KISS Workshop Venus Seismology
Short Course

Part III : Taking the lid off the internal structure of Venus : options for seismic investigations

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Contributions from

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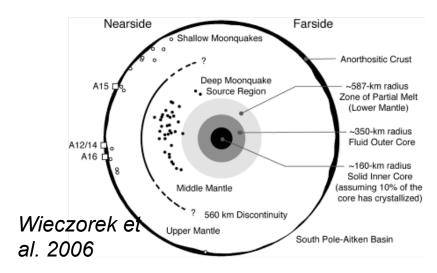
Monday June, 2nd

- Introduction : planetary seismology

- Seismology Basics

- "Classical" seismology for Venus
  - Underlying assumptions
  - Performance Model : Mission duration / S/N trade
  - Seismology with one station
  - Noise map analysis
  - Technological challenges for a Venus seismometer

- "Alternate" seismology : infrasound and remote sensing seismolog(ies)
  - Atmosphere coupling : basics
  - The theoretical background : absorption , amplification, impedance
  - Propagation in the upper atmosphere
  - Infrasound measurement : technology & challenges
  - Various options for quake remote sensing from orbit
  - Orbital measurements : technology & challenges

- Synthesis of possible techniques
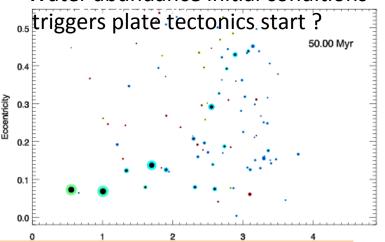
Apollo heritage

Grand Tack scenario : late heavy bombardment – w/ water-rich comets

Wieczorek et al. 2006

Internal structure

Water abundance initial conditions triggers plate tectonics start ?

50.00 Myr
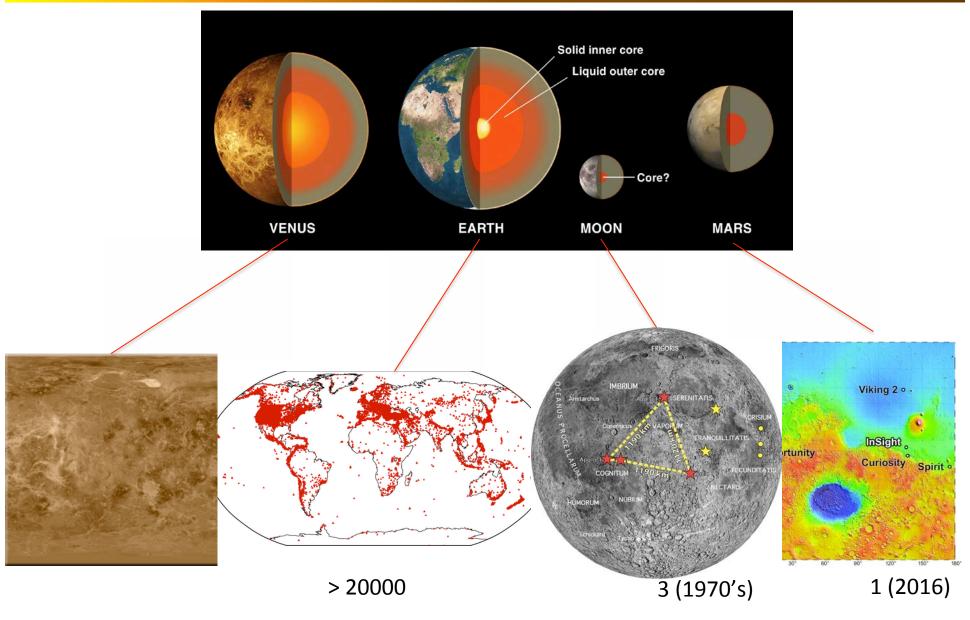
Planetary Seismology tells the story of the solar system

(S Raymond, K. Walsh)

VENUS   EARTH   MOON   MARS

> 20000   3 (1970's)   1 (2016)

- Seismology use the transmission of waves through various materials to derive the structure of the medium seen along the path

Source Pulse

Seismogram

Transmission Reflection

Location, Time

Origine Time

Medium 1 → Medium 2 → ..... → Medium n

Travel Time

Ground motion

Seismometer — Feedback

Arrival Time

Modified after Schearer, 2010

- A seismometer is just a (very) long period, very, very sensitive accelerometer which measures the ground motion…It is most of the time based on analog measurements
  - No « cool factor » …(e.g no laser shooting, no 3D image)
  - However ..
    - Visible IR Imagers , Spectrometers : first microns ⎤
    - Neutrons : up to a meter   ⎬ Superficial
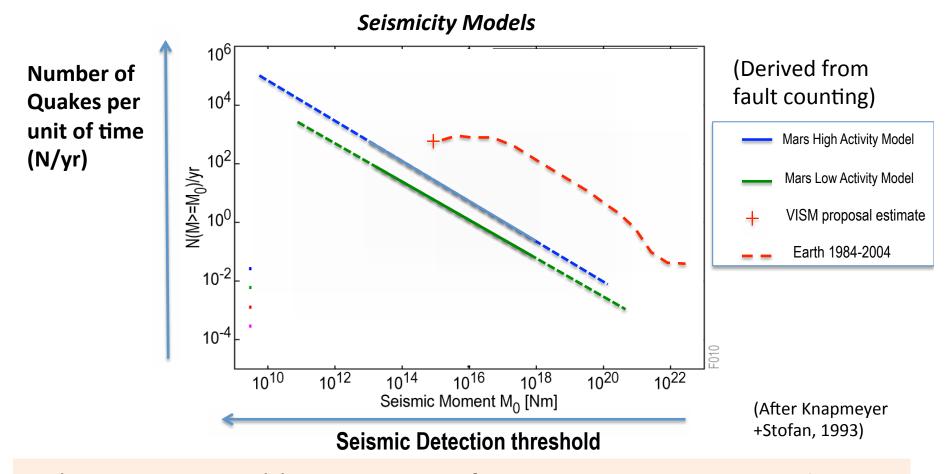   - GPR : meters to km (best cases)   ⎦

- Seismometers : sounding down to the planet core
  - Seismology with several stations (e.g Apollo, Netlander) : sounding with "classical" ray inversion
  - Seismology with one station (like Insight)
    - Surface waves study : crust and upper mantle information
    - Normal modes inversion : global structure, core studies

- Seismic velocities gives constraints on material composition modified by **pressure,** porosity, lithification, fluid saturation … (calibrated in lab)

- Importance of assumptions on seismicity.
- The more sensitive the seismometer is, the more quakes it detects.

Seismicity Models

(Derived from fault counting)

Number of Quakes per unit of time (N/yr)

Legend:
- Mars High Activity Model (blue solid line)
- Mars Low Activity Model (green solid line)
- + VISM proposal estimate
- Earth 1984-2004 (red dashed line)

Seismic Detection threshold

(After Knapmeyer +Stofan, 1993)

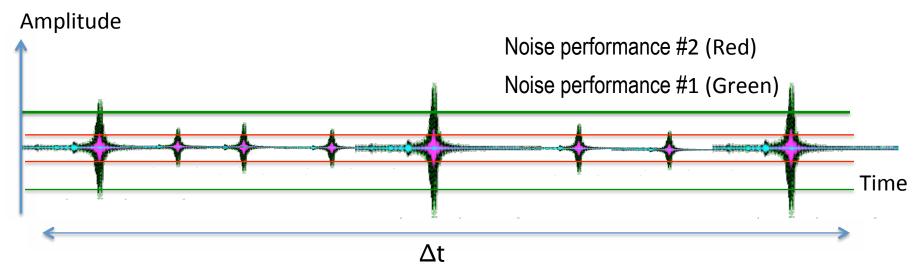## What is a reasonable assumption for Venus seismic activity ?

- A certain number of quake detections is required to inverse the structure
- If the environment or the instrument noise increases, you have to wait longer (statistically) to get the same number of quakes : a longer observation time can recover noise increase, but it's not linear.

Amplitude

Noise performance #2 (Red)

Noise performance #1 (Green)

Time

Δt

- Noise level #1 gets 2 or 3 quakes detection in Δt, when noise level #2 gets 8
- There is **no threshold effect in the performance**, but a graceful degradation as the noise goes higher.
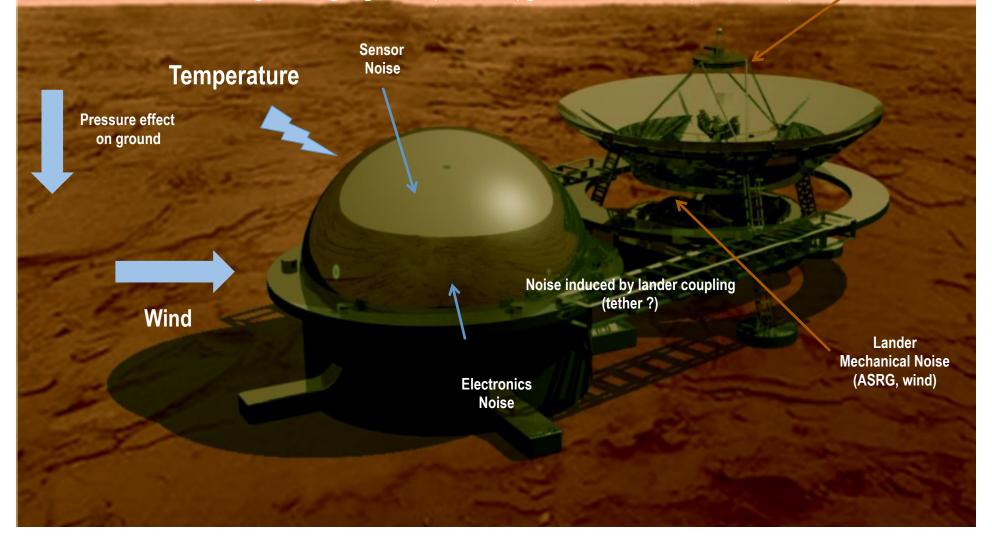
Noise Sources on a Venus long lived lander

Noise sources can be classified as:

Instrument Self Noise; includes contributions from sensor head, electronics and tether
Environmental effects generating noise in the instrument, such as thermal sensitivity)
Environmental effects linked to the system (Lander Noise)
Environmental effects generating large-scale (10–100 m) ground acceleration (Pressure tilt)
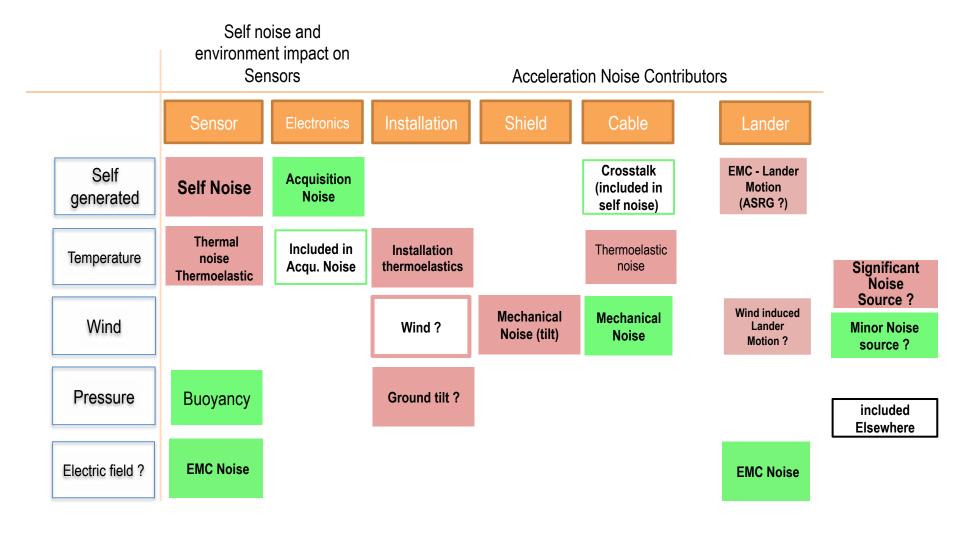
EMC perturbation

Temperature

Sensor Noise

Pressure effect on ground

Wind

Noise induced by lander coupling (tether ?)

Electronics Noise

Lander Mechanical Noise (ASRG, wind)

- Reach the required **sensitivity** and **bandwidth,** with a sufficient coupling with the ground
  - Mechanical design can be very simple and robust
  - Electronics is a more difficult issue
    - Acquisition, feedback if broadband seismometer, possibly tether or transmission device
  - Preliminary guess 10^{-8} m/s^2/$\sqrt{Hz}$ [0.05 – 1 Hz] including environment ?
  - Broadband vs geophone ?

- Reach the **required duration** for the measurement… under Venus conditions
  - Provide power, data processing and telecommunication functions for at least 1 year (TBC)

(Hunter and al)
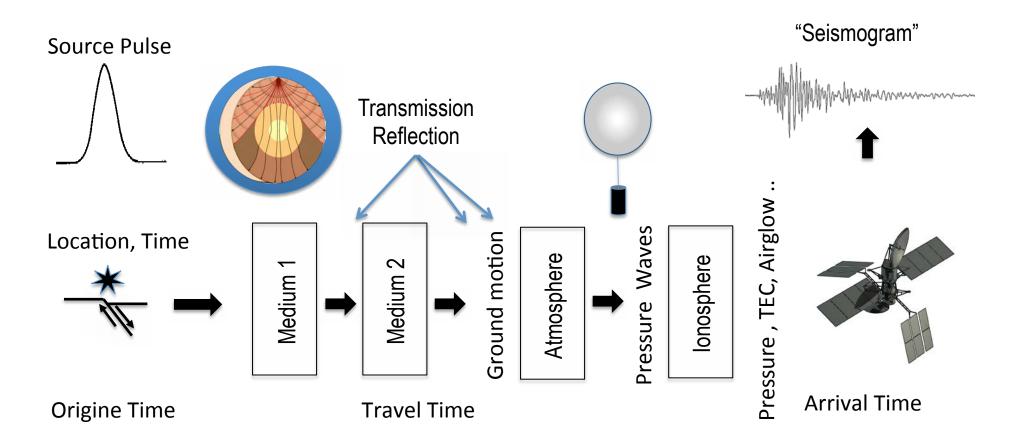
- Interest of having more than one probe ?

Sustaining a Venus probe and the seismometer about one year at 500°C 90 atm is a significant challenge

- Use of Solid Venus / Atmosphere coupling may provide a way forward to avoid qualifying a long lived lander and seismometer to the Venus conditions
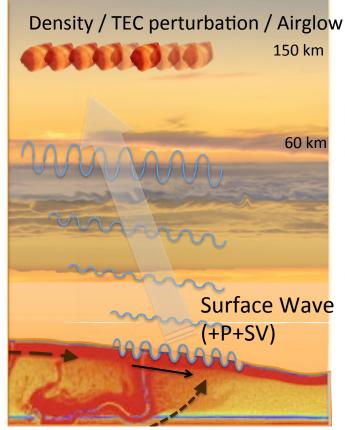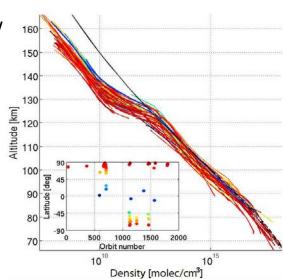
Source Pulse

"Seismogram"

Transmission
Reflection

Location, Time

Medium 1

Medium 2

Ground motion

Atmosphere

Pressure Waves

Ionosphere

Pressure , TEC, Airglow ..

Origine Time

Travel Time

Arrival Time

Modified after Schearer, 2010

- Long period waves couple at the planet surface with atmospheric gravito-acoustic waves propagating upward in the atmosphere [Lognonné et al., 1998; Occhipinti et al., 2006; Hickey et al., 2009]. Due to kinetic energy conservation and to the exponential density decrease in the atmosphere, these waves are amplified and generate significant perturbations in the thermosphere/ionosphere system

Density / TEC perturbation/Airglow

Density / TEC perturbation / Airglow

150 km

60 km

Surface Wave
(+P+SV)

(Mahieux et al, 2012)

Amplification from **6E6 to 6E7** between **150 & 250 km altitude**

$$\sqrt{\frac{\rho(0)}{\rho(z)}} \longleftarrow \boldsymbol{\rho v^2 = constant}$$
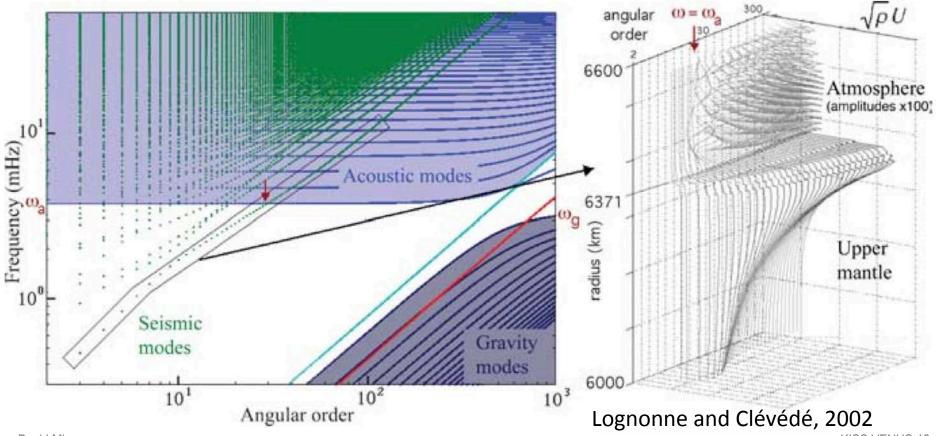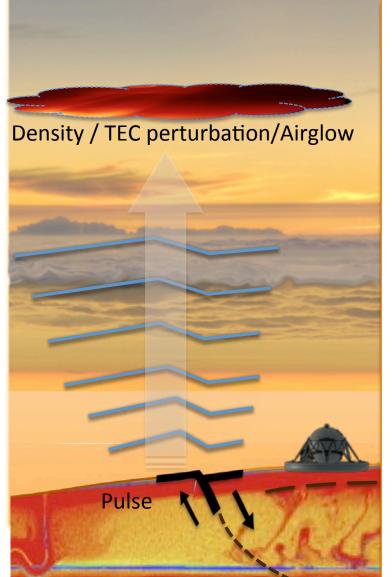
- Acoustic Gravity Wave Theory :
  - ✓ **Hines, 1960**

- Earth atmosphere coupling :
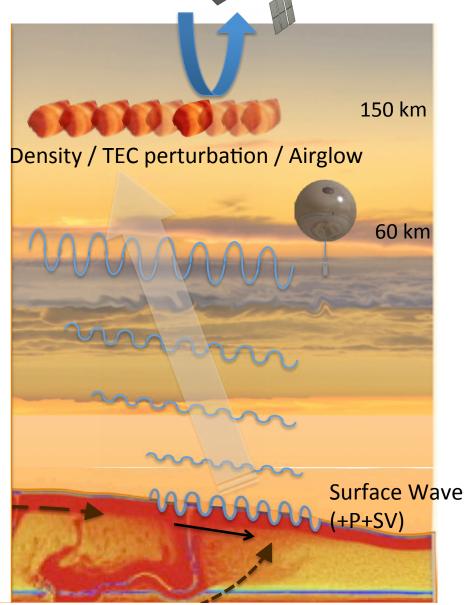 - ✓ **Wolcott et al., 1984**

- Eigenfrequency extended to Earth with ocean & atmosphere:
  - ✓ **Lognonné et al., 1998 ;**
  - ✓ **Artru et al., 2001 ;**
  - ✓ **Lognonné et Clévédé, 2002 ;**

Lognonne and Clévédé, 2002

Solid Venus / Atmosphere coupling

Density / TEC perturbation/Airglow

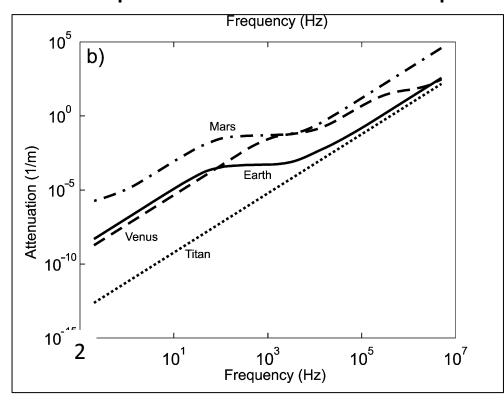Density / TEC perturbation / Airglow

150 km

60 km

Pulse

Surface Wave
(+P+SV)
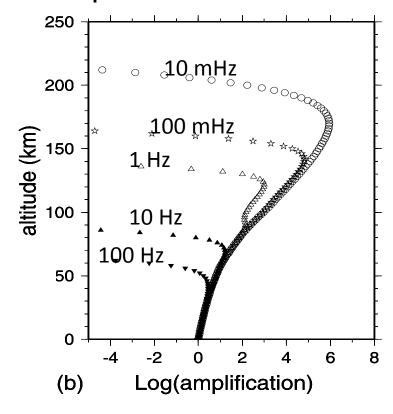
- Competition between absorption and amplification

Frequency dependence of the attenuation coefficient on four planets (Petculescu ,2006)

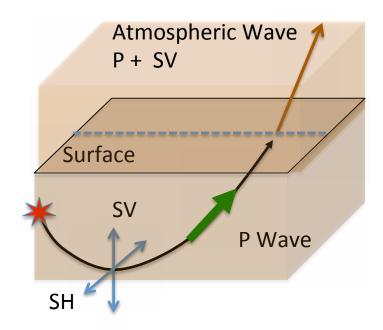Acoustic wave amplification as a function of altitude on Venus from Garcia et al (2005)

Absorption is not a significant factor below 50 km in the atmosphere
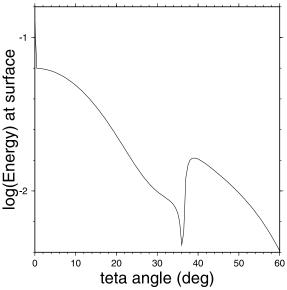**Absorption has large frequency dependent effects above 50 km**

- S waves (shear) do not propagate into fluids but their vertical component can be transmitted at the interface

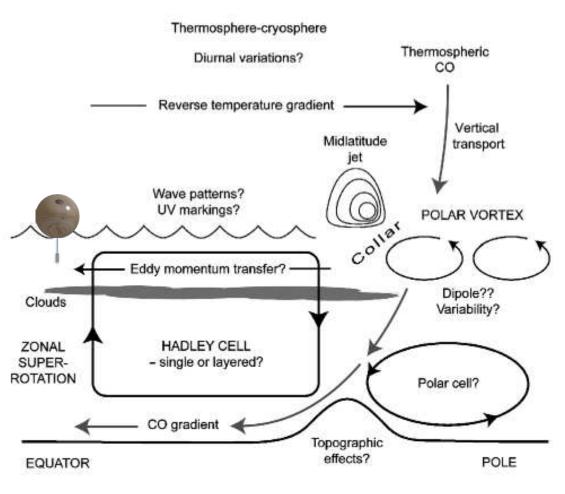- Behavior / impedance of seismic waves at the interface needs to be consolidated

Time integrated azimuthal average of acoustic energy density radiated at the surface (in $J.s/m^3$) as a function of the angle teta (in degree) between the epicenter, the hypocenter and the surface point. Computations are performed for a magnitude 6.0 quake.

(Garcia et al, 2005b)

- Venus Atmosphere is very dynamic
- There are several potential perturbations from the upper atmosphere
  - Local effects :
    - turbulence, wind, motion of the gondola
  - Regional effects
    - Acoustic gravity waves ?
    - Volcanoes , storms ?
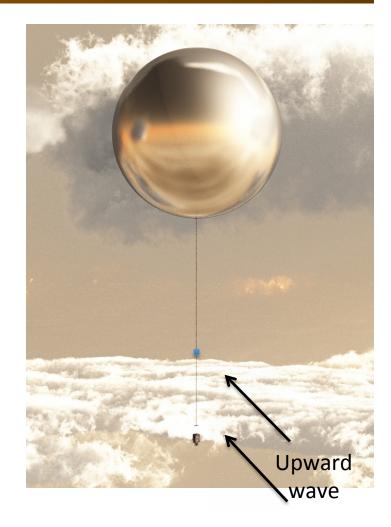
Thermosphere-cryosphere

Diurnal variations?

Thermospheric CO

Reverse temperature gradient

Vertical transport

Midlatitude jet

Wave patterns?
UV markings?

POLAR VORTEX

Collar

Eddy momentum transfer?

Dipole??
Variability?

Clouds

ZONAL SUPER-ROTATION

HADLEY CELL – single or layered?

Polar cell?

CO gradient

Topographic effects?

EQUATOR

POLE

(Taylor, 2006)

There is a need to investigate potential perturbing signals

- Infrasonic sensors may be able to record the seismic signal [0.05 5 Hz] -TBC

  – With some delay (propagation in minutes)

- Several questions remain unanswered
  – What is the optimal altitude
    - Trade- technology / wave amplitude

  – What is the best configuration for the sensor(s) ?
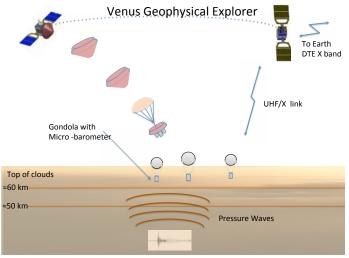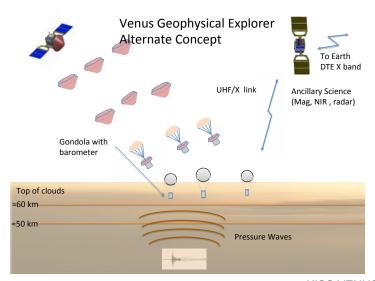   - Filtering of upward waves to discriminate perturbations from signal

Upward wave

- 2 or 3 long lived balloons – typical life duration : about 1 year
- Autonomously powered : solar vs RTG ?
- Overall data management : Limited bandwidth
  – Autonomous event detection
  – Time synchronization between gondolas
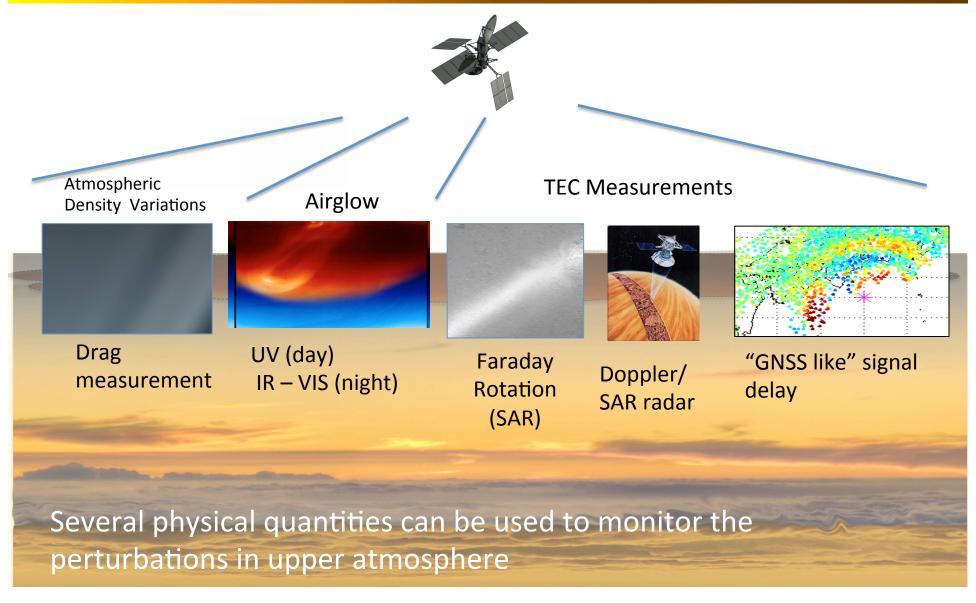 – Need of a relay orbiter

- EDL trade

Atmospheric Density Variations

Airglow

TEC Measurements

Drag measurement

UV (day)
IR – VIS (night)

Faraday Rotation (SAR)

Doppler/ SAR radar

"GNSS like" signal delay

Several physical quantities can be used to monitor the perturbations in upper atmosphere
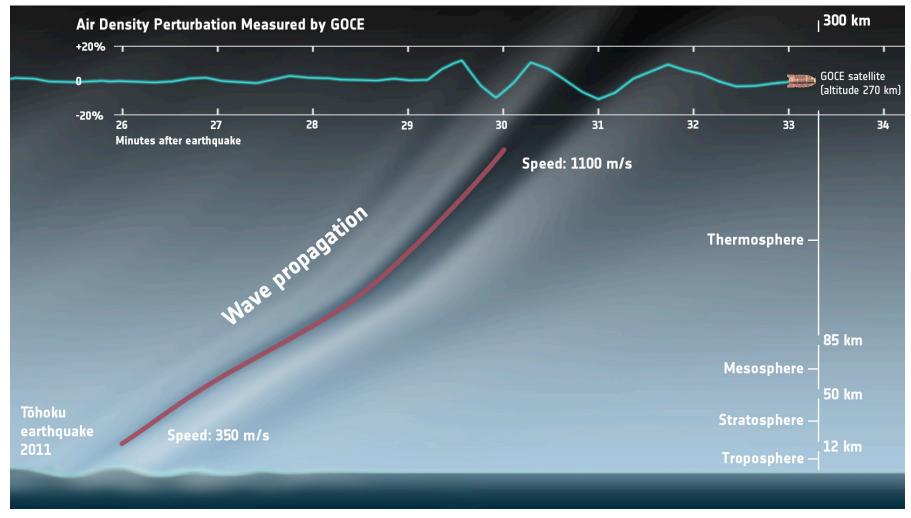
- Direct density fluctuation detection : drag measurement
  - Proof of concept on GOCE (Garcia et, 2013) - Orbit reconstruction ?

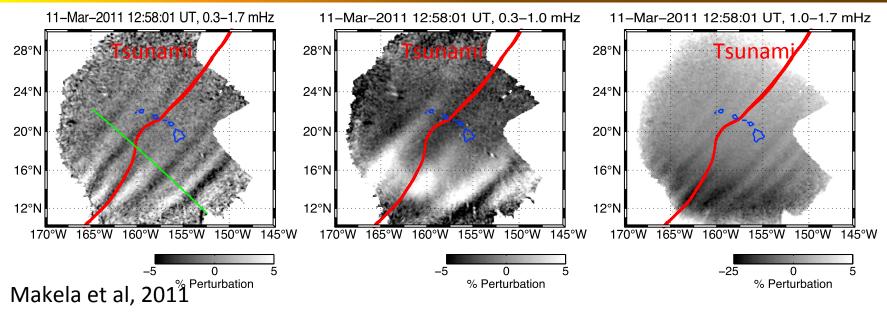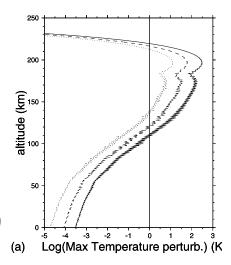Credits: ESA/IRAP/CNES/TU Delft/HTG/Planetary Visions

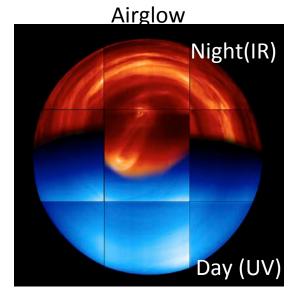11–Mar–2011 12:58:01 UT, 0.3–1.7 mHz   11–Mar–2011 12:58:01 UT, 0.3–1.0 mHz   11–Mar–2011 12:58:01 UT, 1.0–1.7 mHz

Tsunami

Tsunami

Tsunami

% Perturbation

% Perturbation

% Perturbation

Makela et al, 2011

Local adiabatic
temperature
perturbations
created by M=5
M=5.5 M=6
Earthquakes

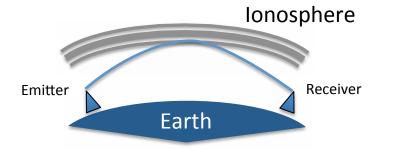(Garcia, 2005b)

(a) Log(Max Temperature perturb.) (K)

Temperature
Perturbations

+ TEC
perturbations

Airglow

Night(IR)

Day (UV)

Credits: ESA/VIRTIS-VenusX IASF-
INAF, Observatoire de Paris
(R.Hueso, Univ. Bilbao)
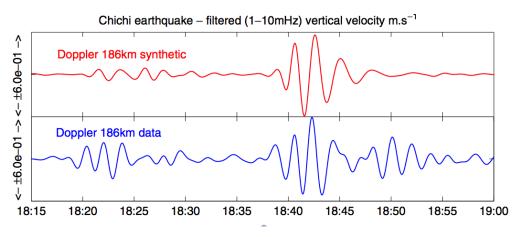
HF waves reflects in E and F layers

Ionosphere

Emitter

Receiver

Earth

Chichi earthquake – filtered (1–10mHz) vertical velocity m.s⁻¹

Doppler 186km synthetic

Doppler 186km data
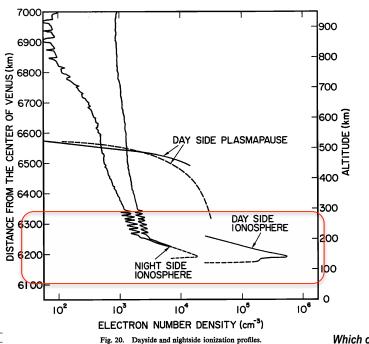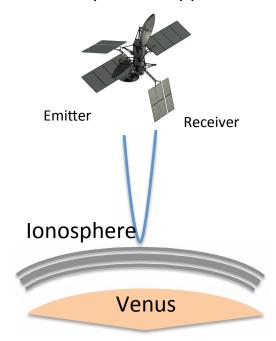
Proof of concept (Artru, 2004) Chi-Chi earthquake M=7.6
(Measure by CTBT Doppler sounder –Francourville, FR)

Fjelbo, 1965 (Mariner)

DAY SIDE PLASMAPAUSE

DAY SIDE IONOSPHERE

NIGHT SIDE IONOSPHERE

DISTANCE FROM THE CENTER OF VENUS (km)

ALTITUDE (km)

ELECTRON NUMBER DENSITY (cm⁻³)

Fig. 20. Dayside and nightside ionization profiles.

Emitter

Receiver

Ionosphere

Venus

Same principle could be used from orbit. Several issues to cover.

Main is resolution v.s. altitude trade Integrated measurement

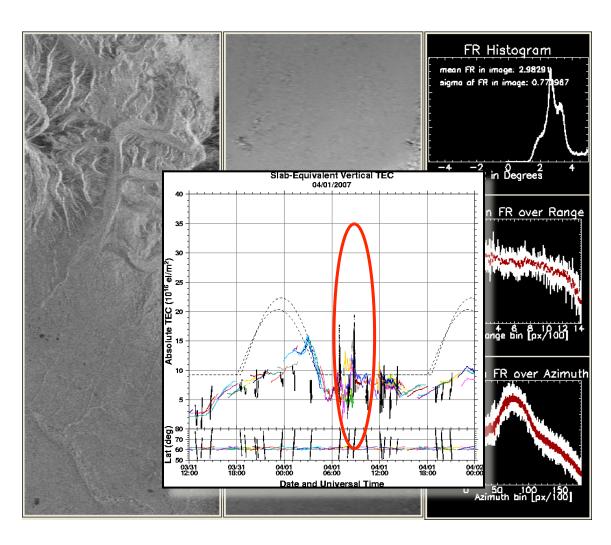*Which options for a seismic experiment on Venus ?*

- **Several techniques can be considered on Earth**

  - **Coherent Scatterers measurement (CS)**
    (Pascal Dubois Fernandez, ONERA,2006)

    - Use reference points on the ground along track

  - **Faraday Rotation Method** (Franz Meyer DLR 2006)

    - Measurement of wave polarization

  - **Sensitivity an issue**

    - Fraction of TEC content

Note: results for L band
At P band, 10 times more sensitive !
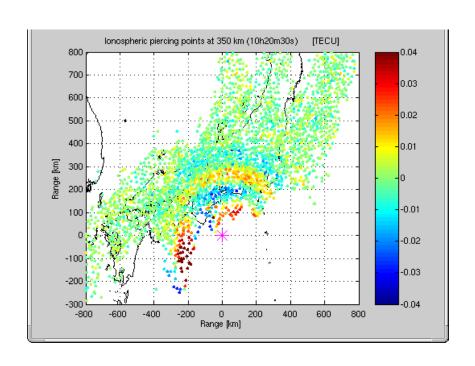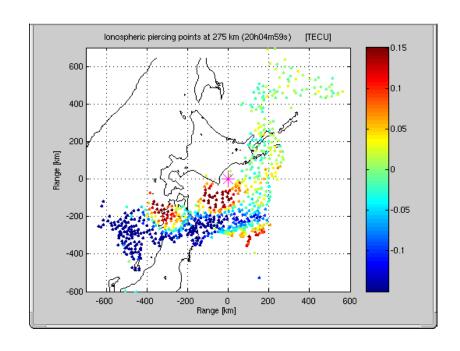

Franz Meyer, DLR

Kii, M6.9, 05/09/2004

Tokachi-Oki, M8.1, 25/09/2003

Atmospheric pulse

Atmospheric pulse + Rayleigh wave

Courtesy IPGP

How to apply to concept to Venus ? Cubesat network ?

- Several trades remain for the orbit detection
  - Permanence of measurement (High orbit ?/ Elliptic orbit ?/ number of satellites required vs revisit time)
- Feasibility of radar related methods ?
- Feasibility of TEC related methods ?
- Night-side measurements only for airglow ?
- Spatial and temporal resolution of the images for inversion ?
  - Spatial : km level of imaging, less if first arrival monitoring (but in this case we need several spacecrafts / measurements)
  - Temporal sampling : 1 image every 10 seconds ?

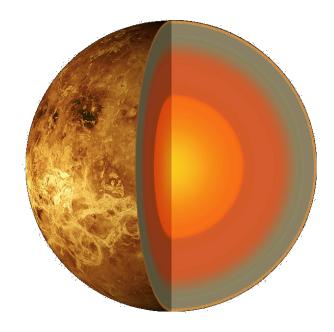Work on feasibility studies will be a lot of fun !

Platform Location/ Number	Environment	Primary Observable	Technology Maturity	Lifetime	Ready for flight
Venus Surface Landers (1 to 3)	460°C, 90 bars	Seismic waves (P waves and S waves)	Low. Electronics to survive at these temperature	3 hours (TRL 6) 3 months (TRL 2)	No
Venus Balloons at 55 km altitude (3 to 5)	20C, 0.4 bars	Gravito-acoustic waves (P waves only)	Mod to high	3 to 6+ months	Yes
Venus Orbiter (1 to 3)	Space with direct and scattered solar radiation	Infrasonic induced variations in thermal emission and electron density → Rayleigh wave dispersion	High	10 years	Yes

- Seismology on Venus is a new and exciting challenge
- Although some of the techniques lack maturity, we are very close to realistic technology demonstration
- After Mars, Venus is the next piece of the puzzle of telluric planets history to be unveiled.

BACKUP

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \partial_j \tau_{ij} + f_i.$$

$$\rho \ddot{\mathbf{u}} = \nabla \lambda (\nabla \cdot \mathbf{u}) + \nabla \mu \cdot [\nabla \mathbf{u} + (\nabla \mathbf{u})^T] + (\lambda + 2\mu) \nabla \nabla \cdot \mathbf{u} - \mu \nabla \times \nabla \times \mathbf{u}.$$

$$\nabla^2 (\nabla \cdot \mathbf{u}) - \frac{1}{\alpha^2} \frac{\partial^2 (\nabla \cdot \mathbf{u})}{\partial t^2} = 0,$$

$$\alpha = \sqrt{\frac{\lambda + 2\mu}{\rho}}.$$

P wave velocity

$$\rho \ddot{\mathbf{u}} = (\lambda + 2\mu) \nabla \nabla \cdot \mathbf{u} - \mu \nabla \times \nabla \times \mathbf{u}.$$

$$\nabla^2 (\nabla \times \mathbf{u}) - \frac{1}{\beta^2} \frac{\partial^2 (\nabla \times \mathbf{u})}{\partial t^2} = 0,$$
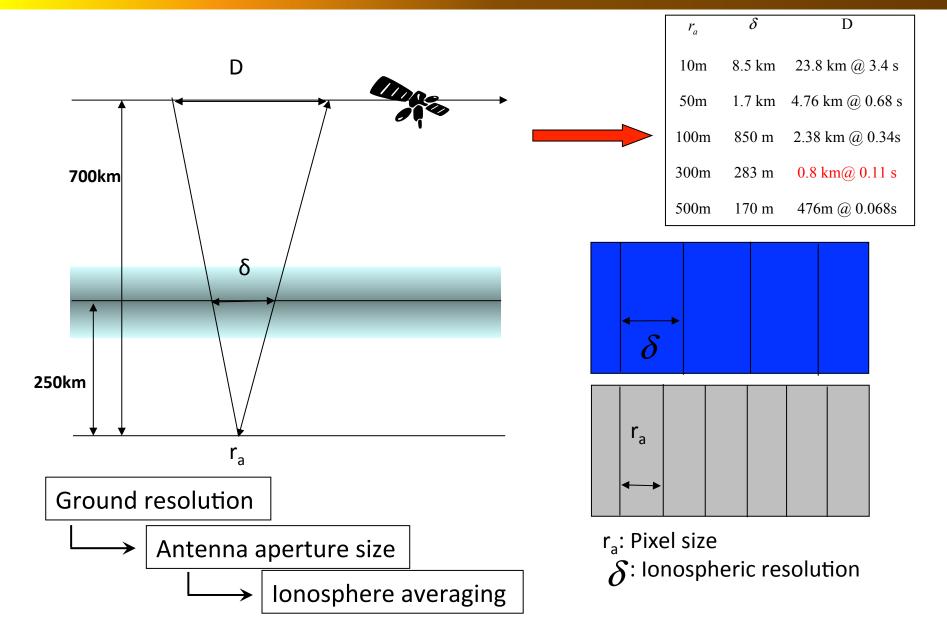
$$\beta = \sqrt{\frac{\mu}{\rho}}.$$

S wave velocity

From Schearer, 2010

Coherent Scaterers geometry and ionosphere

r_a	δ	D
10m	8.5 km	23.8 km @ 3.4 s
50m	1.7 km	4.76 km @ 0.68 s
100m	850 m	2.38 km @ 0.34s
300m	283 m	0.8 km@ 0.11 s
500m	170 m	476m @ 0.068s

D

700km

250km

δ

r_a

Ground resolution

Antenna aperture size

Ionosphere averaging

r_a: Pixel size

δ: Ionospheric resolution

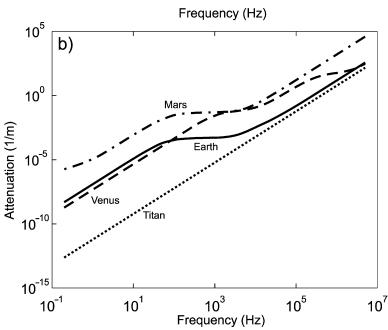- Competition between absorption and amplification

Frequency (Hz)

Figure 1 : Frequency dependence of the attenuation coefficient on four planets (Petculescu ,2006)

Figure 2 (a) Logarithm of classical (full line), rotational (dashed line) and vibrational (dotted line) absorption coefficients as a function of altitude (in km) in the atmosphere of Venus at 0.1 Hz. (b) Logarithm of the acoustic wave amplification factor as a function of altitude (in km) in the atmosphere of Venus assuming a vertical propagation of acoustic waves. Plots are given for different frequencies: 10 mHz (open circles), 100 mHz (open stars), 1 Hz (open triangles), 10 Hz (filled triangles) and 100 Hz (filled inverted triangles).

Garcia, 2005b