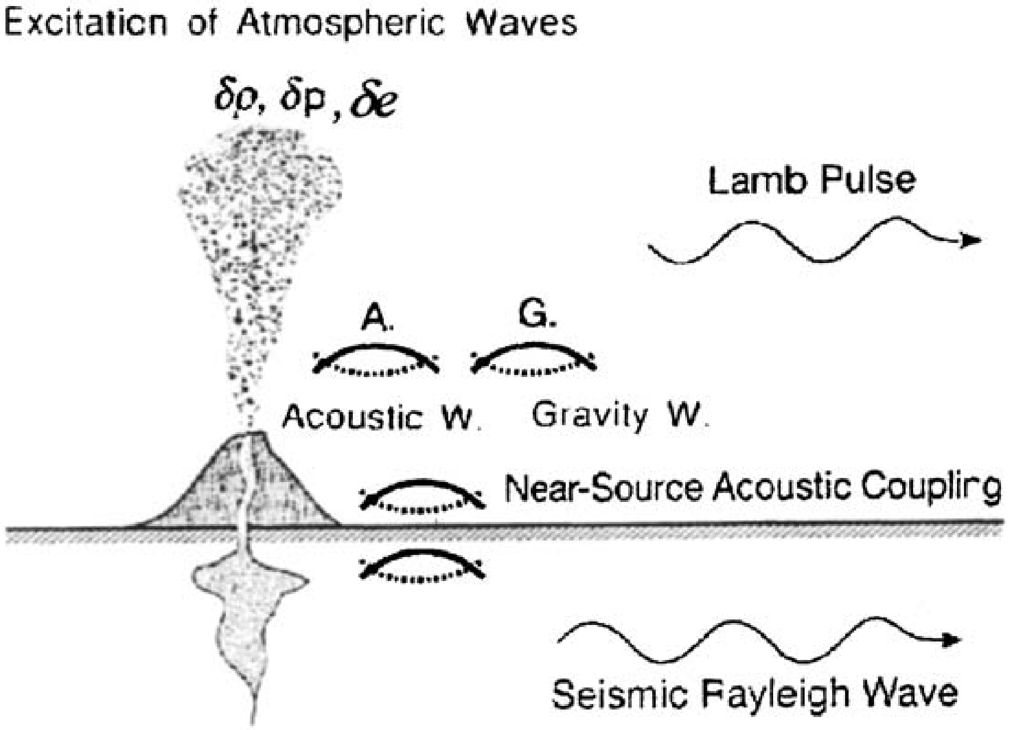


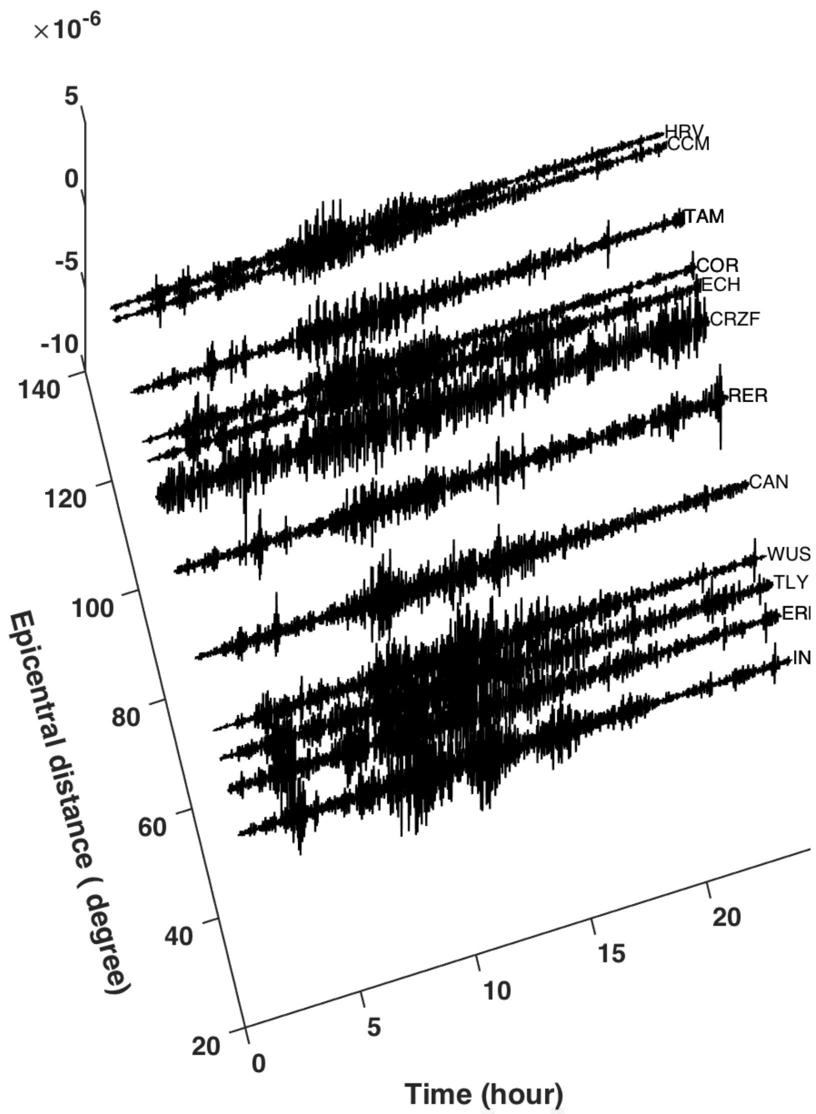


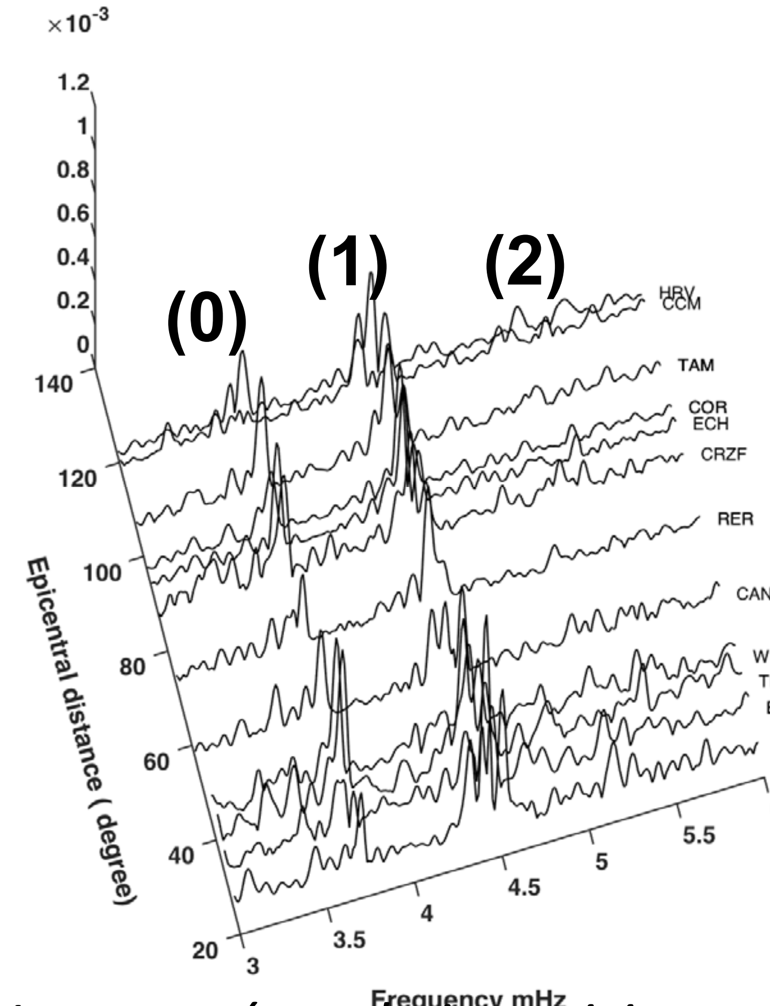


Rayleigh waves forced by the 1991 Pinatubo explosion





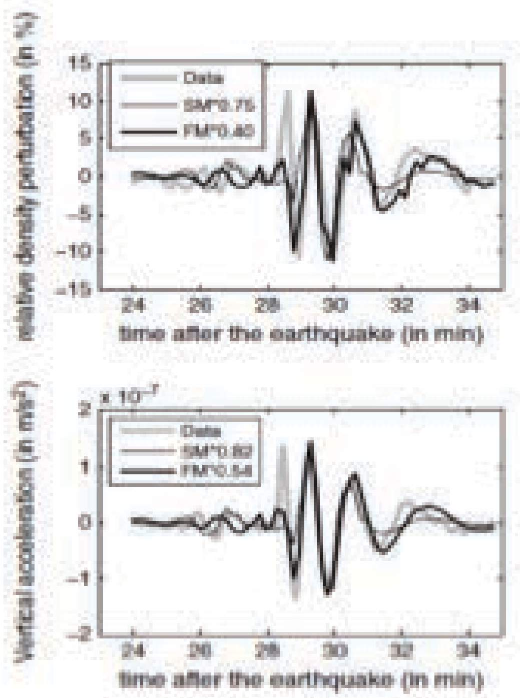


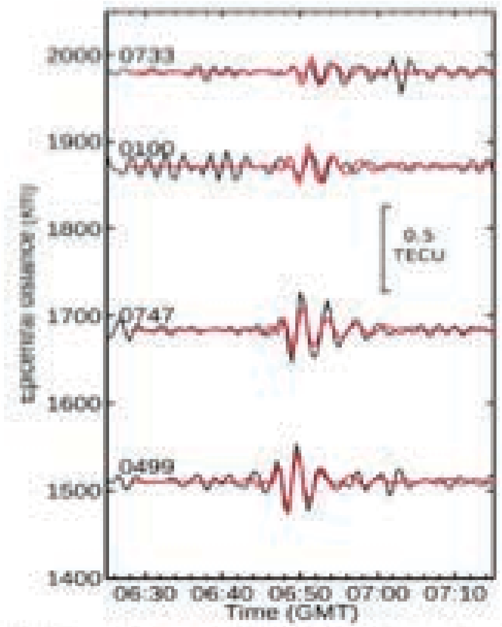


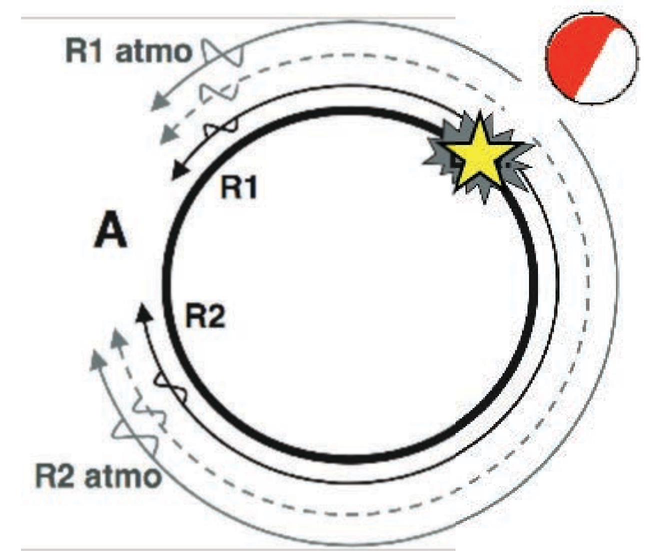
Lognonné et al., in revision

More Rayleigh waves in atmosphere

z=300 km from Total Electronic Content
(Wenchuan, 2008/5/12, M_w=7.9 , Rolland et al., 2011a)

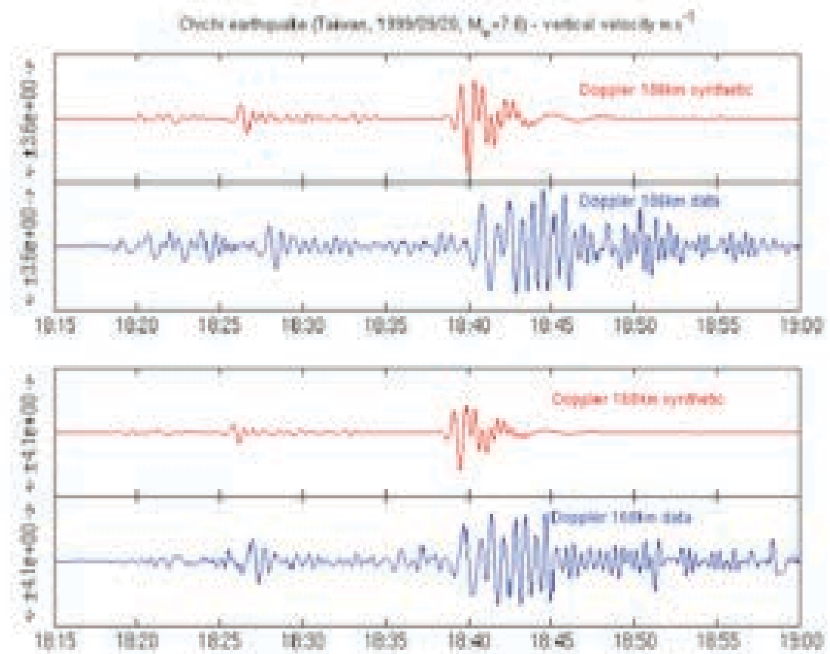


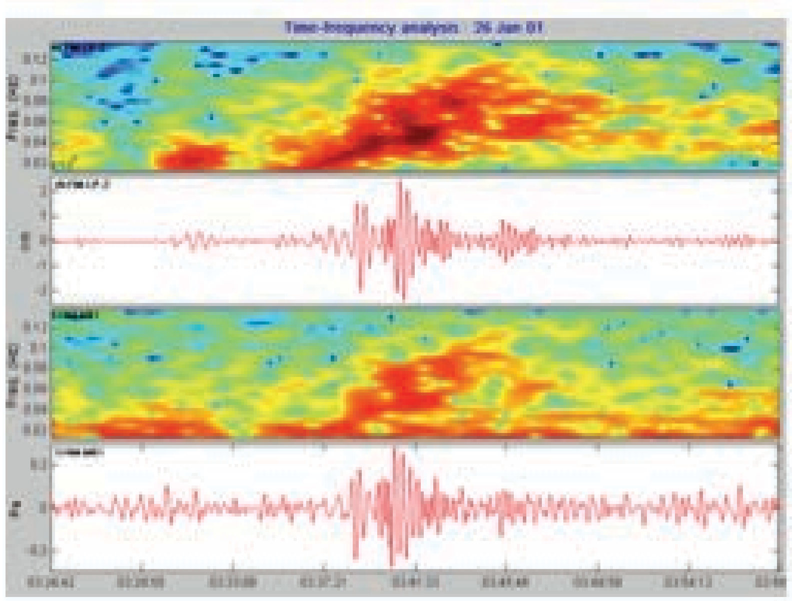




Sketch: Occhipinti et al. (2010)

z=270 km from GOCE density Drag
(Tohoku, M_w=9 , Garcia et al. [2013])



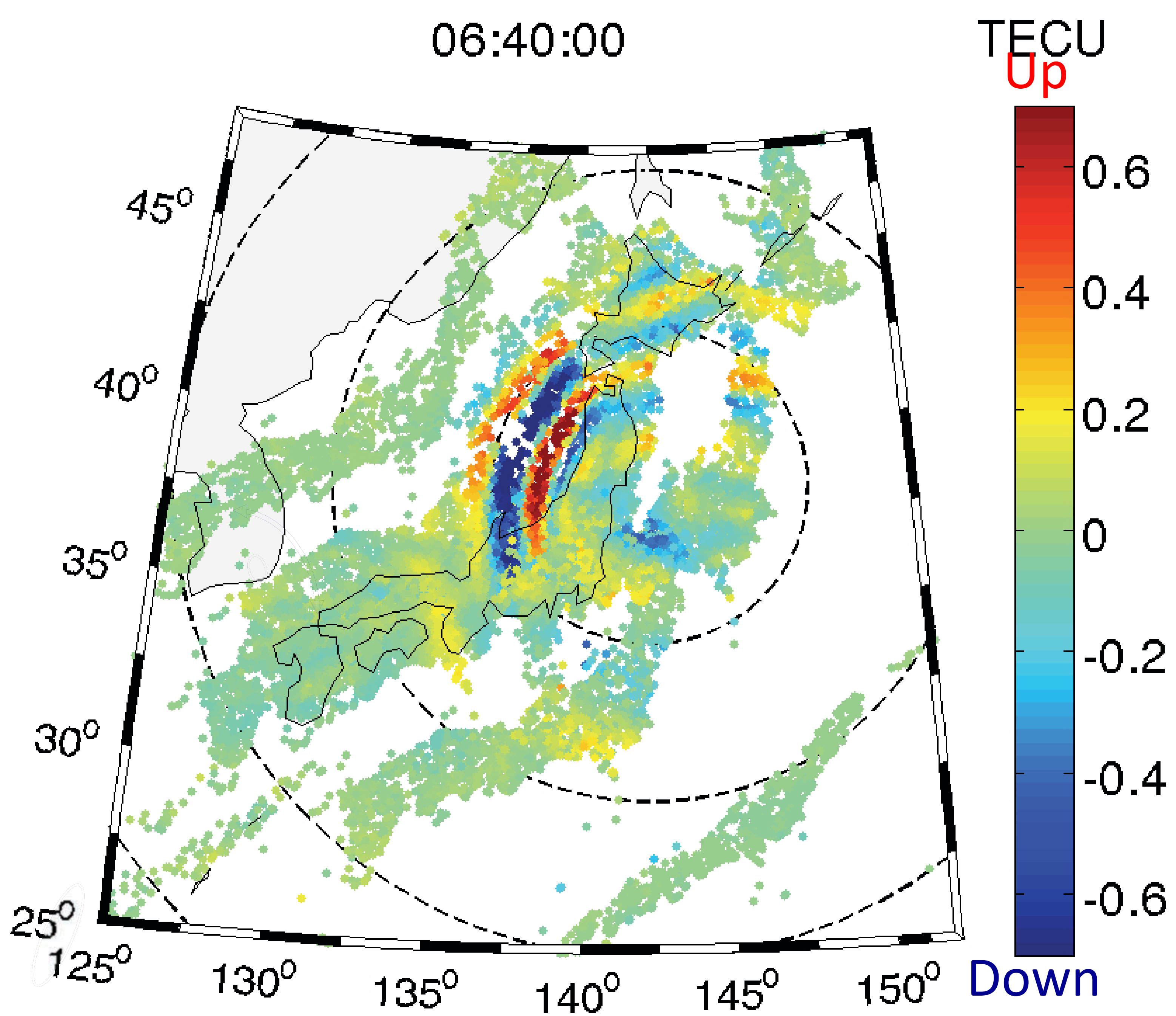


z=168-186 km from Doppler sounder
(Chichi, 1999/9/20, M_w=7.6 , Artru et al., 2004)

z=0 km from Pressure (bottom) and Seismometer (top)
(India, 2001/1/26, M_w=7.7 , Farges et al., 2001)

Normal modes excited by a very large earthquake - Observations

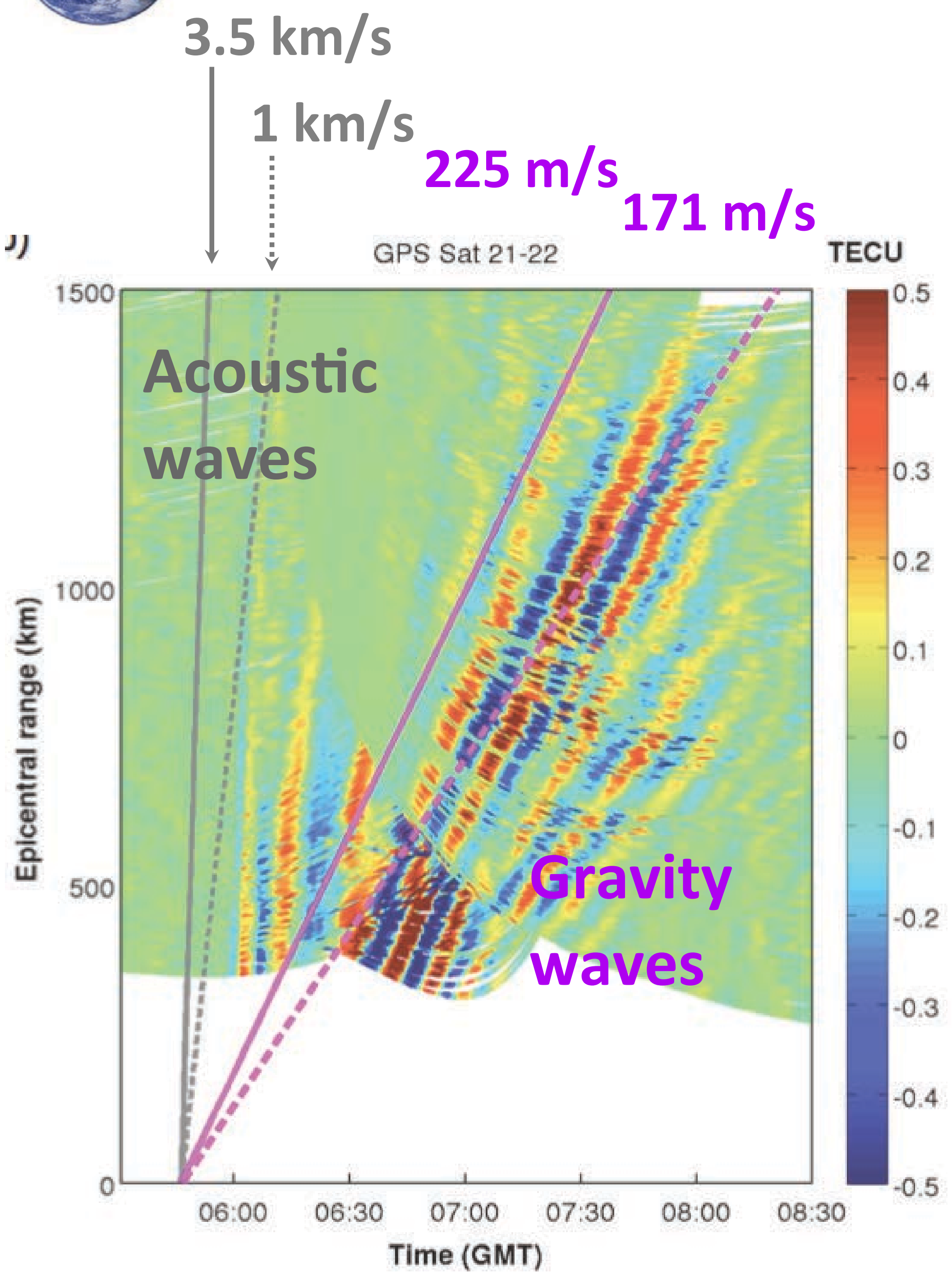
(Tohoku 2011, Mw=9.2)

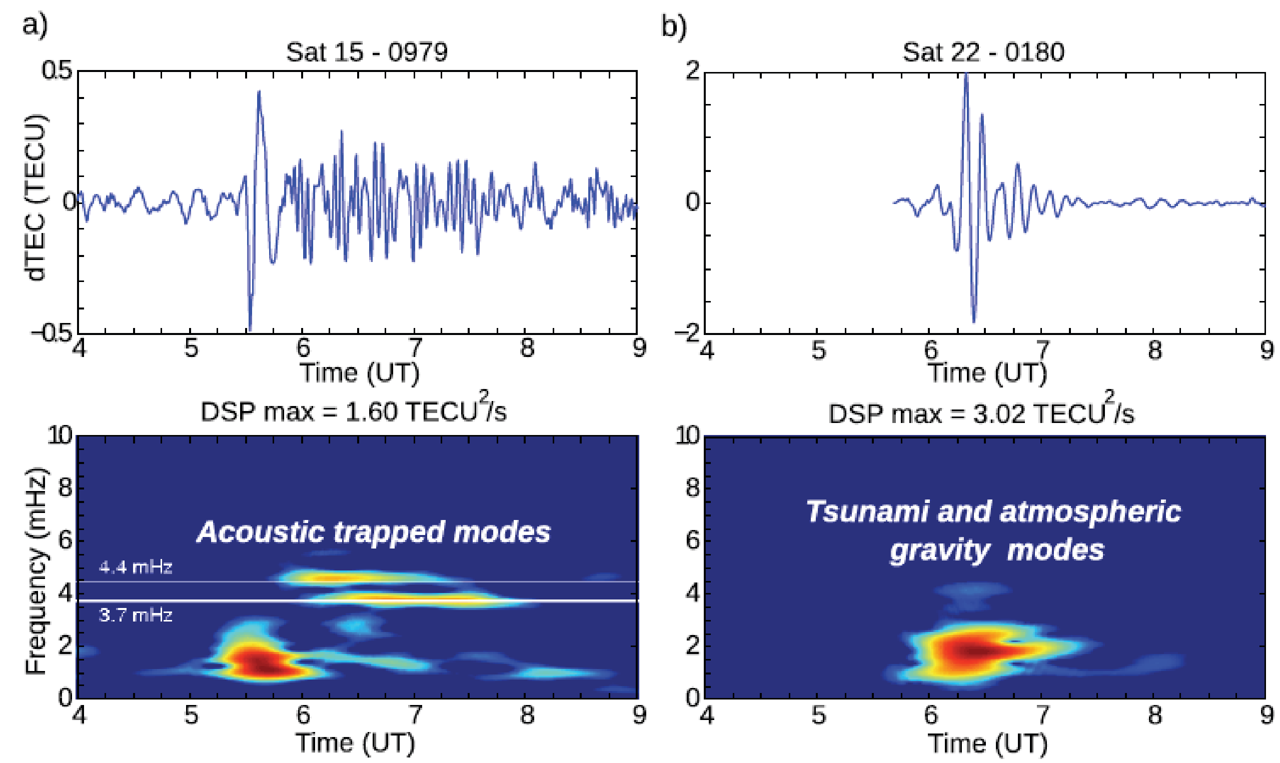


TEC data filtered from 1 to 10 mHz

Rolland et al. (2011)

Multi-mode signal – classification of TIDs

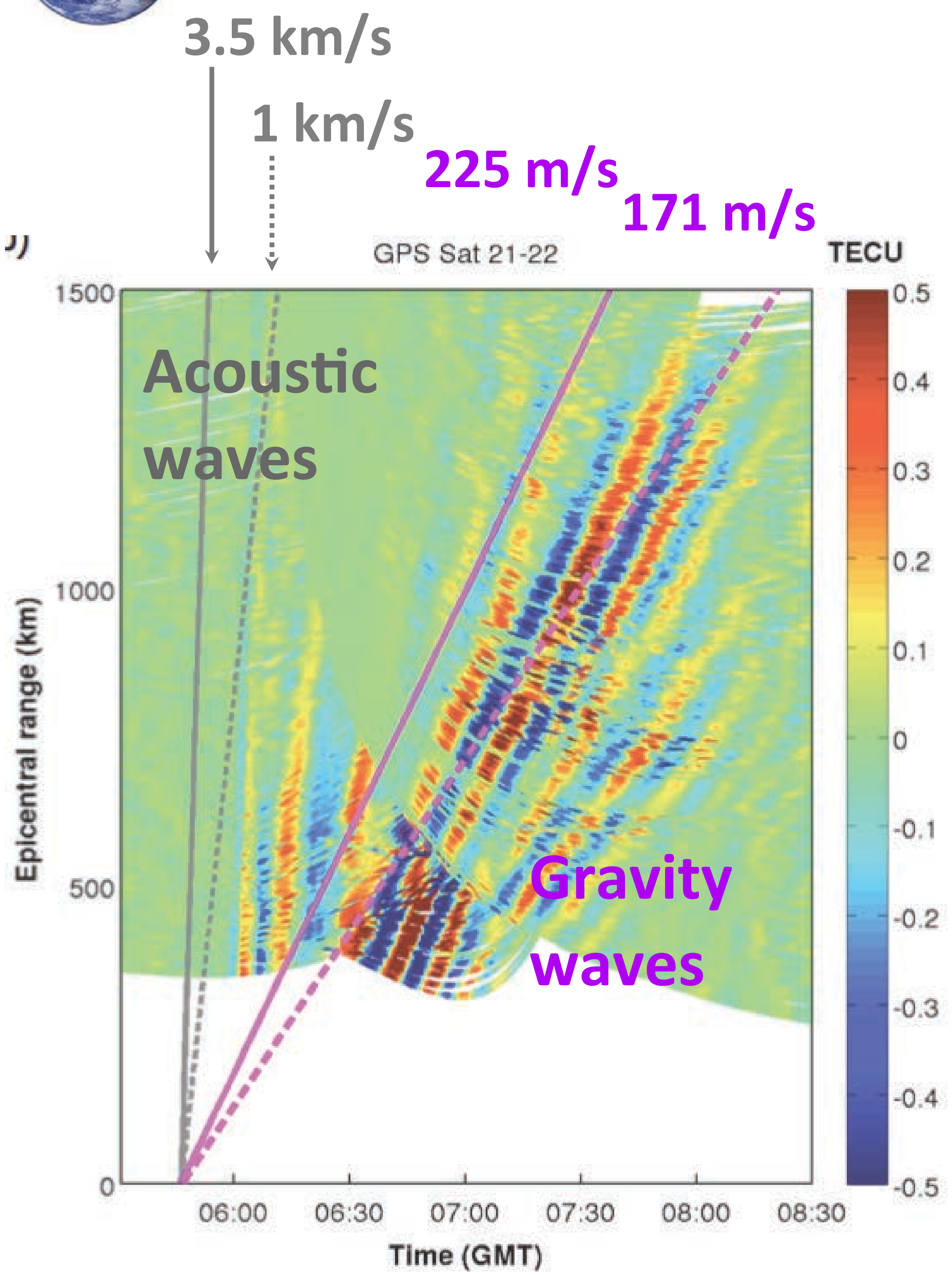


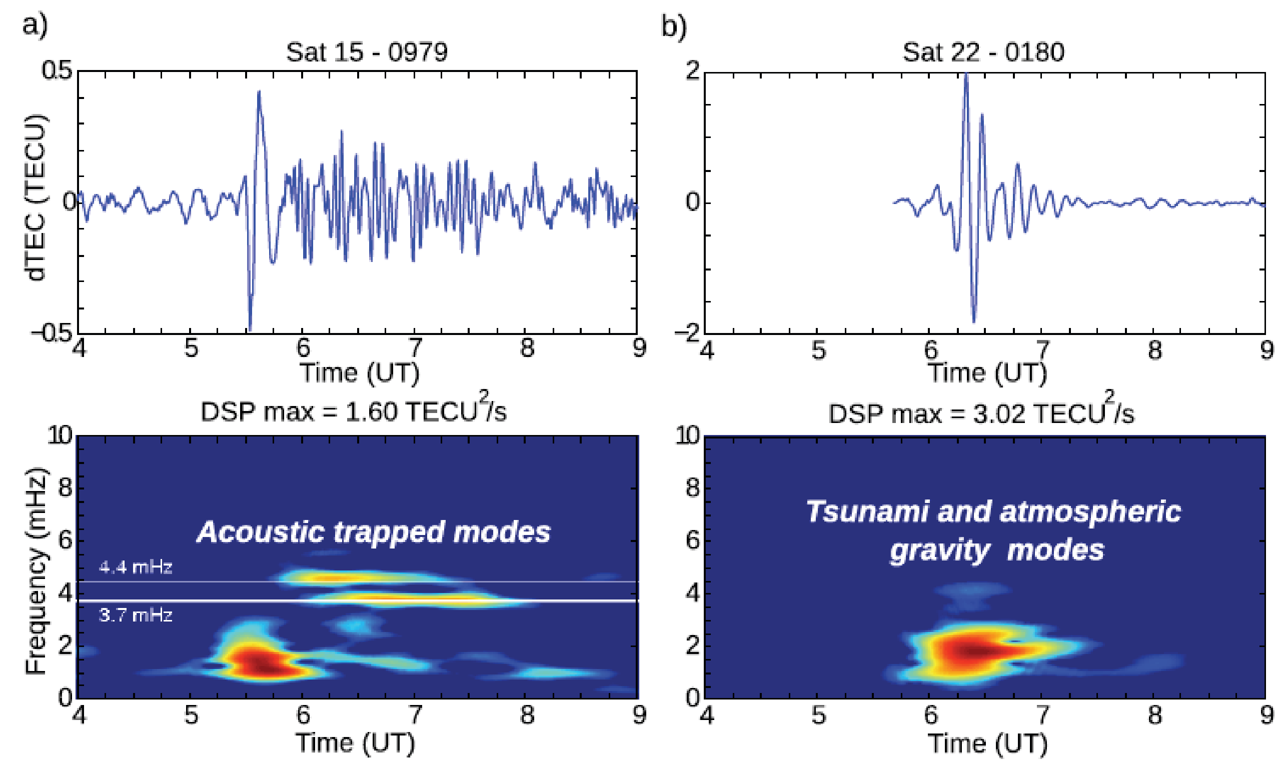


Rolland et al., 2011b

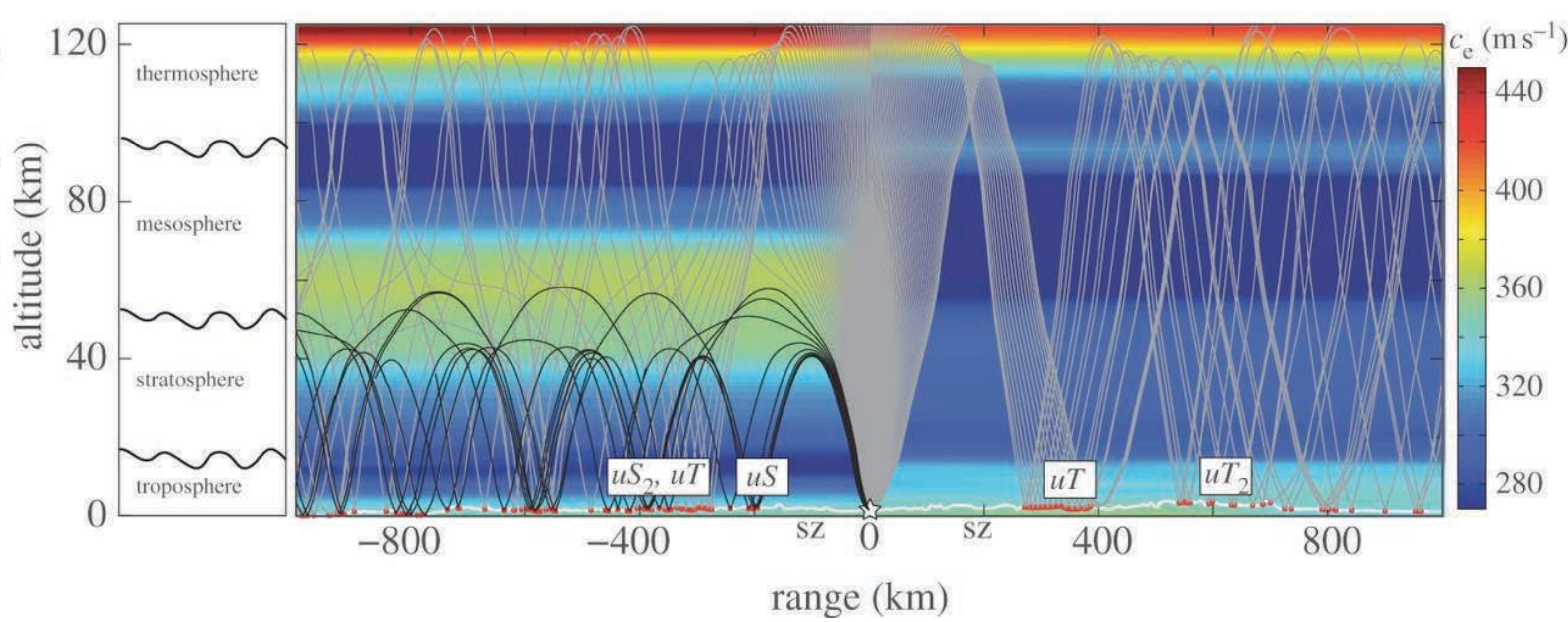
Forcing source	v_h $(km.s^{-1})$	v_z $(km.s^{-1})$	Δf (mHz)	λ (km)	A $(TECU)$	τ (min)
Rayleigh waves	4 ± 1	1 ± 0.3	4.3 - 10	$\sim 5.10^2$	2.10^{-2} - 1	10-30
Seismic rupture	1 ± 0.3	1 ± 0.3	1 - 10	$\sim 10^2$	2.10^{-2} - 1.5	10-30
Tsunami	0.2 ± 0.05	~ 0.05	0.5 - 3	$\sim 10^2$	~ 3	10-60

Multi-mode signal – classification of TIDs



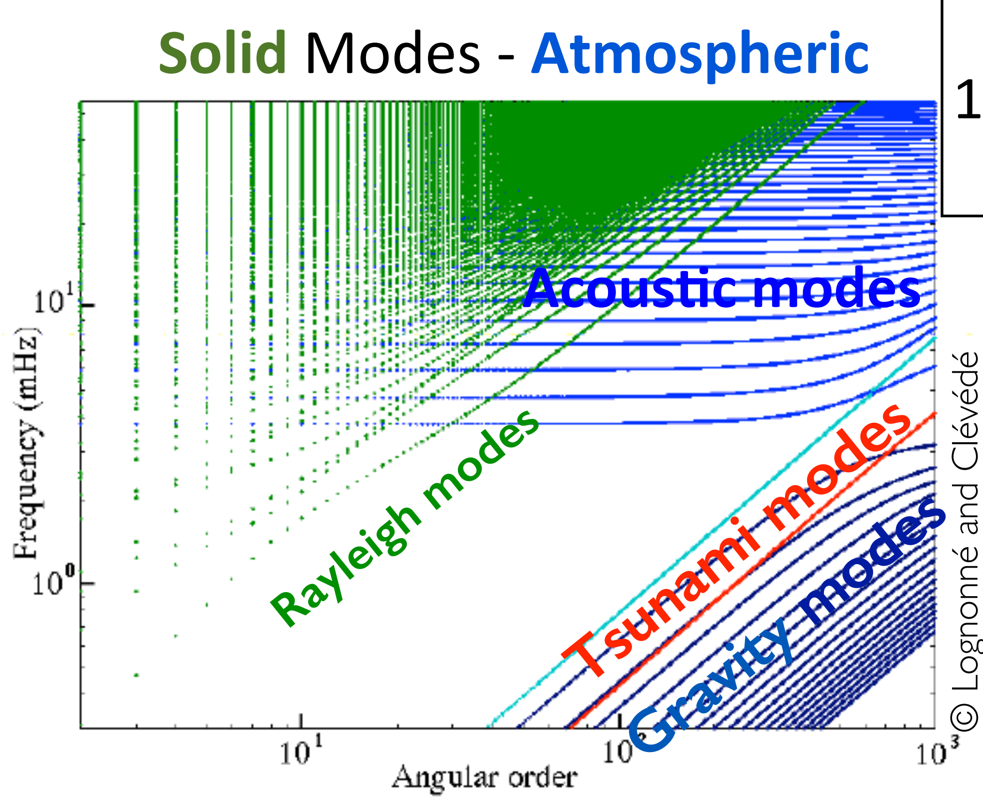


Rolland et al., 2011b

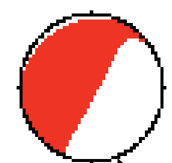


Hedlin & Walker (2012)

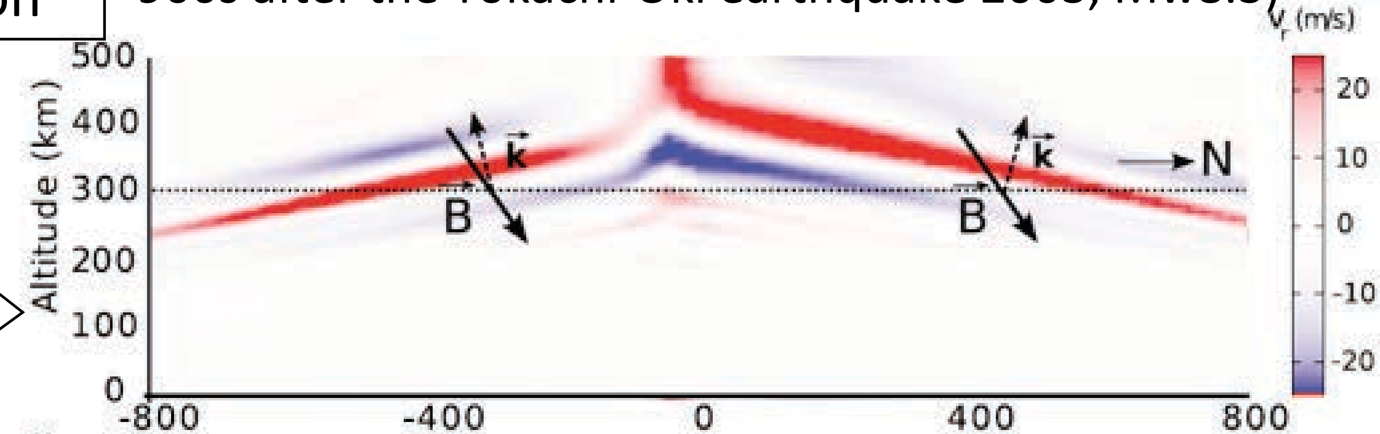
A full model for GPS derived ionospheric perturbation induced by an earthquake: Rayleigh waves forcing



Rayleigh
1D Solid Modes
summation

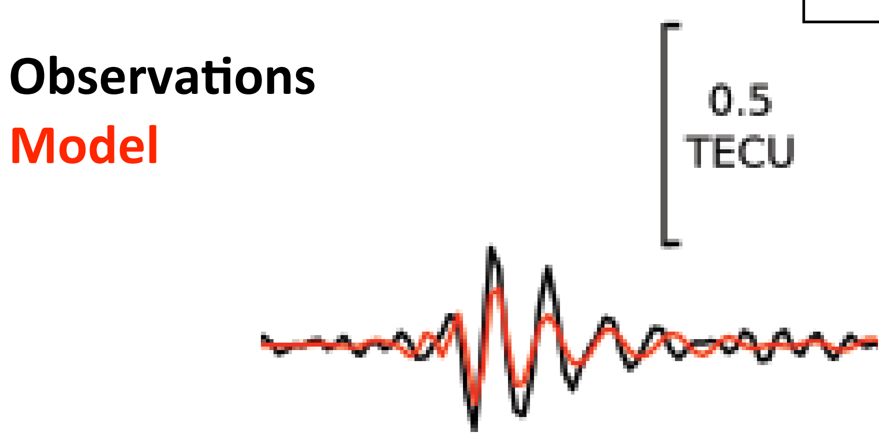


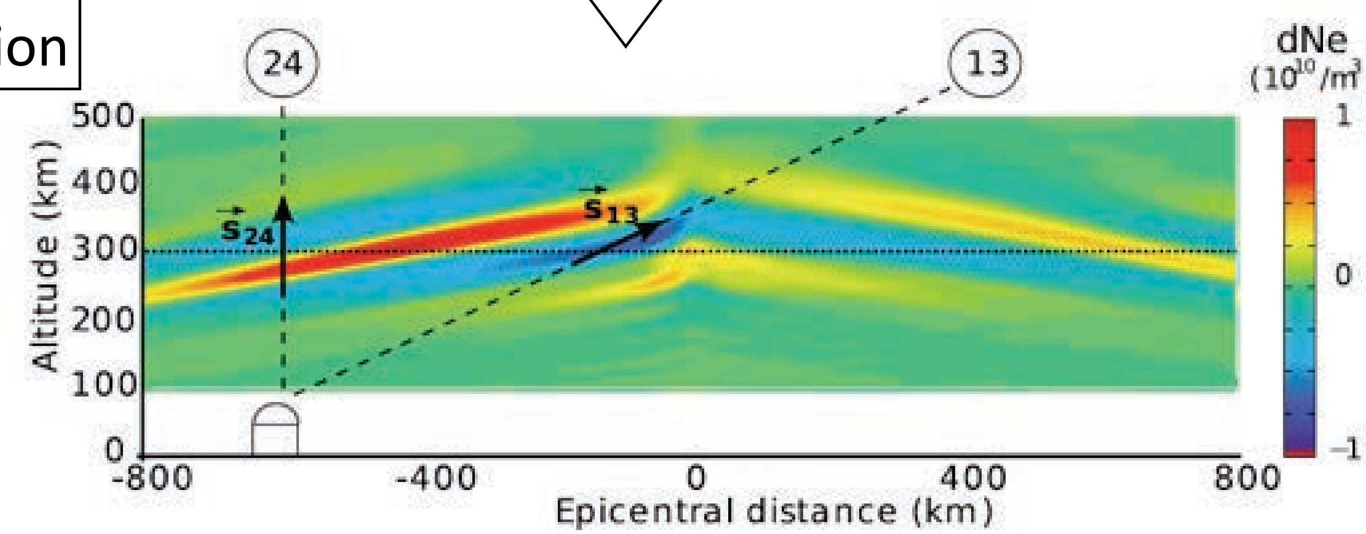
3D model of neutral velocity (vr)
900s after the Tokachi-Oki earthquake 2003, Mw8.3)



MHD coupling

Integration
GPS satellite-station

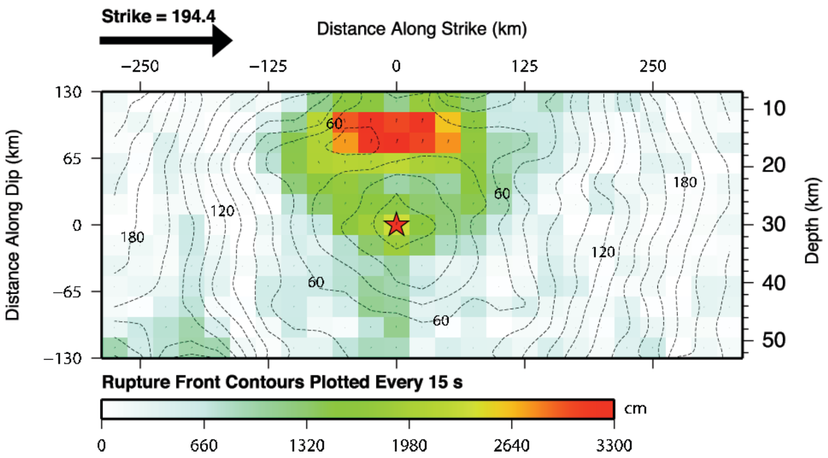


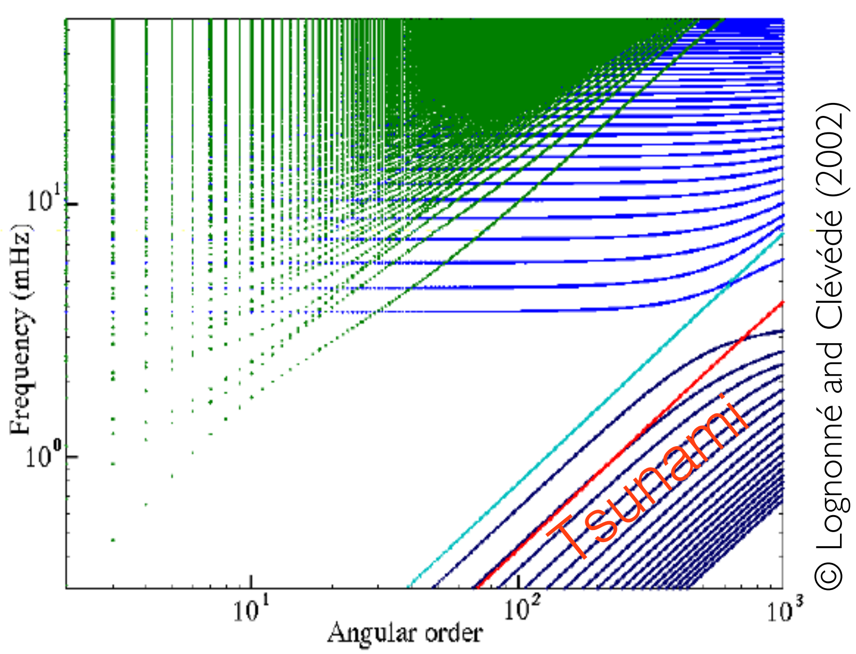


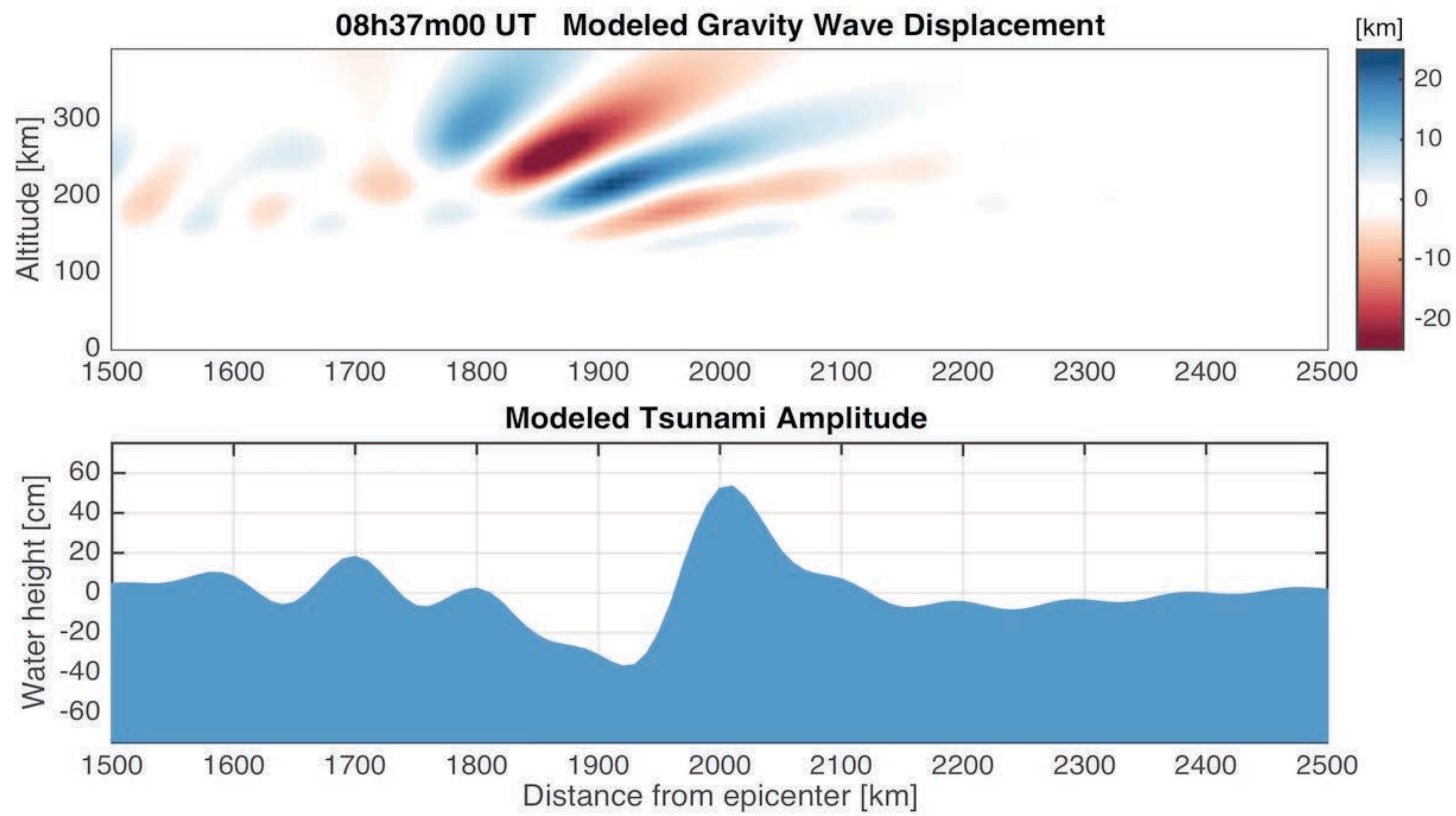
Rolland et al., 2011a

3D model of perturbed ionospheric density (dNe)

Tsunami-induced atmospheric waves modeling



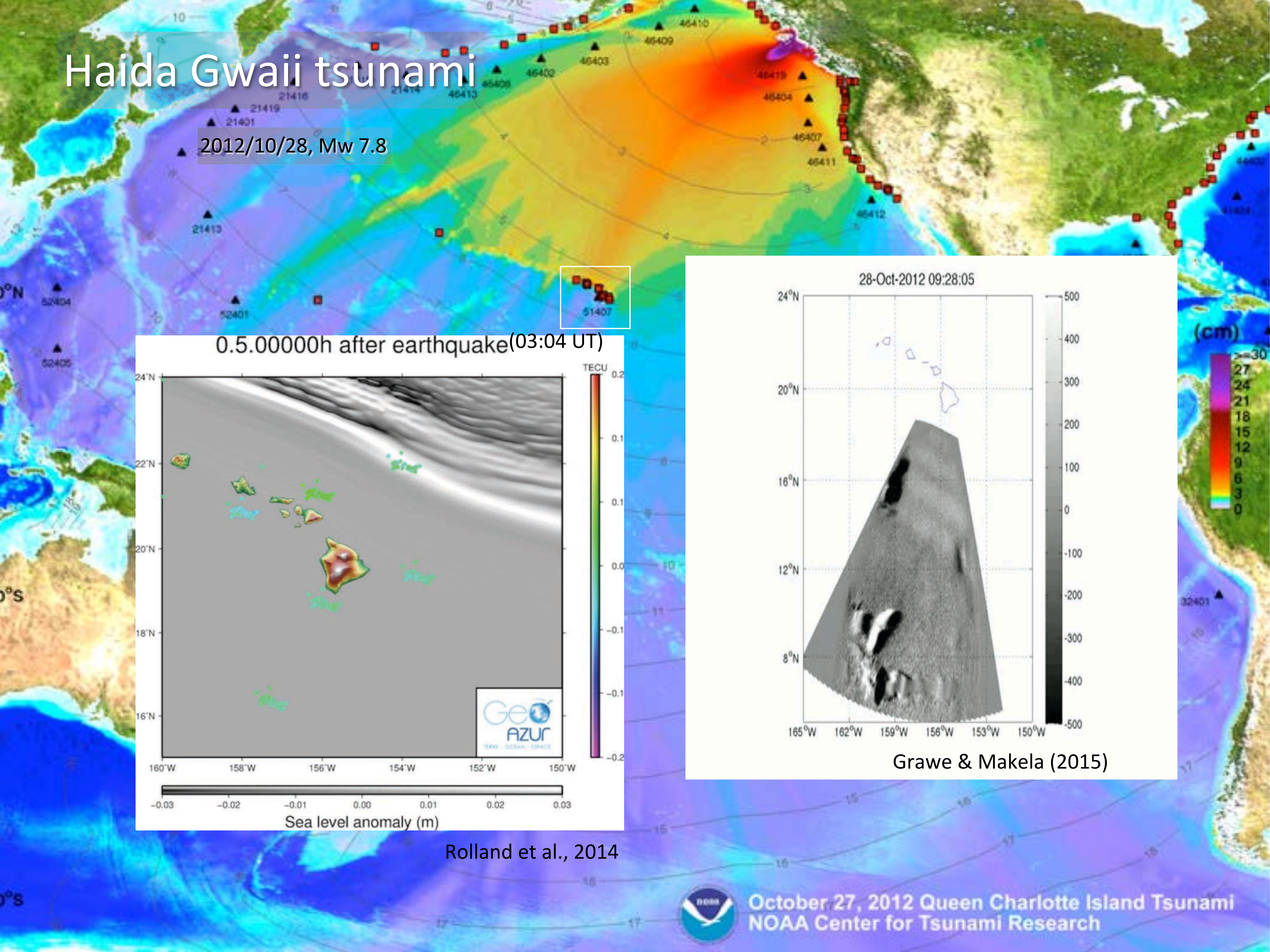




Coïsson et al. (2015)

Haida Gwaii tsunami

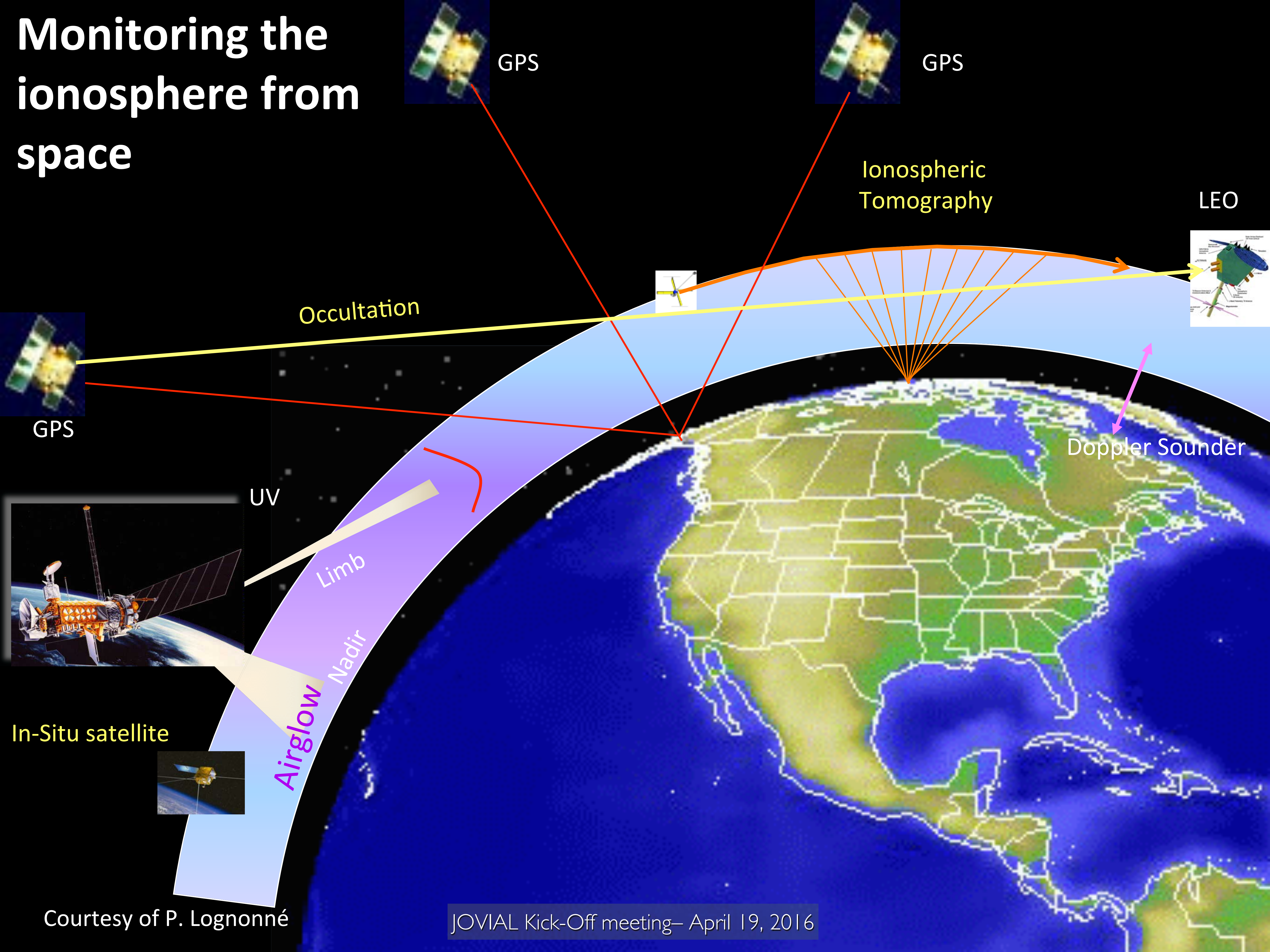
2012/10/28, Mw 7.8



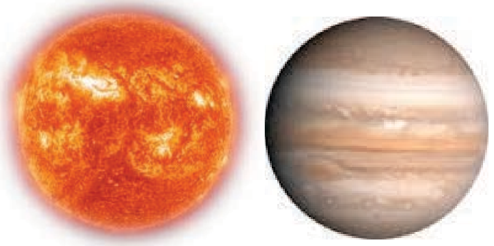
Rolland et al., 2014

Grawe & Makela (2015)

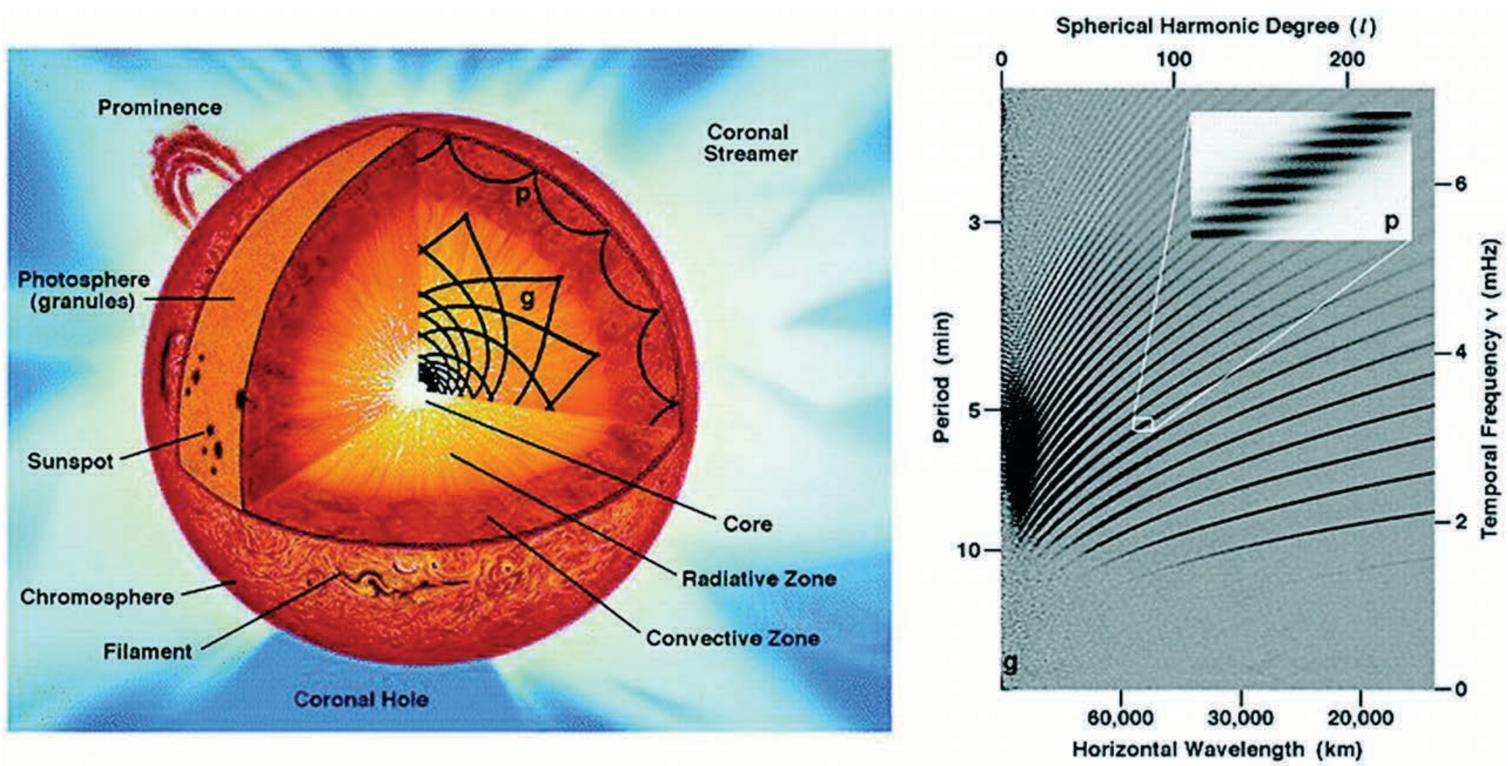
Monitoring the ionosphere from space



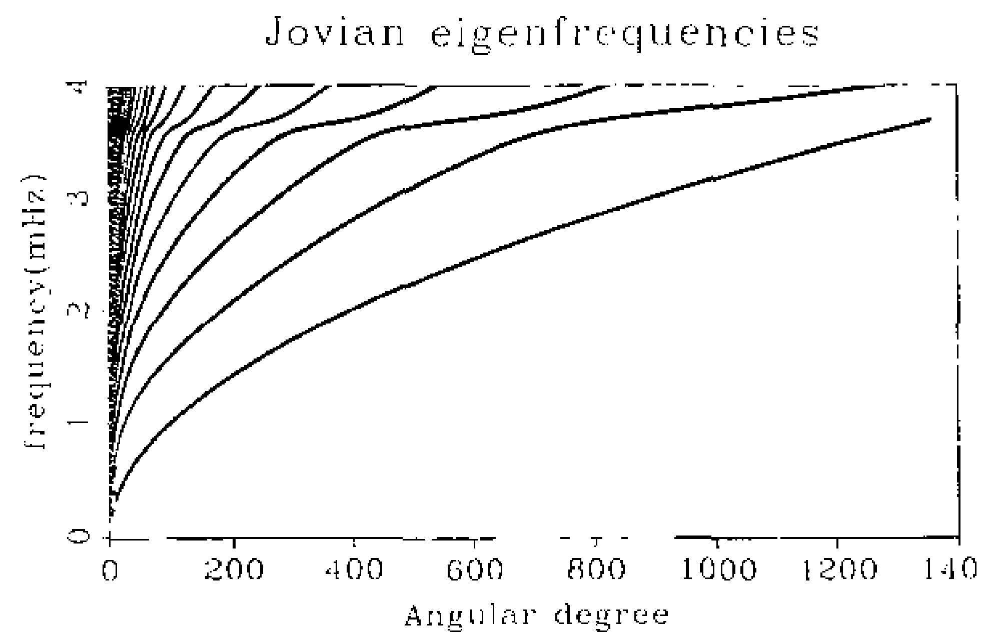
Courtesy of P. Lognonné

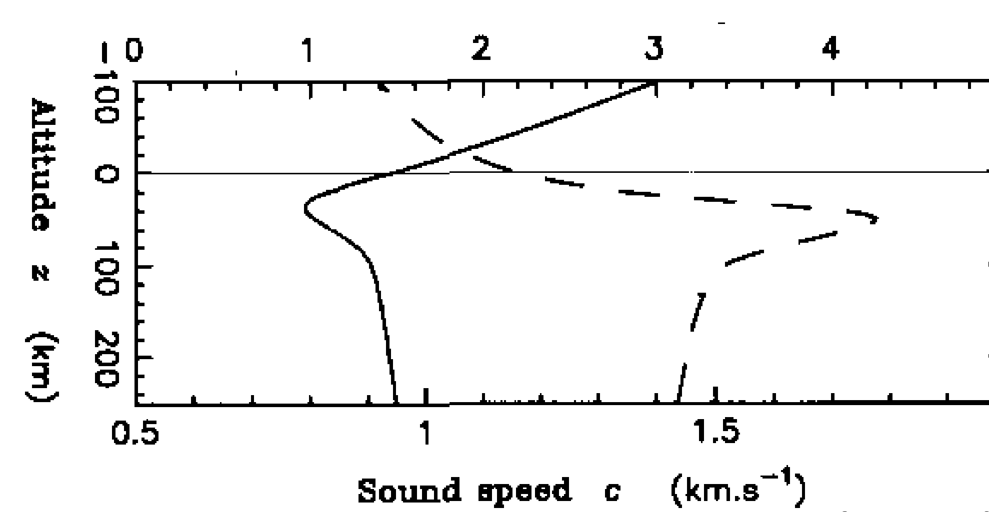


Solar and Jovian Seismology



Source: W. Leibacher

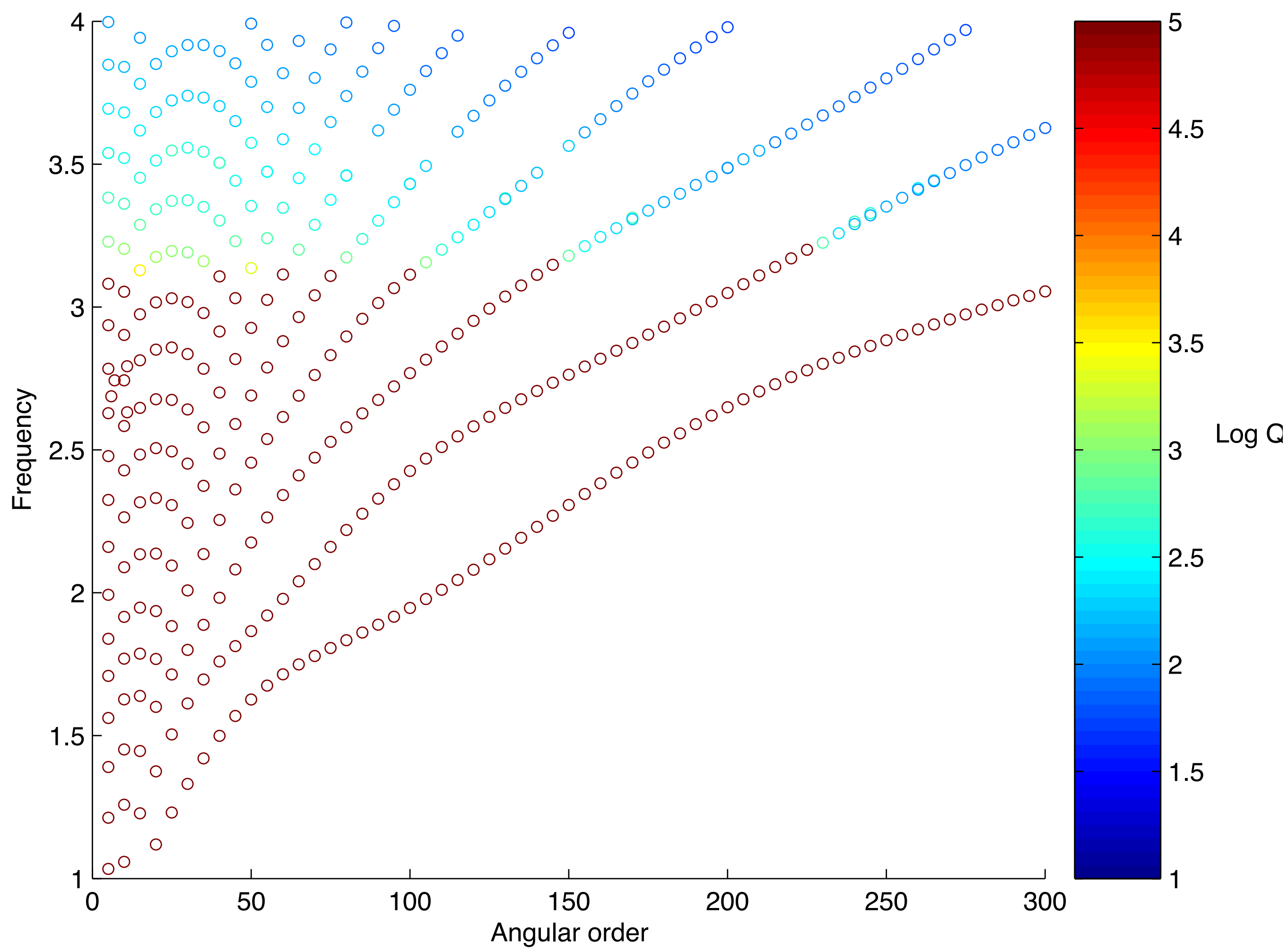




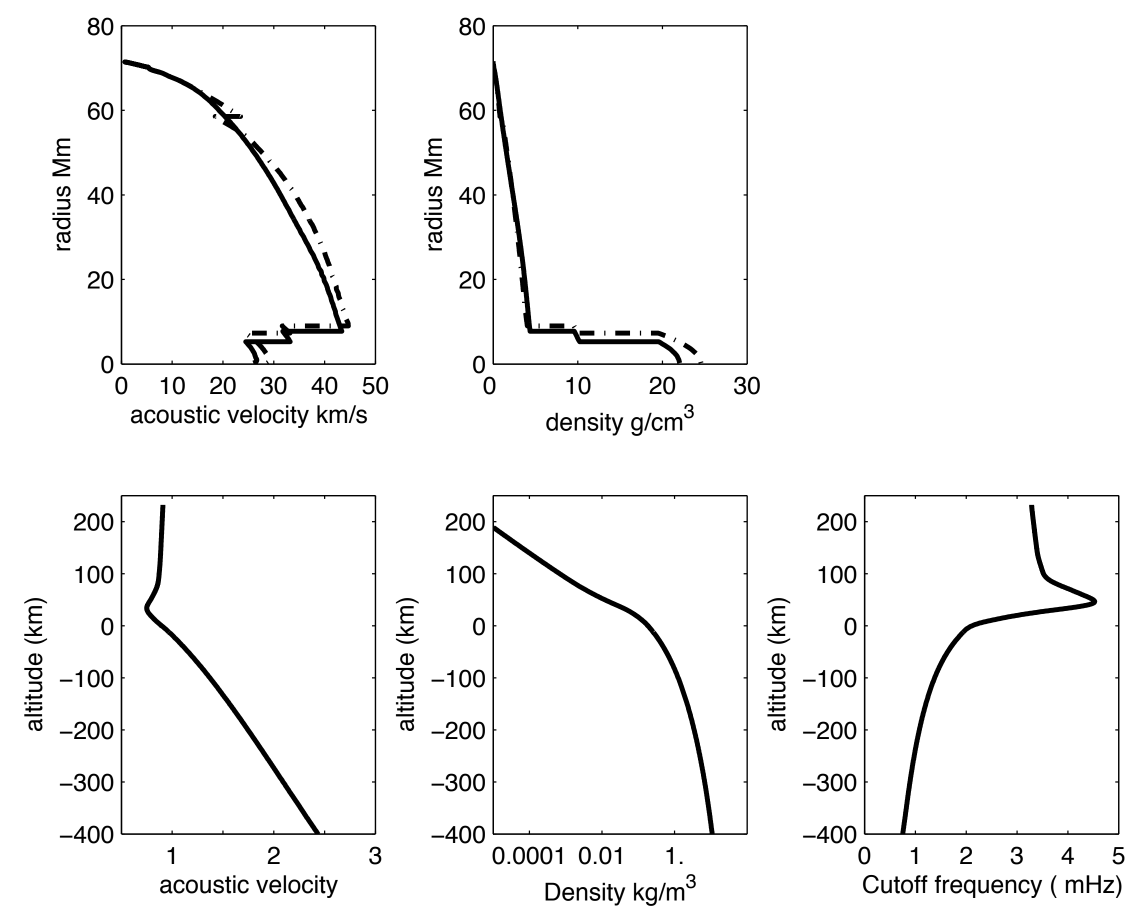
Lognonné et al. (1994)

Using Earth Normal mode software for Jupiter

- Earth normal modes software can be used to compute both acoustic and gravity Jovian Normal modes, including those weakly or not trapped by the troposphere
- See *Lognonné & Johnson, 2013* for example



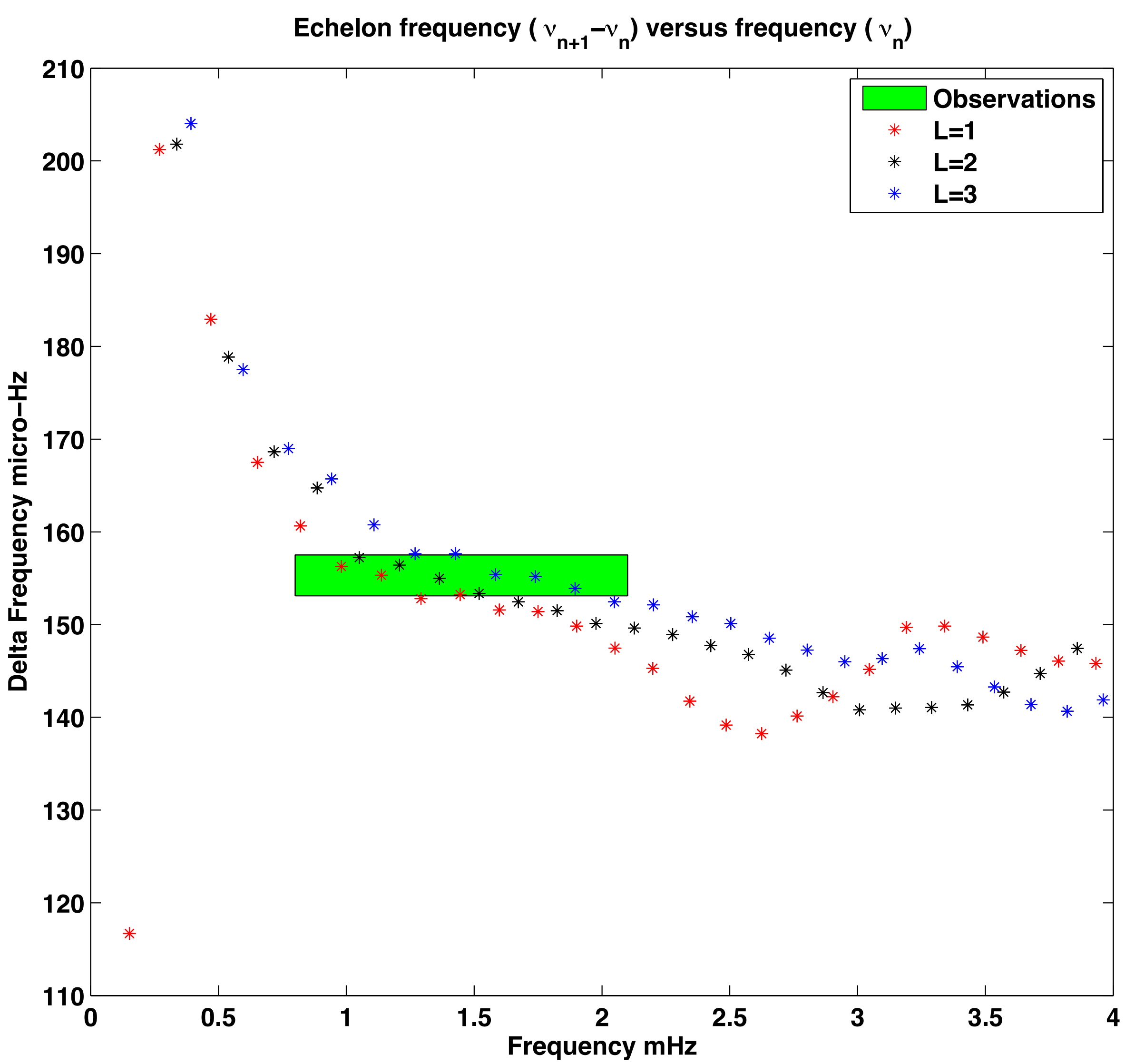
Lognonné & Johnson (2015)

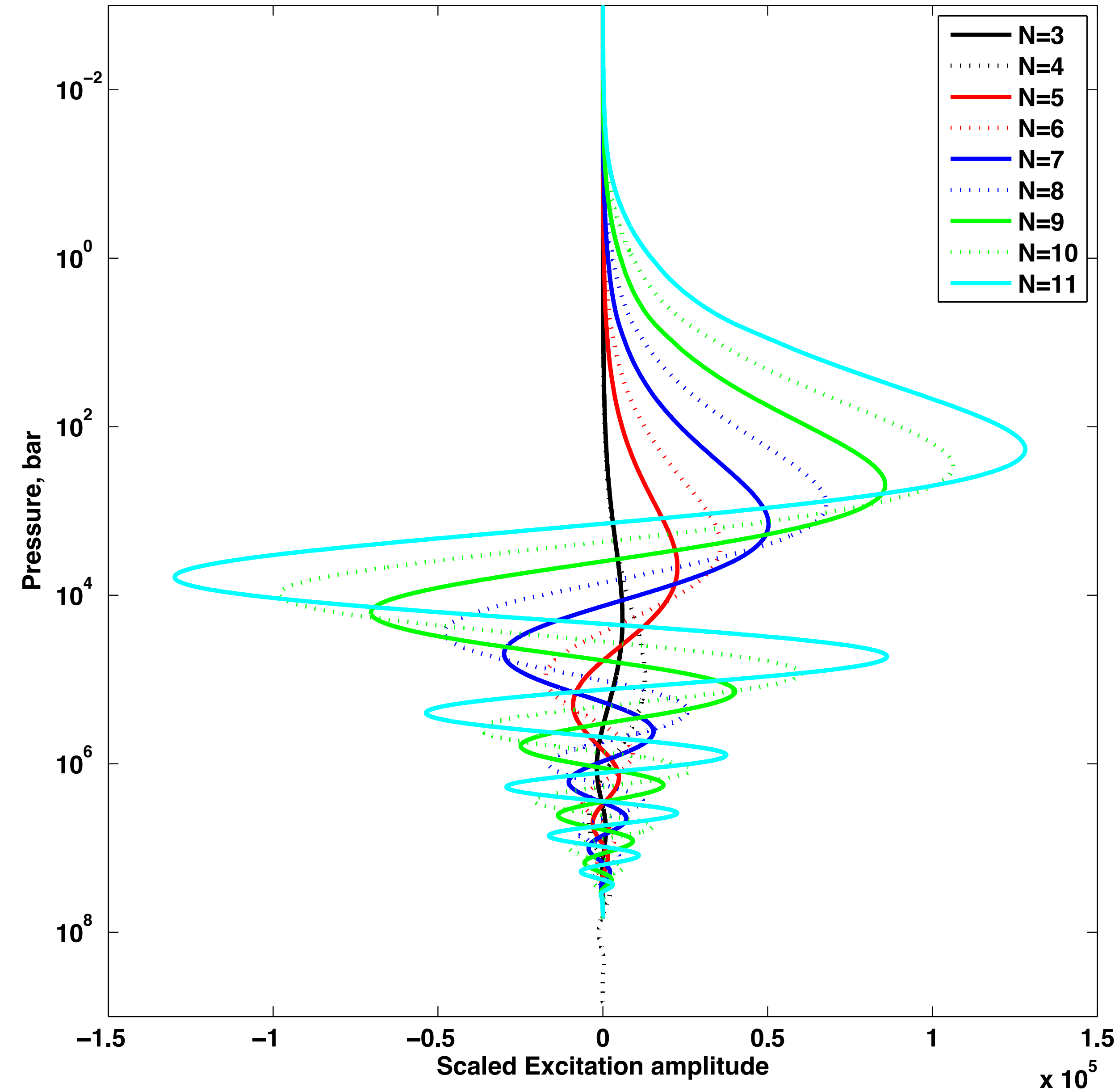


Seismic properties of Jupiter for different models (*Mosser 1996*)

Possible constraints on the excitation depth

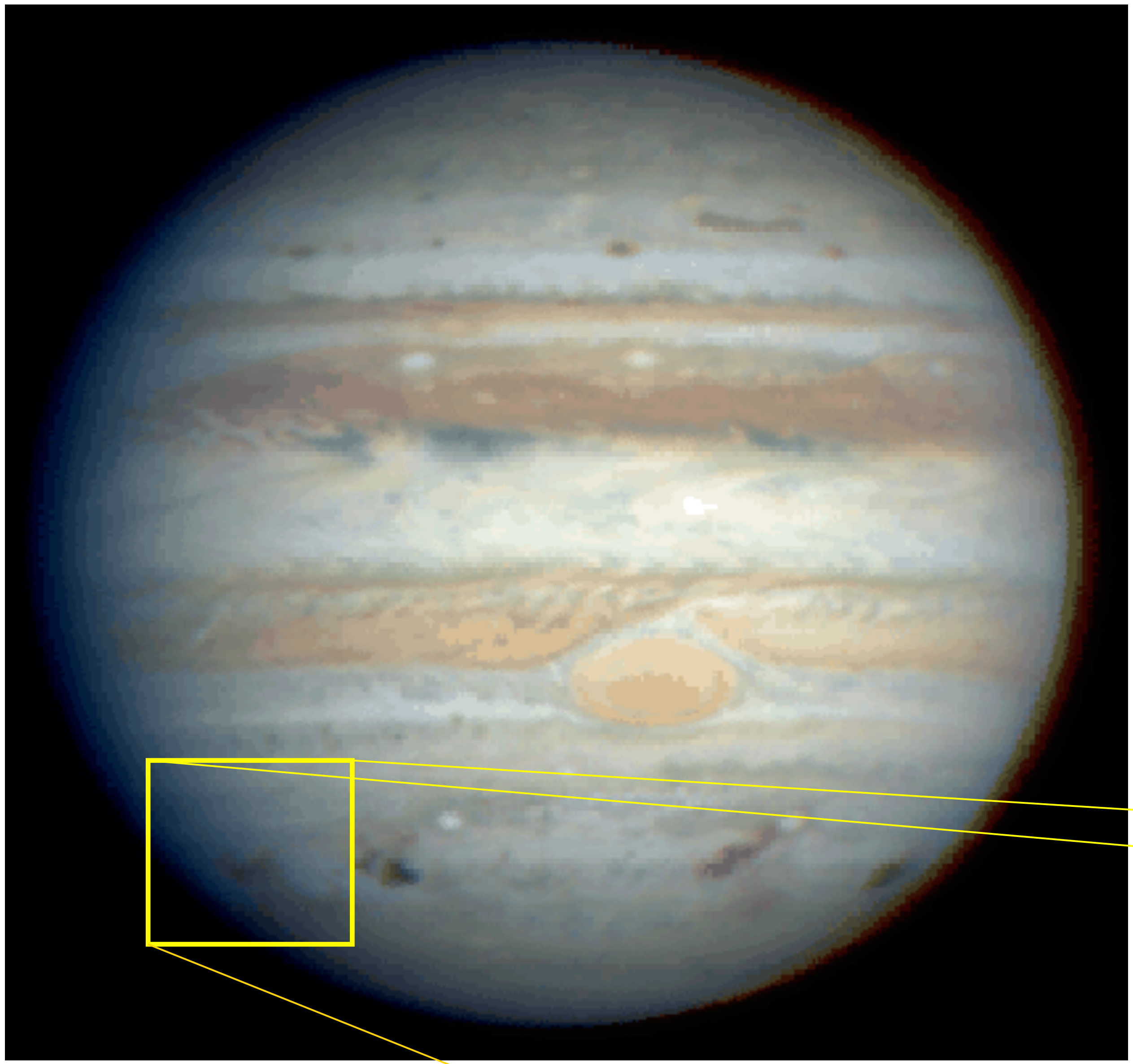
- From the Echelon frequency proposed by *Gaulme et al., 2011*, we can then suggest than the excitation is preferentially those of harmonics n=6-8, so likely at depth of 100 bars





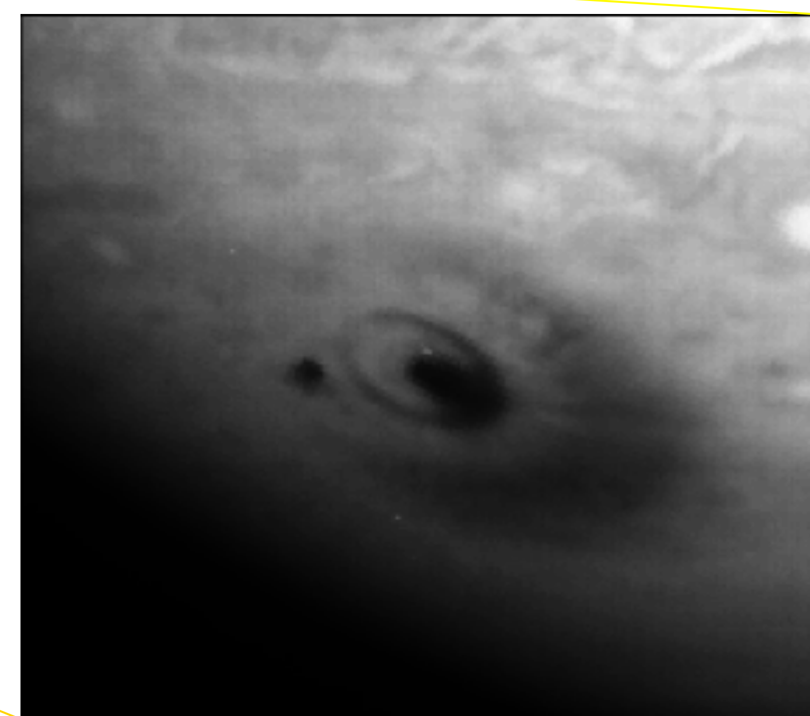
Lognonné & Johnson (2015)

Shomaker-Levy 9 impact



- NASA HST, WFC in optical mode
- July 22, 1994 Shoemaker-Levy 9 impact
- Quake equivalent magnitude M=9
- Vertical displacement 100m but with clouds-albedo modification
- No seismic waves observed on ground and space observations
- Gravity waves observed

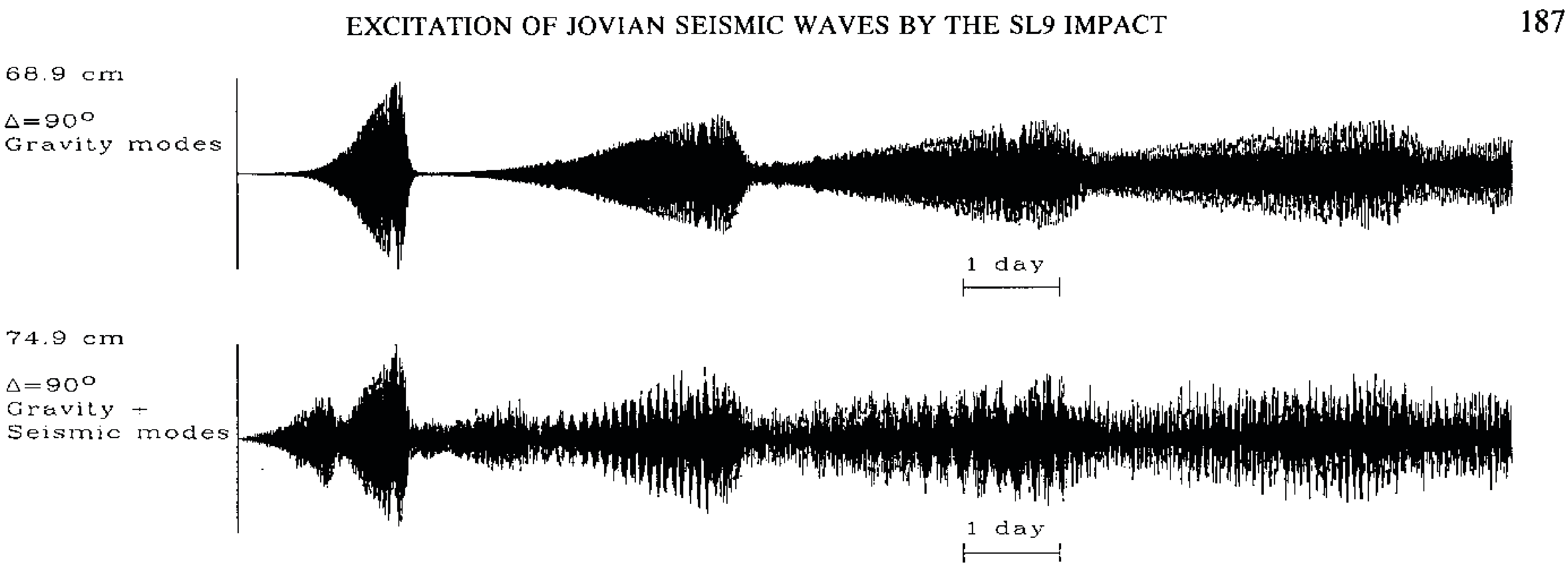
130,000 km



H. Hammel et al, MIT

Normal modes (modeling) ...

- Both gravity modes and acoustic modes



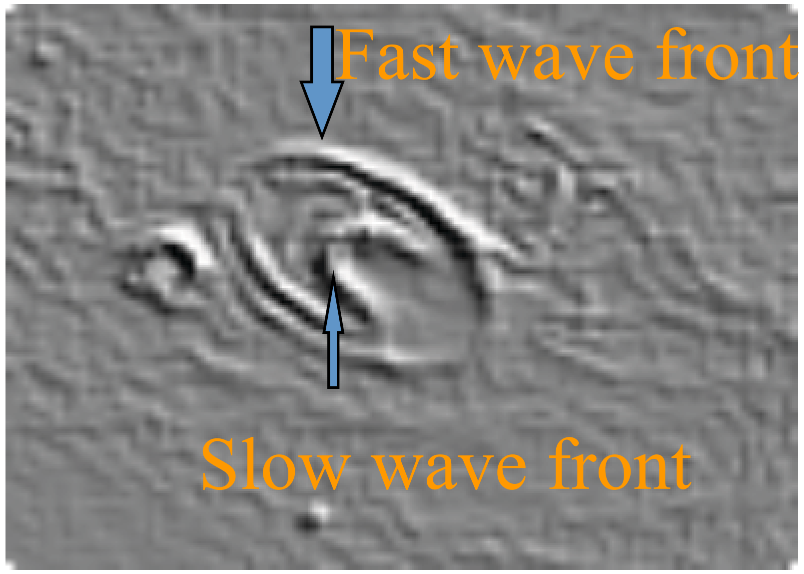
Lognonné et al. (1994)

Gravity waves sensing on Jupiter

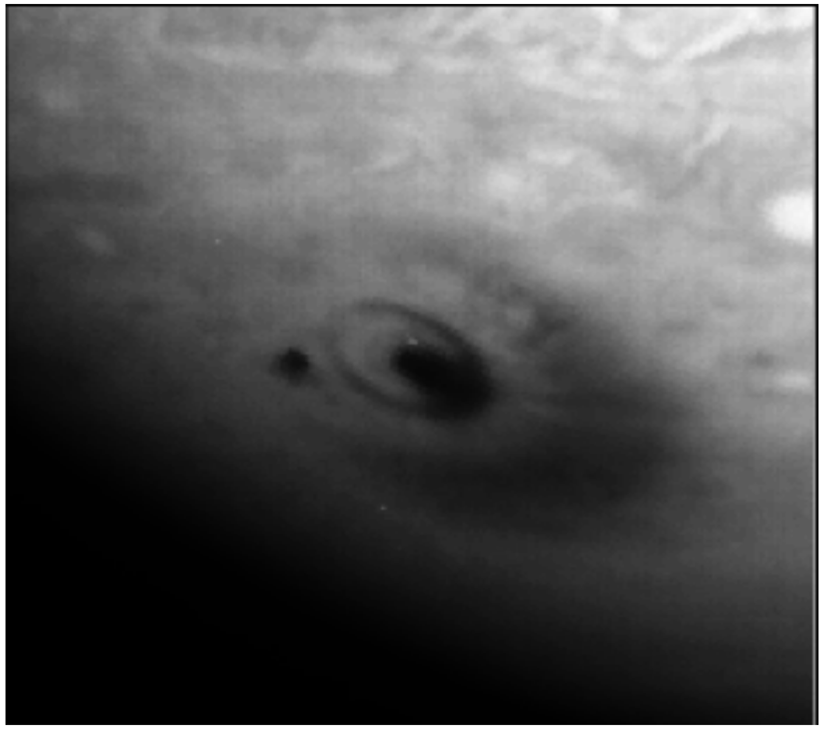
Impact of the Shoemaker Levy-9:

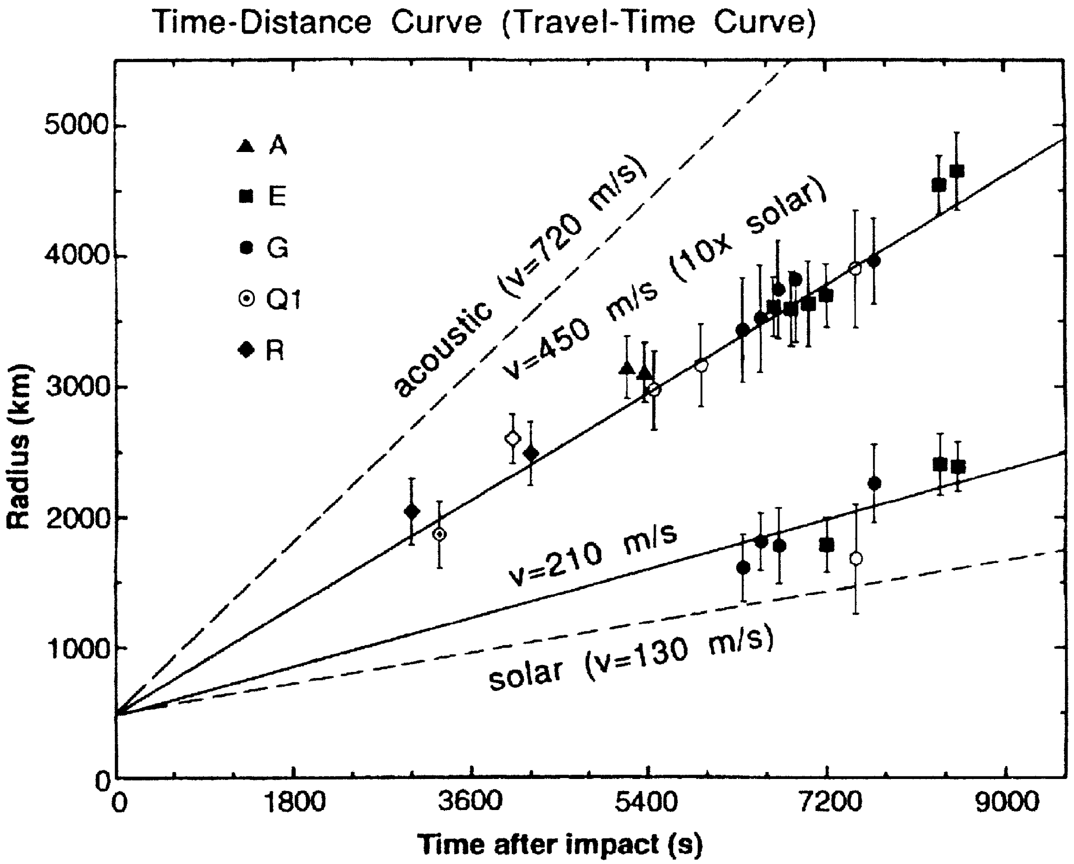
Gravity waves detected by HST

Gravity waves



Hammel et al., 1995



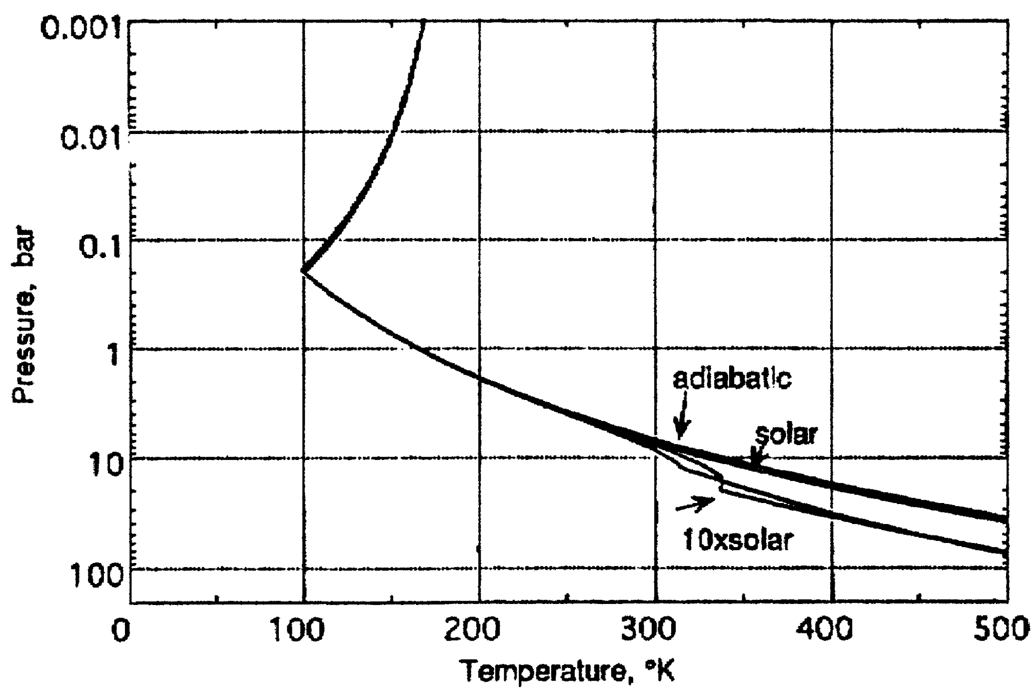


Kanamori (2004)

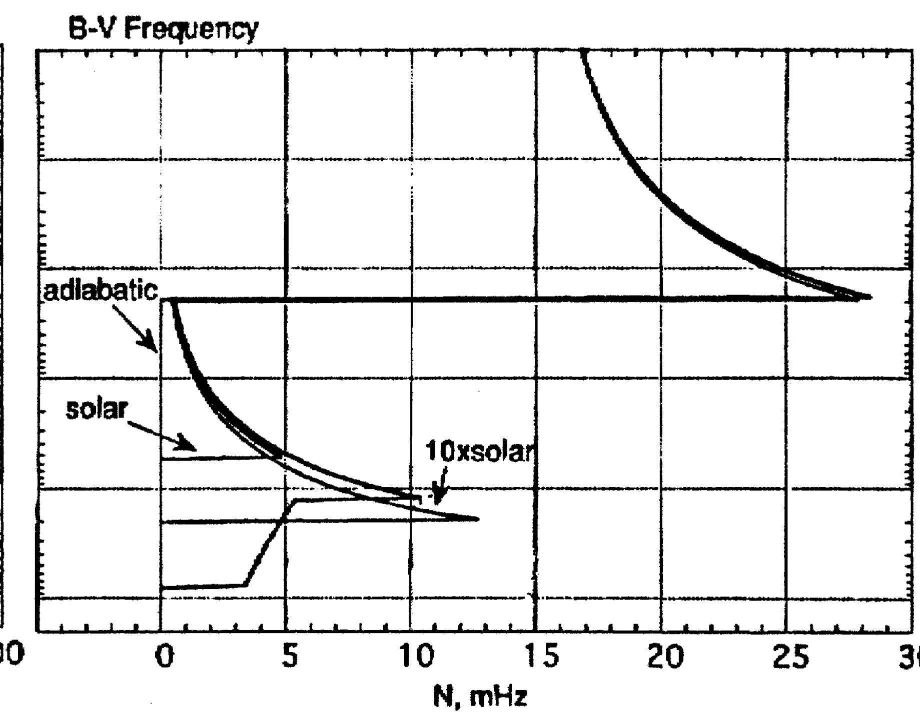
Hodochrones are still too fast for the present models of Jupiter


Thank you !

Temperature in the Jovian Atmosphere



Brunt-Vaisala (Buoyancy) Frequency in the Jovian Atmosphere

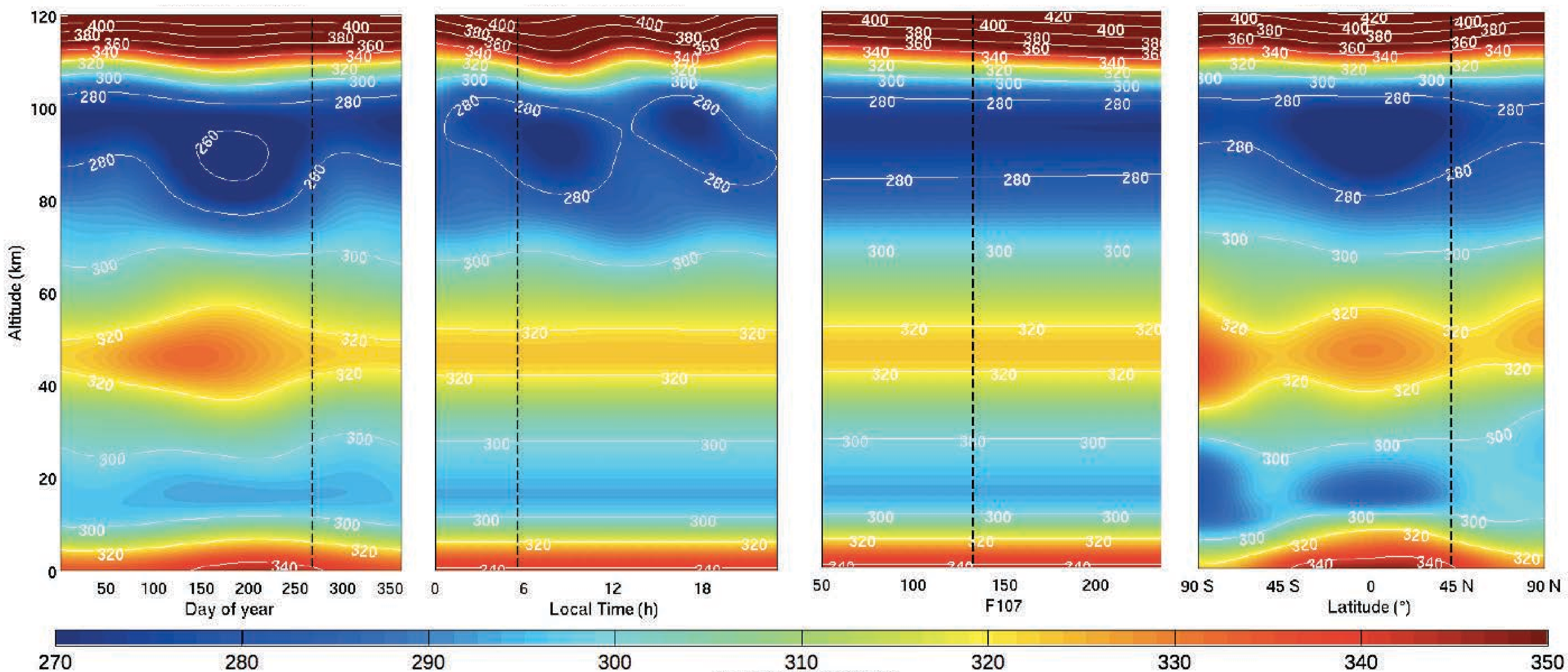


Kanamori (2004)

Variability of the Earth's atmosphere

Atmosphere model NRLMSISE-00

Seasonal — Local time — Solar flux — Latitude

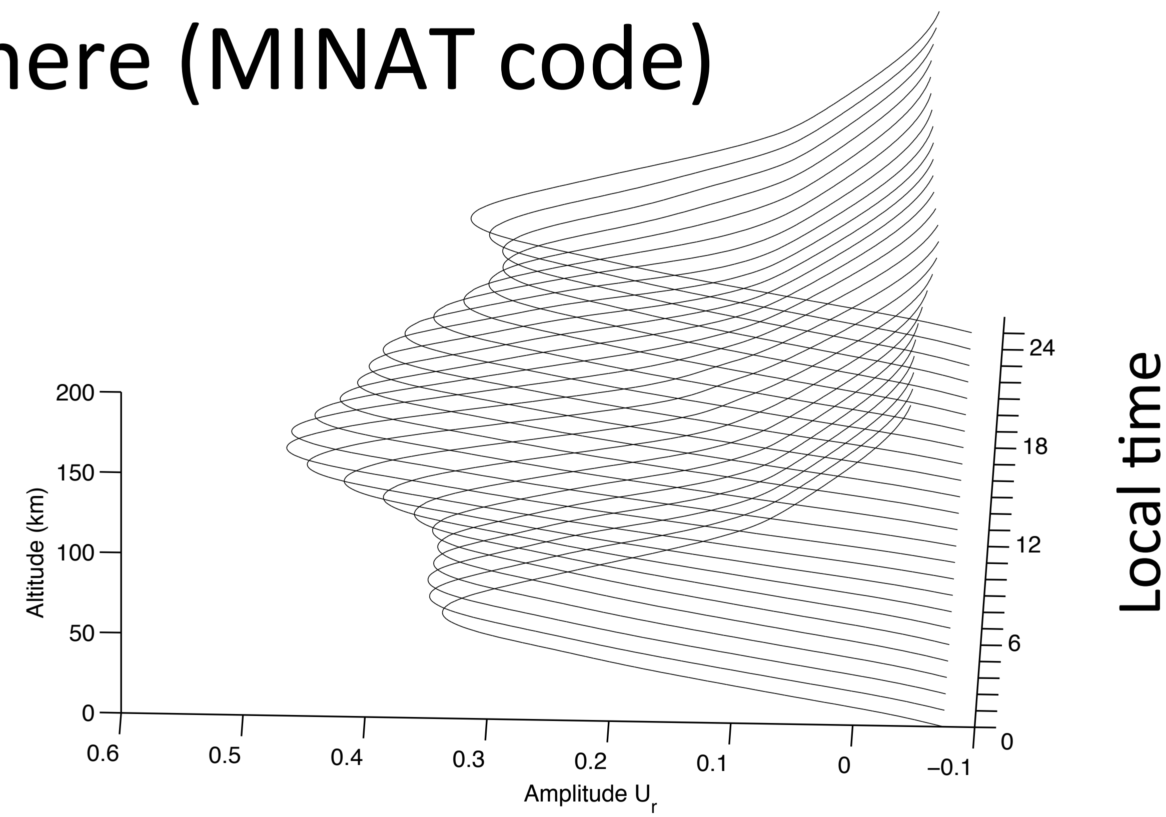


Sound speed (m/s)

Variability of the Earth’s atmosphere

Normal modes model
Solid Earth + Atmosphere (MINAT code)

Amplitude of mode 0S29 in atmosphere



Part of energy transferred from solid to the atmosphere

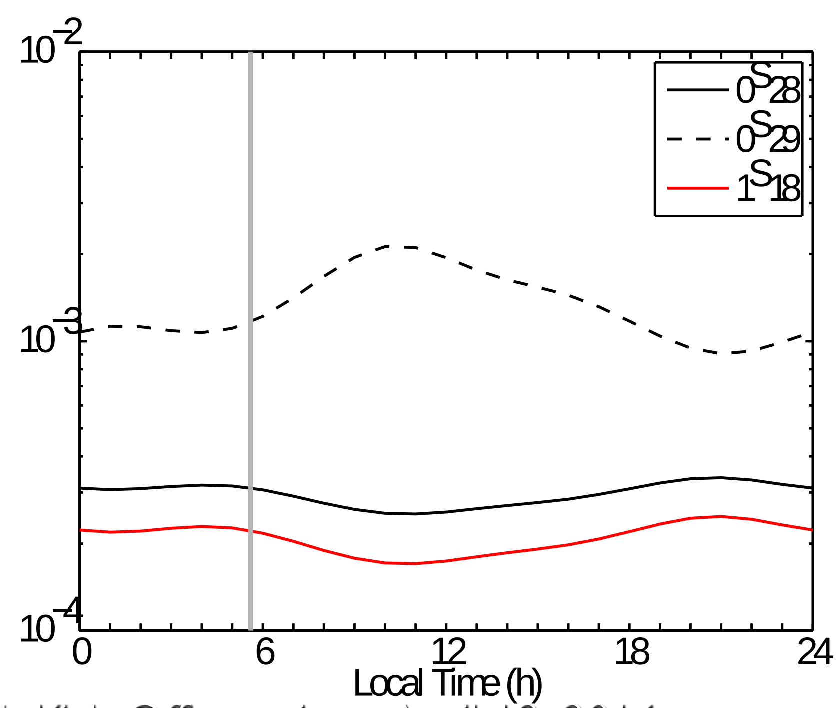


TABLE 1 Summary of the boundary conditions for different types of surfaces and discontinuities. The function $F(\omega)$ is given by Lognonné *et al*. (1998) and is associated with the radiating surface

Type of Surface	Stress	Displacement
Solid–solid	$[-p_0 \mathbf{n}_0 \nabla_\Sigma \cdot \mathbf{u} + p_0 \nabla_\Sigma \mathbf{u}(\mathbf{n}_0) + \delta \mathbf{T}_{\text{elastic}} \cdot \mathbf{n}_0]_-^+$	$[\mathbf{u}]_-^+$
Solid–liquid	$[-p_0 \mathbf{n}_0 \nabla_\Sigma \cdot \mathbf{u} + p_0 \nabla_\Sigma \mathbf{u}(\mathbf{n}_0) + \delta \mathbf{T}_{\text{elastic}} \cdot \mathbf{n}_0]_-^+$	$[\mathbf{u} \cdot \mathbf{n}_0\, \mathbf{n}_0]_-^+$
Liquid–liquid	$[-p_0 \mathbf{n}_0 \nabla_\Sigma \cdot \mathbf{u} + p_0 \nabla_\Sigma \mathbf{u}(\mathbf{n}_0) + \delta \mathbf{T}_{\text{elastic}} \cdot \mathbf{n}_0]_-^+$	$[\mathbf{u} \cdot \mathbf{n}_0\, \mathbf{n}_0]_-^+$
Free solid surface	$\delta \mathbf{T}_{\text{elastic}} \cdot \mathbf{n}_0 = 0$ and $p_0 = 0$	
Free atmospheric surface	$\delta p = \kappa \nabla \cdot \mathbf{u} = 0$	
Radiating atmospheric surface	$\delta p = F(\omega)\ \rho(\mathbf{g}_0 \cdot \mathbf{n}_0)(\mathbf{u} \cdot \mathbf{n}_0)$	

Practically:

- Rayleigh and Acoustic waves are modelled with Radiative BL at low altitude or FS at high altitude (600-400 km e.g. where waves are damped by attenuation)
- Tsunami and gravity waves are modelled with FS at high altitude (600-400 km range e.g. where waves are damped by attenuation)

Neutral atmosphere / ionosphere coupling

Neutral atmosphere → ionosphere

$\mathbf{v_n}$ $\mathbf{v_i}$

In a geomagnetic field B

Momentum conservation equation

"Small" fluctuations around the equilibrium

$\omega \ll \nu_{in}$

$$\rho_i \left(\frac{\partial \mathbf{v_i}}{\partial t} + (\mathbf{v_i} \cdot \nabla)\, \mathbf{v_i} \right) = -\nabla \mathbf{p} + \rho_i \frac{q_i}{m_i} (\mathbf{v_i} \wedge \mathbf{B}) + \rho_i \mathbf{g} - \rho_i \nu_{in} (\mathbf{v_i} - \mathbf{v_n})$$

Lorentz force

Neutral drag on ions

Continuity equation

$$\frac{\partial N_e}{\partial t} + \nabla \cdot (N_e \mathbf{v}_i) = 0$$

→ Finite difference scheme
3D spherical grid