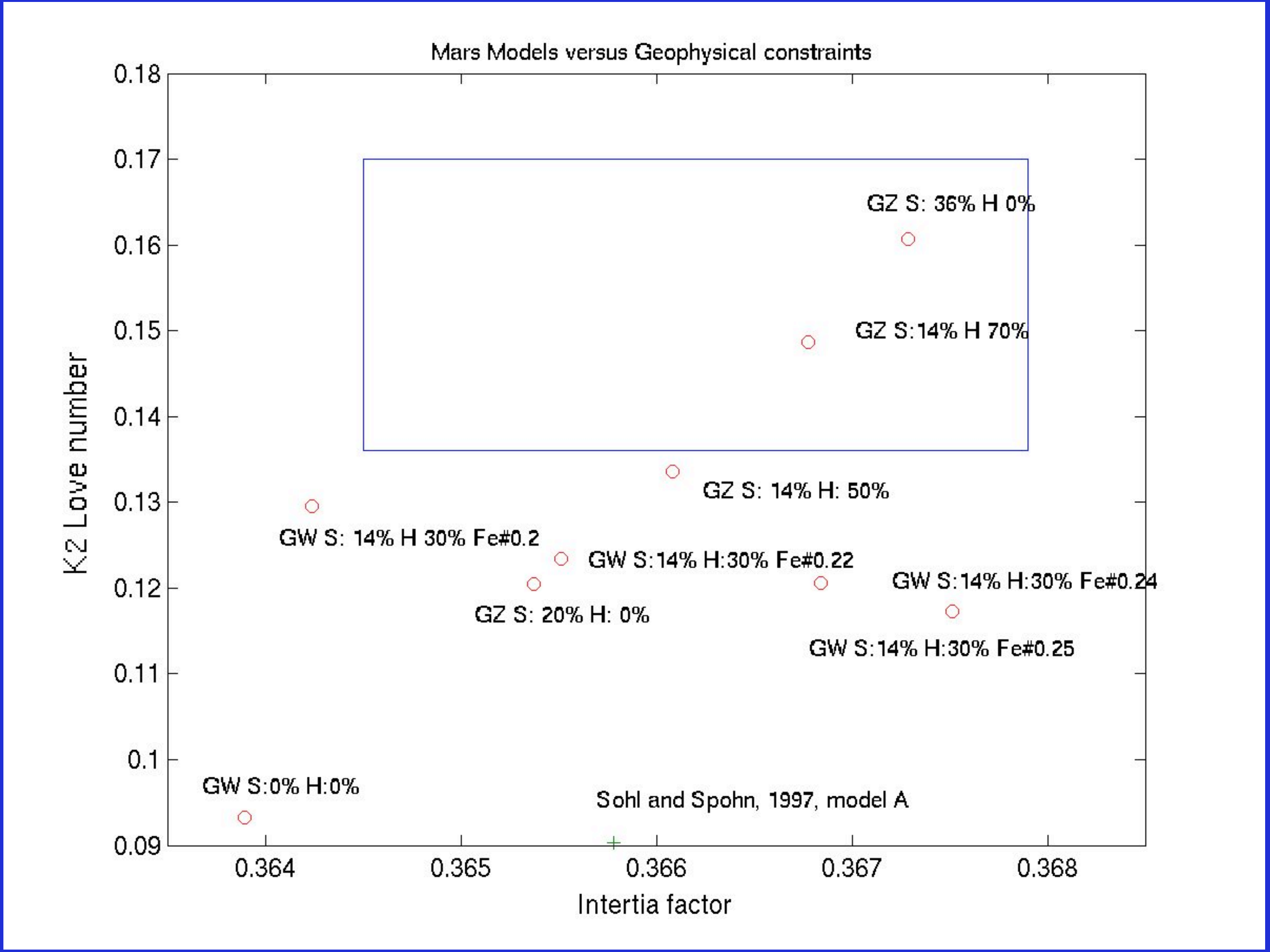
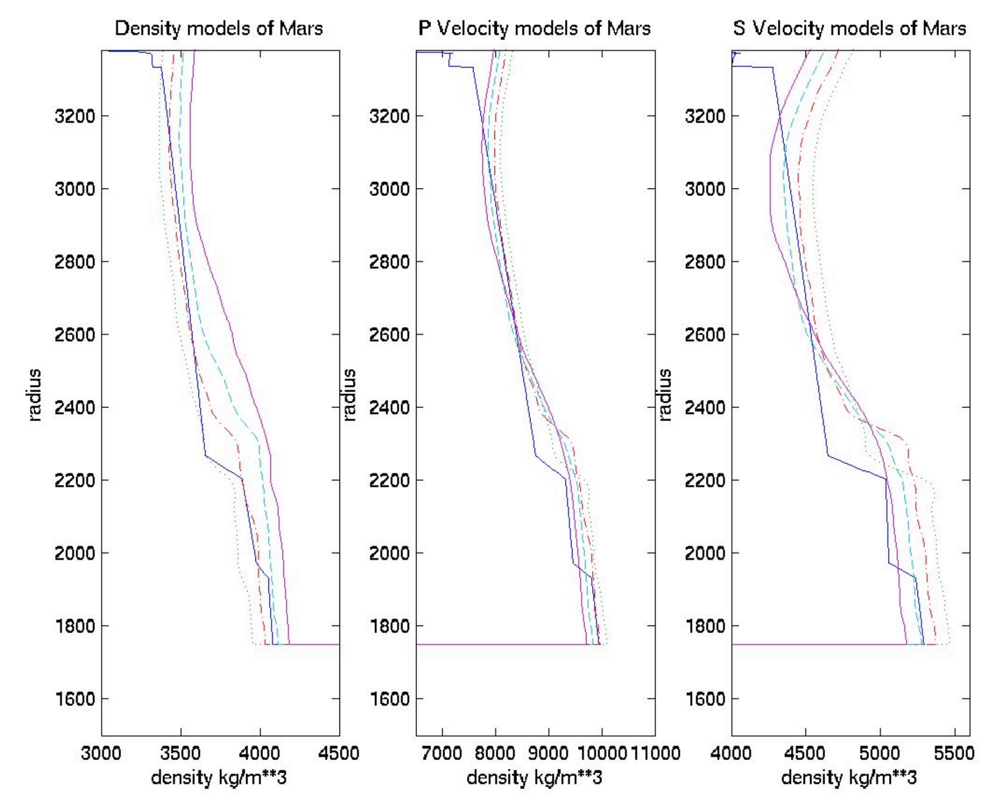
Fit with data

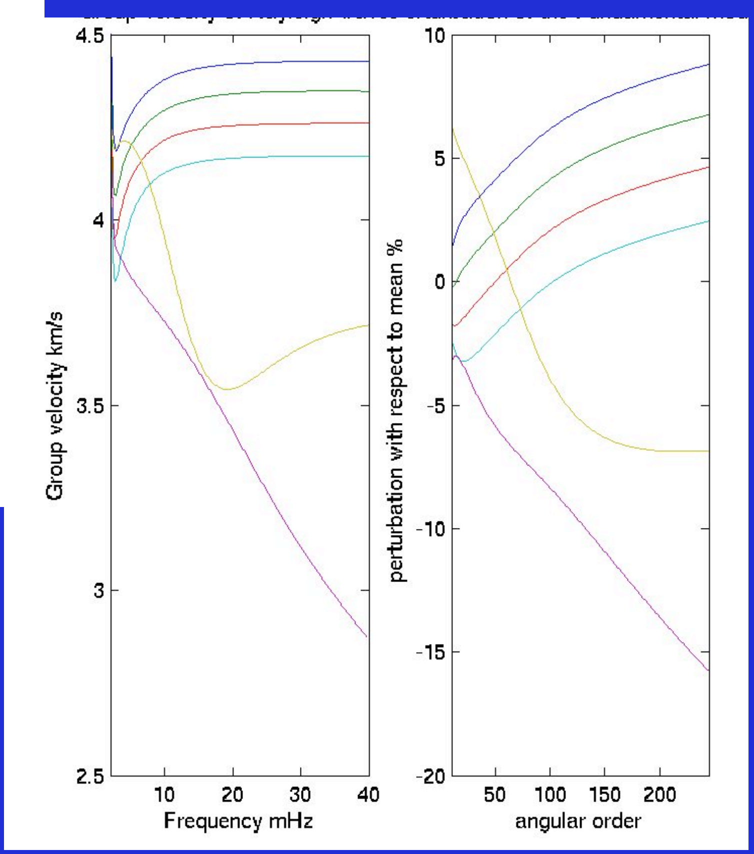


- Love number data support large core possibly with Hydrogene!
- Such large core are not compatible with a spinel-perovskite discontinuity in the mantle T
- Did Mars have such discontinuity in the past?

Mantle structure

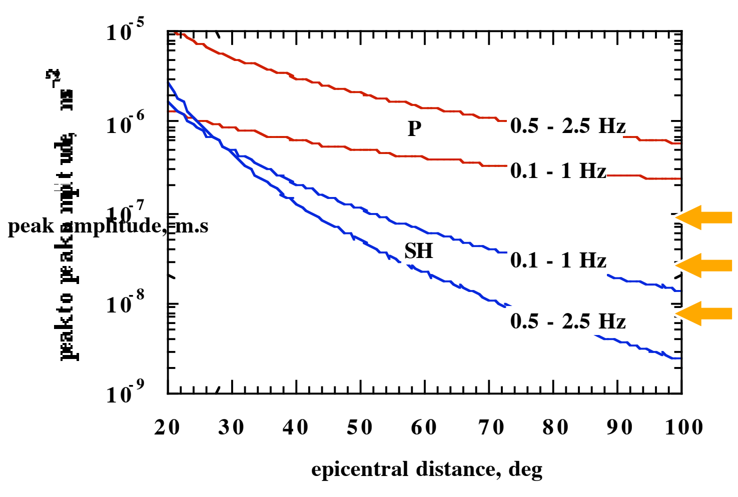


Mocquet et al., 1998



- Large effect of the FeO content
- Crustal thickness unknown, etc
- Large seismic effects

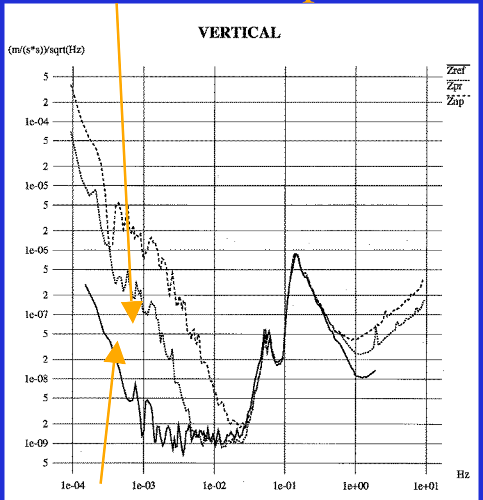
Basis for seismology on Mars : signal to noise



5 ng
2 ng
0.5 ng

Quake with seismic moment of 10**15 Nm
About 15 quakes per year with such moment

Wind/shadow protected



vault

•Signal

- Seismic activity can be estimated by comparison with the Moon
- Quakes on Mars, like on the Moon can be generated by thermoelastic cooling of the lithosphere
- Attenuation has a strong effect on short period remote events amplitudes

$$a = a_0 \exp^{-\omega T/2Q}$$

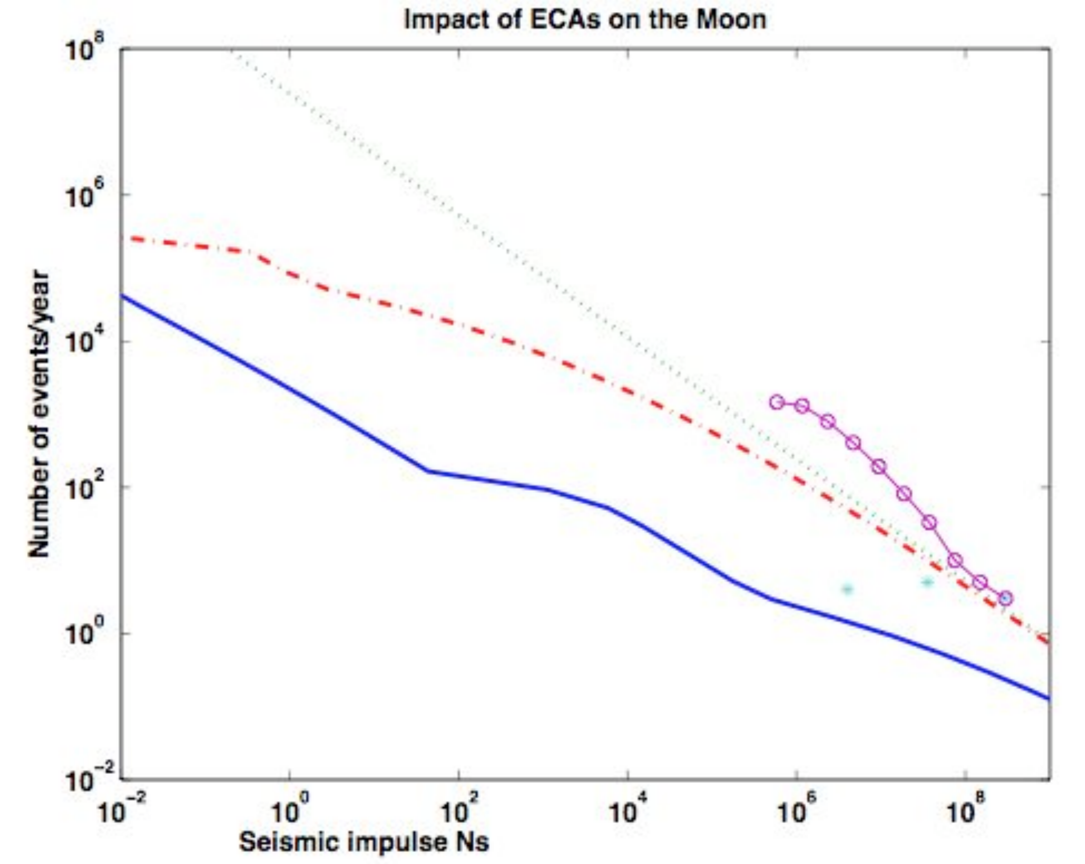
- About: 15 quakes/year Ms=4.2; 55 quakes/year Ms=3.2
  - Amplitude increase by about 30 for one magnitude init at long period

- Noise
  - Put the seismometer on the ground (NOT Viking example)
  - Use the station as sun/wind protection
  - Use meteo data to decorrelate the residual noise

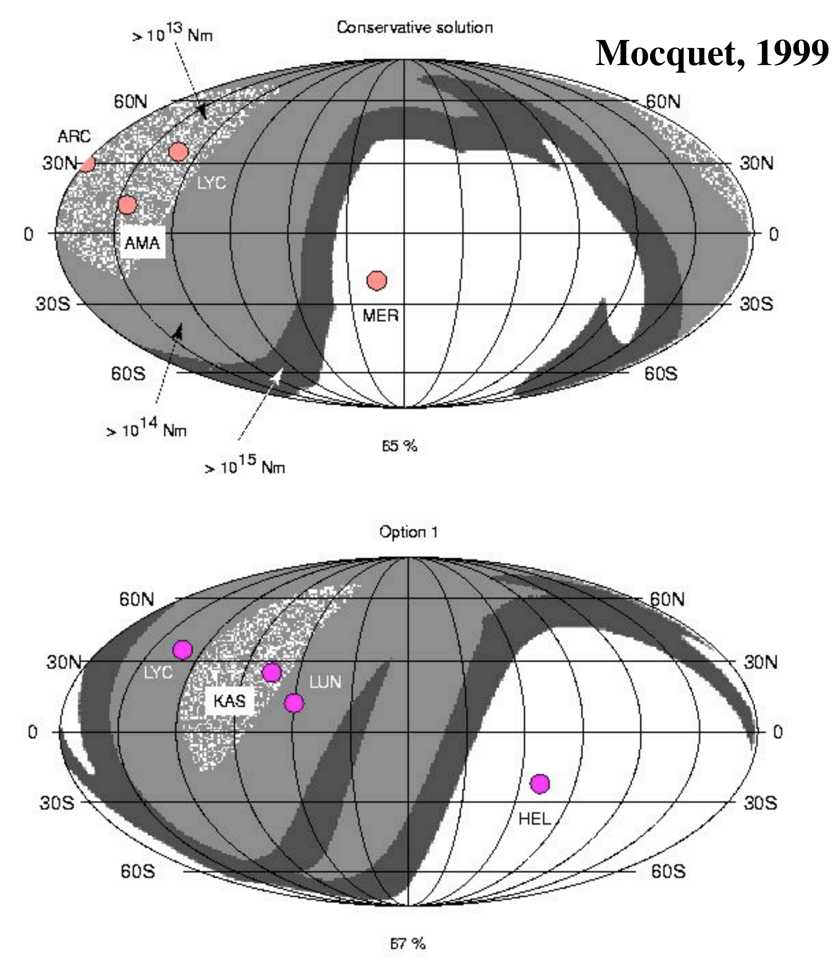
Impacts

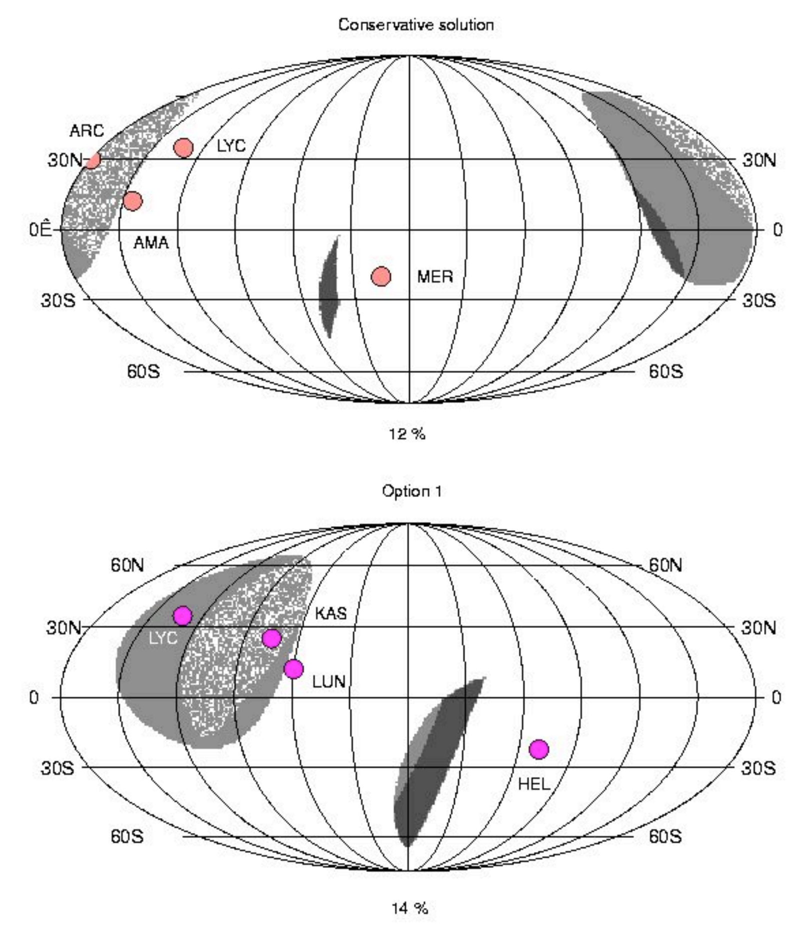
$$m\frac{dv}{dt} = \frac{1}{2}C_D\rho v^2 A - mg$$

$$\frac{dm}{dt} = \frac{1}{2}\frac{C_H}{Q}\rho v^3 A$$

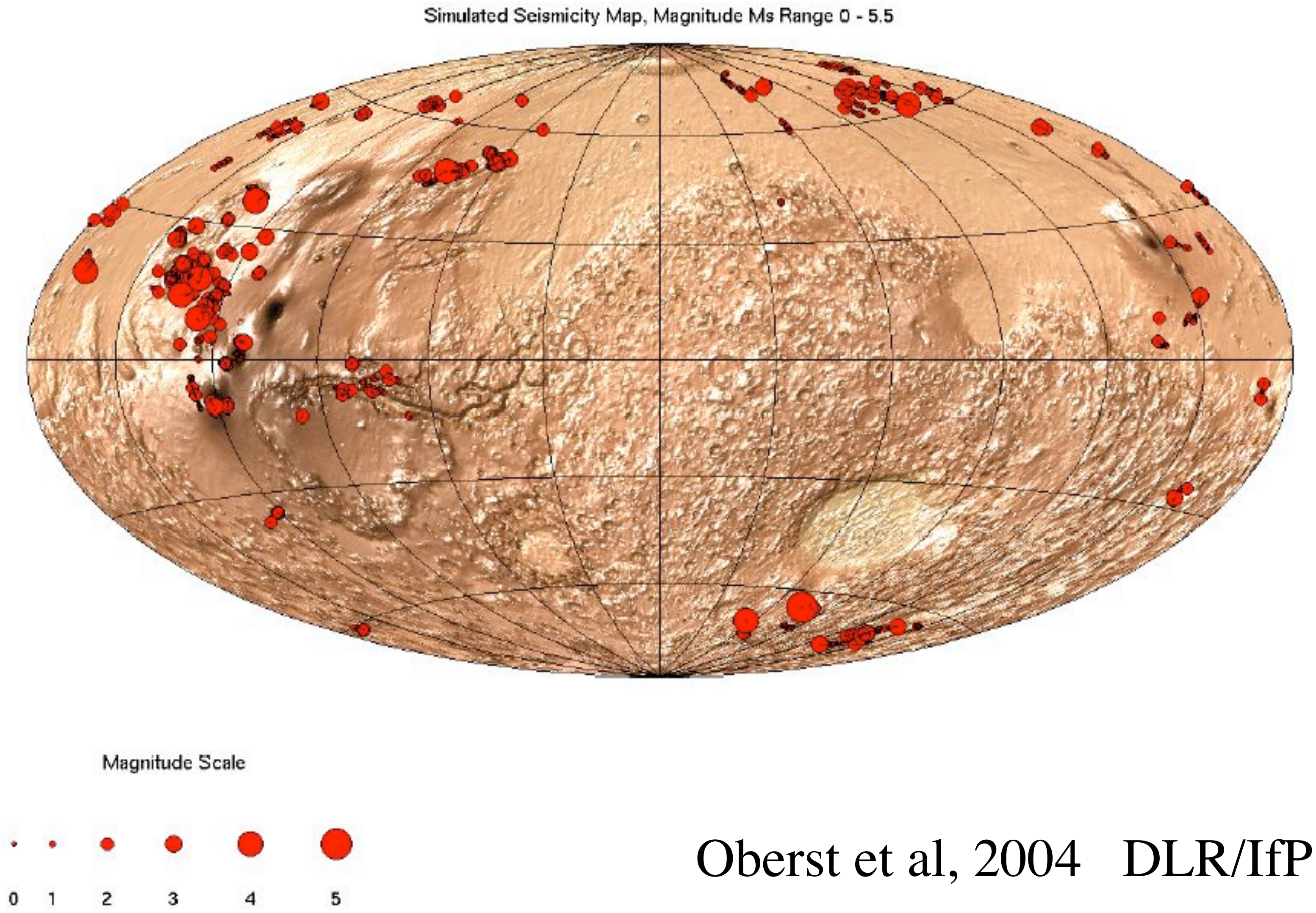


Seismic Network efficiency for P and S waves detections


Mocquet, 1999



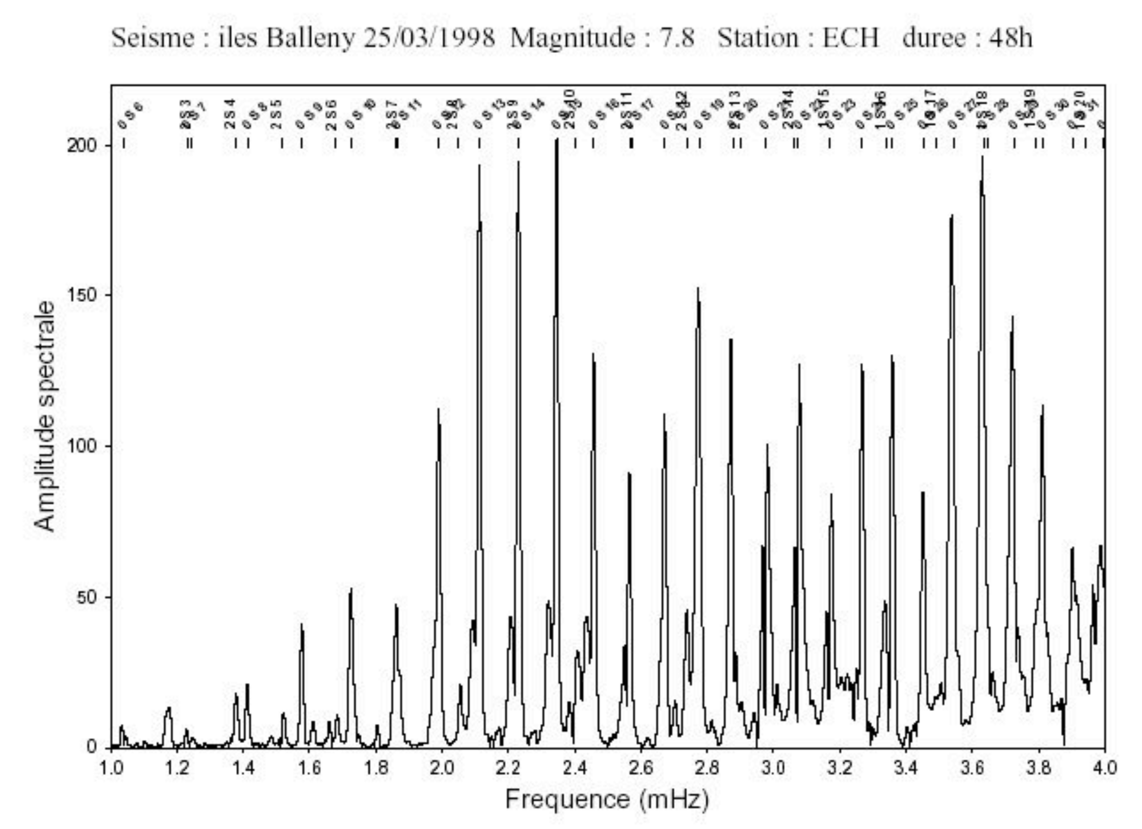
- Seismic activity, from thermoelastic cooling of the lithosphere indicate about 50 quakes with Moment > 10^{14} N.m per year (10 with Moment > 10^{15} N.m)
- For realistic noise level (10^{-9} ms^{-2}/Hz$^{1/2}$ in 0.1-1 Hz), 60 % of the quakes might be detected



Oberst et al, 2004   DLR/IfP

Normal mode seismology

- Normal modes (free oscillations) are bell-like global oscillations of the planet
- They typically request magnitudes Ms >7 quakes on the Earth to be observed



Normal modes equation

- Normal modes are solution of the gravito-elastodynamic

$$\rho \frac{d\mathbf{v}}{dt} = \nabla.\mathbf{T} + \rho\left(\mathbf{g} - \mathbf{\Omega}\wedge(\mathbf{\Omega}\wedge\mathbf{r}')\right) - 2\rho\mathbf{\Omega}\wedge\mathbf{v},$$

With

$$\rho - \rho_0 + div(\rho_0\mathbf{u}) = 0.$$

$$\mathbf{g} = \mathbf{g}_0 - \nabla\Phi_1$$

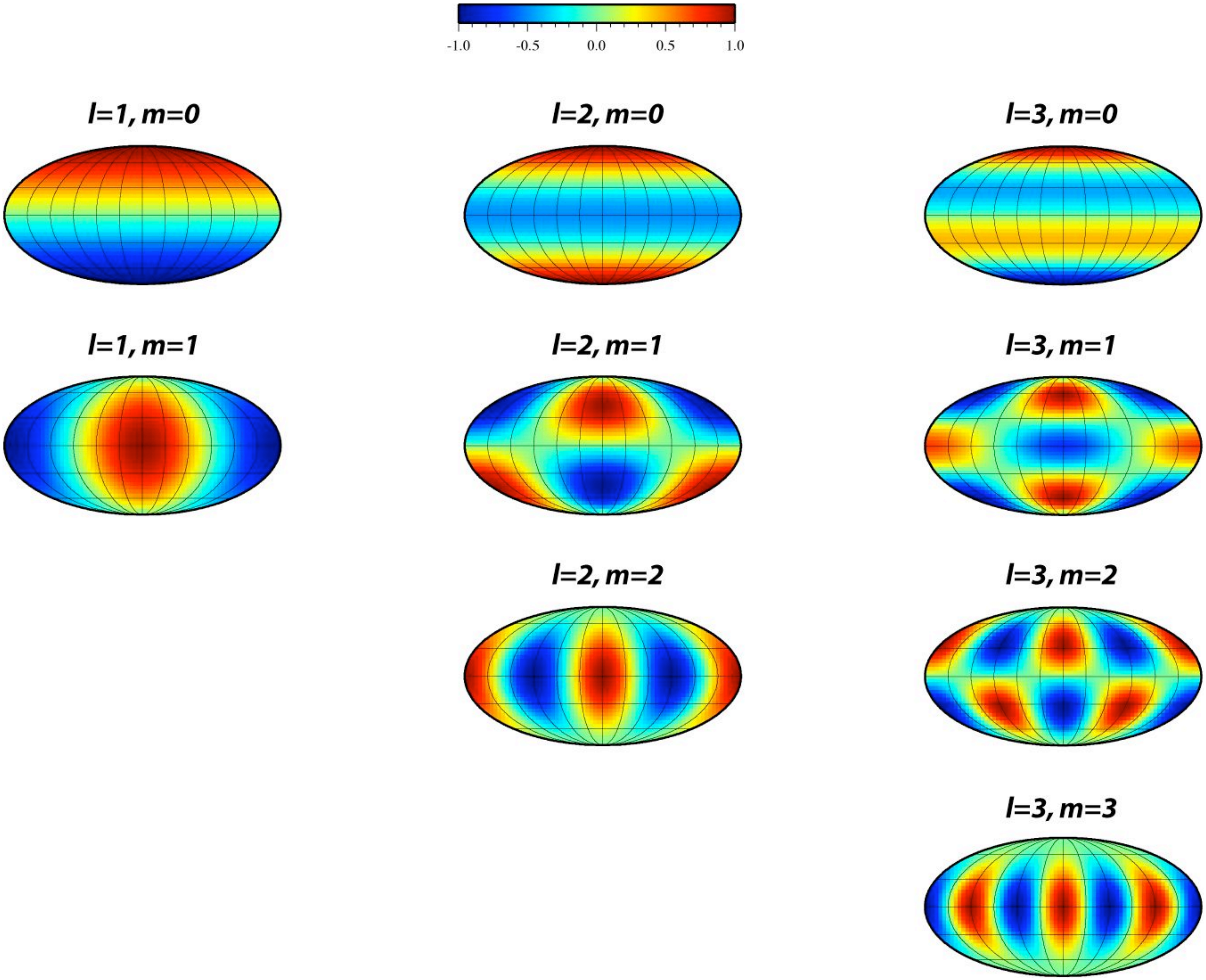
$$\mathbf{T} = \mathbf{C} : \nabla\mathbf{u} - \mathbf{u}.\nabla\mathbf{T}_0$$

$$\nabla^2\Phi_1 = -4\pi\mathcal{G}div(\rho_0\mathbf{u}).$$

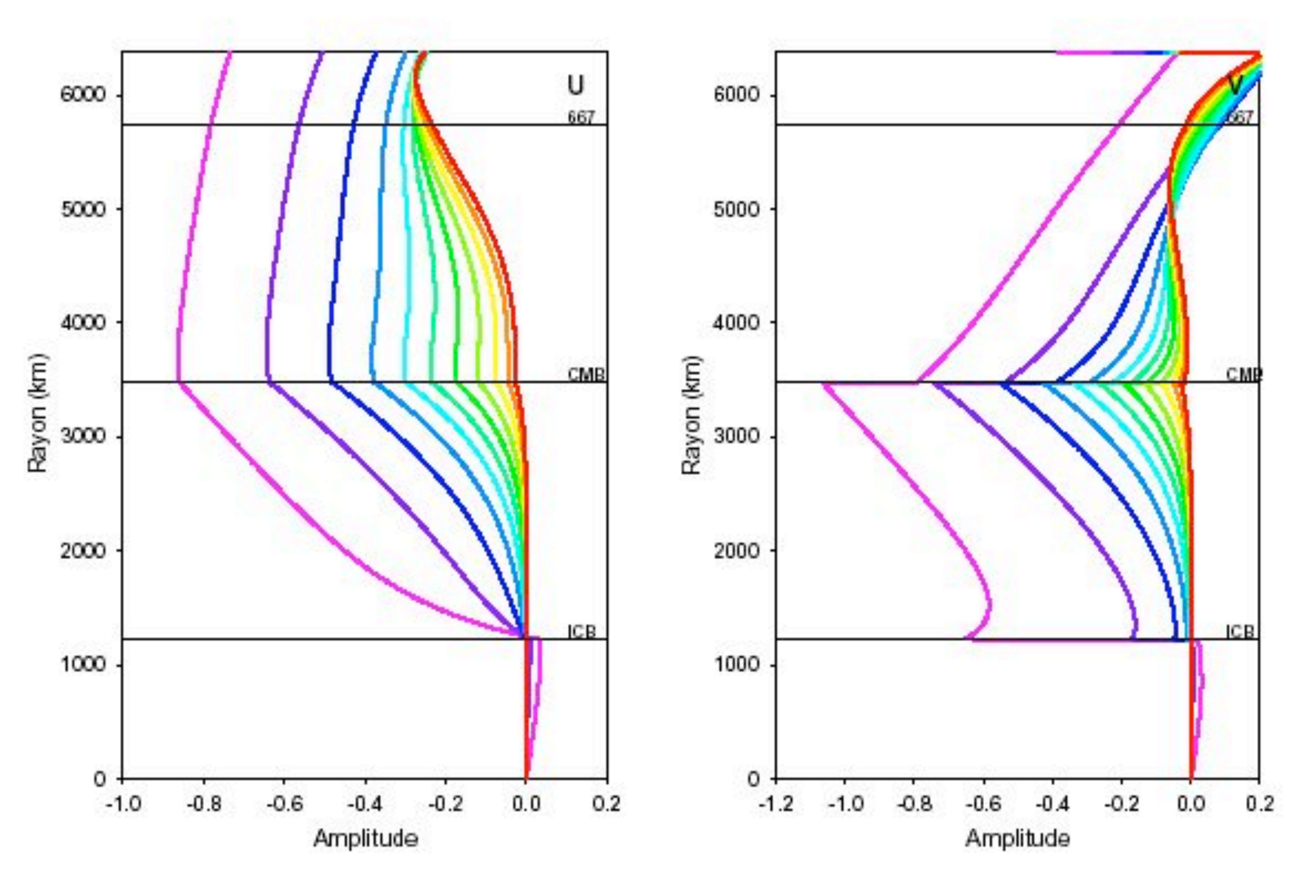
- Normal modes are sensitive to C but also to density
- Solution $u = u_{n,\ell,m}e^{i\omega t}$ is given by

$$\mathbf{u}_{n,\ell,m} = \mathcal{U}_{n,\ell}(r)Y_\ell^m(\theta,\phi) + \mathcal{V}_{n,\ell}(r)\nabla Y_\ell^m(\theta,\phi) + \mathcal{W}_{n,\ell}(r)\mathbf{e}_r\wedge\nabla Y_\ell^m(\theta,\phi)$$

and obtained eigenfrequencies depend on the two number l and n (and not three, i.e. including m)


-1.0
-0.5
0.0
0.5
1.0
l=1, m=0
l=2, m=0
l=3, m=0
l=1, m=1
l=2, m=1
l=3, m=1
l=2, m=2
l=3, m=2
l=3, m=3

- Amplitude of Normal modes is more and more localized toward the Earth surface when angular order increases
- Normal modes lead therefore to surface waves for high angular orders



Normal modes of planets with different size

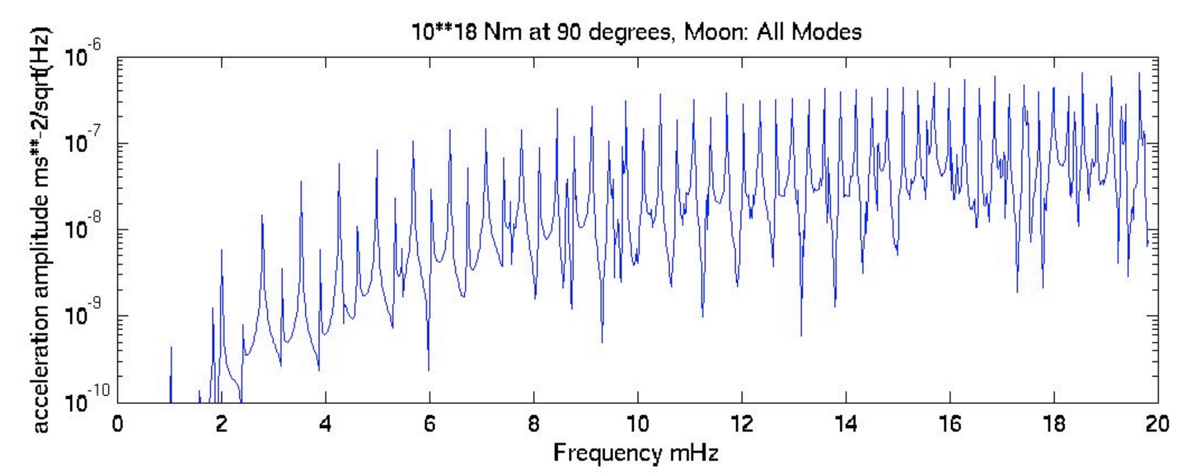
- Some rough idea on the excitation of Normal modes on a planet
  - Most of the energy for shallow quakes is released in the excitation of the Fundamental branch ($_0S$)
  - Period of a Normal mode is proportional to
    - c T ~2 π a /L
    - Where a is planetary radius and With typicall values of c ~~3.5-4.5 km/s
    - Density of normal mode with respect to frequency is therefore proportional to the inverse of a
  - Maximum of fundamental is a a depth of λ/3
  - Kinetic Energy of a normal mode is therefore proportional to
    - E(L) ~ $1/2\ \rho\ 4\ \pi\ a^2\ \lambda\ v^2$
    - Exitation of Normal mode by a Seismic source releasing Po seismic energy in a frequency bandwidth Dw leads to

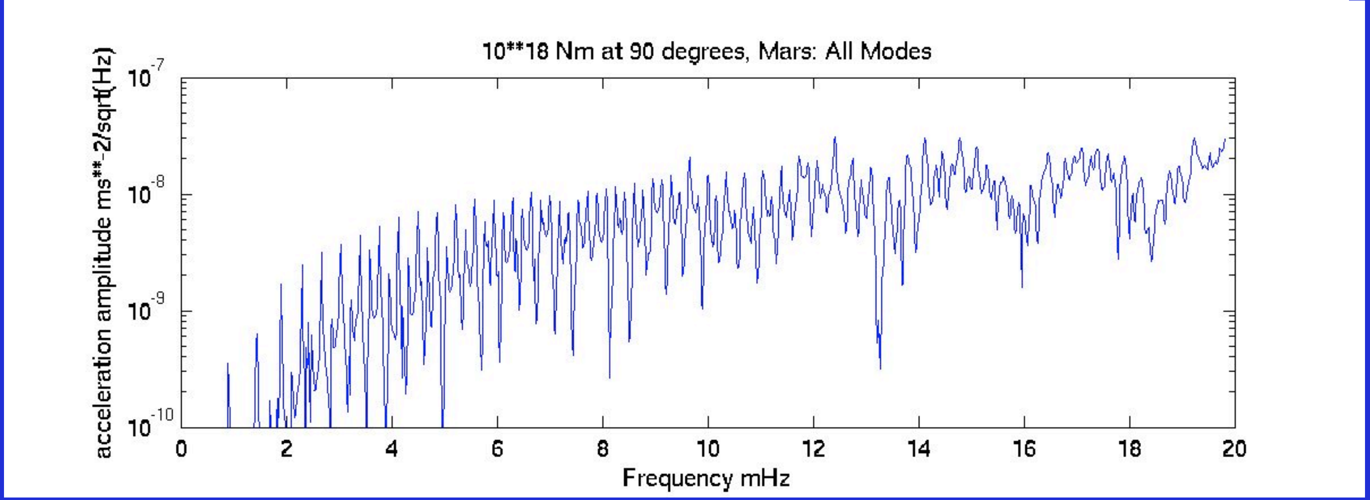
$$\frac{P_0}{\Delta w} = 2\pi a^2 \lambda v^2 \frac{1}{c/_{2\pi a}} = a^3 T^3 \gamma^2$$

$$\gamma(L) \approx \gamma_0 L^{3/2} a^{-3} = \gamma(T) = \gamma_0^{'} T^{-3/2} a^{-3/2}$$

    - Spectral amplitude of Normal modes are proportional to $Q\gamma(L)$

Comparison between Mars and Moon

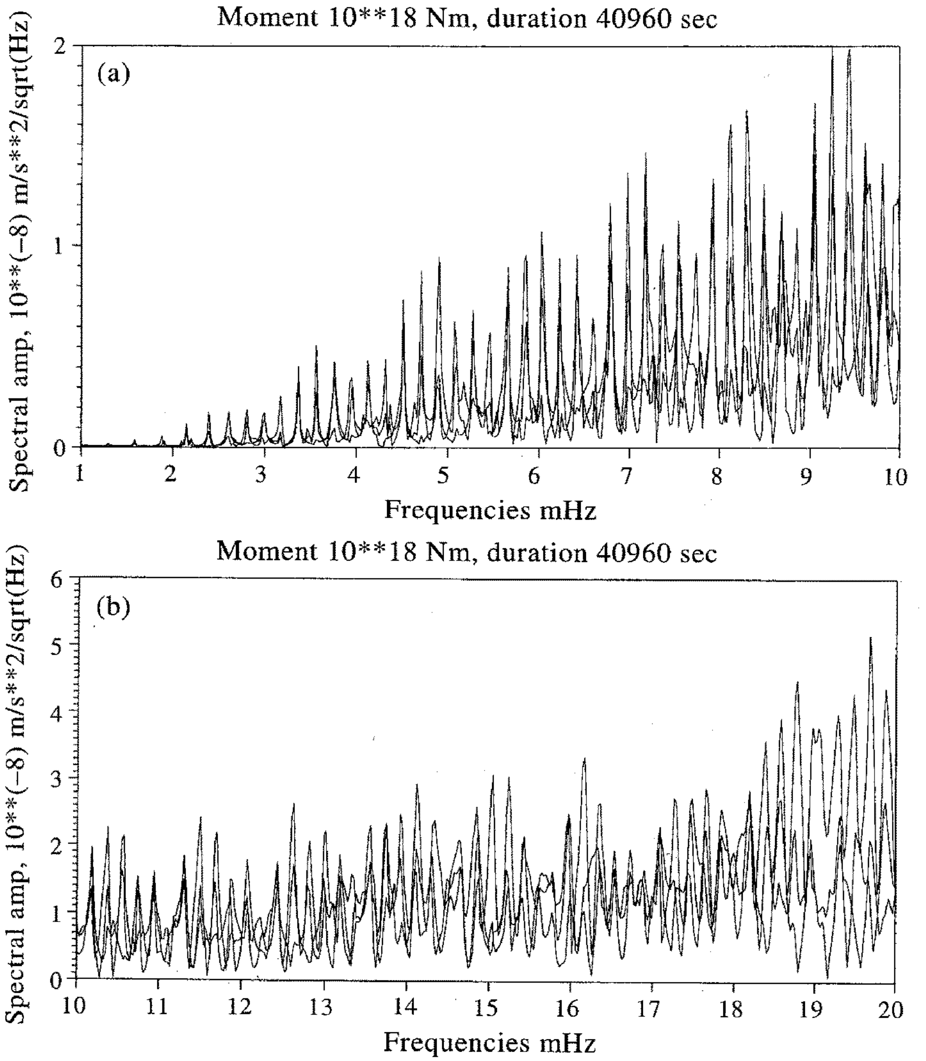




- Amplitudes are larger on small and cold (high Q) planets
- Amplitude are above the detection threshold on Mars for the largest expected quakes

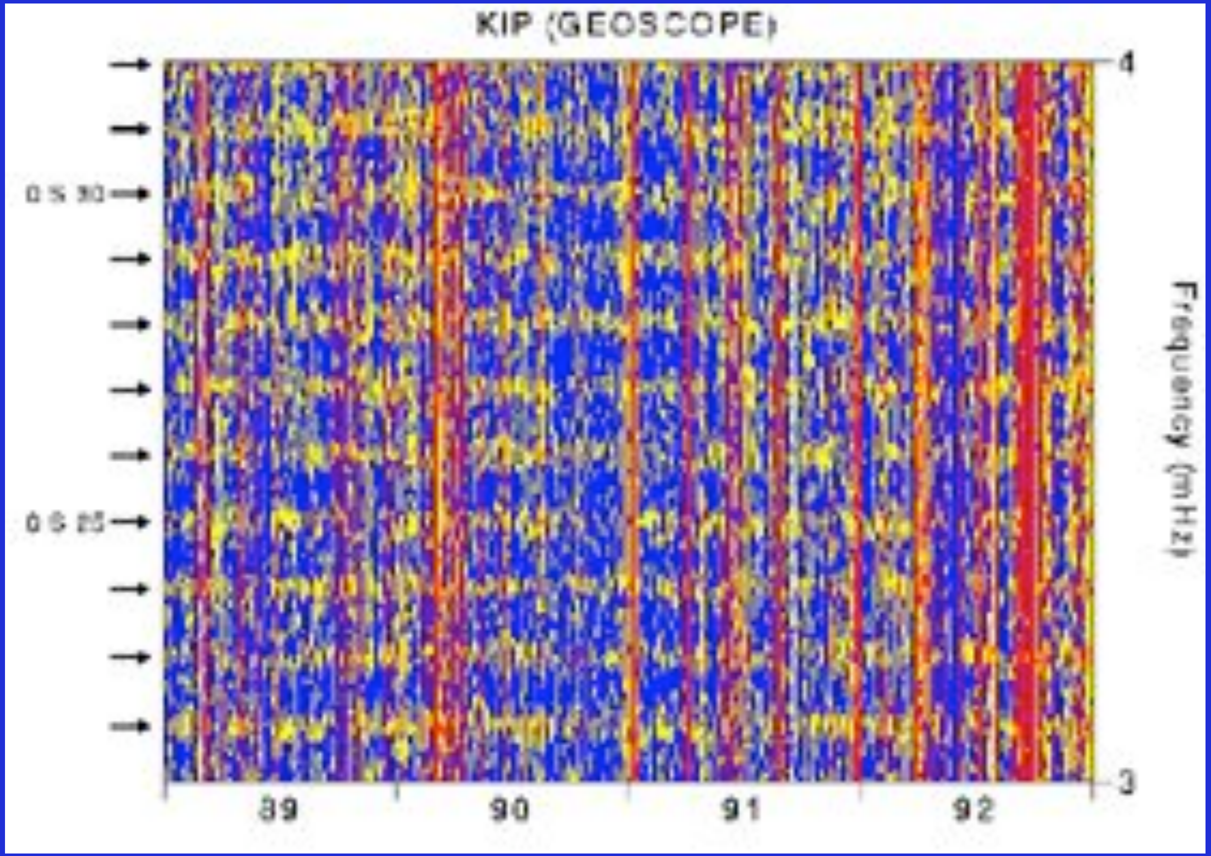
challenge... normal modes (1)

Up: spectral amplitude density for a 10^{18} Nm quake, for the different epicentral distances. Amplitude exceed the 10^{-9} $\mathrm{ms^{-2}Hz^{-1/2}}$ level (considered as a conservative estimate of the Martian vertical noise) at frequencies higher than 3 mHz. At frequencies higher than 5-7 mHz, the signal to noise ratio exceed 5. Down: Same but for the frequency window 10mHz-20mHz. Note that some peaks are still resolved with a 12 hours time serie in that band which is not possible on Earth



challenge... normal modes (1)

The continuous excitation of normal modes may offer an other possibility for normal modes detection. For a bandwith of 0.2 mHz (mean spacing between the fundamental modes), the detection level will be 10^{-11} ms^{-2} (1 ngal) for a noise of $5x10^{-10}$ $m/s^2/Hz^{1/2}$. Expected amplitudes on Mars might be of 2-3 ngals.



Example of continuous excitation on the KIP Geoscope station (Tanimoto 1998)

Excitation mechanism

- Tanimoto (1998), Kabayashi & Nishida, (1998):
  - Stochastic excitation by turbulences (~Sun modes):
  - $p = \rho v^2 (\lambda/H)^{2/3}$, time $\tau = H/v (\lambda/H)^{2/3}$
    - Kolmogorov theory for the boundary layer turbulences
  - estimate of turbulences:
  - $\rho v^2/H = \rho \alpha \Delta T g$
    - equ. Reynolds stress generated by buyancy forces
  - $(1-A) P /4 = \rho C_p \Delta T v$
    - Energy budget
    - Mean velocity of 4 m/s

v=6 m/s is needed to explain observations

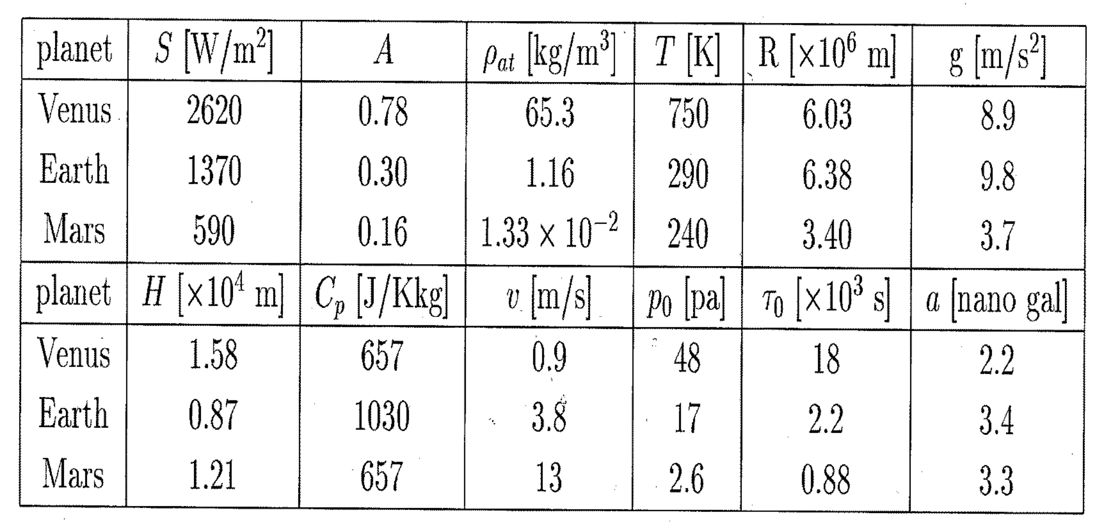
v=4 m/s is provided by energy balance

- good order of magnitude
- very simple theory (non exact forces, Atmosphérique coupling) ...

challenge... normal modes (2)

The continuous excitation of normal modes may offer an other possibility for normal modes detection. For a bandwith of 0.2 mHz (mean spacing between the fundamental modes), the detection level will be 10^{-11} ms^{-2} (1 ngal) for a noise of $5x10^{-10}$ $m/s^2/Hz^{1/2}$. Expected amplitudes on Mars might be of 2-3 ngals.

- Kobayashi & Nishida, (1998)

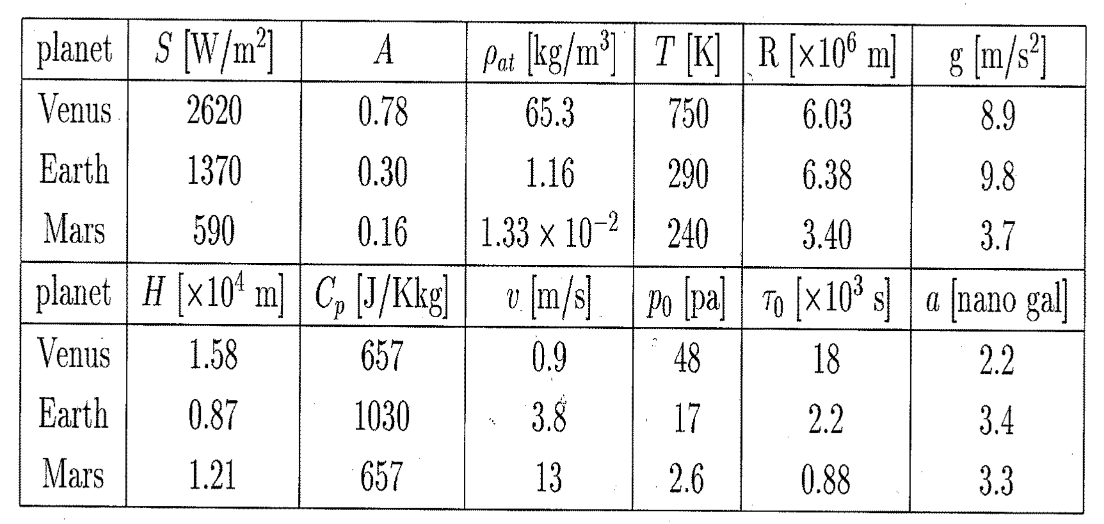


planet	S [W/m^2]	A	ρ_{at} [kg/m^3]	T [K]	R [$\times 10^6$ m]	g [m/s^2]
Venus	2620	0.78	65.3	750	6.03	8.9
Earth	1370	0.30	1.16	290	6.38	9.8
Mars	590	0.16	1.33×10^{-2}	240	3.40	3.7
planet	**H [$\times 10^4$ m]**	**C_p [J/Kkg]**	**v [m/s]**	**p_0 [pa]**	**τ_0 [$\times 10^3$ s]**	**a [nano gal]**
Venus	1.58	657	0.9	48	18	2.2
Earth	0.87	1030	3.8	17	2.2	3.4
Mars	1.21	657	13	2.6	0.88	3.3

challenge... normal modes (2)

The continuous excitation of normal modes may offer an other possibility for normal modes detection. For a bandwith of 0.2 mHz (mean spacing between the fundamental modes), the detection level will be 10^{-11} ms^{-2} (1 ngal) for a noise of $5x10^{-10}$ $m/s^2/Hz^{1/2}$. Expected amplitudes on Mars might be of 2-3 ngals.

◆Kobayashi & Nishida, (1998)



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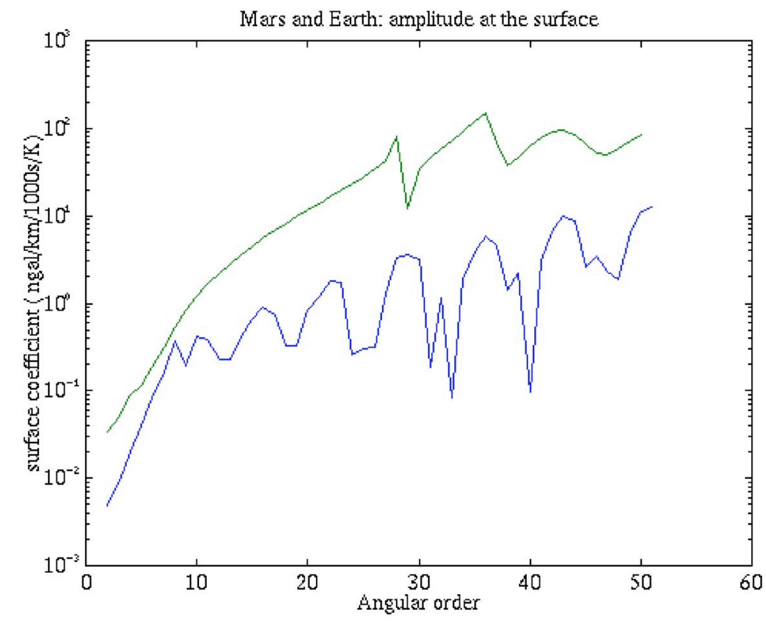
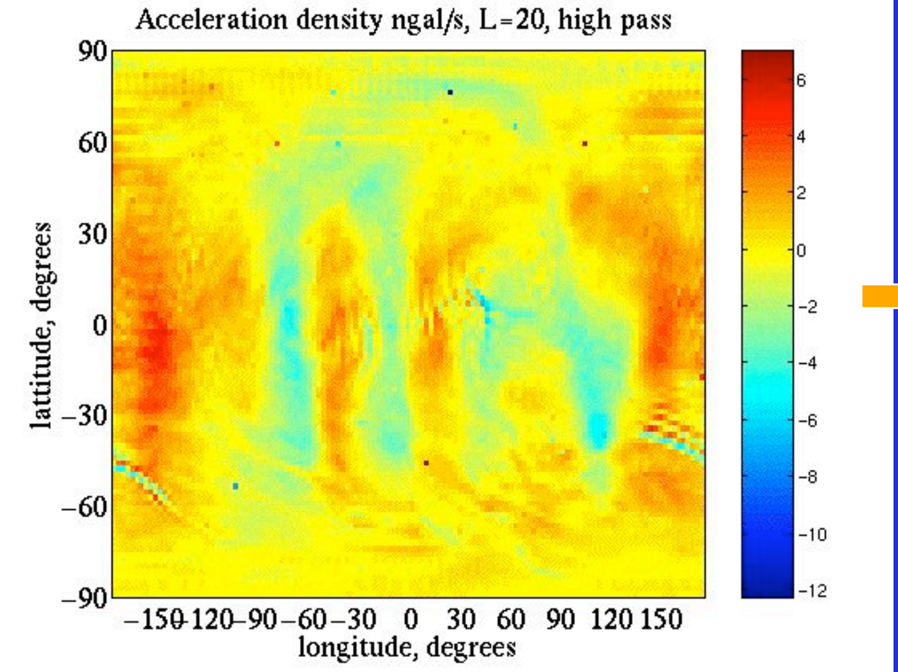
- Sensitivity to boundary layer turbulences can be computed by taking into account the real interior/atmospheric coupling (*Lognonne et al*, 1996)

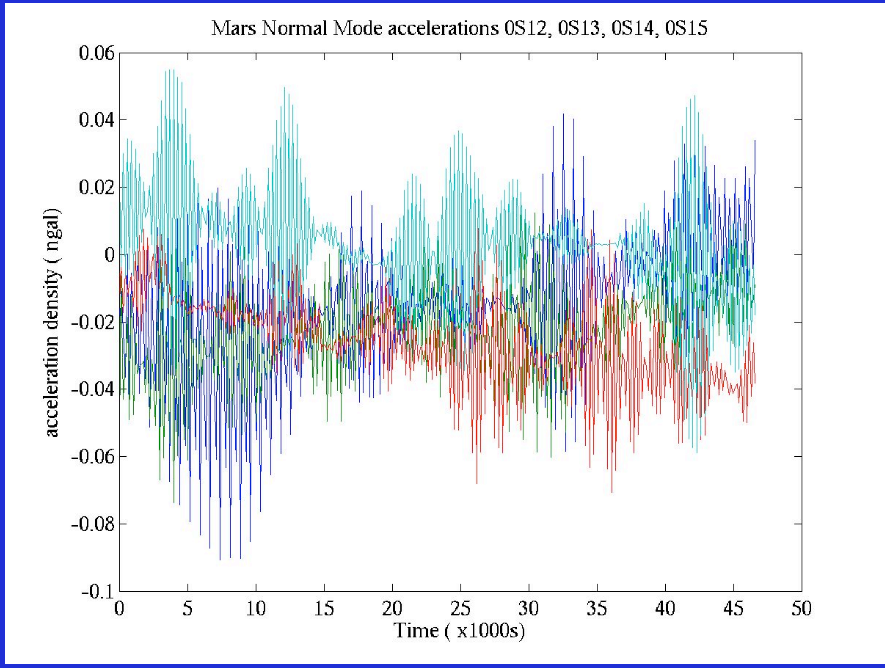


More detailled analysis…

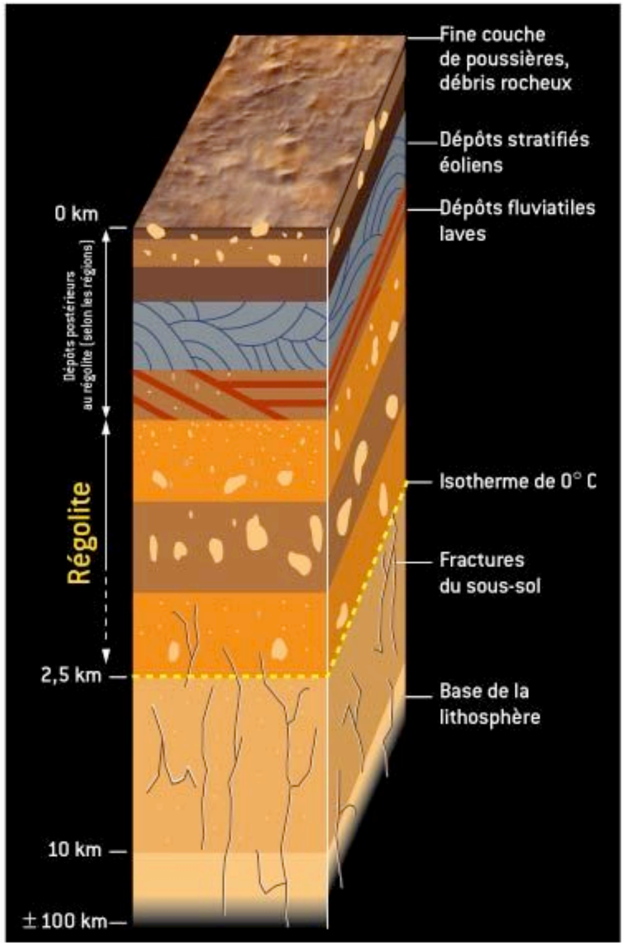
- Take a Global Circulation model of Mars (Forget and Lognonné, in preparation)
- Compute the pressure glut of the atmosphere
- Compute the normal modes

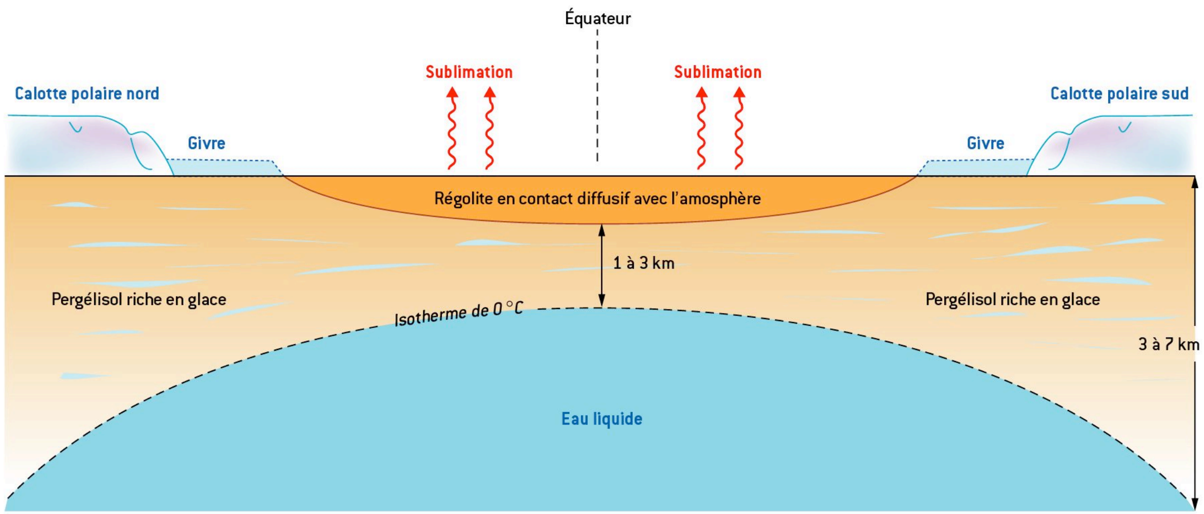
$$a_{\ell,m}(t) = \int_{-\infty}^{t} d\tau\; e^{i\sigma_\ell (t-\tau)} \int_{0}^{+\infty} dz\; A_\ell(z) \int d\Sigma\; \bar{Y}_\ell^{m}(\theta,\phi)\, \frac{Mp(z,\theta,\phi,\tau)}{R\rho_0(z)}$$





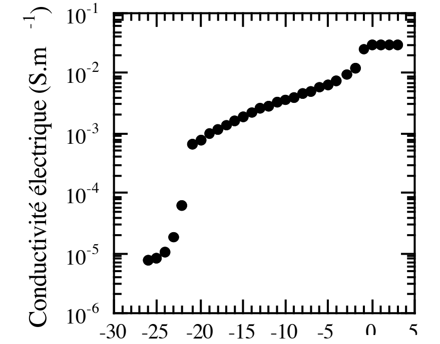
Subsurface exploration….



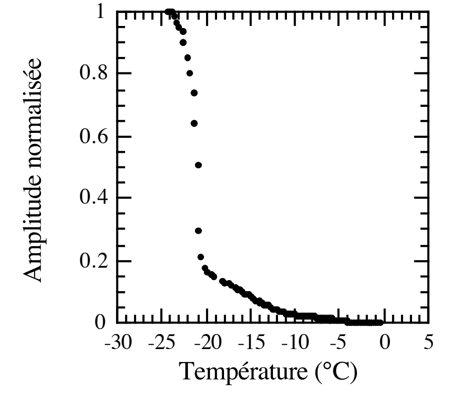


Water detection

The first resource on the surface of another planet ...

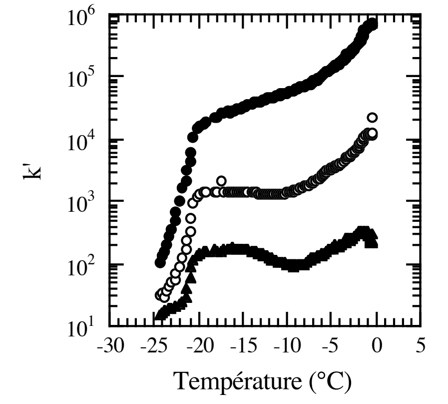


- First parameter (Mag): electrical conductivity jump.
- Passive method using the ionospheric magnetic field as a source for the generation of telluric currents



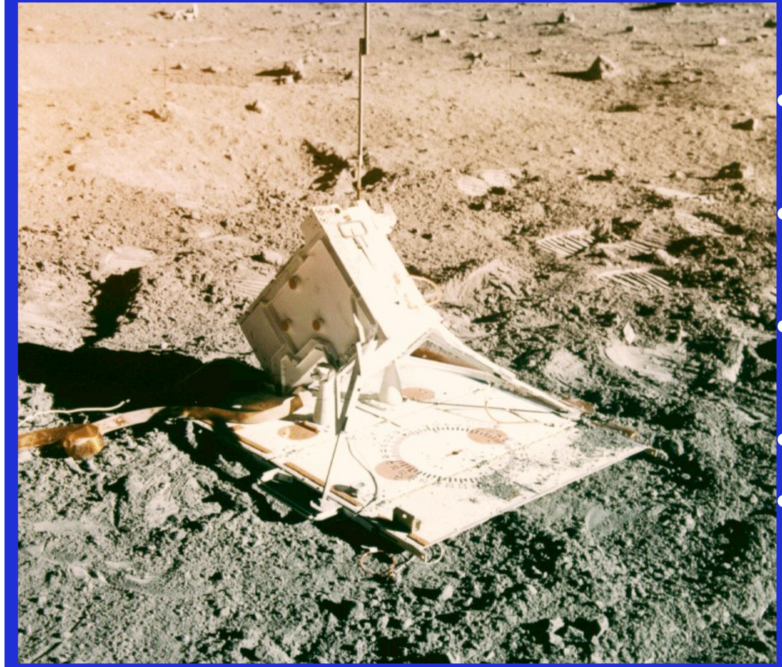
Guichet, 1998

- Second parameter (Seis): seismic attenuation
- Passive method possible only if local cracks or small quakes or impacts detected



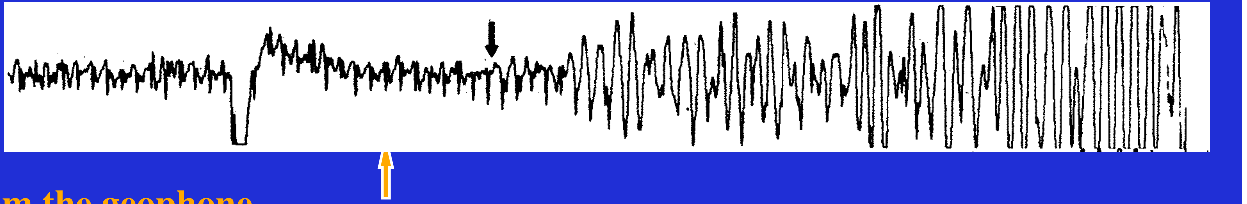
- Third parameter (GPR): permittivity jump
- Active method enabling a 1 D profil below the landers

Past experiences in Active seismology



- Active seismic experiment was performed on the Moon on Apollo 14,16,17
- Recording at 3 km for 2.7 kg, with geophone (narrow band) and saturation: broad band SP are much better
- Burried sources (e.g. penetrator) will have much higher efficiency
- Penetration depth of 1.4 km achieved
- Safety protocol on human flight achieved

Mortar with seismic sources, Apollo 16

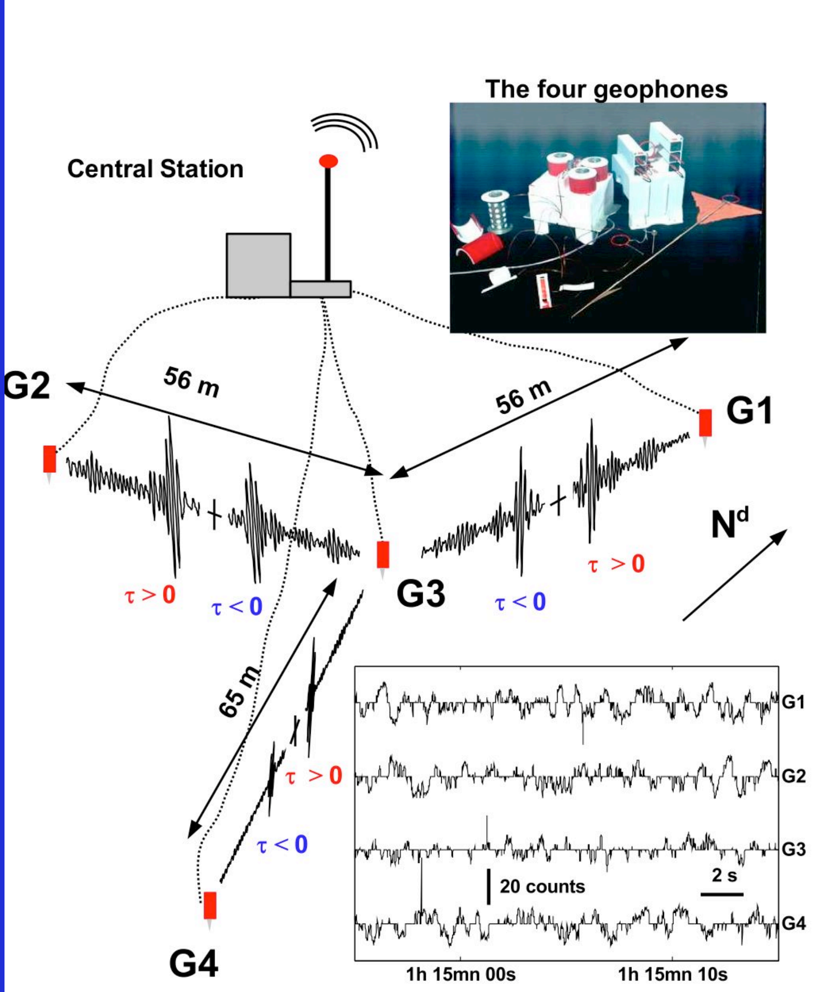


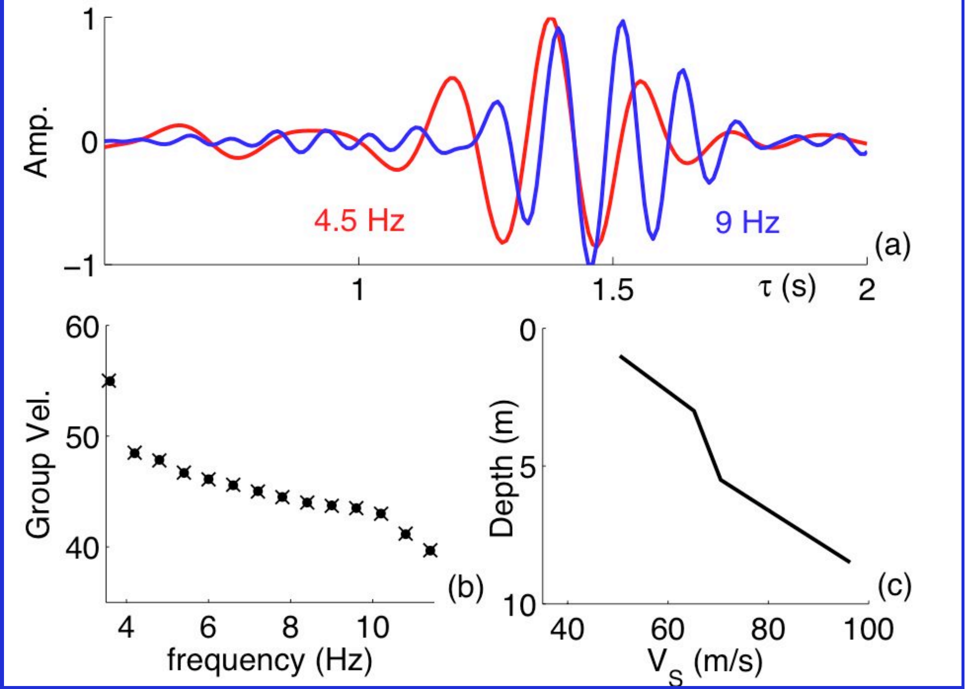
Apollo 17, 454 g of explosives, 1.2 km from the geophone

Transmitter noise

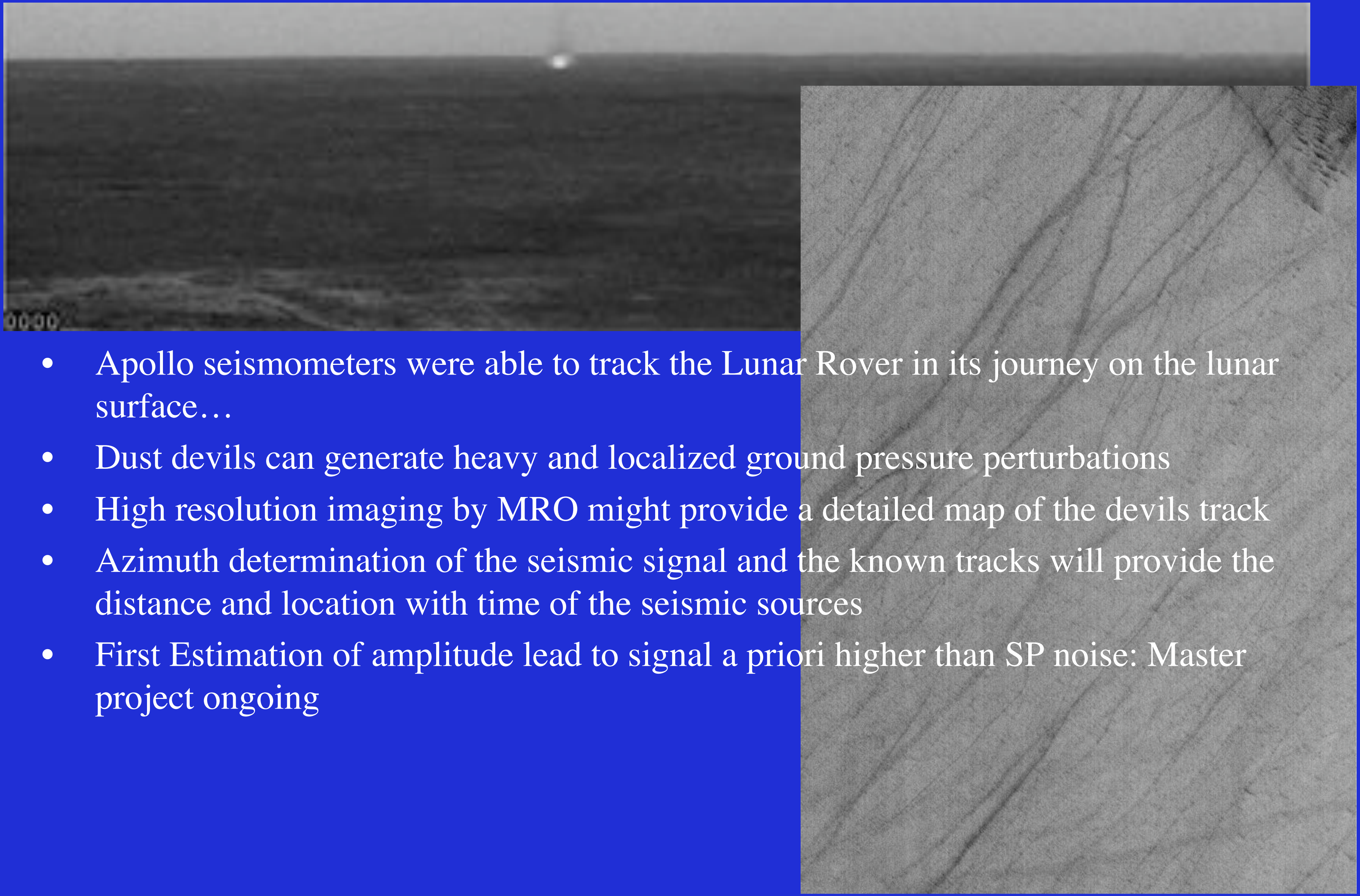
Shallow structure…

- Thermal noise = seismic noise
- With a network and by correlation, the position of the source can be extracted and the structure inverted (Larose et al., 2005)





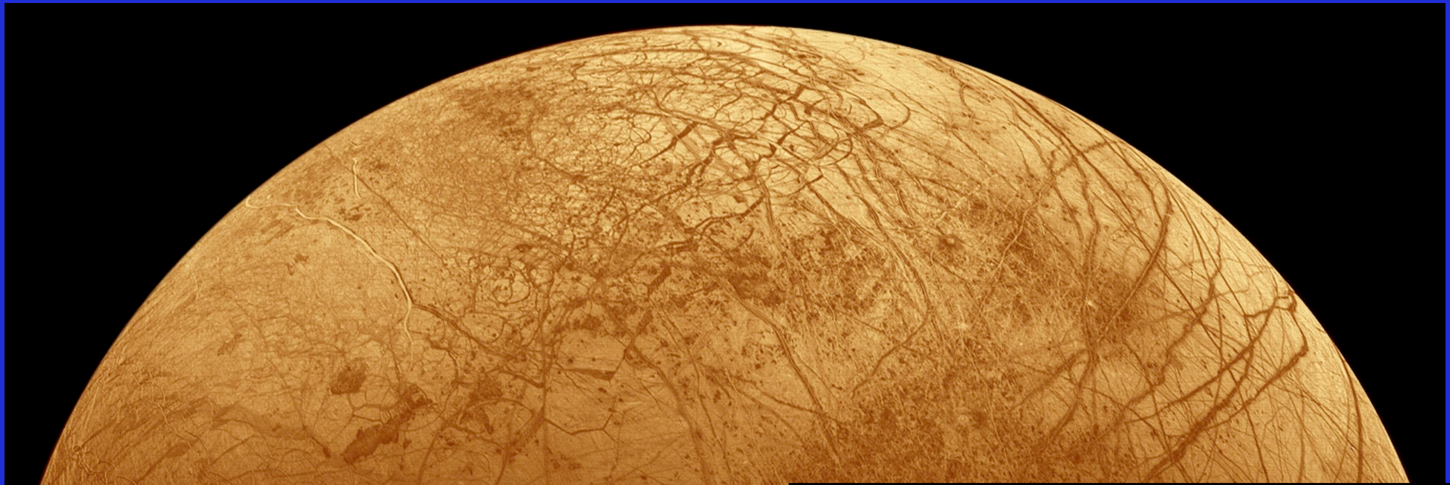
Dust devils = uncontrolled seismic sources

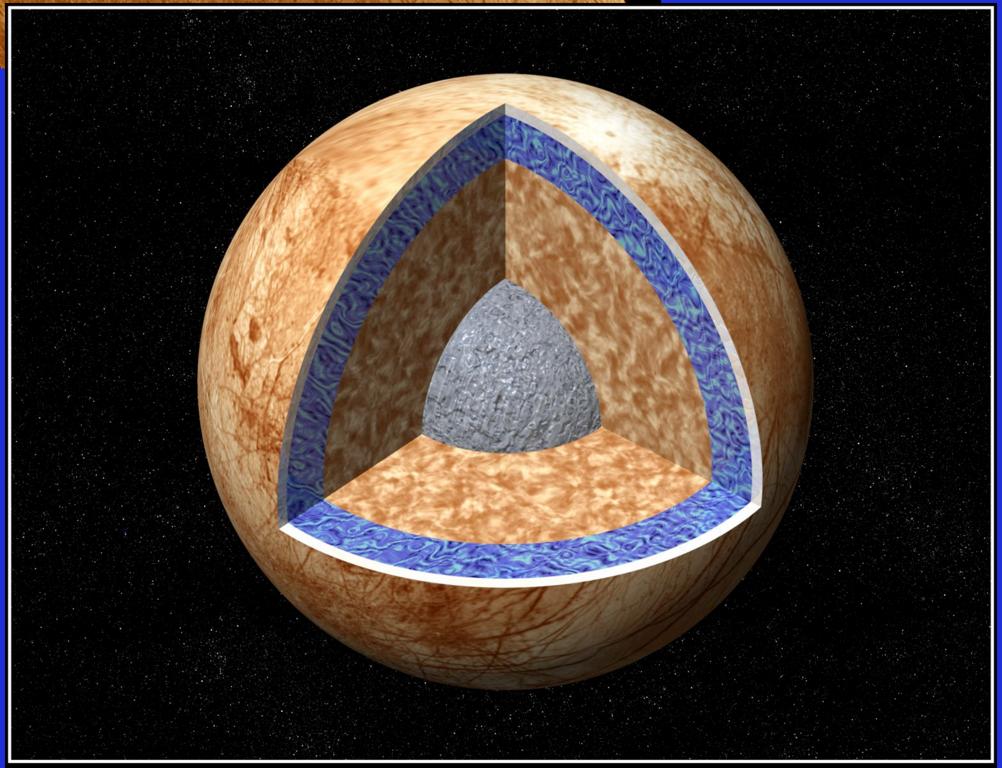


- Apollo seismometers were able to track the Lunar Rover in its journey on the lunar surface…
- Dust devils can generate heavy and localized ground pressure perturbations
- High resolution imaging by MRO might provide a detailed map of the devils track
- Azimuth determination of the seismic signal and the known tracks will provide the distance and location with time of the seismic sources
- First Estimation of amplitude lead to signal a priori higher than SP noise: Master project ongoing

Further perspectives

- Seismology on Europa
- Remote sensing seismology





The Interior of Europa

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Europa

Europa… Seismic sounding

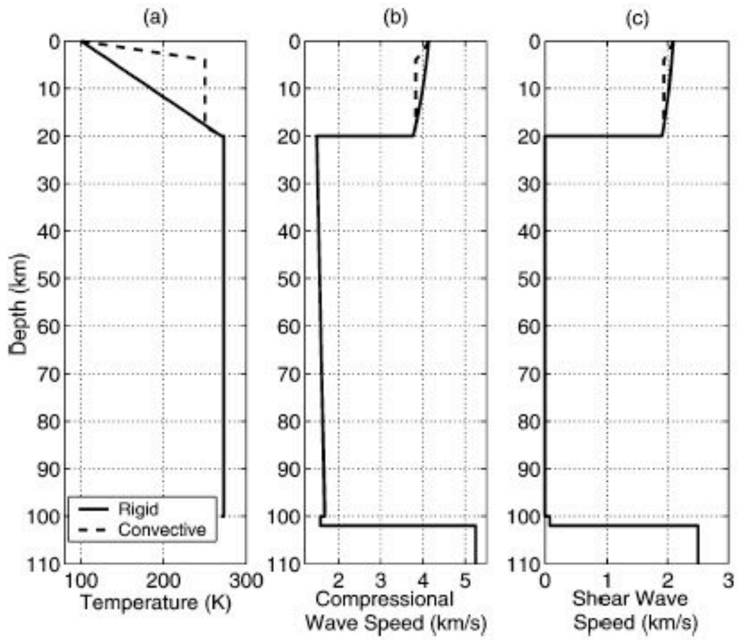


Fig. 1. Temperature, compressional wave speed, and shear wave speed profiles for 20 km thick rigid and convective ice shell models. The solid and dashed lines represent the rigid and convective ice shell models, respectively.

- Shear waves verify the propagation equation

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial x}(\mu \frac{\partial u}{\partial x}) + \frac{\partial}{\partial z}(\mu \frac{\partial u}{\partial z})$$

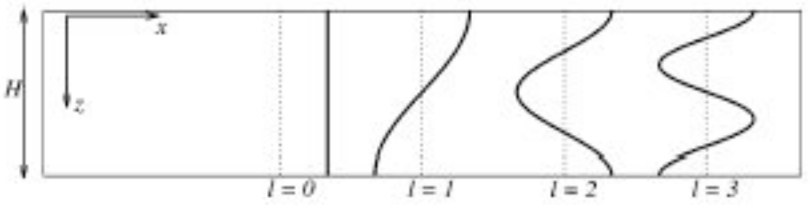
$$T_x = \mu \frac{\partial u}{\partial z}$$

Where u and T are the horizontal displacement and stress

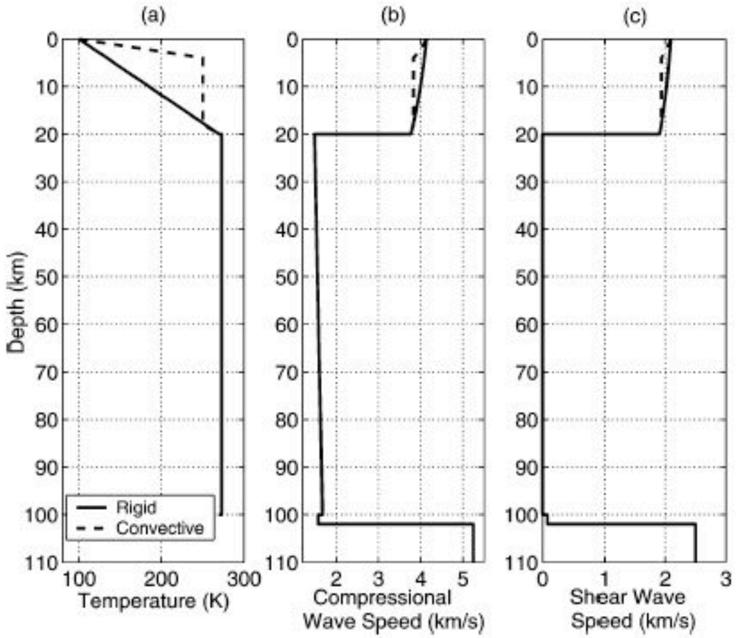
- They must have zero stress at the surface and bottom of the ice shell and therefore, we have

$$u(x,z) = u(z)e^{i(\omega t - kz)}$$

$$\Rightarrow u(z) = u_0 \cos(\pi \ell \frac{z}{H})$$



Europa… Seismic sounding



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Where u and T are the horizontal displacement and stress

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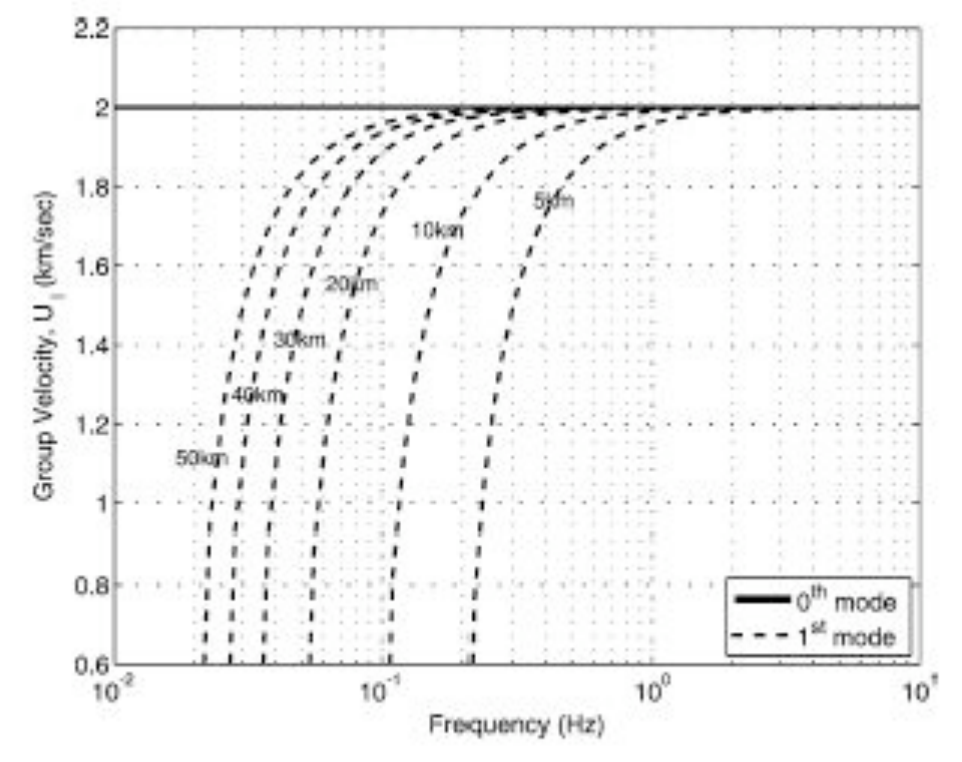
$$u(x,z) = u(z) e^{i(\omega t - kz)}$$

$$\Rightarrow u(z) = u_0 \cos(\pi \ell \frac{z}{H})$$

- This leads, for each mode (i.e. for a given l) to a cutoff frequency below which energy does not propagate and to dispersion curves of the group velocity



$$\frac{\omega^2}{c_x^2} = k^2 + \frac{\pi^2 \ell^2}{H^2}$$

$$\Rightarrow \omega_c = \frac{c_s \pi \ell}{H}$$

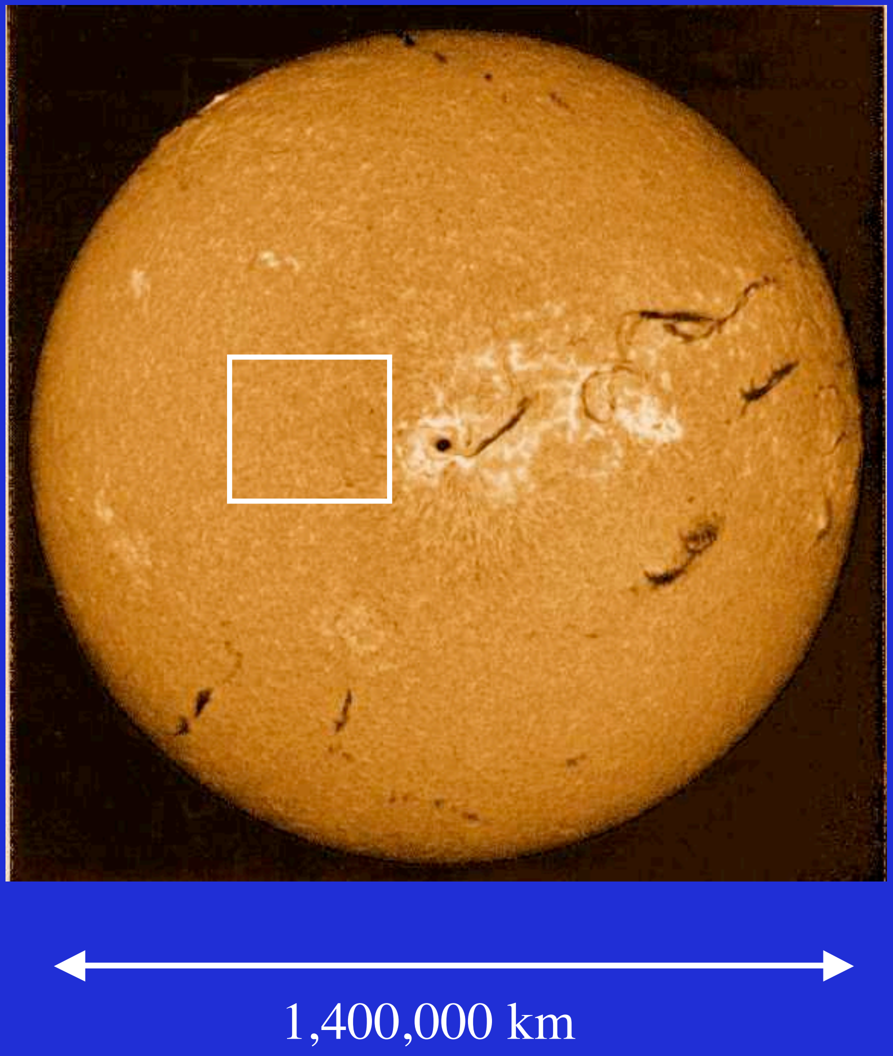
$$\Rightarrow U_g = c_s \sqrt{1 - \frac{\pi^2 \ell^2 c_s^2}{H^2 \omega^2}}$$

- processing of the seismic signal with frequency will provide constraints on the shell thickness

Last but not least…

Remote sensing seismology on Venus

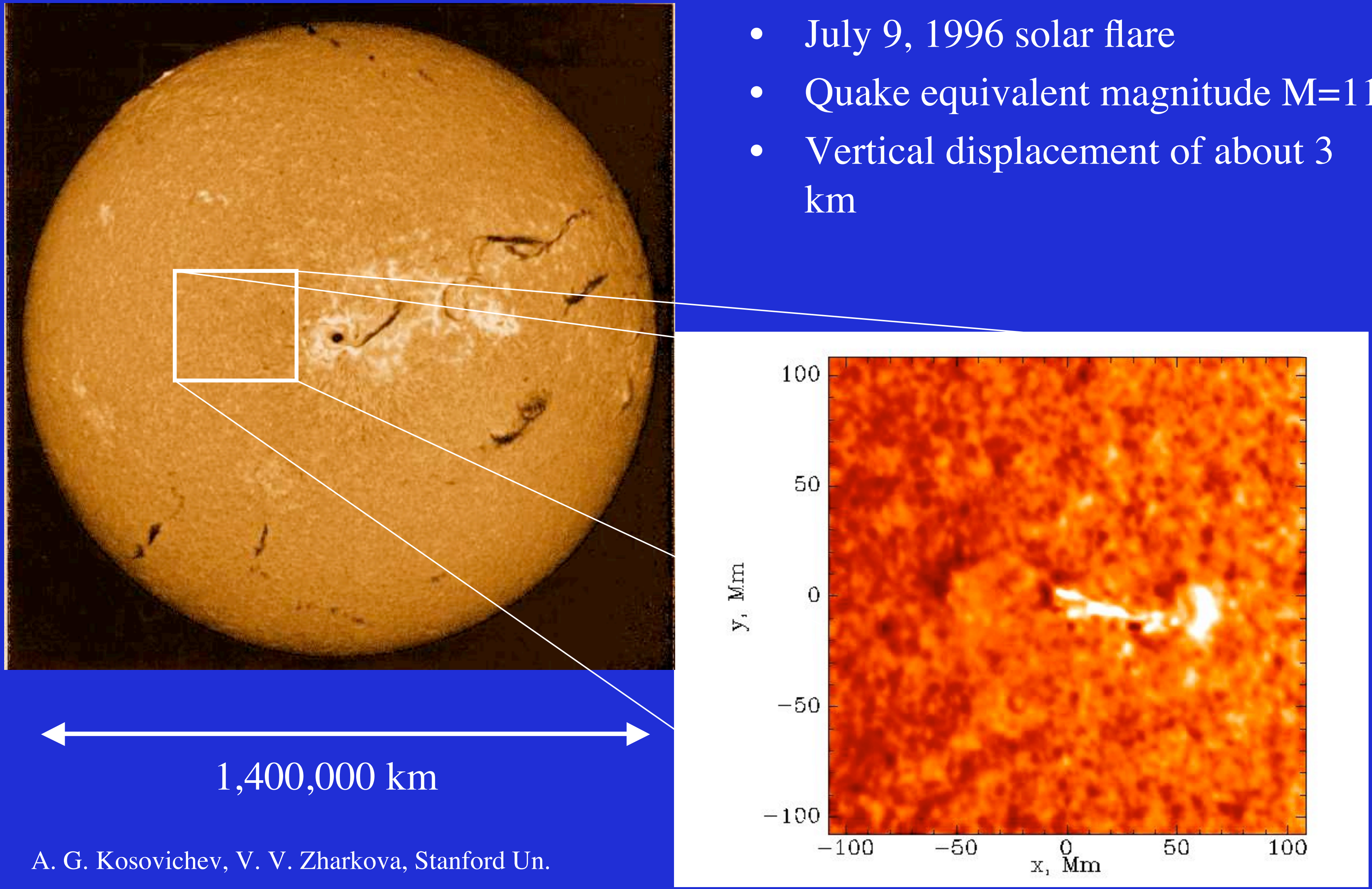
Exemple 1: seismic remote sensing of the Sun



- ESA/NASA spacecraft observation with MDI (Michelson Doppler Interferometer Instrument)
- Sun velocity is measured by a using emission of Ni in the photosphere
- 1024x1024 pixels provide the vertical velocity of the Sun every 60 sec with 20 m/s of error

Exemple 2: seismic remote sensing of Jupiter

- July 9, 1996 solar flare
- Quake equivalent magnitude M=11
- Vertical displacement of about 3 km

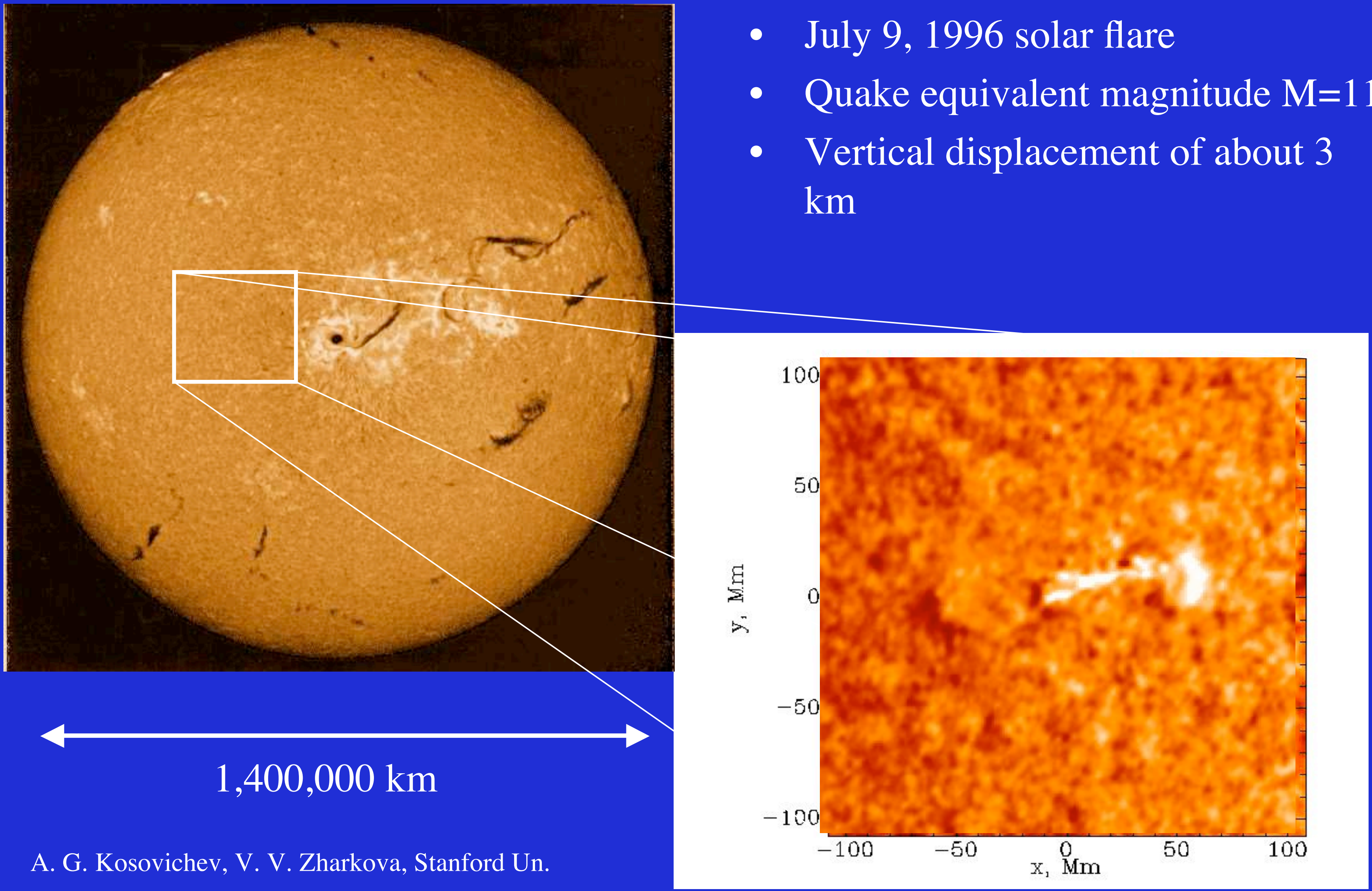


1,400,000 km

A. G. Kosovichev, V. V. Zharkova, Stanford Un.

Exemple 2: seismic remote sensing of Jupiter

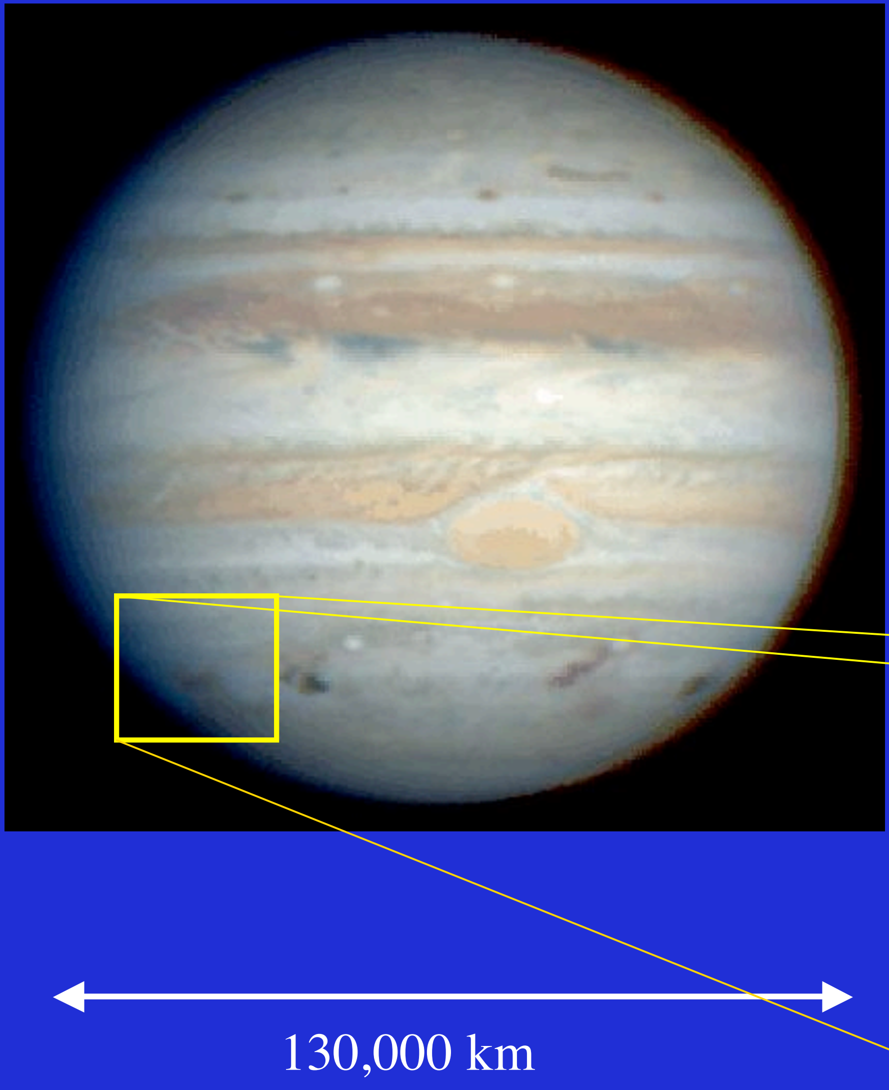
- July 9, 1996 solar flare
- Quake equivalent magnitude M=11
- Vertical displacement of about 3 km

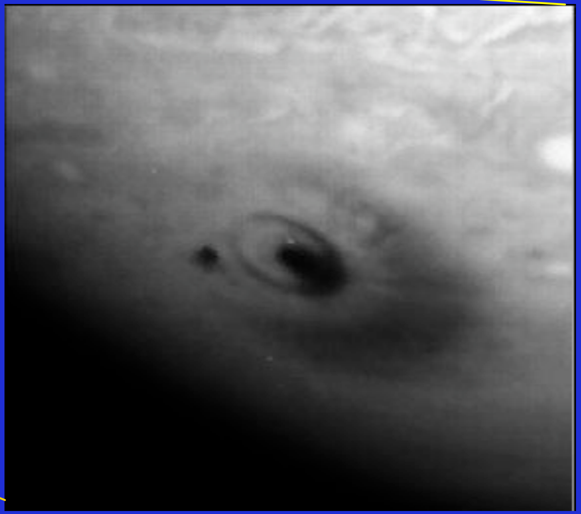


A. G. Kosovichev, V. V. Zharkova, Stanford Un.

Exemple 2: seismic remote sensing of Jupiter

- 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
- Tsunami/gravity waves observed





H. Hammel et al, MIT

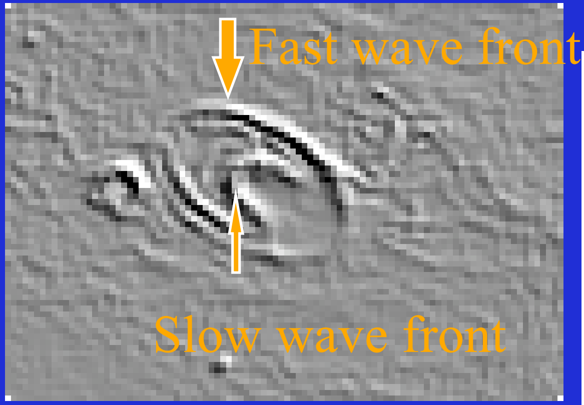
SL9 impact

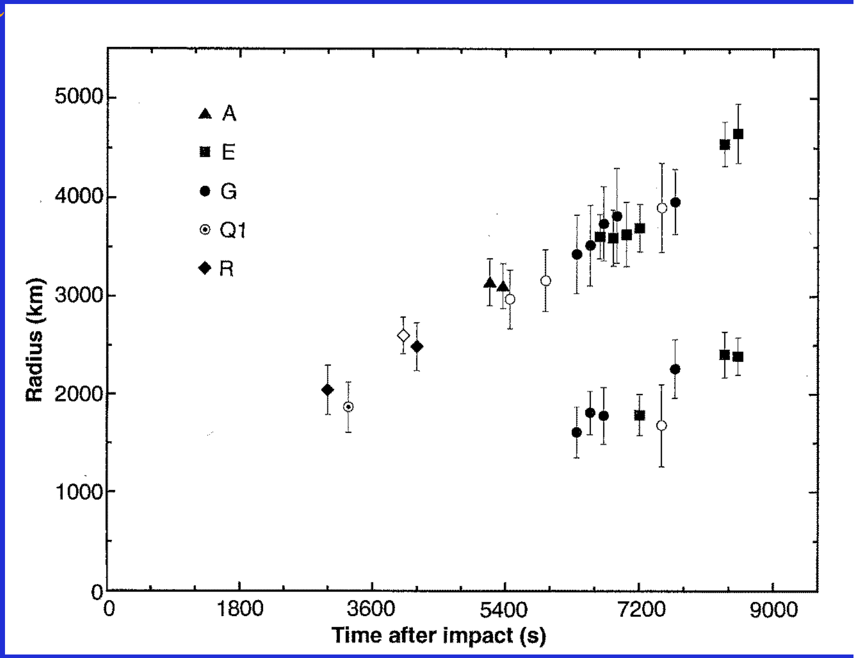

MPI für Astronomie Heidelberg
Centro Astronomico
Hispano Aleman Almeria

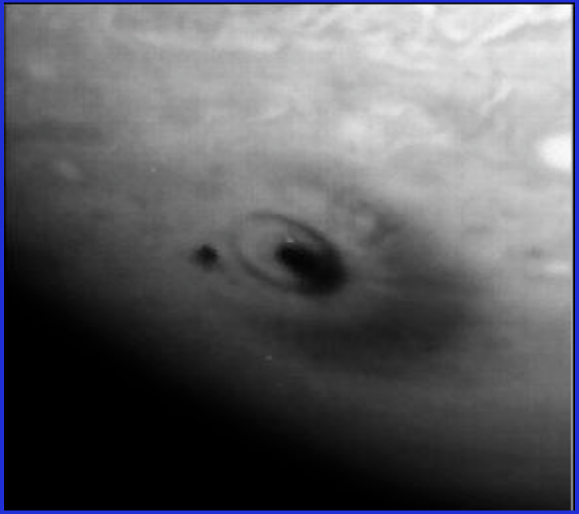
Exemple 2: seismic remote sensing of Jupiter

- Impact of the Shoemaker Levy-9:
  Gravity waves detected by HST

Gravity waves







Hodochrones are still too fast for the present models of Jupiter

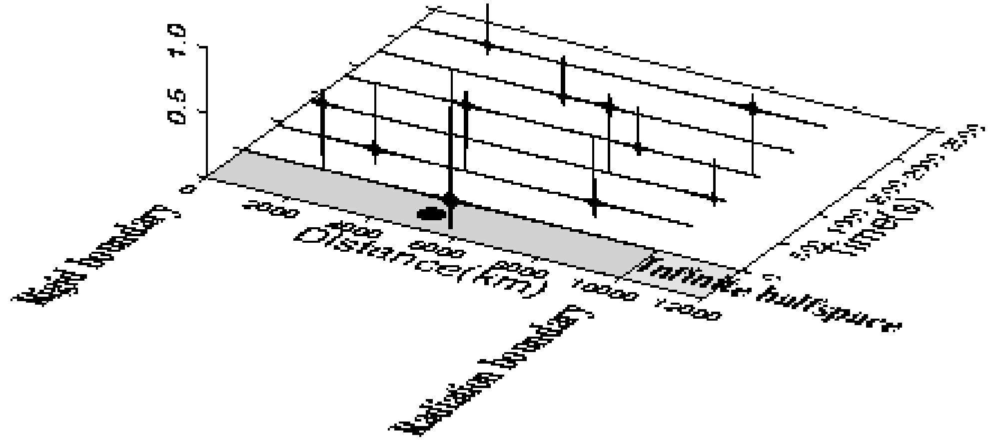
Hammel et al., 1995

Théorie des modes propres: 1D

- exemple d'un milieu semi-infini

$$\frac{\partial^2 u}{\partial t^2} - c^2 \frac{\partial^2 u}{\partial x^2} = 0,$$

$$\frac{\partial\ u}{\partial t} + c\frac{\partial u}{\partial x} = 0, x = L$$



◆ impact:

- ◆ opérateur non-hermitien
- ◆ opérateur symétrique
- ◆ modes bi-orthogonaux

• modes & fréquences complexes
• sommation de modes possible

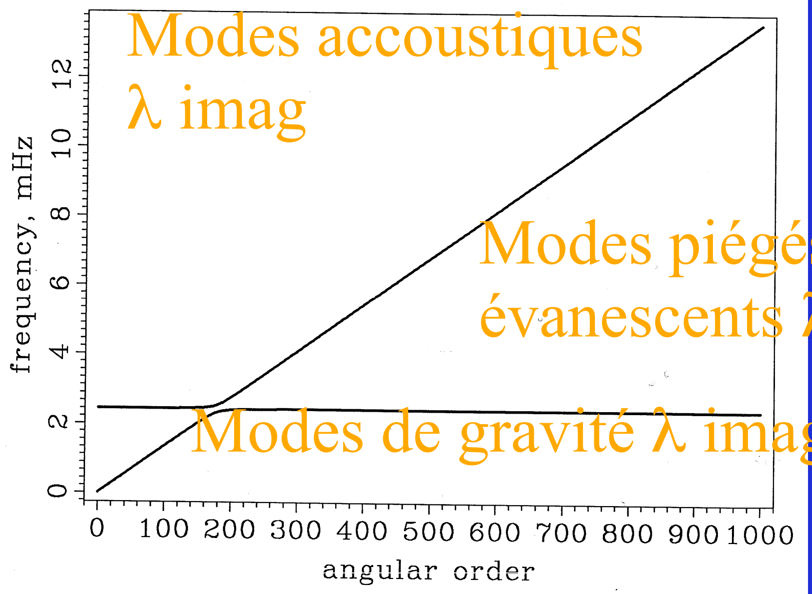
$$\int u_n(x)u_{n'}(x)dx - i\rho_\infty v_\infty \frac{u_n(L)u_{n'}(L)}{\omega_n + \omega_{n'}} = \delta_{n,n'}$$

Approche asymptotique

Théorie des modes 3D

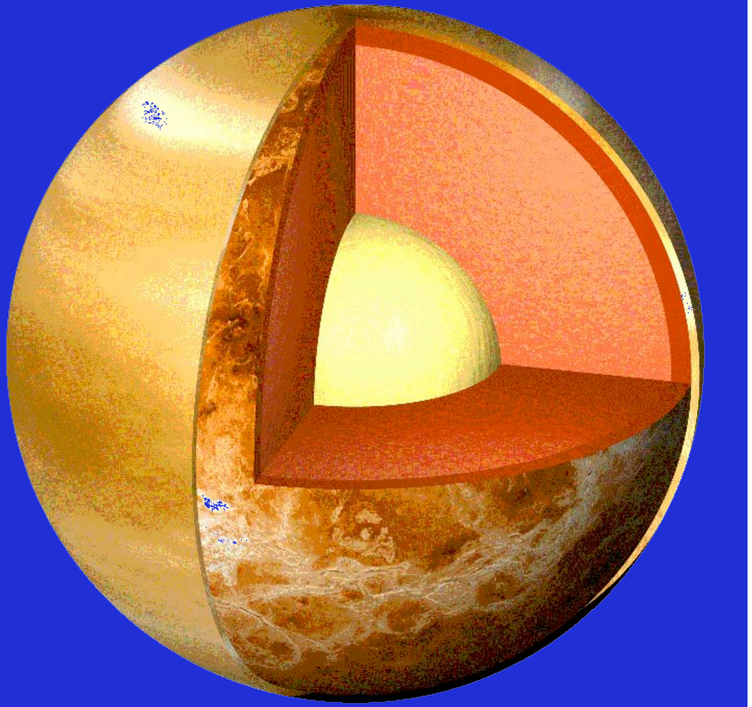
- condition de radiation au sommet de l'atmosphère
- densité d'énergie: $E=\rho u^2 = \text{cte} \exp(-\lambda z/r_0)$
- condition aux limites:
  - $0 = P - (C_{11}-\lambda)/C_{12}\, \rho g U$

- terme supplémentaire
- dépendance fréquentielle

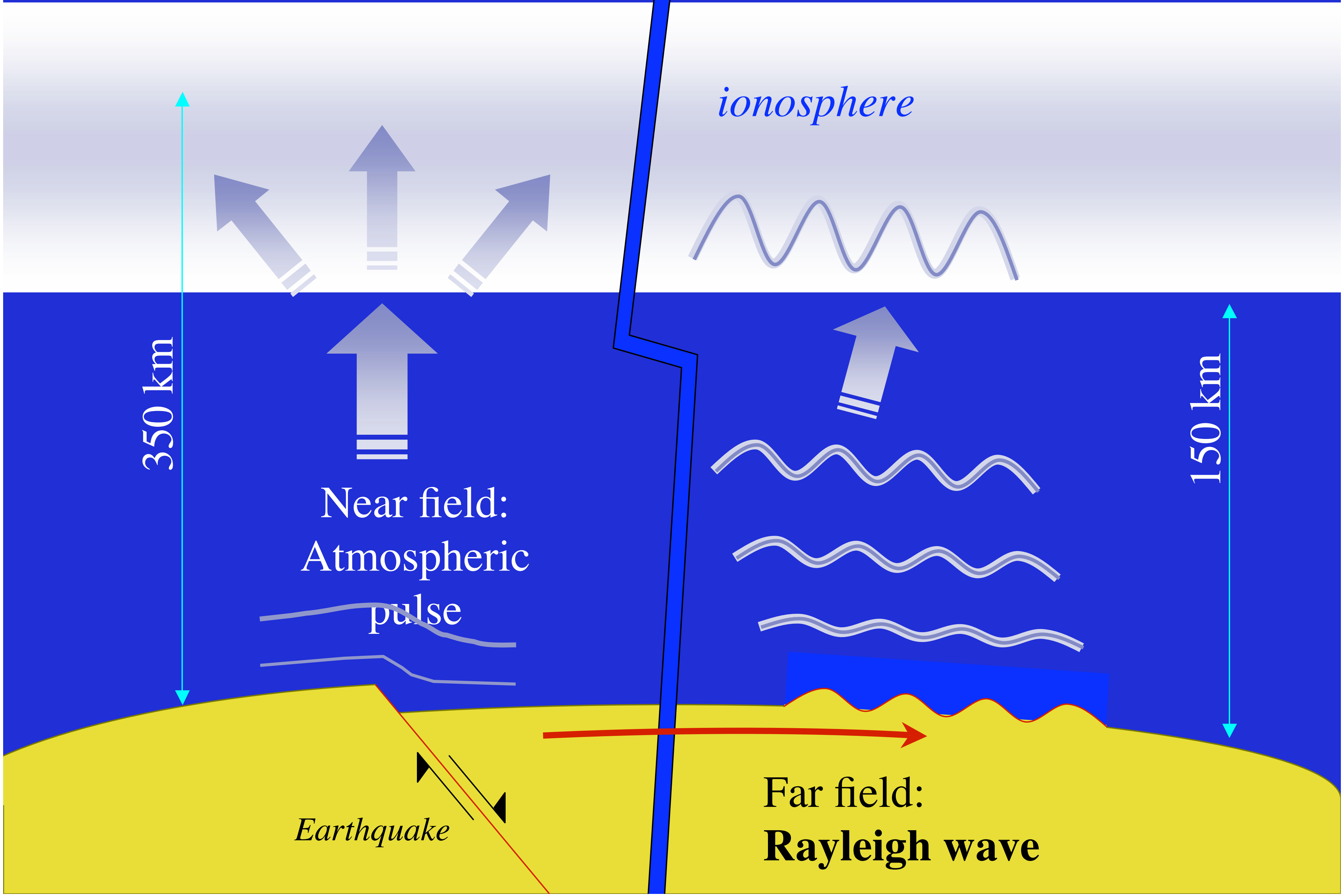


Venus background

- Venus interior is still unknown (gravity data only)
- The resurfacing history of Venus provide an average age of 300-500 Myears for most of the planetary surface
- Rate of volcanism comparable to Earth intraplate activity are found
- Seismic activity of venus might generate a few Ms=6 per month
- On Earth, typically a few Ms=7
- What is the real activity?
- What is the detailled crustal structure?
- What is the upper mantle structure?



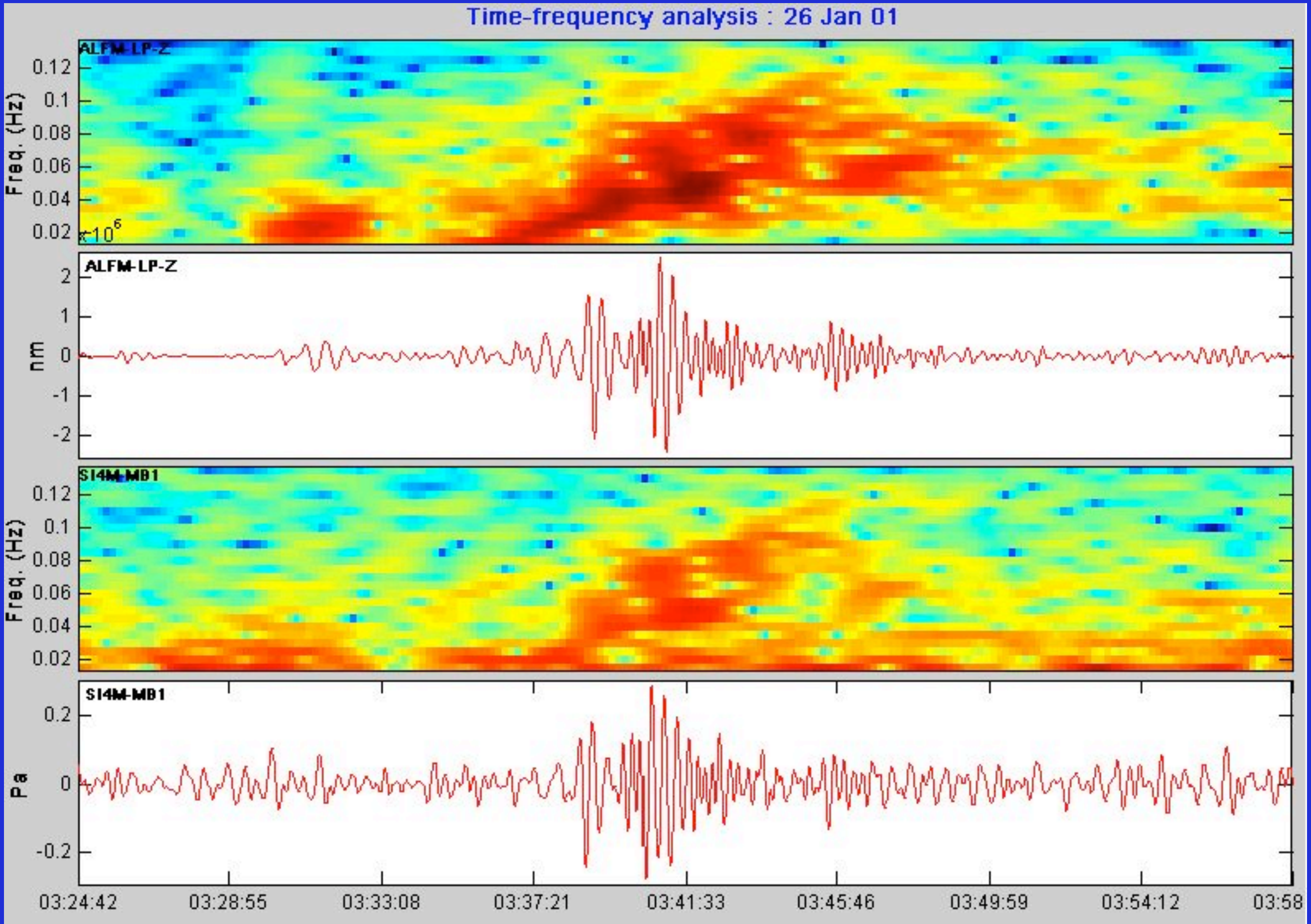
Generation mechanism of infrasonic waves by seismic waves



Pressure and seismic signal at ground level

- India quake, january 26, Ms=8

- CTBT Station: Javhlant, Mongolia

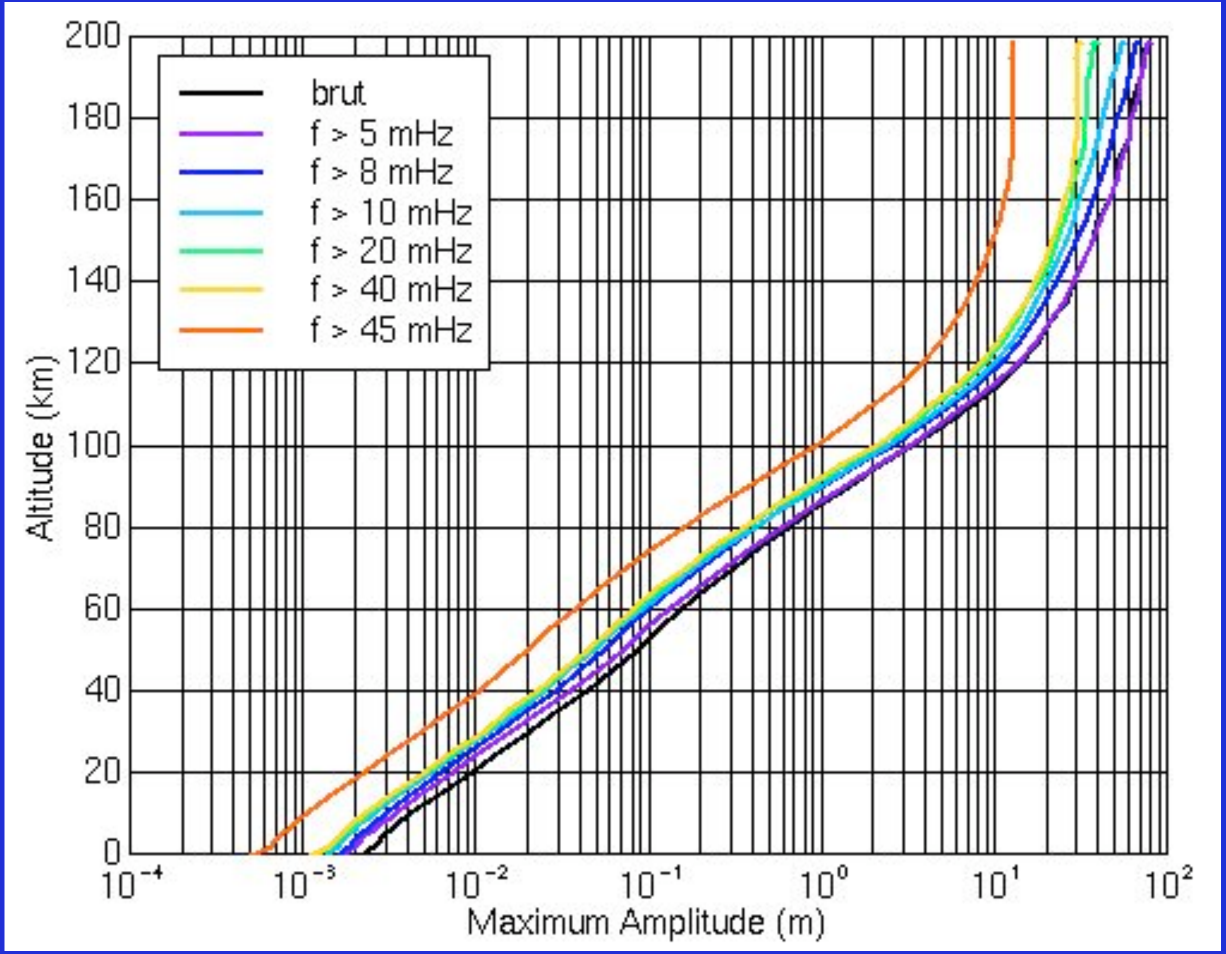


CEA-DASE
(Farges et al., 2002)

Atmospheric propagation

- Attenuation due to viscosity is important above 100 km height and strongly constraints the attenuation of waves (Artru et al., 2001)

Mexico earthquake, 1985. Amplitudes with altitude for Rayleigh waves in France (Ms=8)



amplification -----> attenuation

Coupling atmosphere-ionosphere

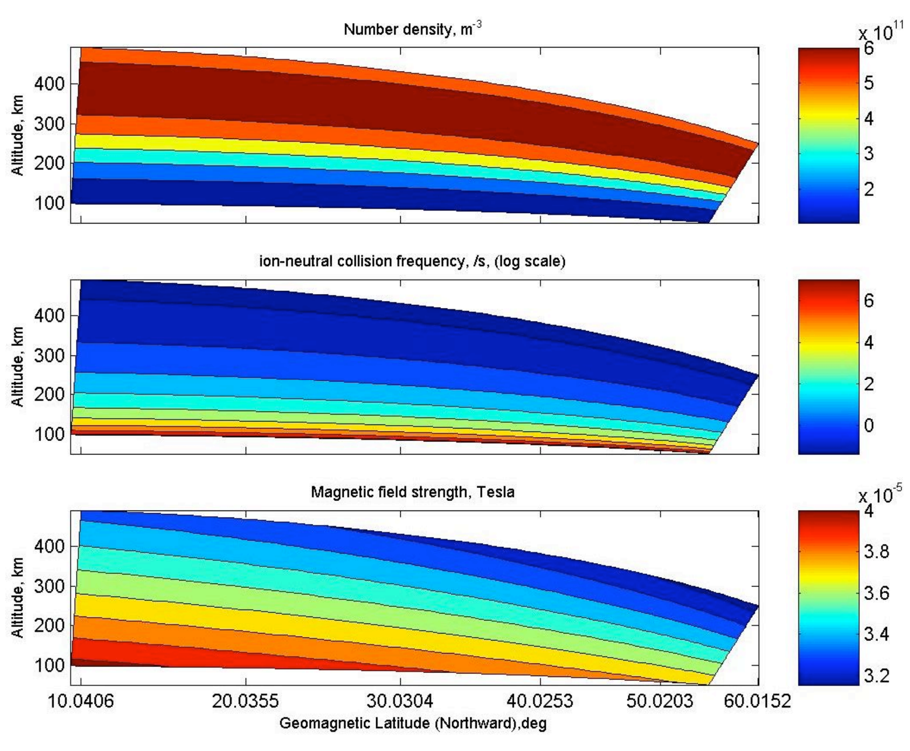
$$\frac{d\vec{v}_i}{dt} = \frac{eB}{M_i}\left(\frac{\vec{E}}{B} + \vec{v}_i \times \vec{n}\right) - \frac{k_B T \nabla N_i}{M_i N_i} + \vec{g} + \nu_{in}(\vec{u} - \vec{v}_i)$$

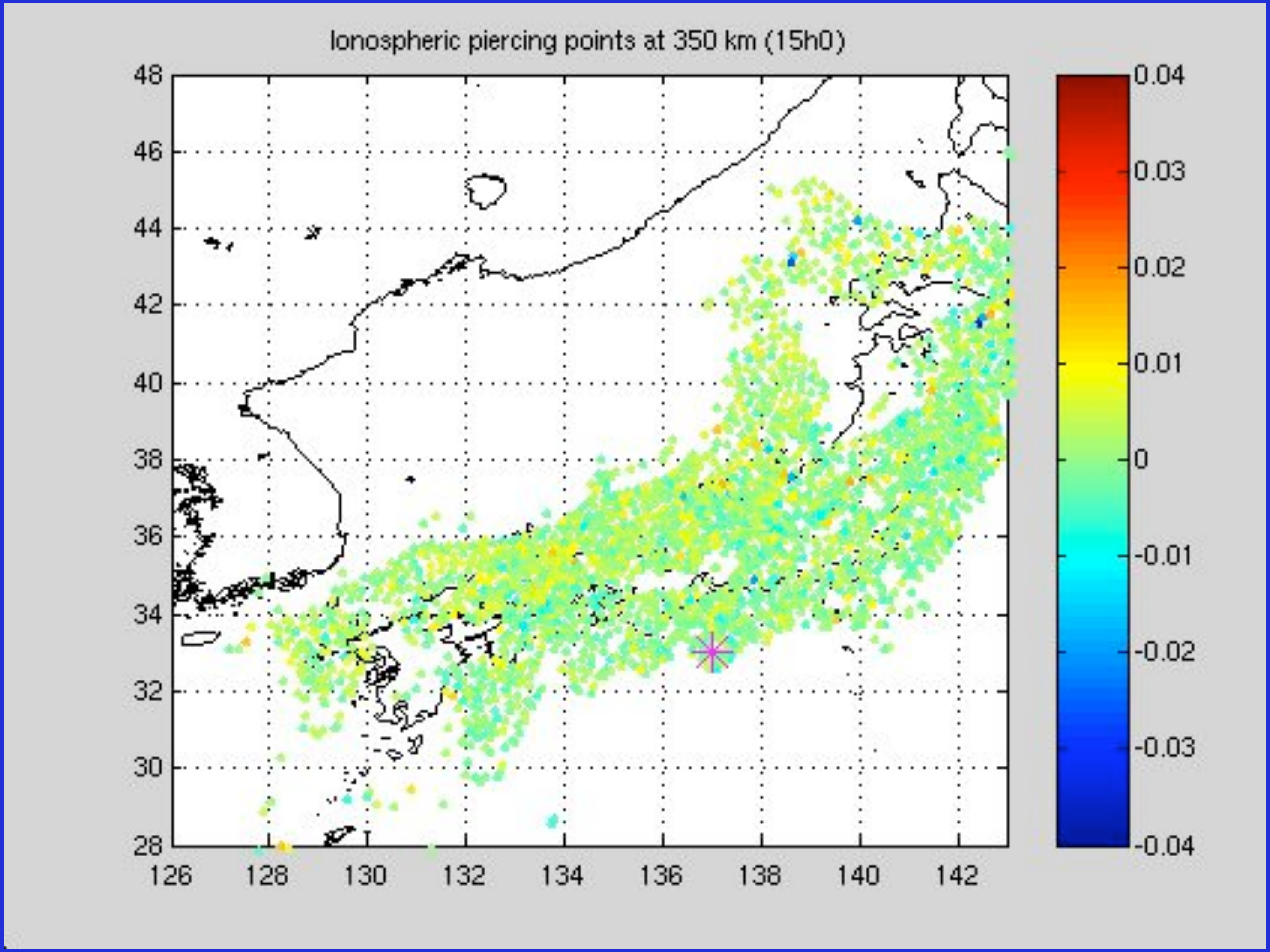
100 s^{-1} ~larger term

1-10 s^{-1}

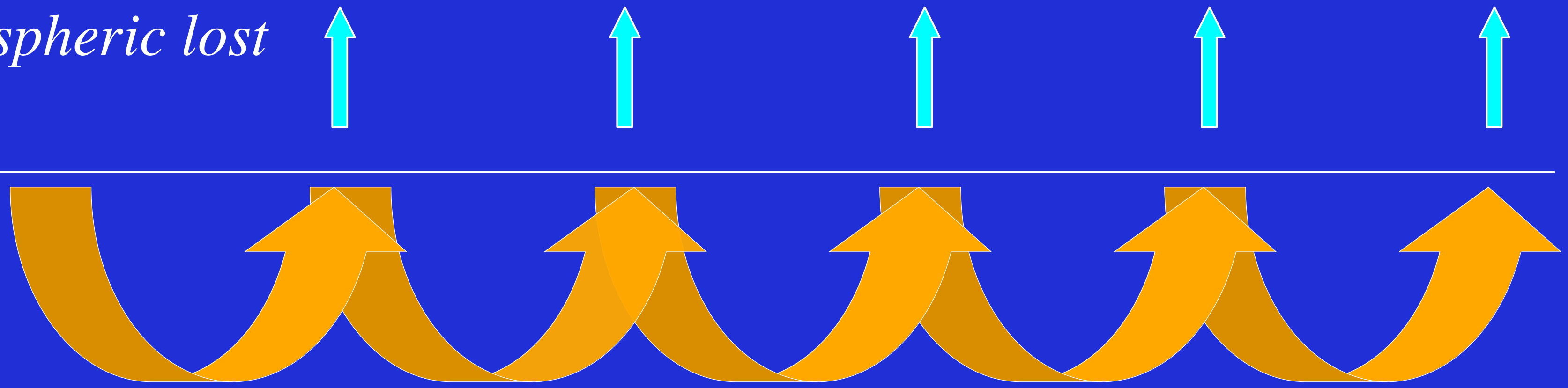
Can be neglected

- gravity can be neglected for the time variations
- control of the signal altitude is by the neutral-ion collision frequency




Ionospheric piercing points at 350 km (15h0)
48
46
44
42
40
38
36
34
32
30
28
126
128
130
132
134
136
138
140
142
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04

Surface waves energy lost?



Atmospheric lost

Solid Earth lost (Q)

Amplitude Conversion

$$t = \frac{2\rho_{\text{int}} c_{\text{int}}}{\rho_{air} c_{air} + \rho_{\text{int}} c_{\text{int}}} \approx 2$$

$$r = \frac{\rho_{air} c_{air} - \rho_{\text{int}} c_{\text{int}}}{\rho_{air} c_{air} + \rho_{\text{int}} c_{\text{int}}} \approx -1$$

Energy Conversion

$$T = \frac{\rho_{air} c_{air}}{\rho_{\text{int}} c_{\text{int}}} t^2$$

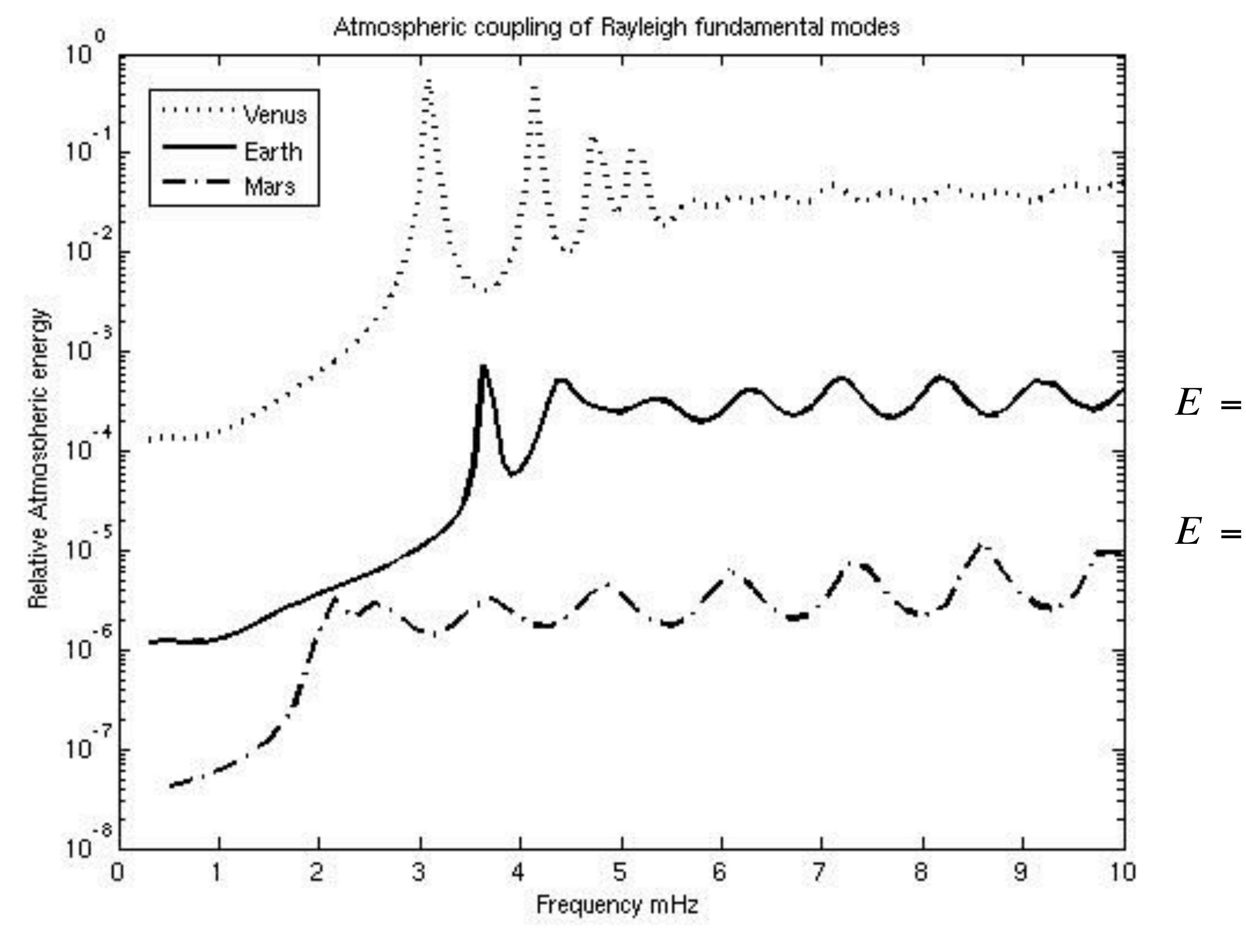
$$R = r^2$$

Energy balance

$$E = T + T\,\mathrm{Re}^{-\frac{2\pi}{Q}} + \ldots + T\left(\mathrm{Re}^{-\frac{2\pi}{Q}}\right)^p + \ldots$$

$$E = \varepsilon \frac{2Q}{\pi} \rho_{air} c_{air} \Big/ \rho_{\text{int}} c_{\text{int}}$$

Atmospheric coupling for several planets…



$$E = T + T\,\mathrm{Re}^{-\frac{2\pi}{Q}} + \ldots + T\left(\mathrm{Re}^{-\frac{2\pi}{Q}}\right)^{p} + \ldots$$

$$E = \varepsilon \frac{2Q}{\pi} \rho_{air} c_{air} \Big/ \rho_{\mathrm{int}} c_{\mathrm{int}}$$

Jupiter

$$\rho_0 \frac{\partial \vec{v}}{\partial t} = -\vec{\nabla} p + \rho_1 \vec{g}_0 + \rho_0 \vec{g}_1$$

$$\frac{\partial \rho_1}{\partial t} + div(\rho_0 \vec{v}) = 0$$

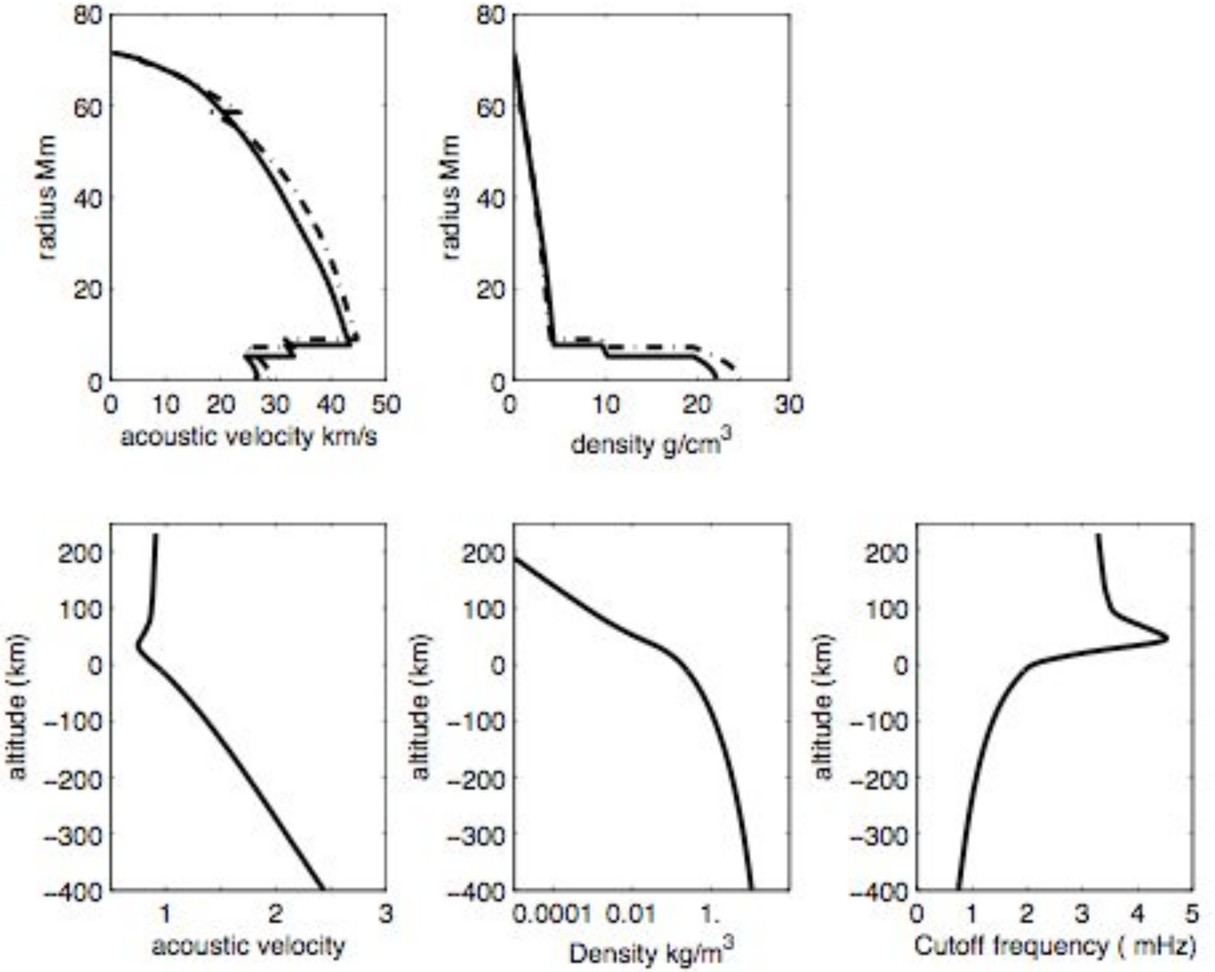
$$div(\vec{g}_1) = -4\pi G \rho_1$$

$$\frac{\partial p}{\partial t} = -\gamma p_0 div(\vec{v}) - \rho_0 \vec{g}_0 . \vec{v}$$

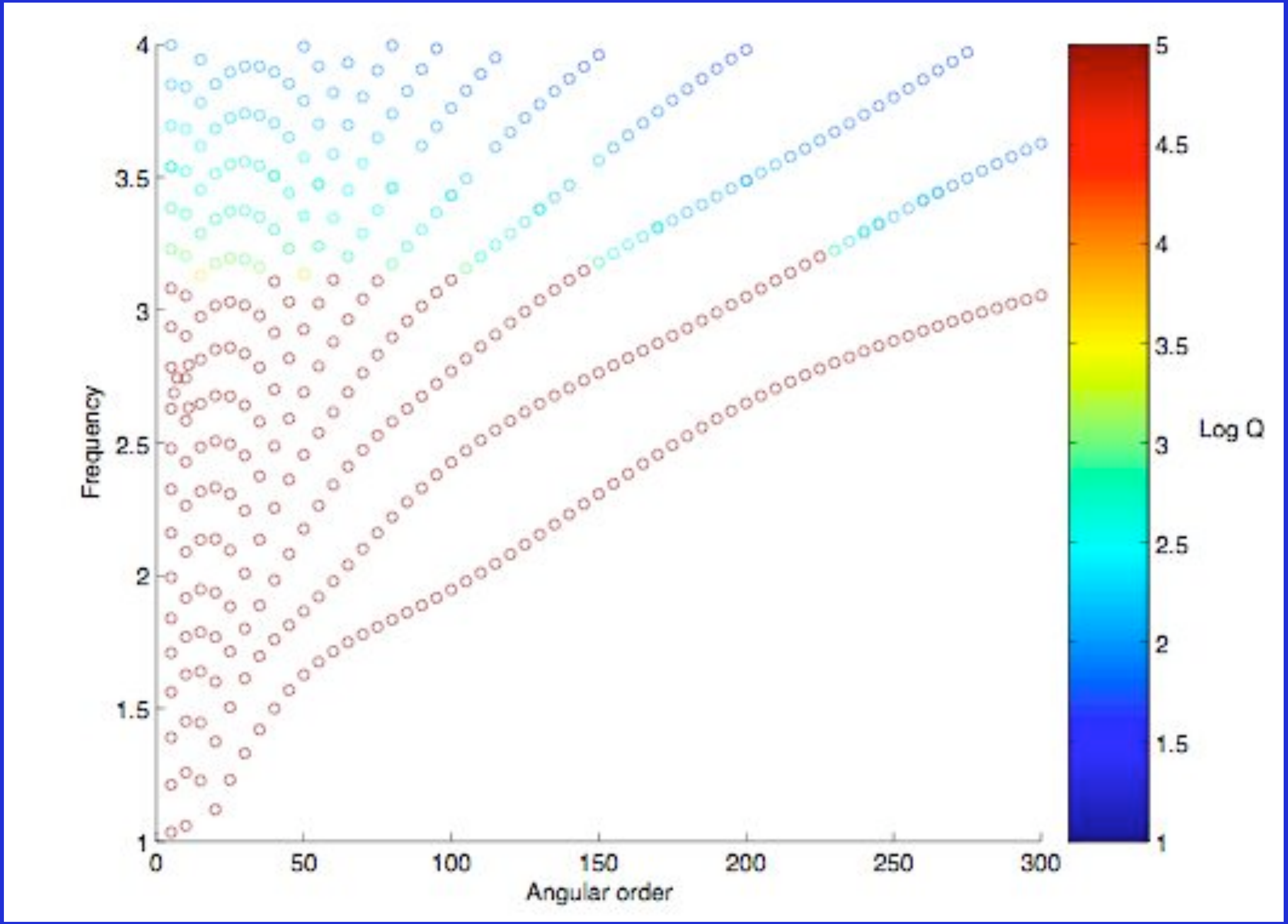
$$(\frac{\partial^2}{\partial t^2} + \omega_c^2)\frac{\partial^2 \psi}{\partial t^2} - c^2 \frac{\partial^2}{\partial t^2} \nabla^2 \psi = 0$$

where the cutoff frequency is given in first approximation by $\omega_c = \frac{c}{2H_\rho}$ and where

$\psi = c^2 \sqrt{\rho_0} div(\vec{v})$ is related to the square root of the acoustic energy $c\gamma_0 p_0 div^2(\vec{v})$,

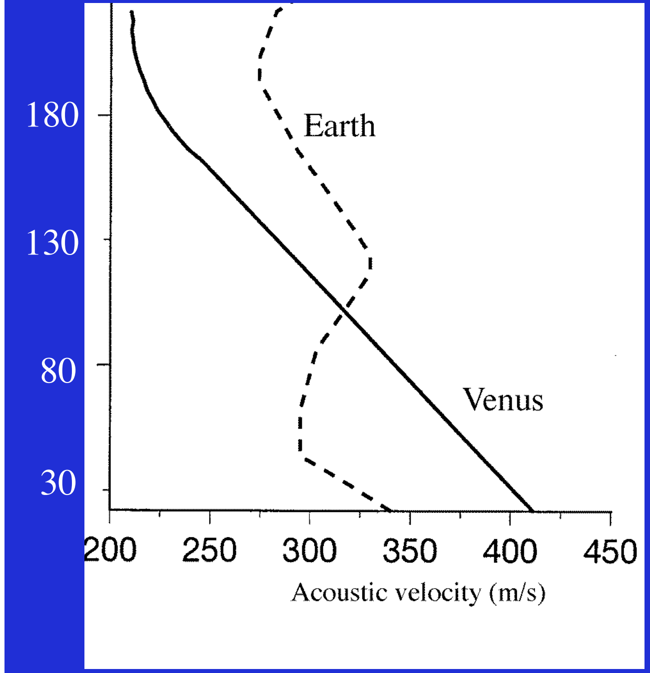


80
60
40
20
0
radius Mm
0
10
20
30
40
50
acoustic velocity km/s
80
60
40
20
0
radius Mm
0
10
20
30
density g/cm^3
200
100
0
−100
−200
−300
−400
altitude (km)
1
2
3
acoustic velocity
200
100
0
−100
−200
−300
−400
altitude (km)
0.0001
0.01
1.
Density kg/m^3
200
100
0
−100
−200
−300
−400
altitude (km)
0
1
2
3
4
5
Cutoff frequency (mHz)


Frequency
1
1.5
2
2.5
3
3.5
4
Angular order
0
50
100
150
200
250
300
Log Q
1
1.5
2
2.5
3
3.5
4
4.5
5

Venus Background for atmospheric seismology

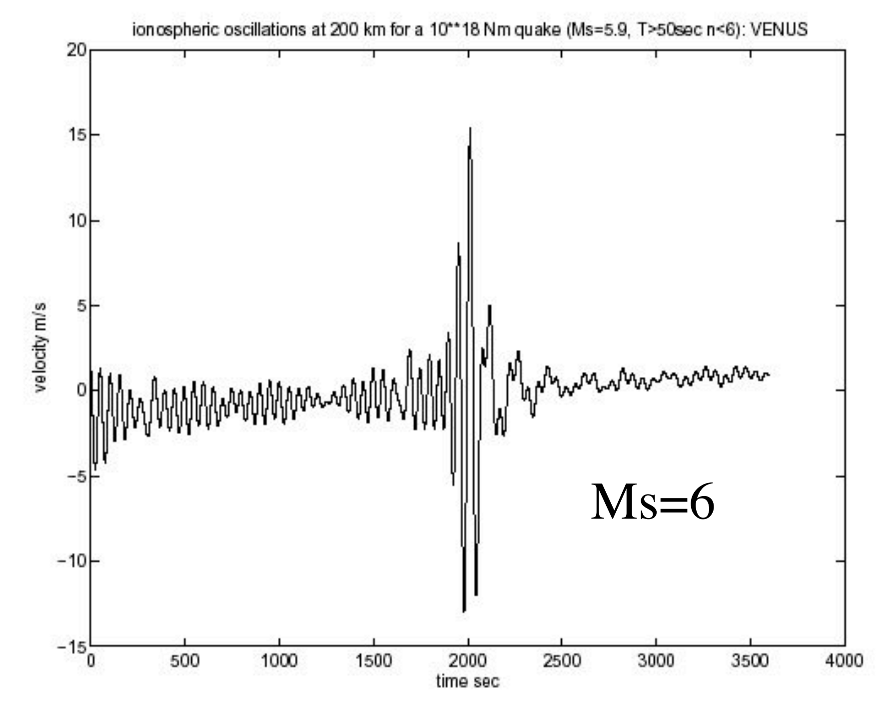
- Maximum ionisation in Venus ionosphere is reached at about 140 km, an altitude comparable to HF sounding altitude on Earth

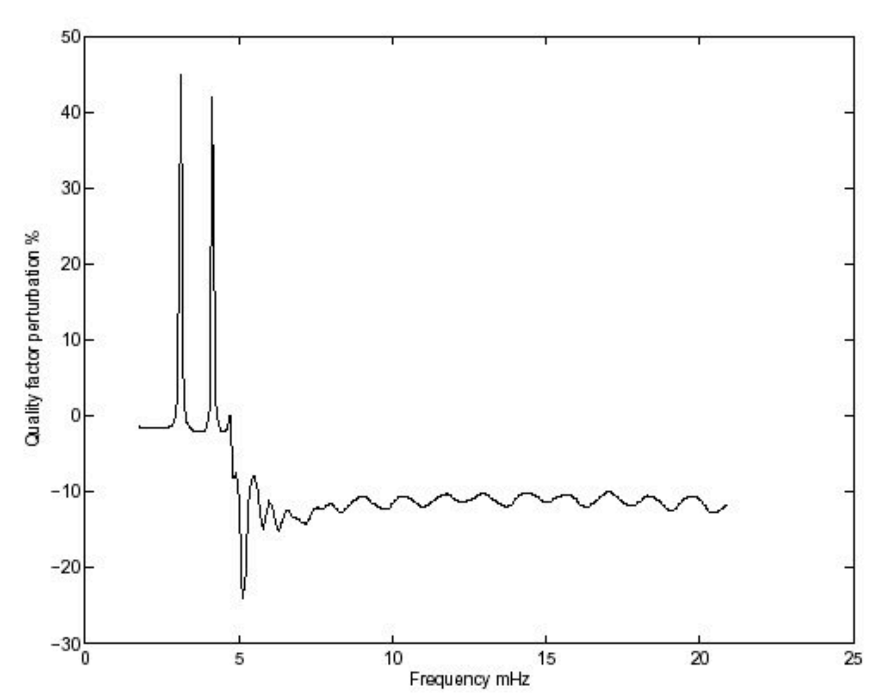


- Ground acoustic jump is much better
  - At the surface, pressure is about 90 bar, density of about 60 kg/m3, acoustic velocities slightly higher (410 m/s)
  - Ground coupling (ρc) is about 60 greater than on Earth
  - One bar level is reached at about 50 km of altitude, after an amplification by about 10 for acoustic waves
  - Acoustic signals from ground are expected to be about 600 times greater at the same altitude and for the same quake (almost 2 magnitudes)

Venus

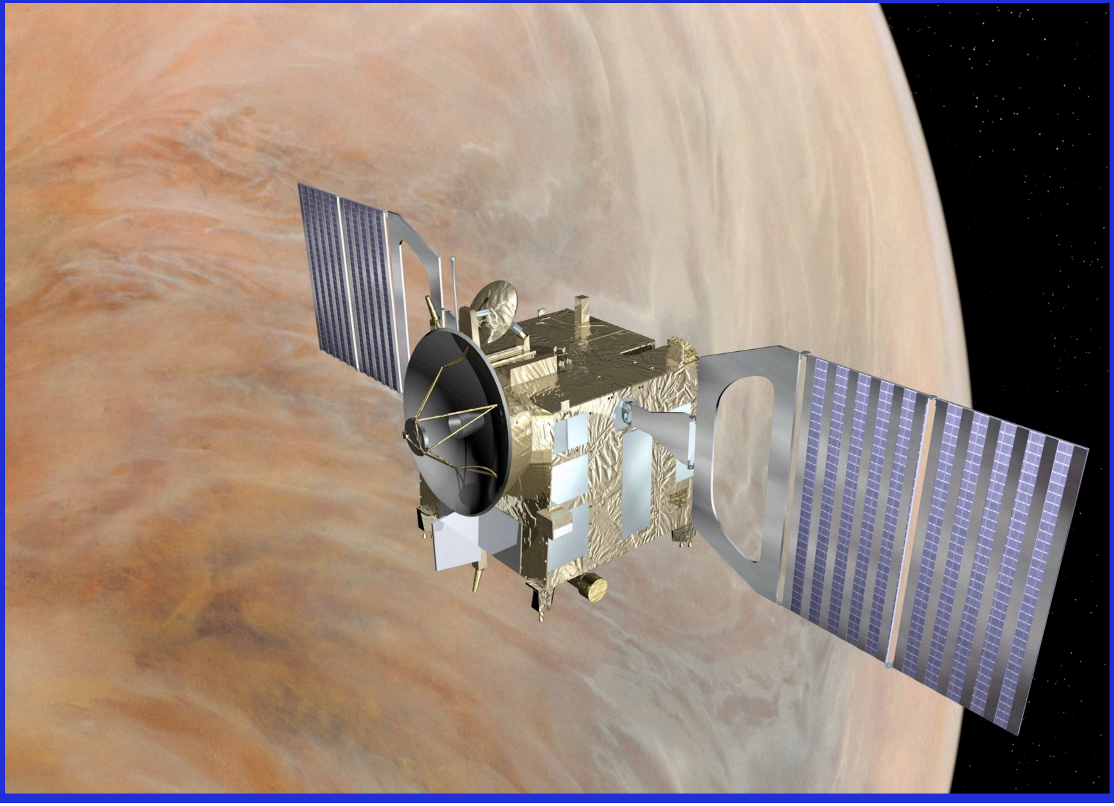
- Les signaux acoustiques sont a priori 600 plus importants pour une détection à une altitude identique et une même magnitude (Lognonné, 2004)
- Effets principaux:
  - Gain de presque deux magnitudes en détectabilité
  - Perte atmosphérique importante de l’énergie des ondes sismiques (15%)





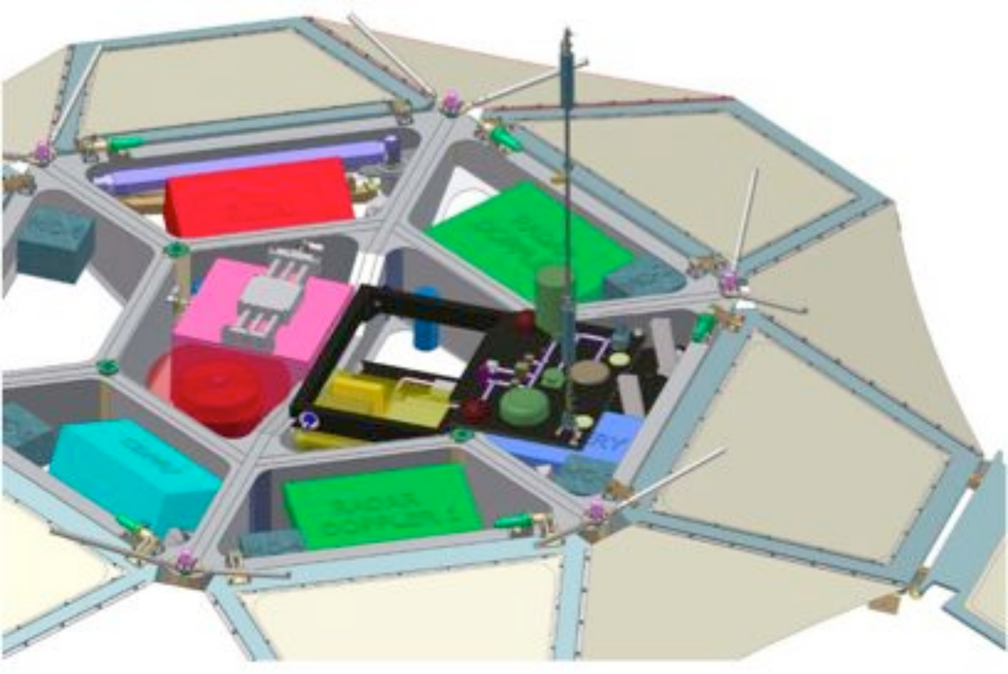
Venus : reconnaissance soon ?

- Search for quake plumes will be performed by ESA Venus Express mission (Garcia et al., 2004)
  - on the way…
  - monitoring of temperature perturbation with a spectro-imaging IR instrument (VIRTIS)
  - airglow detection of CO$^\bullet$ and O$^\bullet$



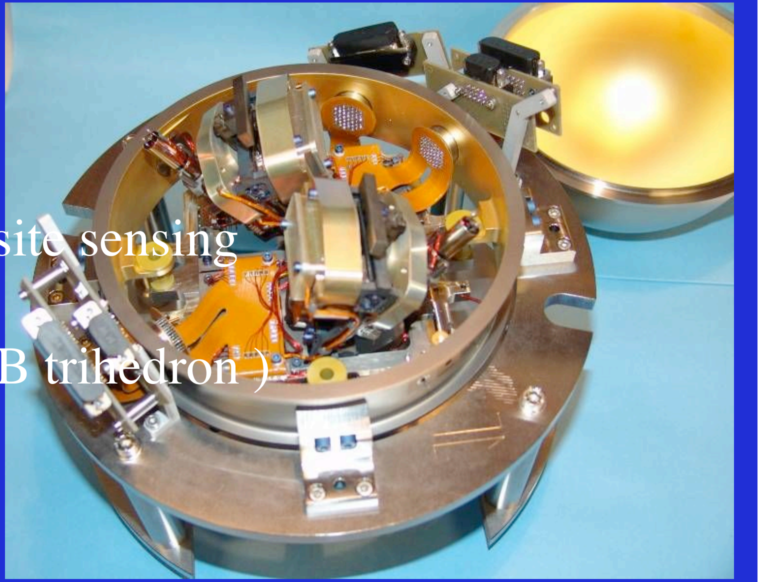
EXOMARS

- Large (~1 G€) ESA mission in phase B2
- Launch in 12/2013
- Two elements
  - Lander with a Geophysical and Environemental Package
  - Rover with an exobiology/geochemistry payload



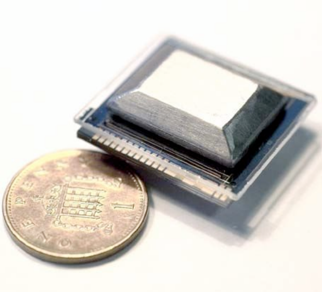
SEIS description

- Objectives : fundamental geophysics, seismic & volcanic activity evaluation, subsurface sounding

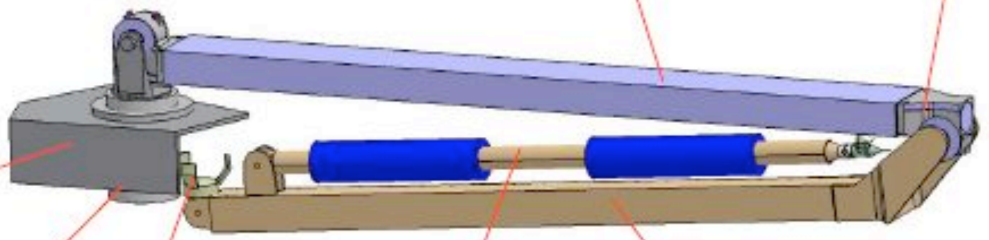


- The Seismometer Experiment is composed of :
  - Two Very Broad Band seismometers, in opposite sensing directions
  - 2 Short Period sensors (one completes the VBB trihedron)
  - An acquisition electronics
  - A deployment system

- SEIS package main performances :
  - VBB ($<10^{-9}$ m.s^{-2} Hz$^{-1/2}$ from 10^{-3} up to 10 Hz)
  - SP ($< 5\ 10^{-8}$ m.s^{-2} Hz$^{-1/2}$ from 10^{-2} up to 100 Hz)



Possible SEIS Deployment



Motor Gear Unit 1
E-motor +gear head
(motor within the tube)

Lever 1 (CFRP)
rectangular tube
(30x30x1)

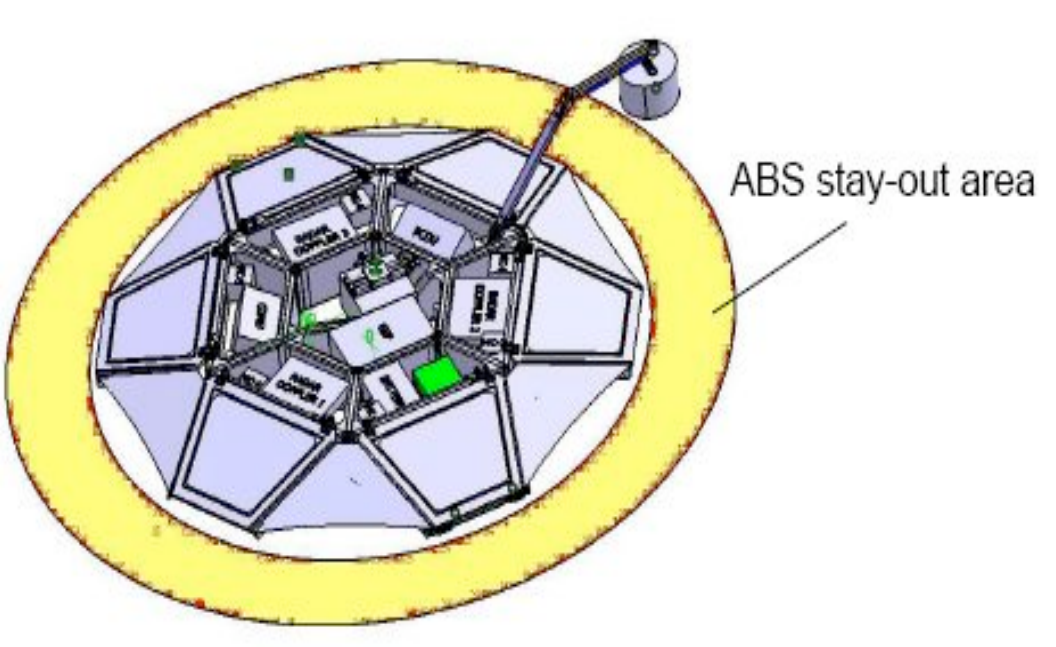
Motor Gear Unit 2
E-motor +gear head
(motor within the tube)

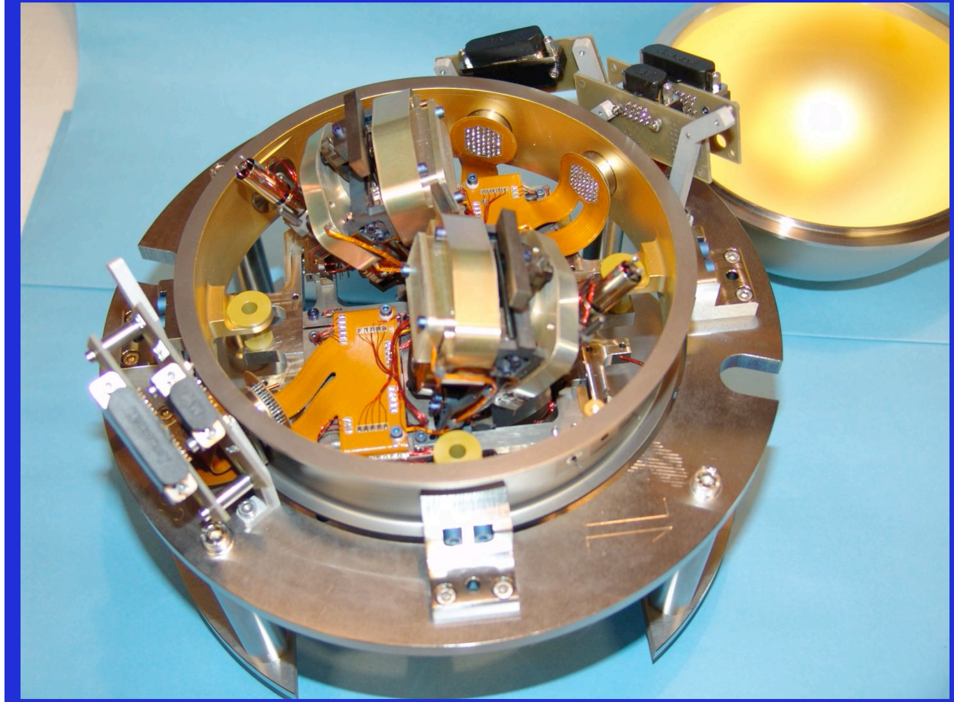
Bracket

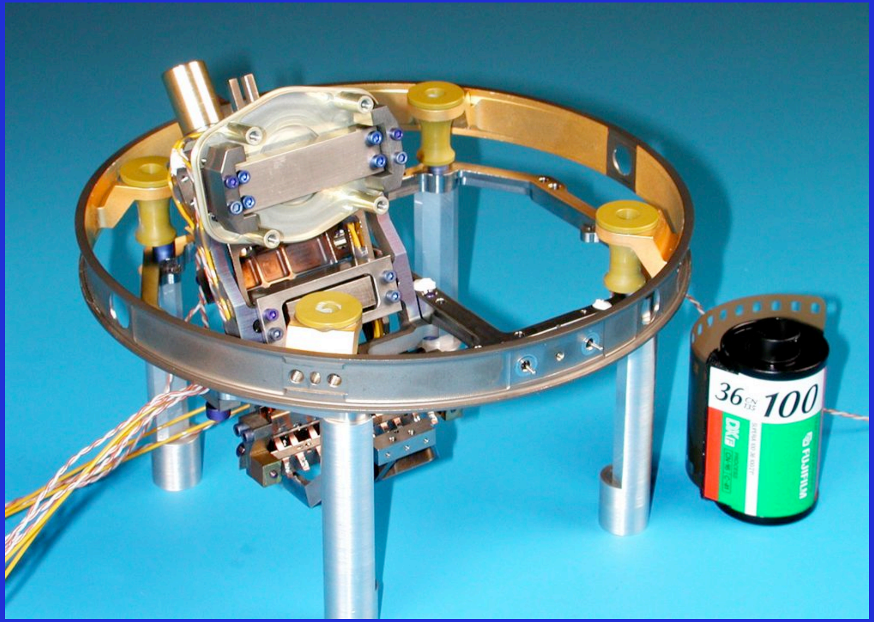
Motor Gear Unit 3

Grapple Fixture

ATM Boom Segment






36
100
FUJIFILM

Guadeloup event recorded in Paris