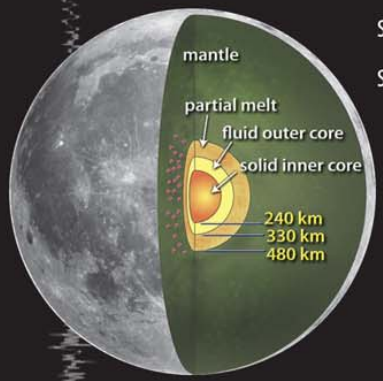
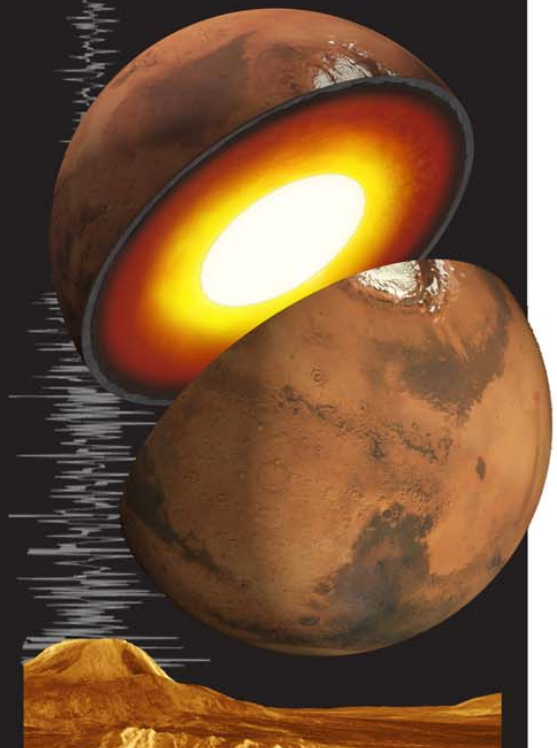
Keck INSTITUTE FOR SPACE STUDIES





New Frontiers of Planetary Seismology

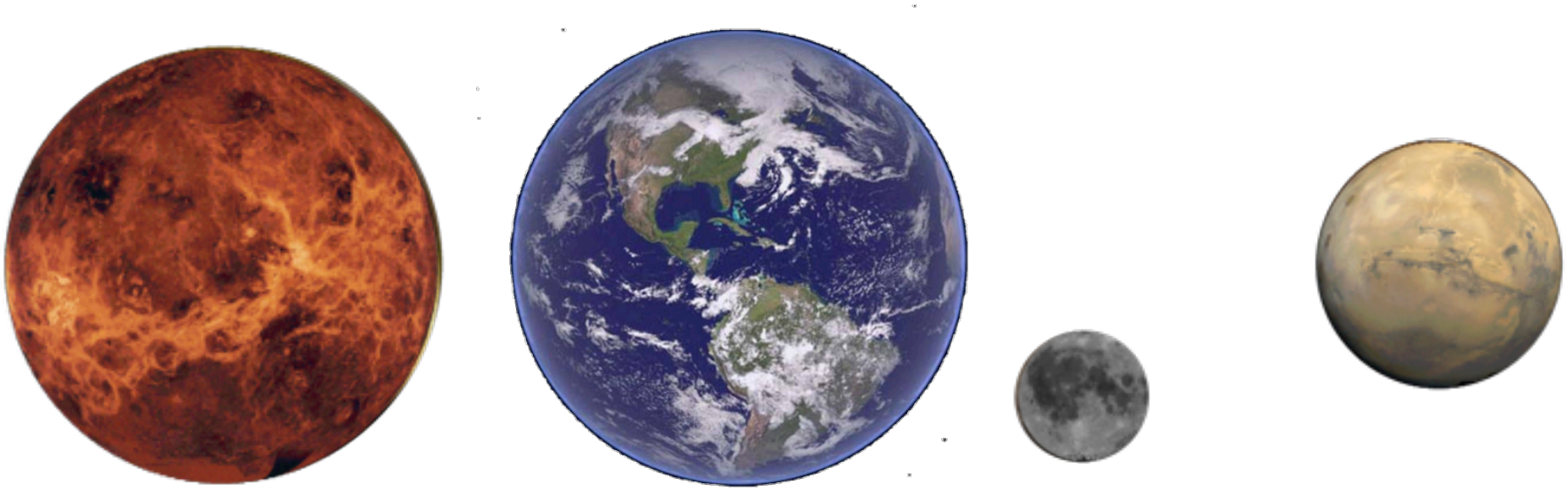
Prof. Philippe Lognonné

Institut de Physique du Globe de Paris
Université Paris Diderot-Sorbonne Paris Cité, France

université PARIS DIDEROT PARIS 7

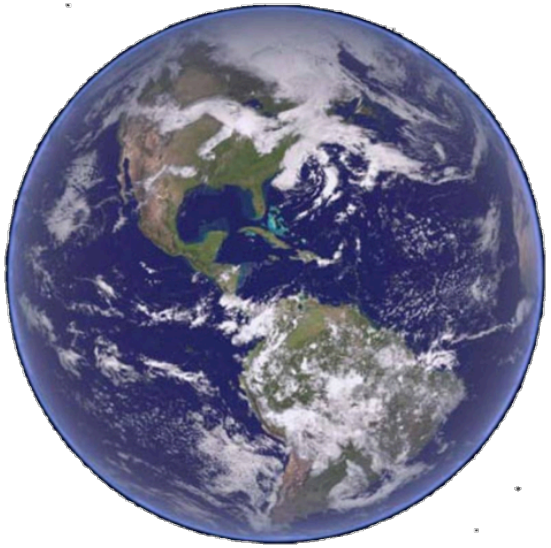
IPGP INSTITUT DE PHYSIQUE DU GLOBE DE PARIS

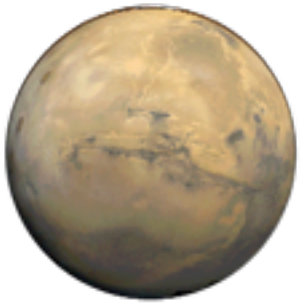
New frontiers of Planetary seismology



The interior of the terrestrial planets…

New frontiers of Planetary seismology

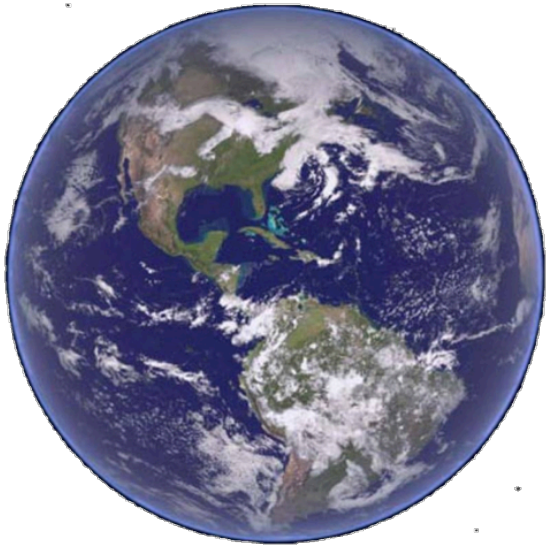



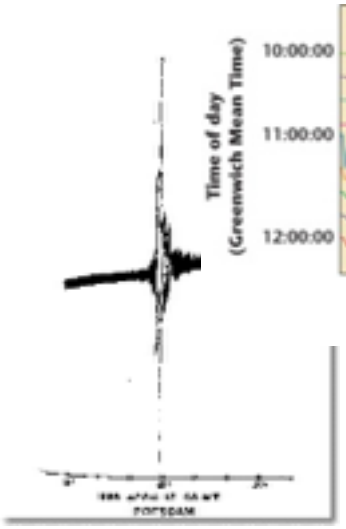


The interior of the terrestrial planets…

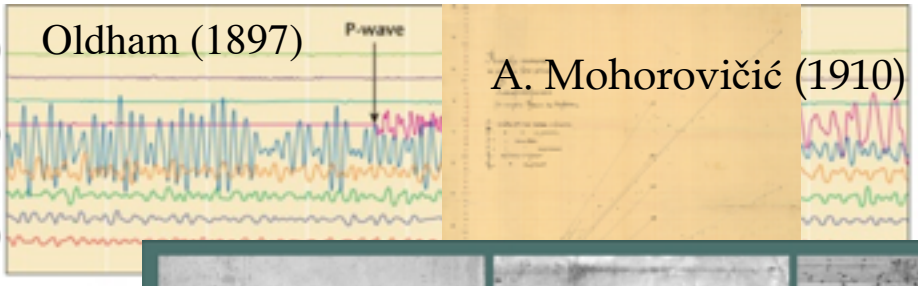
Thanks to many collaborators and colleagues :
J.Gagnepain-Beyneix, T.Kawamura, T.Gudkova, R.Garcia, R.Weber, C.Johnson for the Moon journey
B.Banerdt, D.Mimoun, S de Raucourt, K.Hurst, R.Garcia and all the InSight Science and Technical team for Mars journey
L.Rolland, R.Garcia and the TWIST team for Earth Journey

The first success story

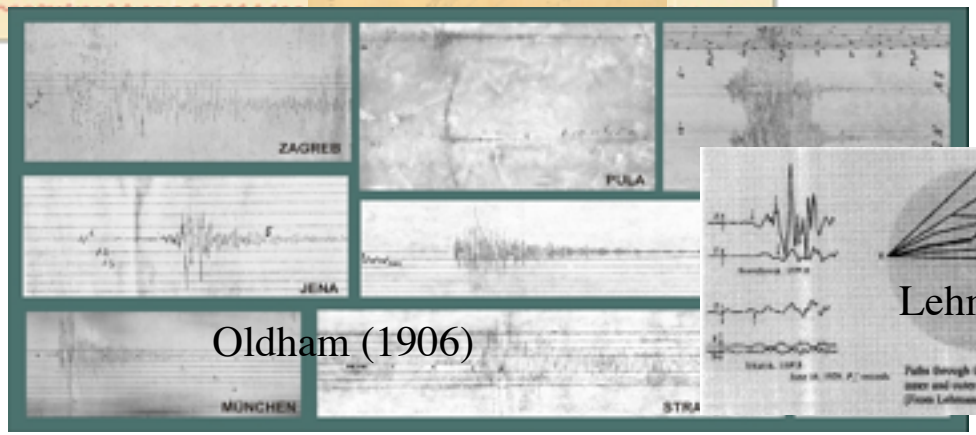




Oldham (1897)



A. Mohorovičić (1910)

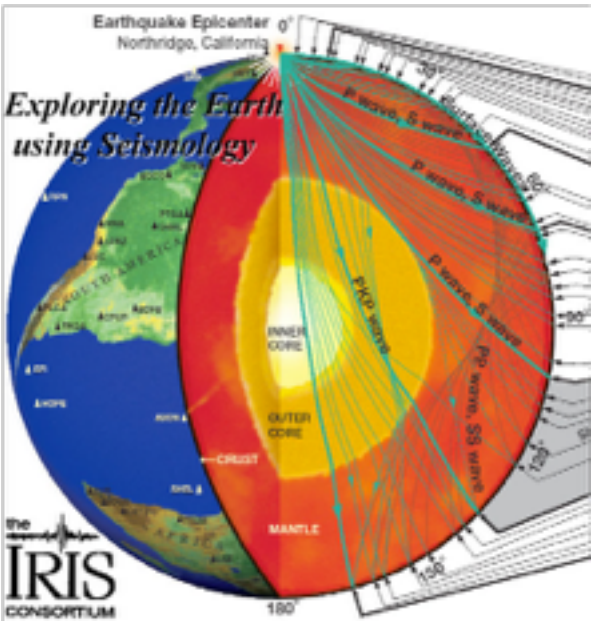


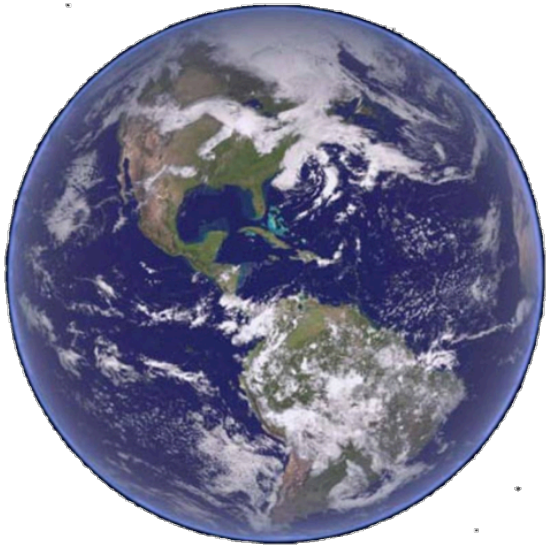
Oldham (1906)

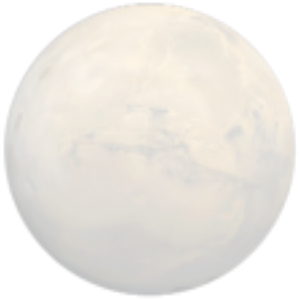
Lehman (1936)

von Rebeur-Pacshwitz (Nature, 1889)

The first success story

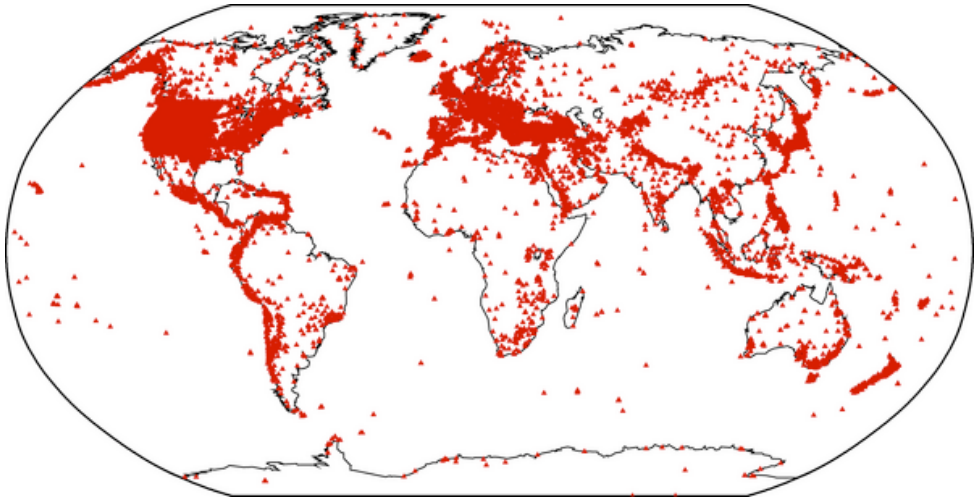






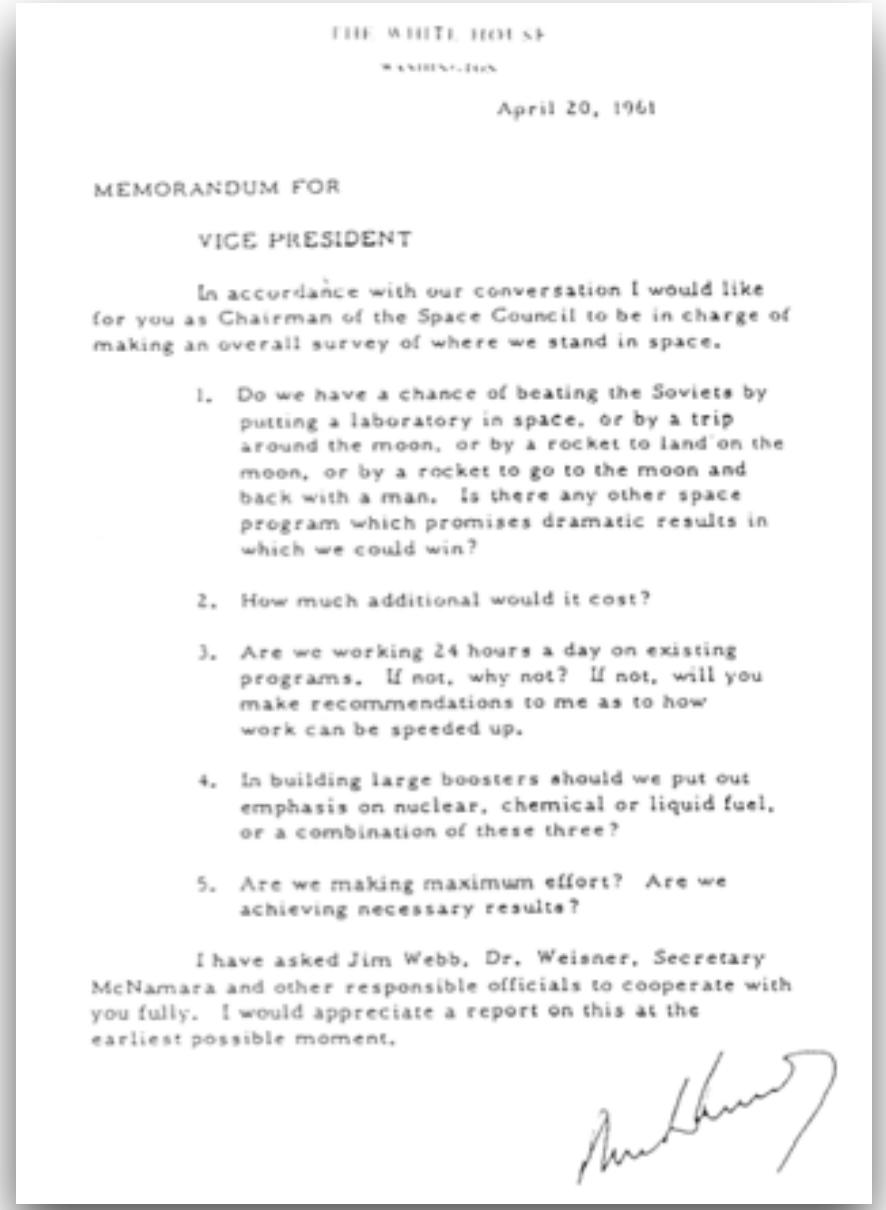
1980-90

geoscope



>20000 stations, many of them with direct access to data

The second success story



THE WHITE HOUSE

WASHINGTON

April 20, 1961

MEMORANDUM FOR

VICE PRESIDENT

In accordance with our conversation I would like for you as Chairman of the Space Council to be in charge of making an overall survey of where we stand in space.

1. Do we have a chance of beating the Soviets by putting a laboratory in space, or by a trip around the moon, or by a rocket to land on the moon, or by a rocket to go to the moon and back with a man. Is there any other space program which promises dramatic results in which we could win?

2. How much additional would it cost?

3. Are we working 24 hours a day on existing programs. If not, why not? If not, will you make recommendations to me as to how work can be speeded up.

4. In building large boosters should we put out emphasis on nuclear, chemical or liquid fuel, or a combination of these three?

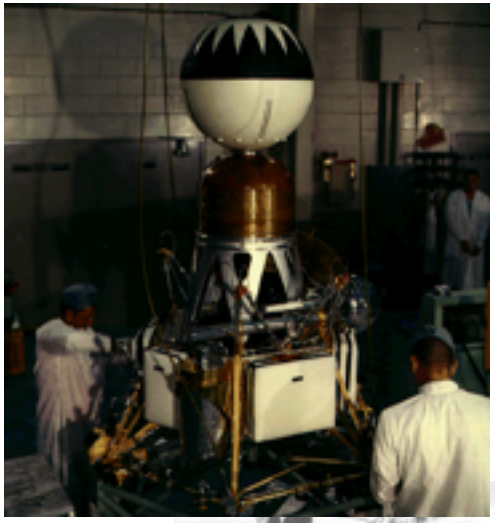
5. Are we making maximum effort? Are we achieving necessary results?

I have asked Jim Webb, Dr. Weisner, Secretary McNamara and other responsible officials to cooperate with you fully. I would appreciate a report on this at the earliest possible moment.

Definitively NOT driven by seismology…

The second success story

But with piggy back seismology inside



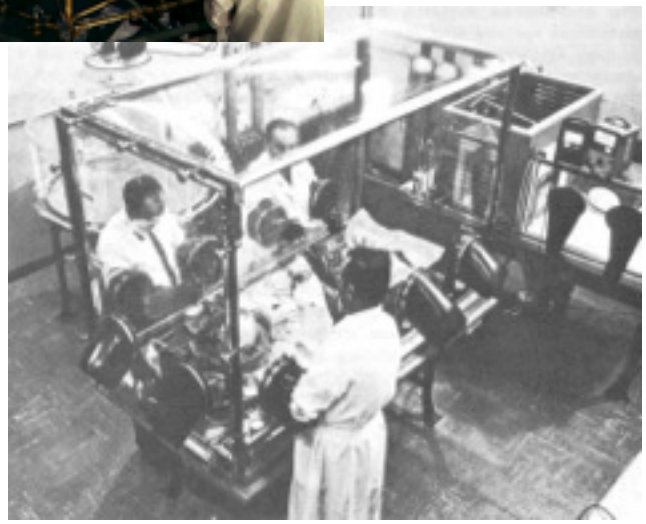
Seismometer and Ranger at JPL

Apollo 14 crew training the ALSEP (and seismometer) deployment

Ranger 3
1/26/1962

Ranger 4
4/23/1962

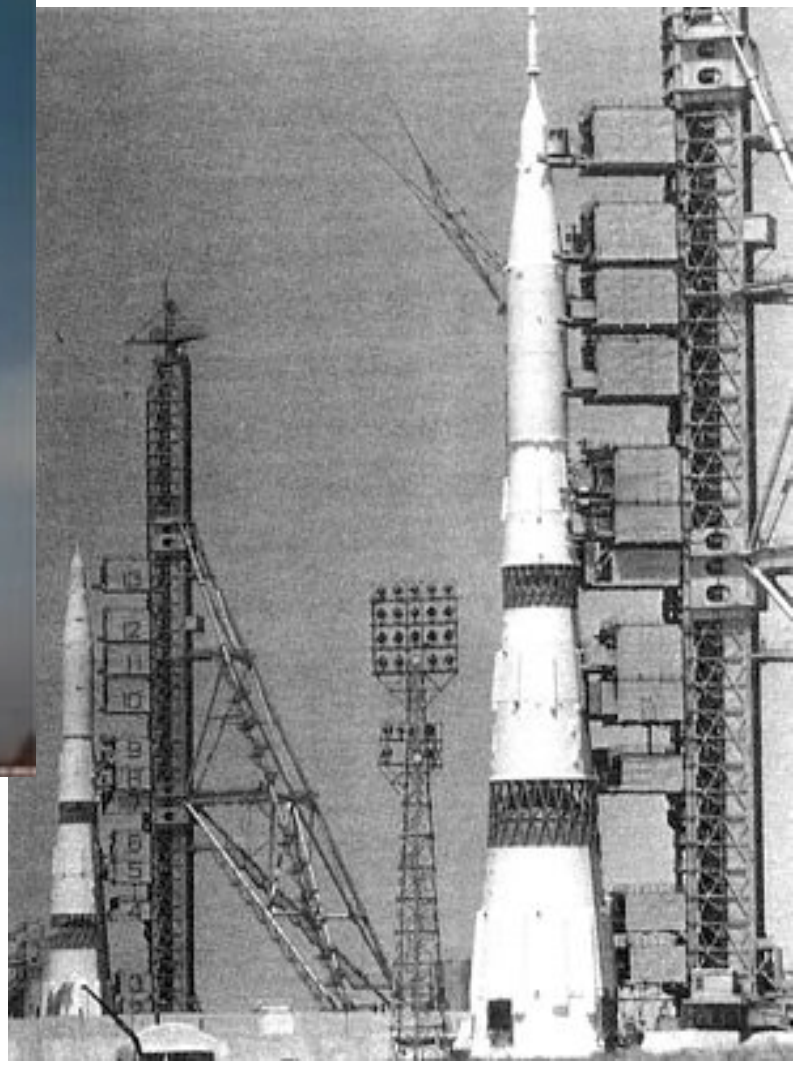
Ranger 5
10/18/1962



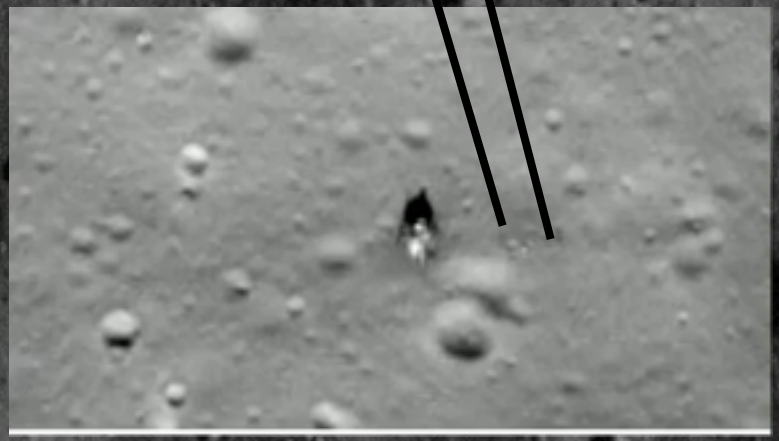
Sterile seismometer assembly at Aeronutronic

A double success

Cape Canaveral, USA, 7/16/1969

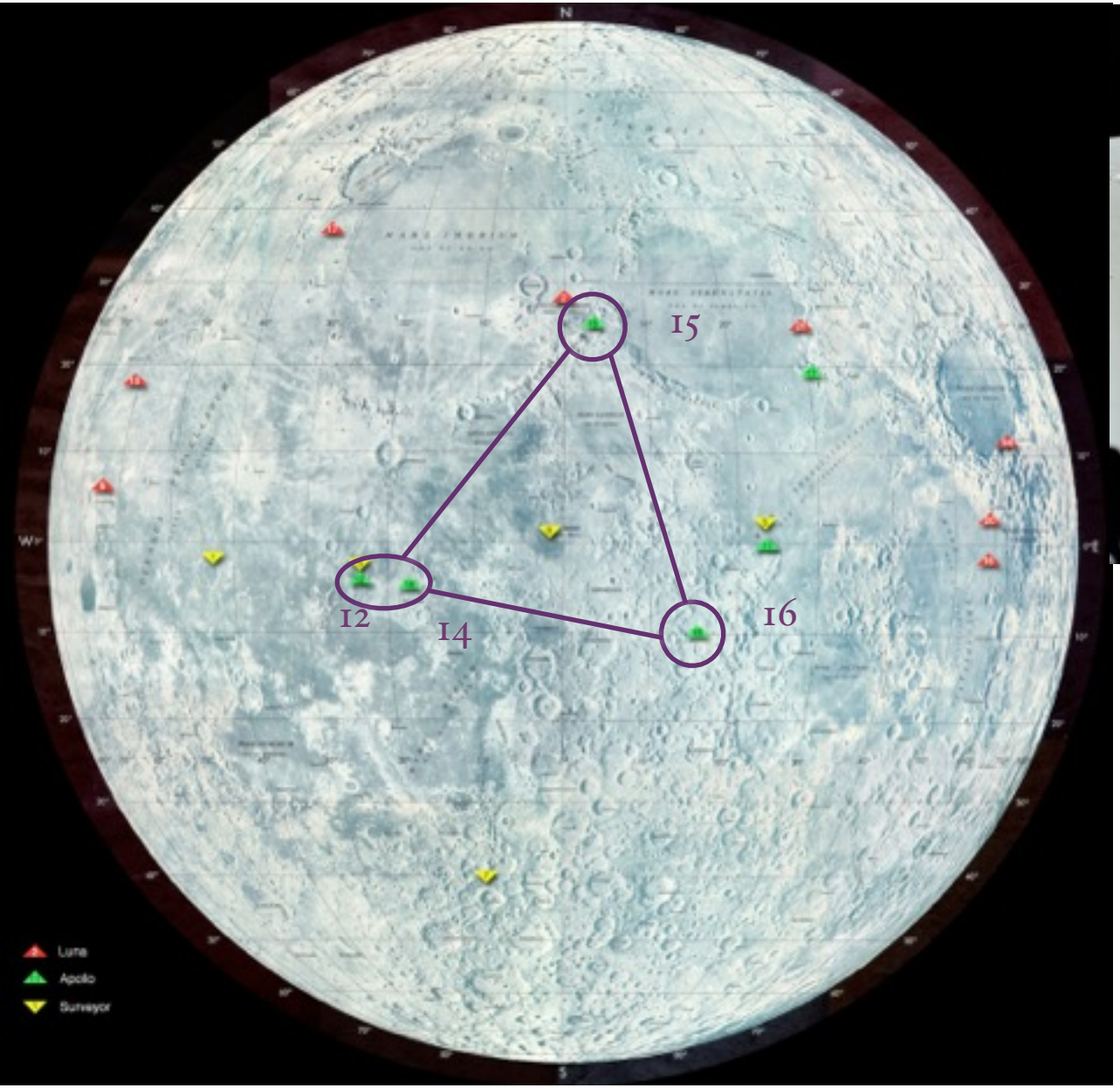


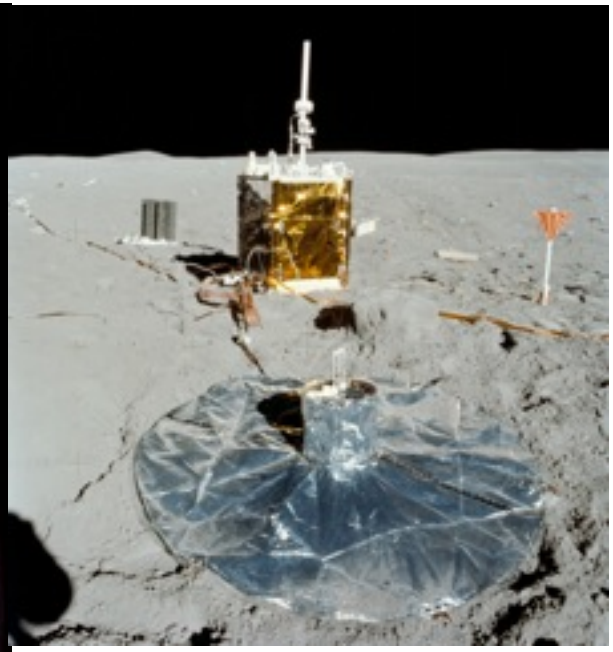
Baïkonour, USSR, 7/3/1969

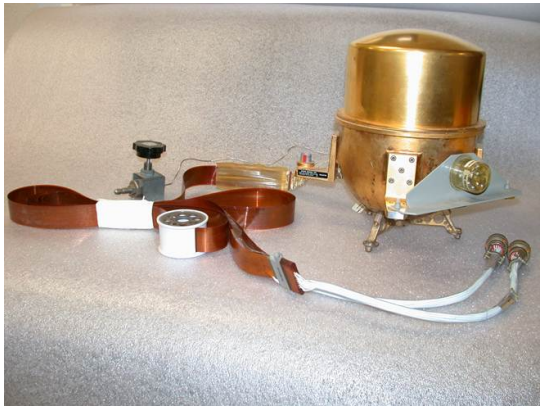


500 meters

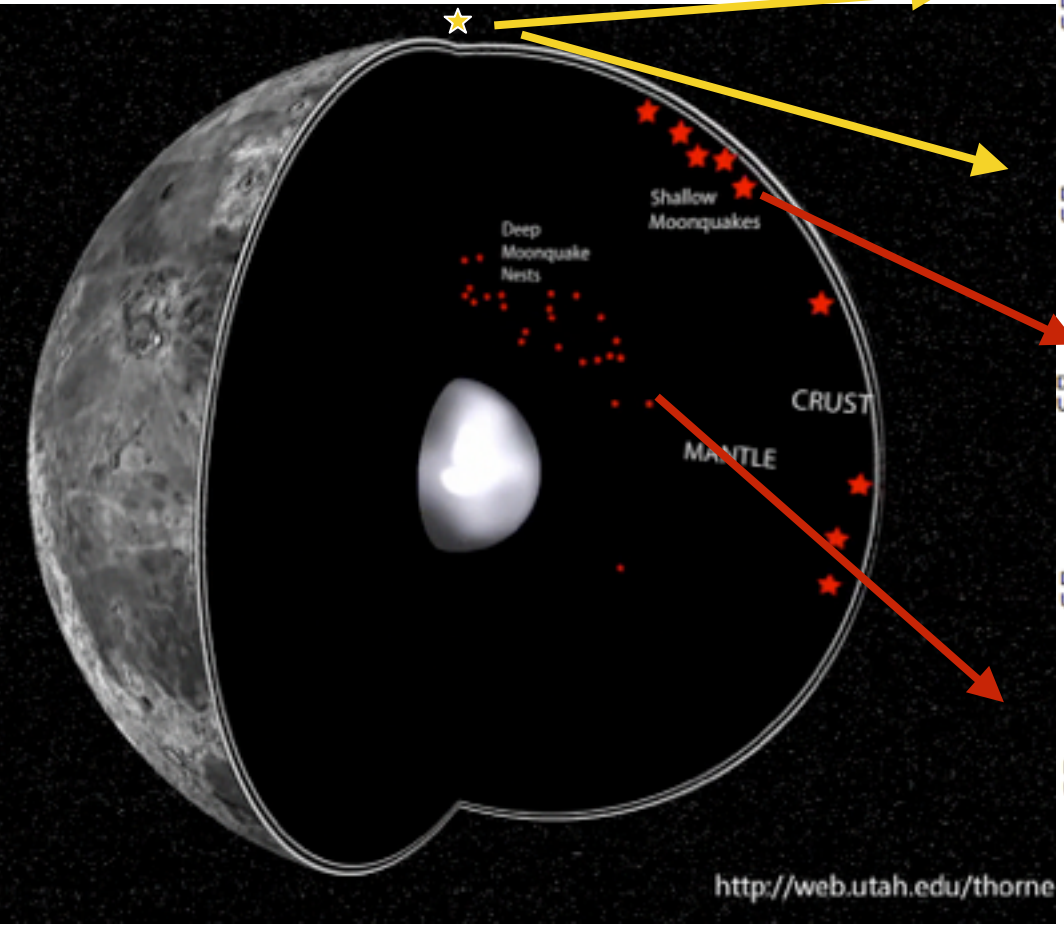
Apollo seismic network

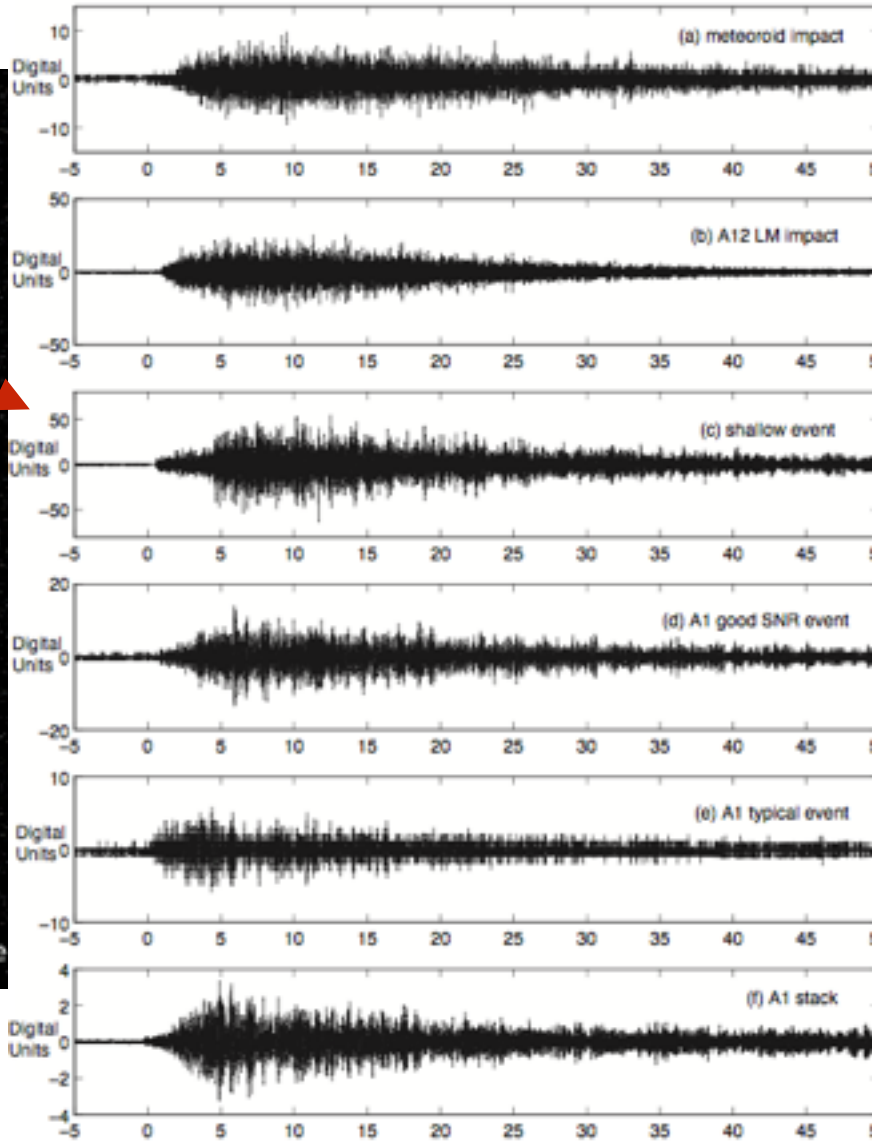






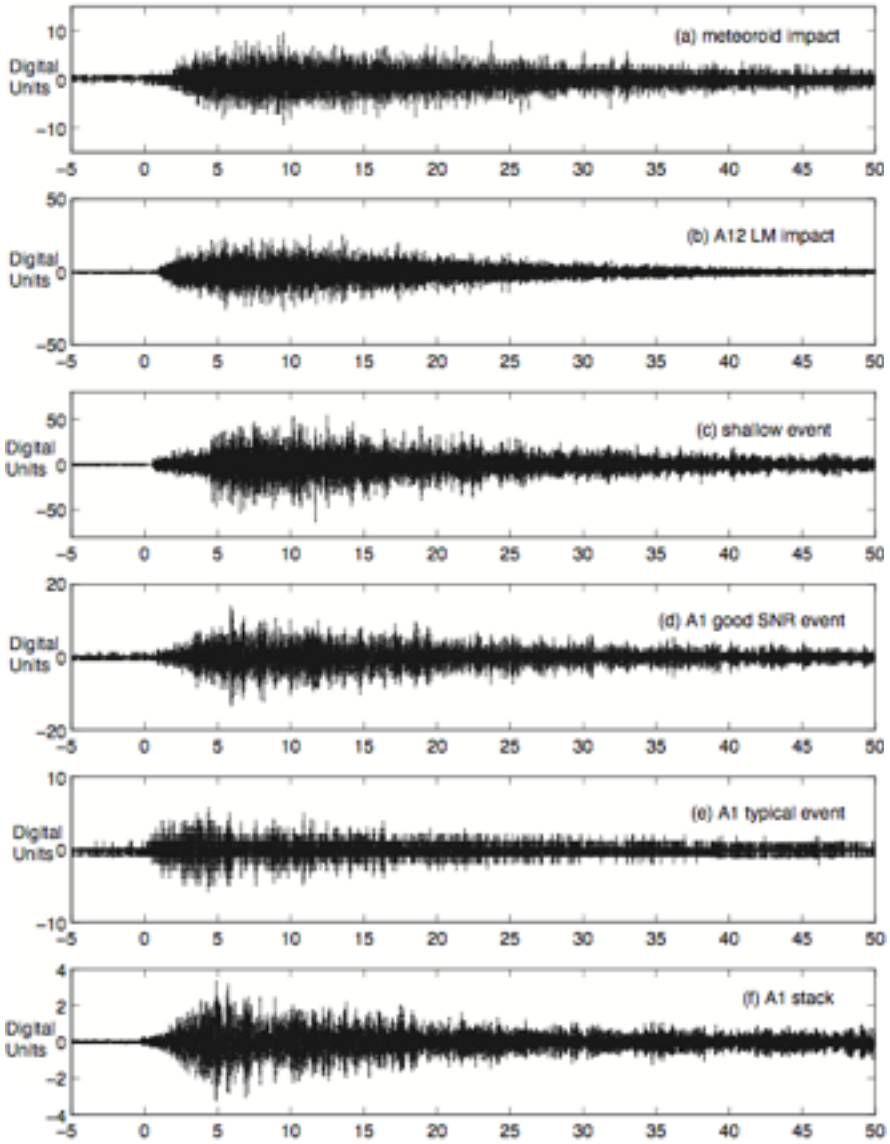
Lunar quakes zoology

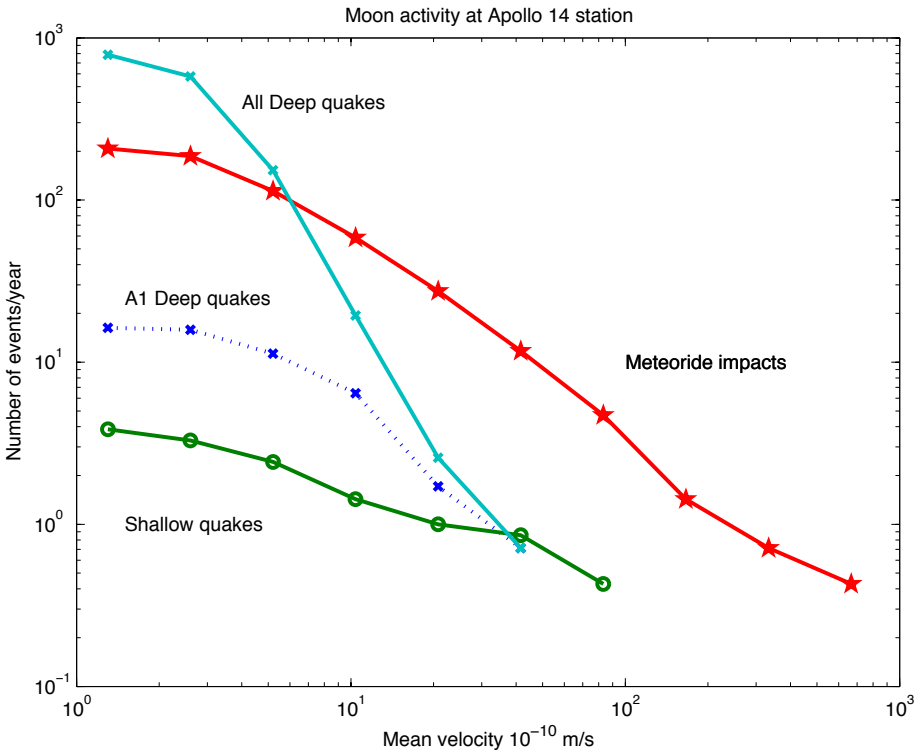




Lognonné & Johnson, 2007

Lunar quakes zoology

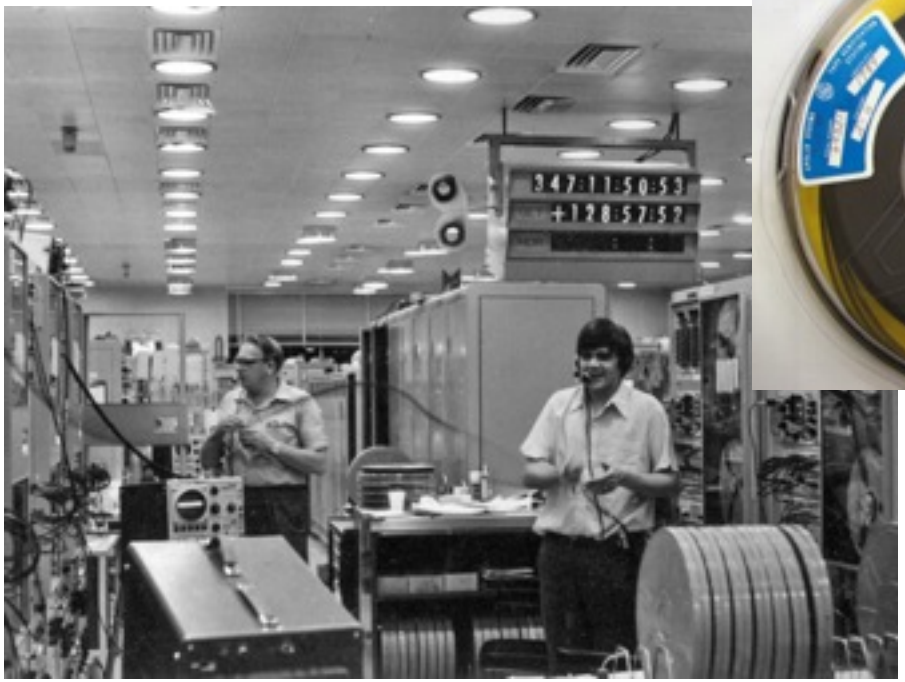




Lognonné & Johnson, 2007

Modern Apollo seismology: painful gift of Lunar A

- In the late 1990, JAXA decided to transfer the “old” tape recorded Apollo data on exabytes in the frame of the Lunar-A penetrator mission
- Lunar-A was cancelled in 2007, but this effort lead to a renew of the Apollo seismic data analysis….
- Data are now available in various electronic forms and recovery effort continue…



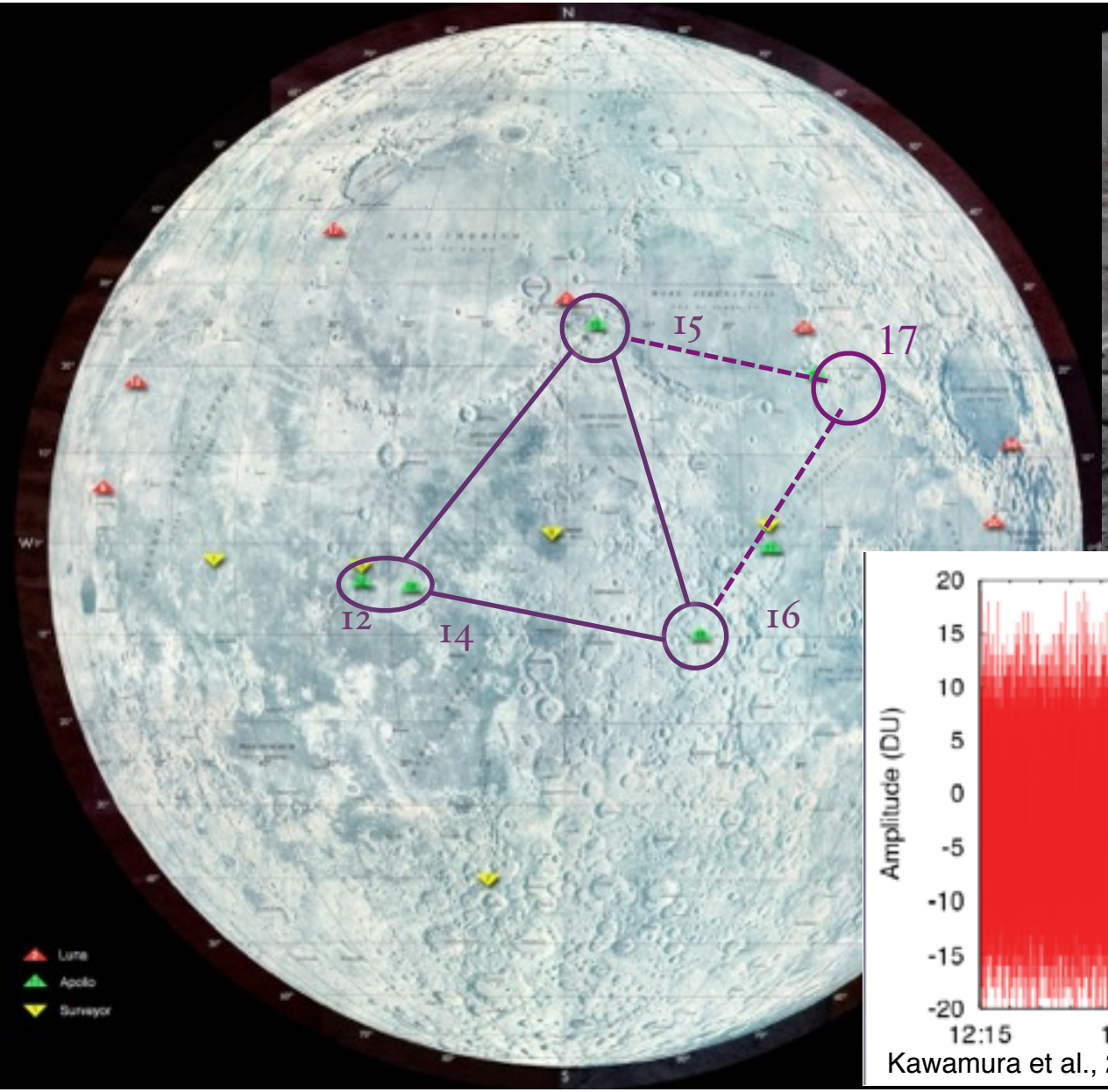
Apollo 17 data facility…

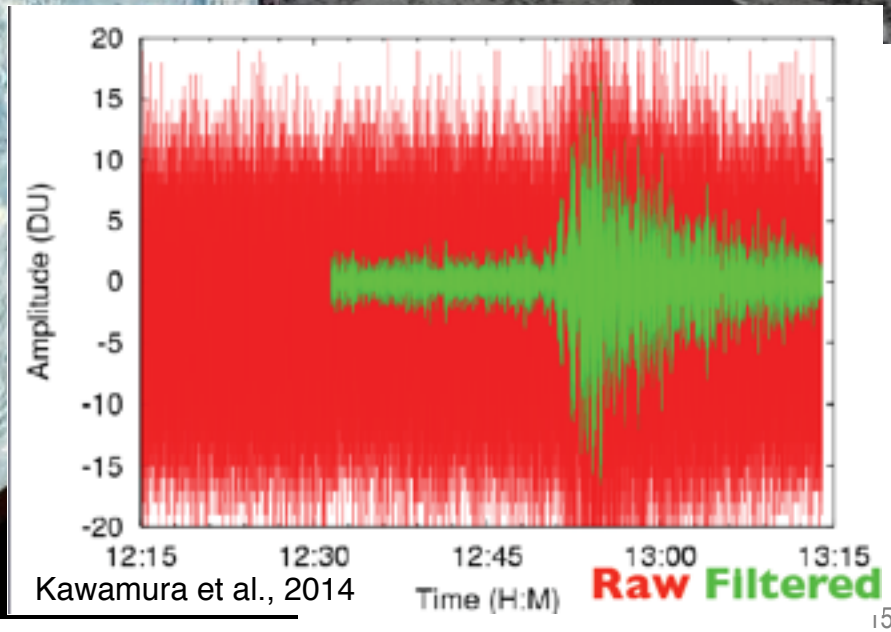
Original ALSEP data

Lunar-A penetrator


The most recent Apollo seismic data….

Apollo seismic network

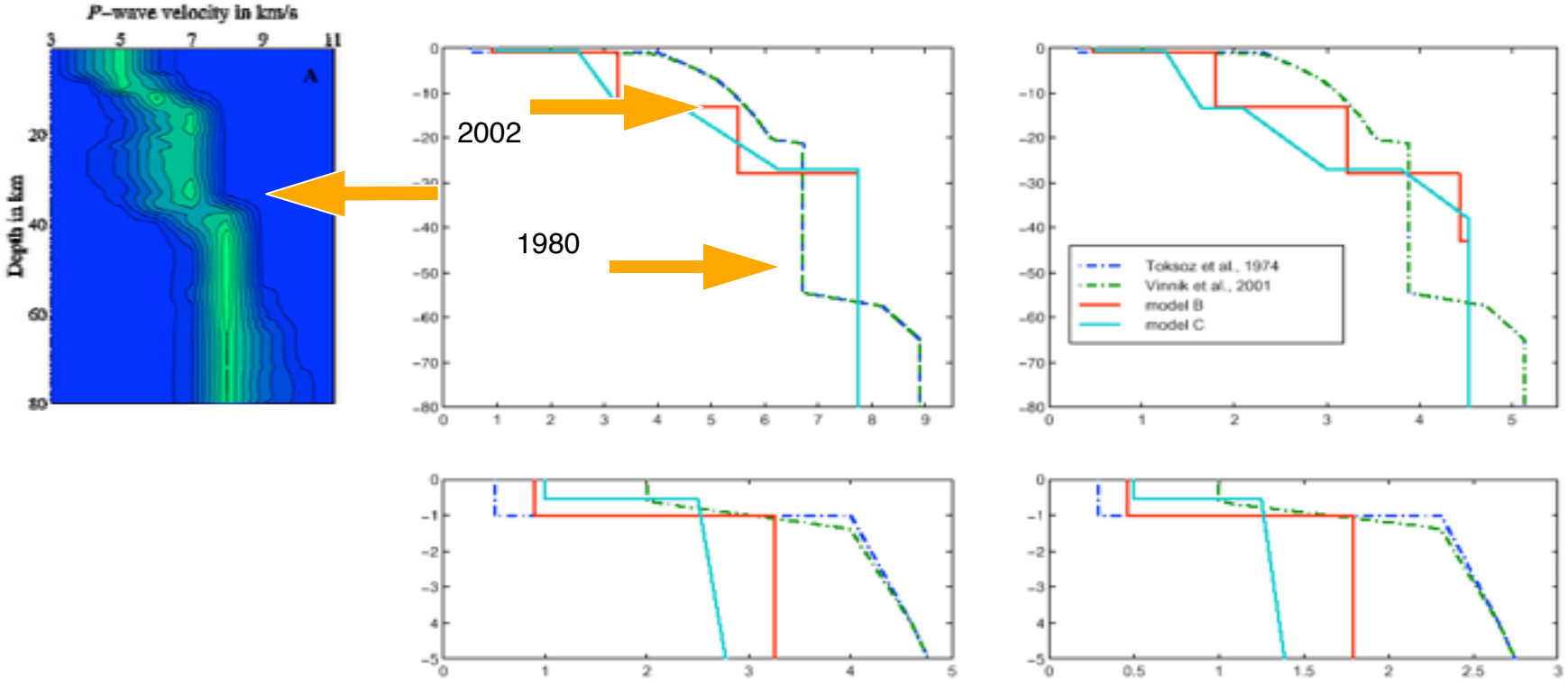




Kawamura et al., 2014

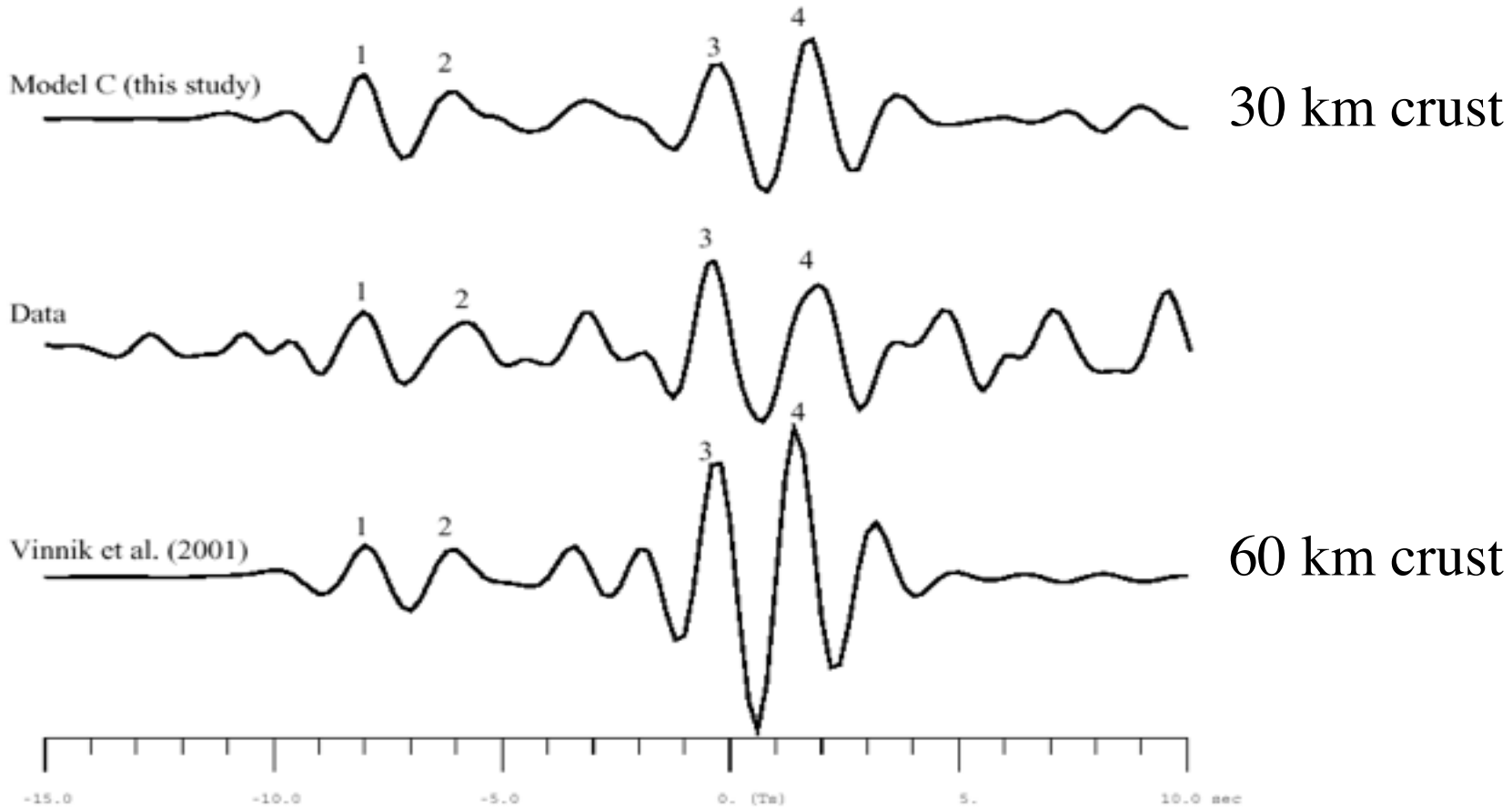
Modern Apollo seismology: a new crust

- Crustal thickness was estimated to 60 km between 1970-1980 by Toksoz et al. and Nakamura et al.
  - This implied large volume of primary crust and an bulk U content much larger than Earth
- All re-estimations were however providing thinner crust, from 30 km (Lognonné et al., 2003, Beyneix et al., 2007) to 38 km (Khan et al, 2002)



Moon receiver function (Apollo 12 site)

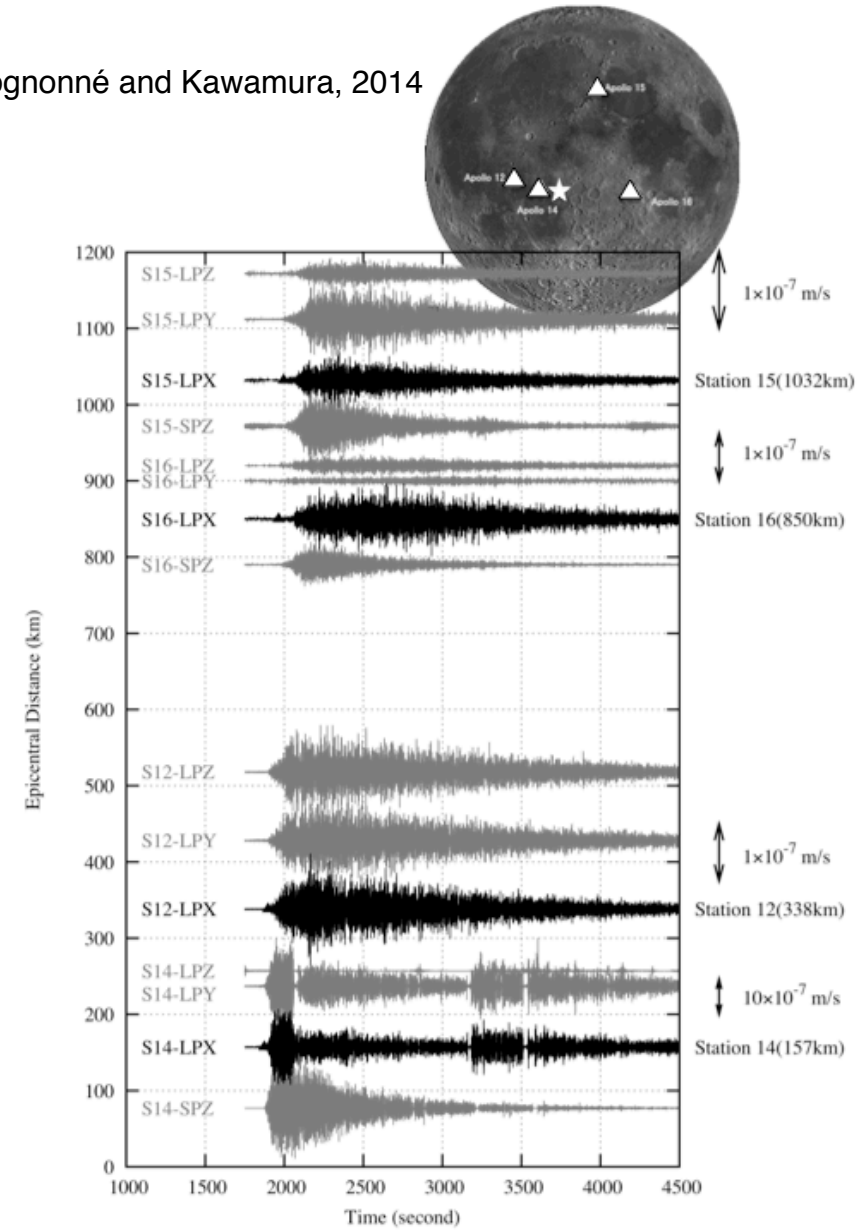
- This apparent contradiction is mainly related to two different models family having *similar travel times*…

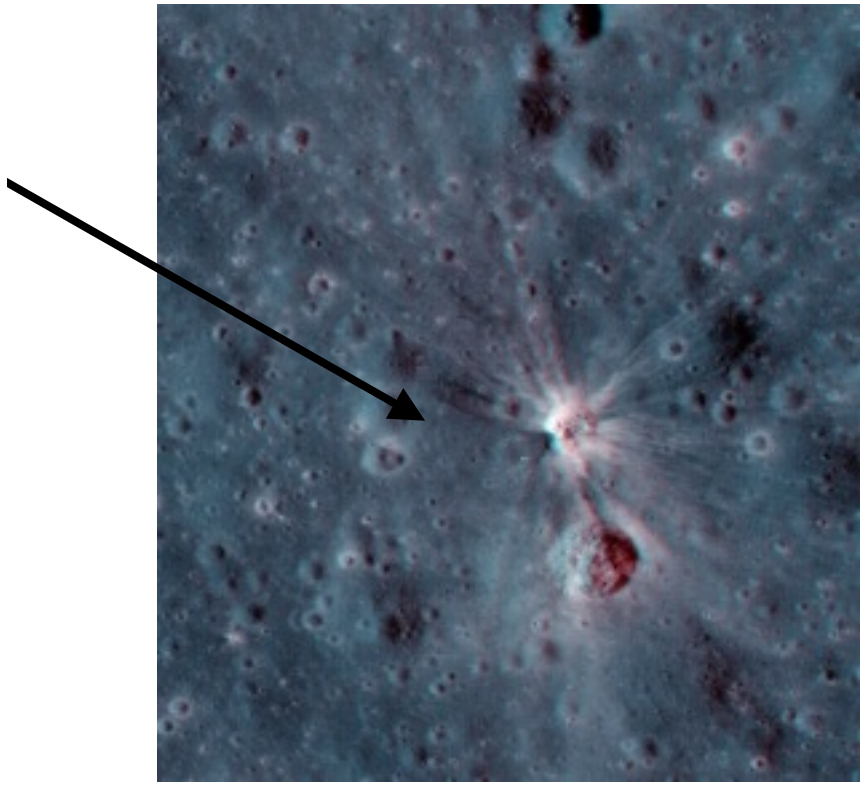


Vinnik et al., 2001

Lunar impacts… Lightening the crust

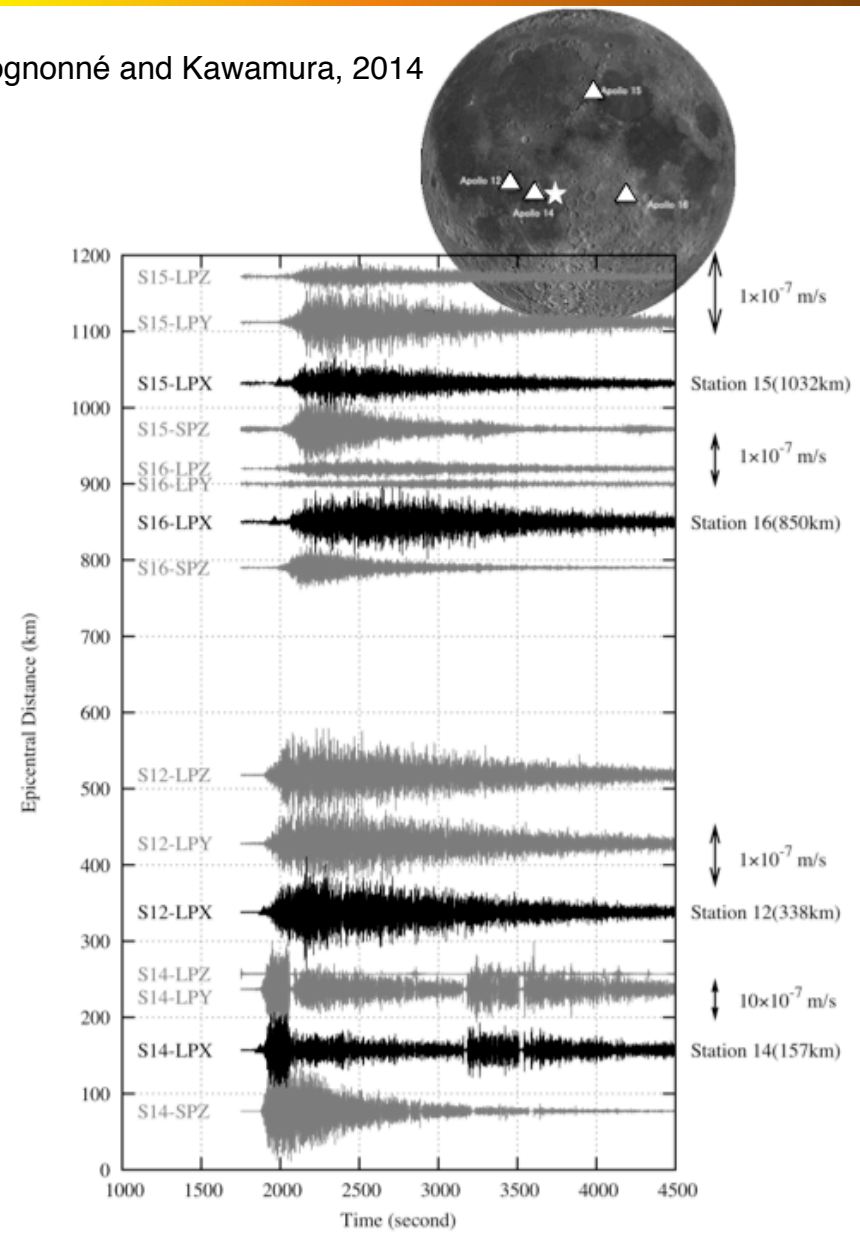
Lognonné and Kawamura, 2014

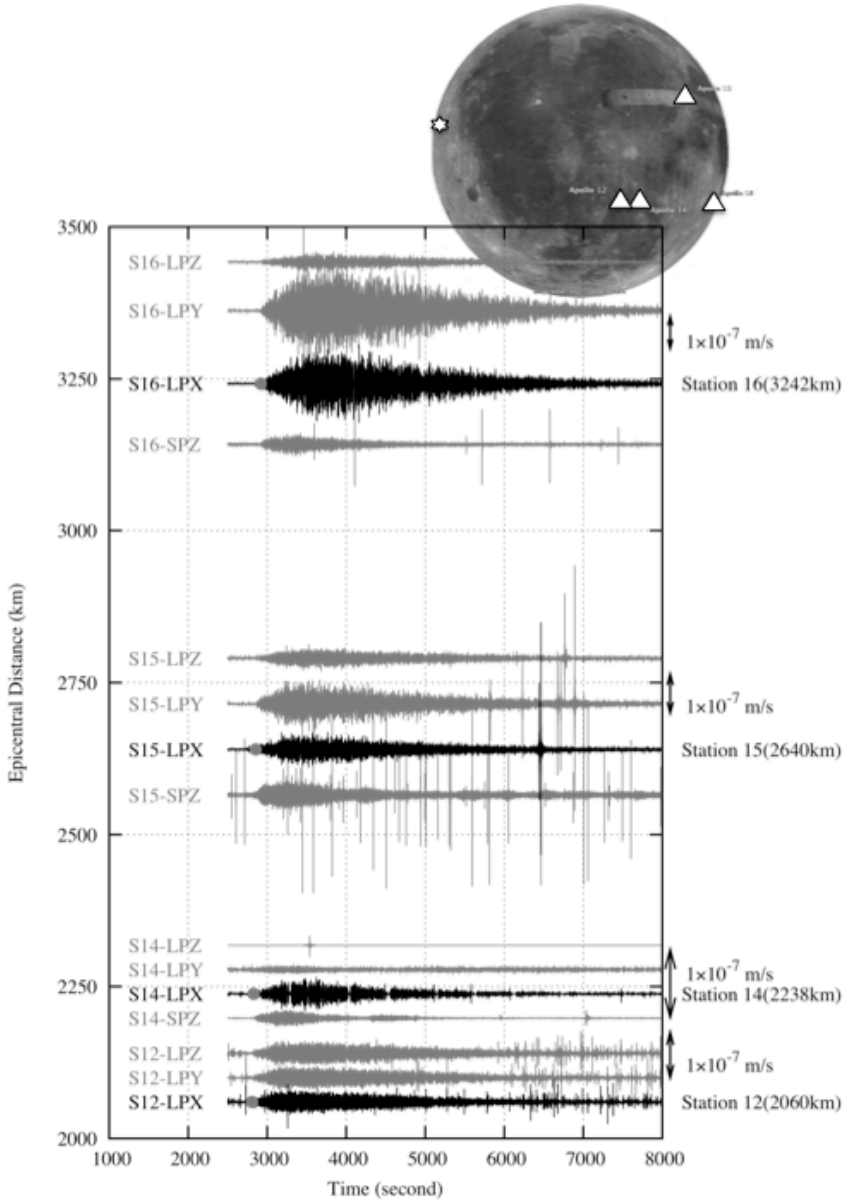


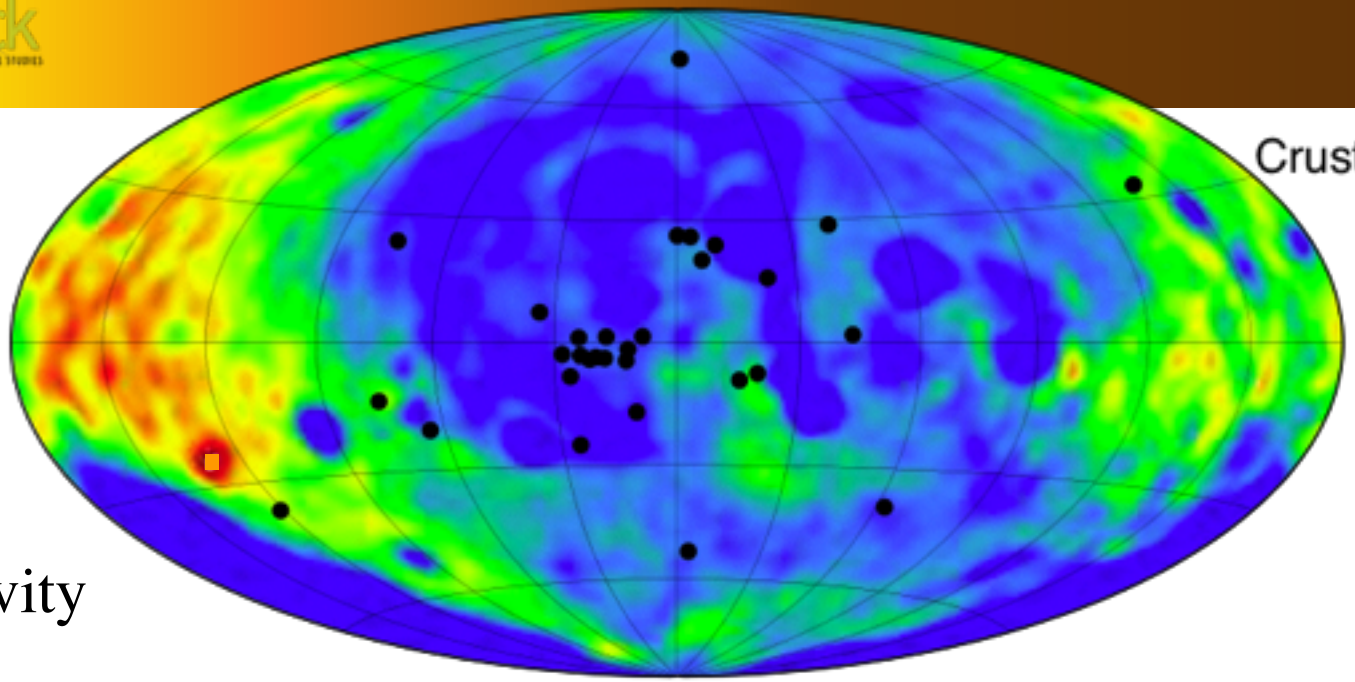


Lunar impacts… Lightening the crust

Lognonné and Kawamura, 2014

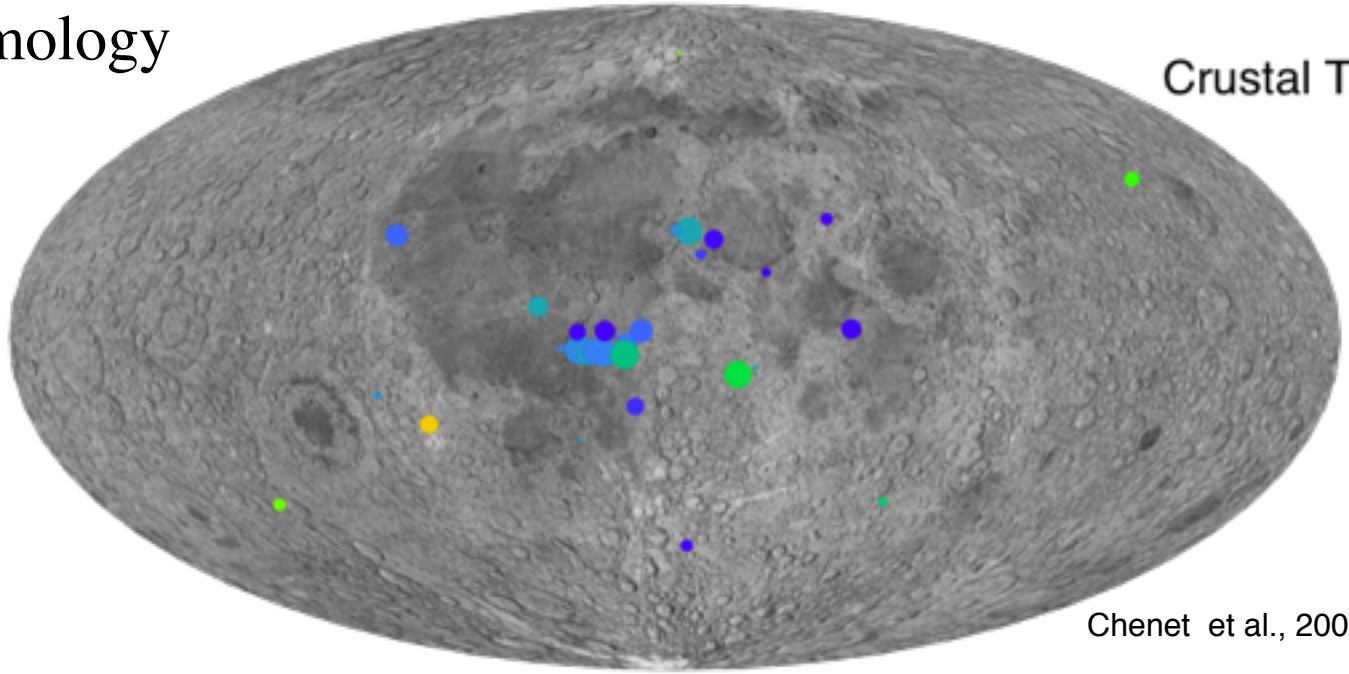






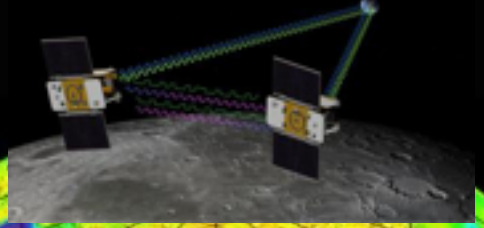
Gravity

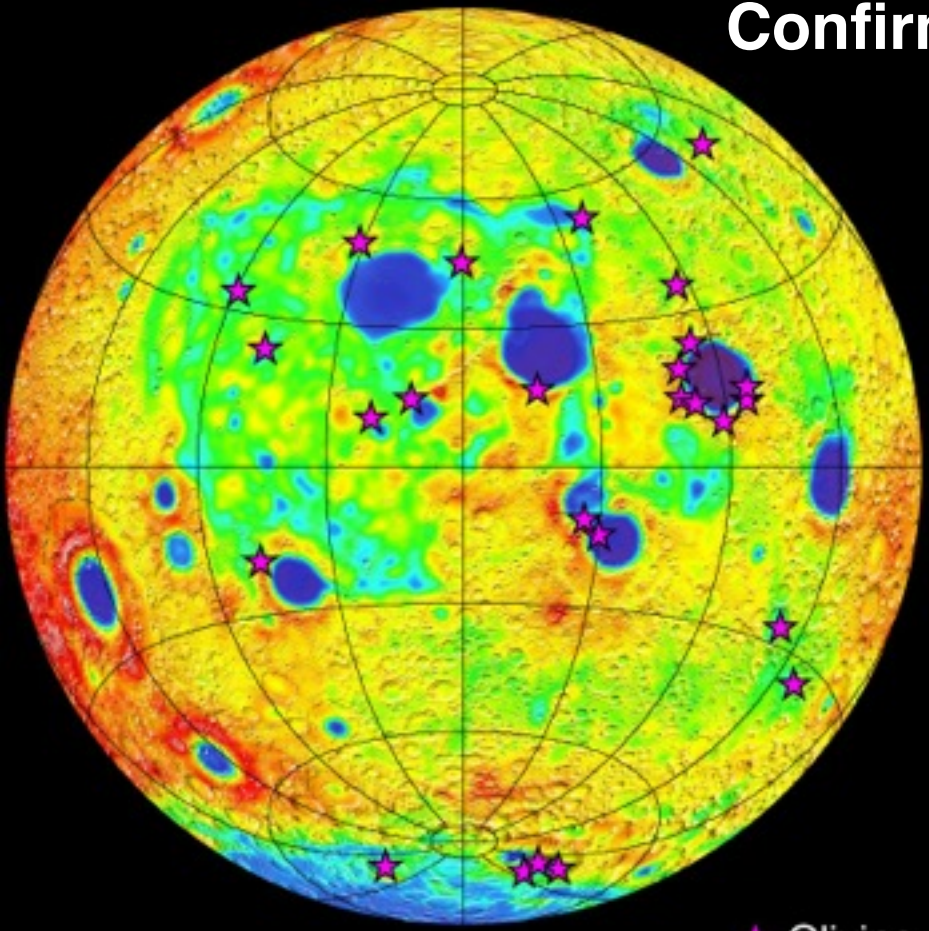
Seismology



Chenet et al., 20016

GRAIL Confirmation





★ Olivine-rich exposures

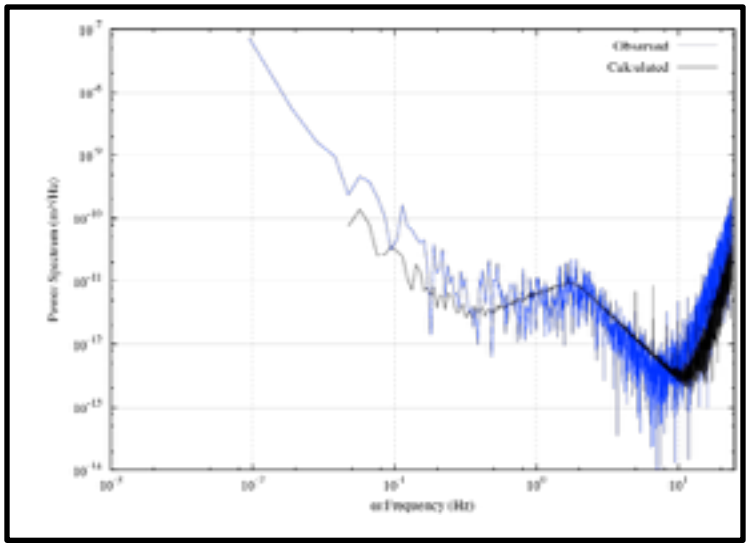
Crustal thickness (km)

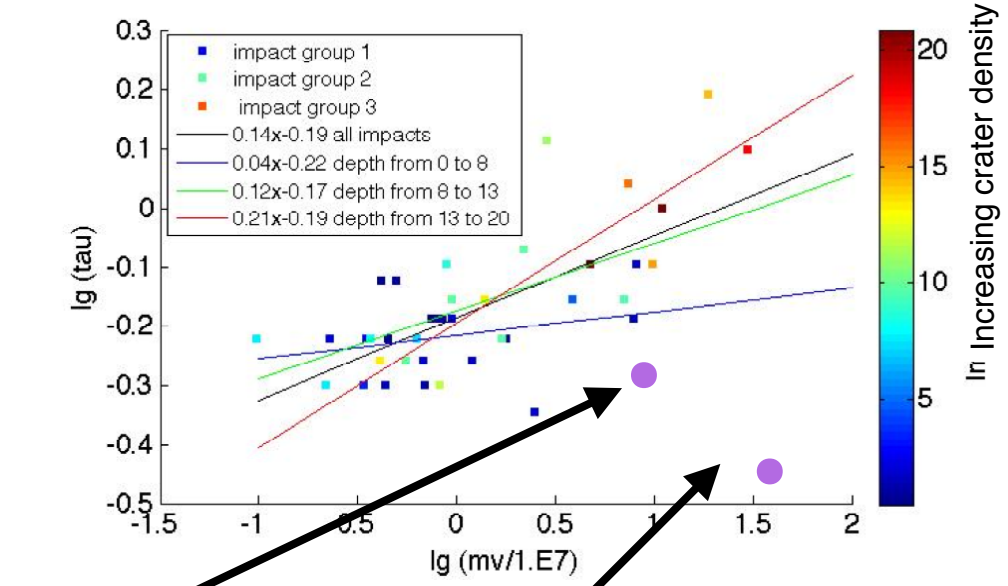
Wieczorek et al., 2013

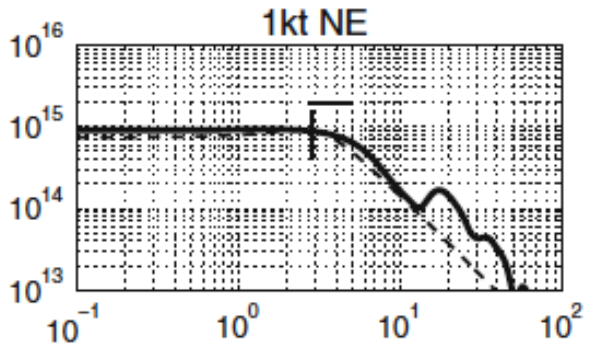
Impact source properties….

- Natural impacts have a long lasting seismic source likely due to the low seismic velocities of the surface and high (20km/s) impact velocities

Gudkova et al, 2014



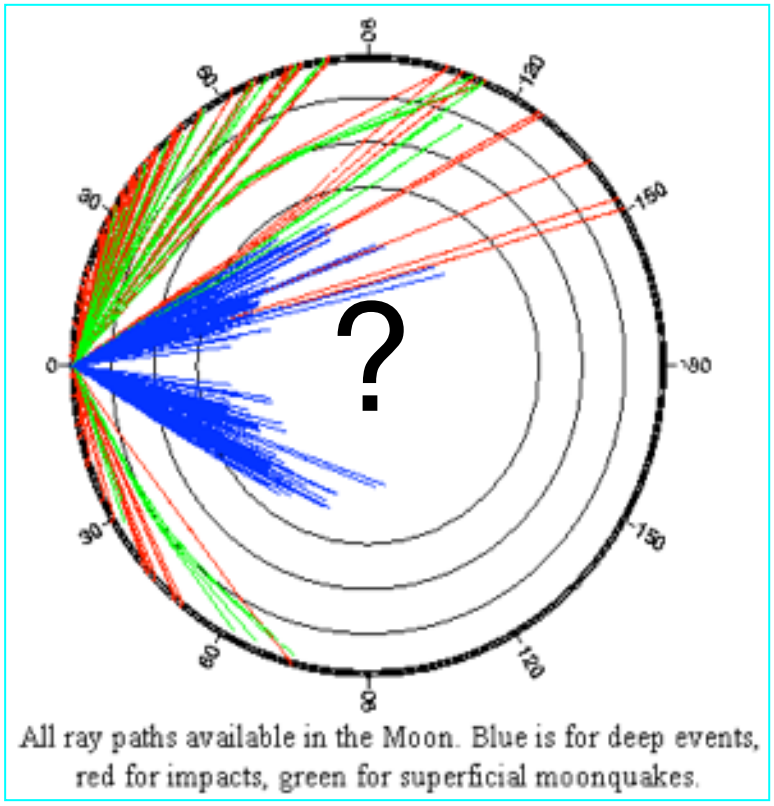




1 kT nuke in Granit (Xu et al, 2014)

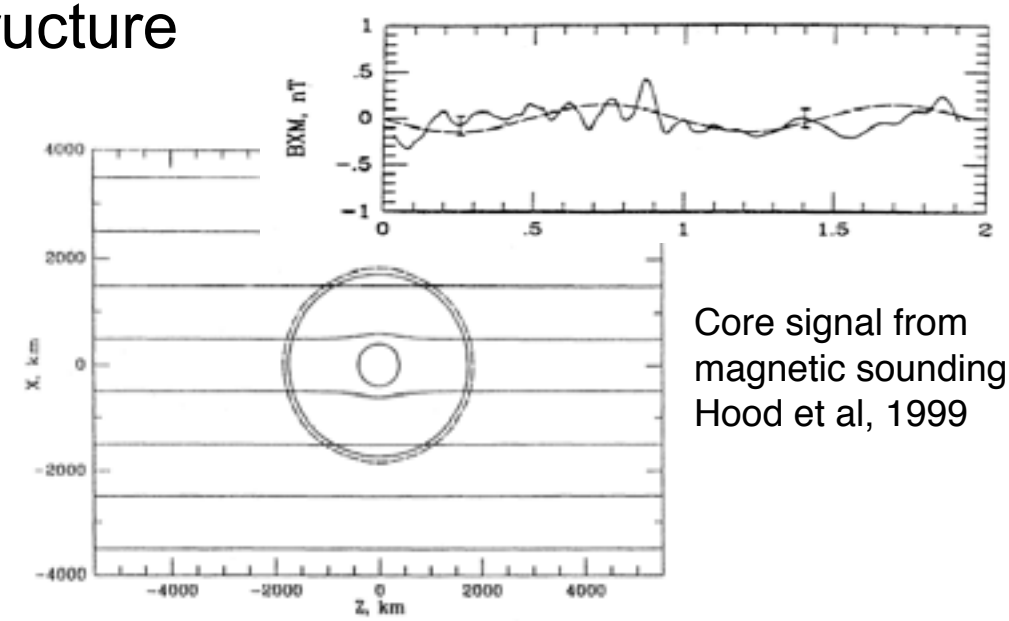
Core…?

- Until 2010, Seismology was in a pre-Oldham configuration regarding the lunar core structure



All ray paths available in the Moon. Blue is for deep events, red for impacts, green for superficial moonquakes.

Lognonné and Johnson, 2007



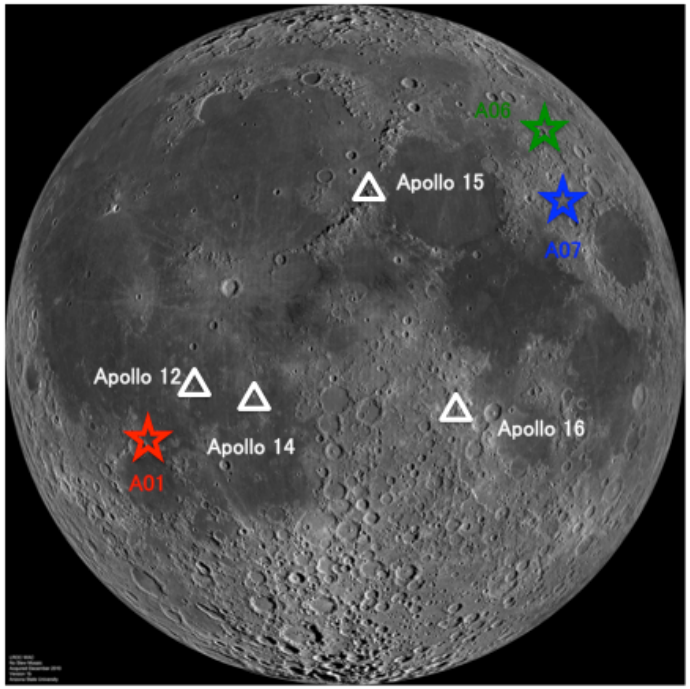
Core signal from magnetic sounding, Hood et al, 1999

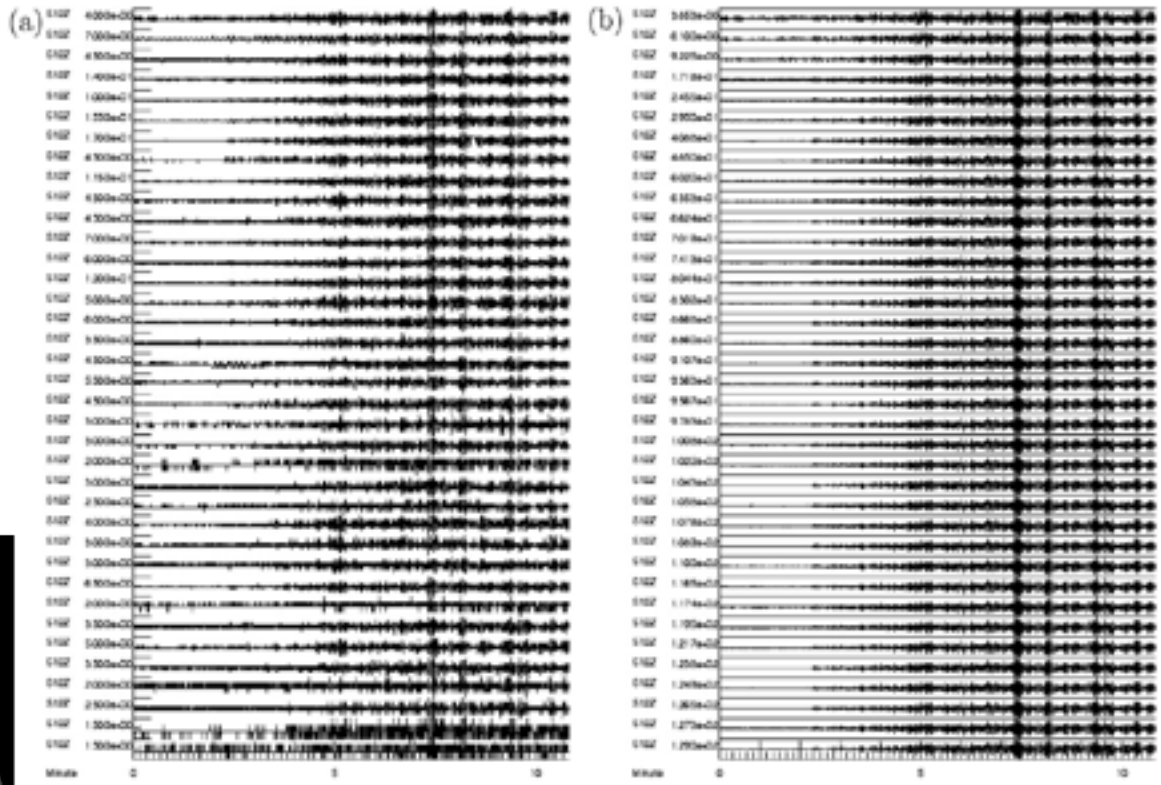
Core signal from libration monitoring, William et al, 2001

Back to the Deep Moonquakes

- Deep Moonquakes repeat at the same fault at rate of several per months
- Are triggered by the Earth tide

Kawamra et al, 20134

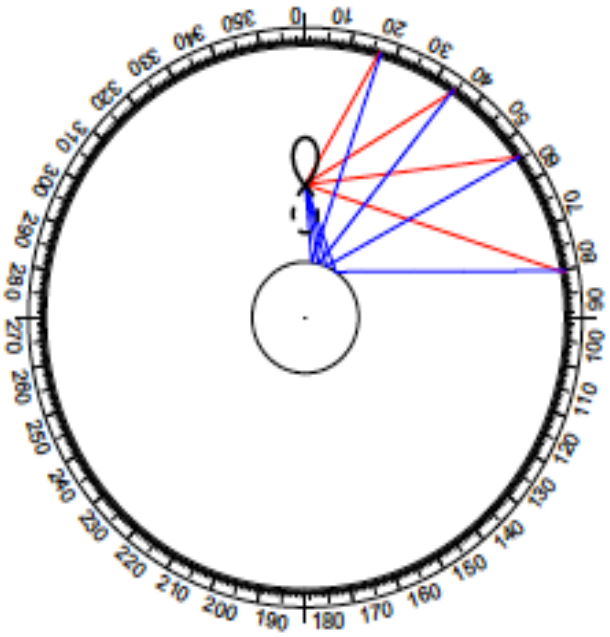


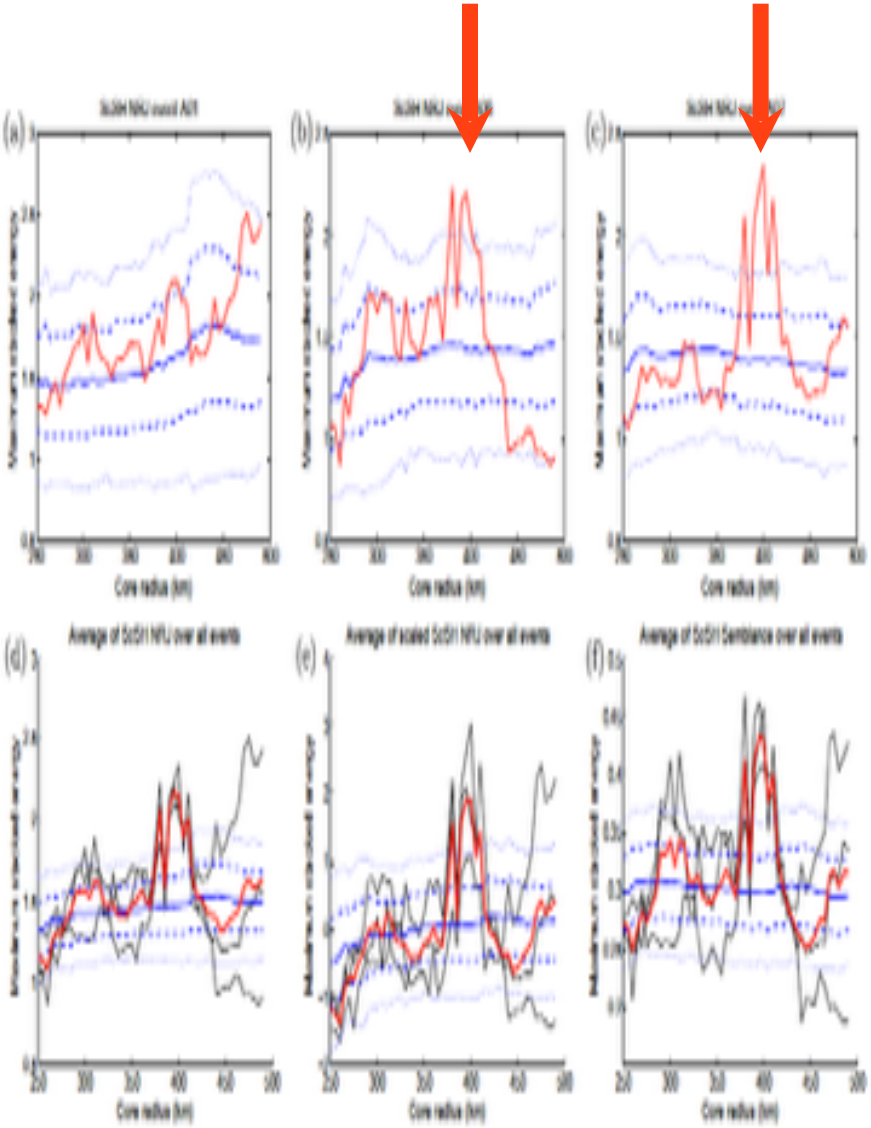


Garcia et al, 2013

- Are beneath the Apollo stations and lighten the deep Moon interior

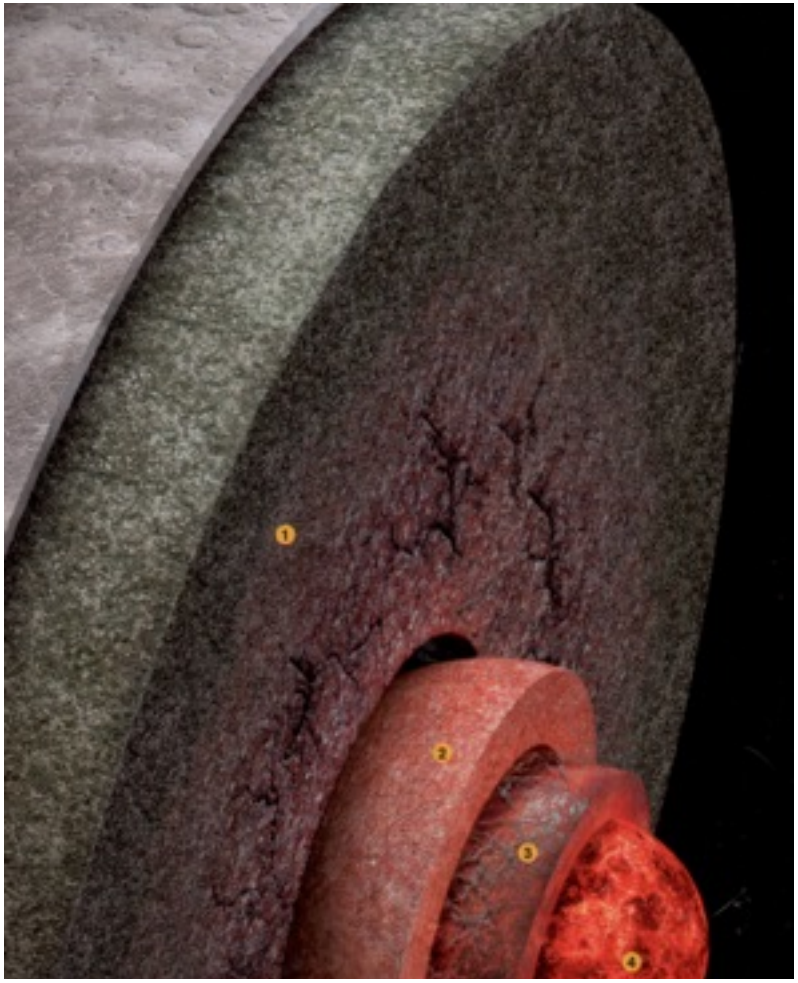
Seismic discovery of the core (1/2)

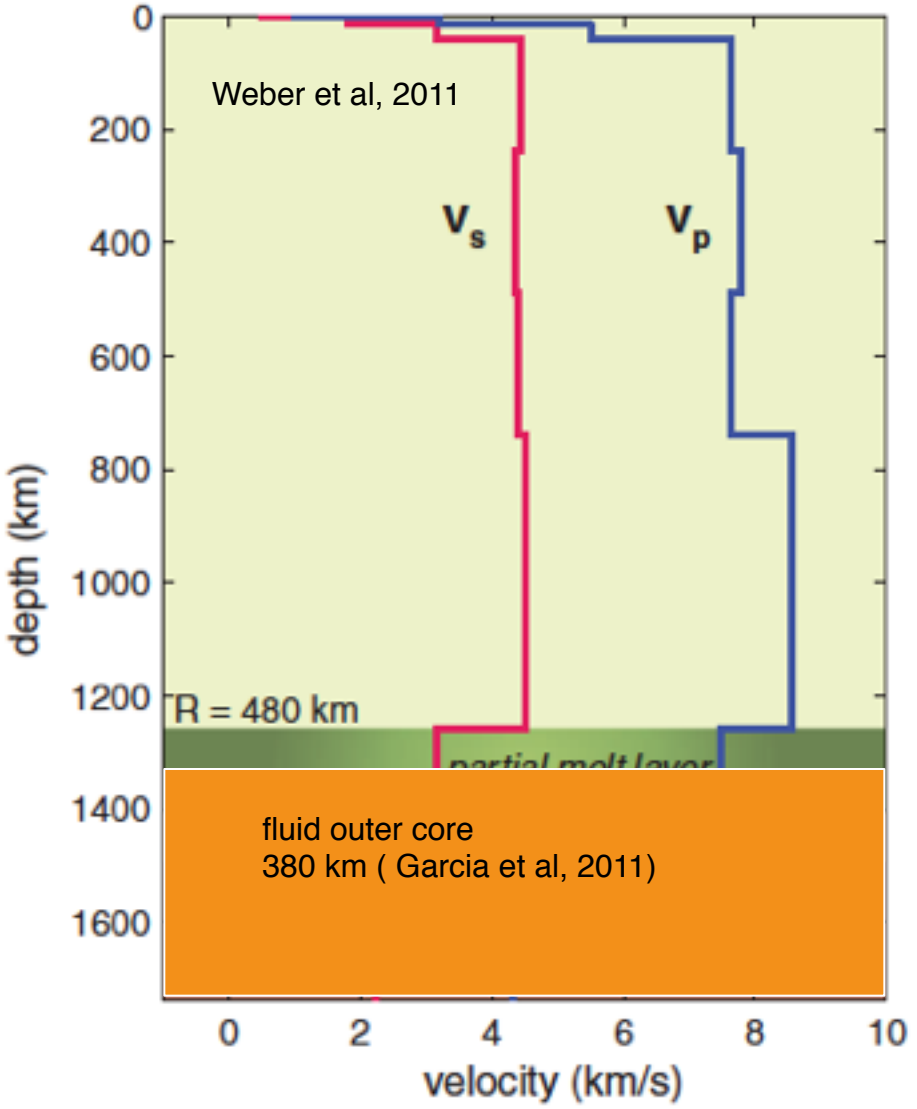




Garcia et al., 2011
Weber et al, 2011

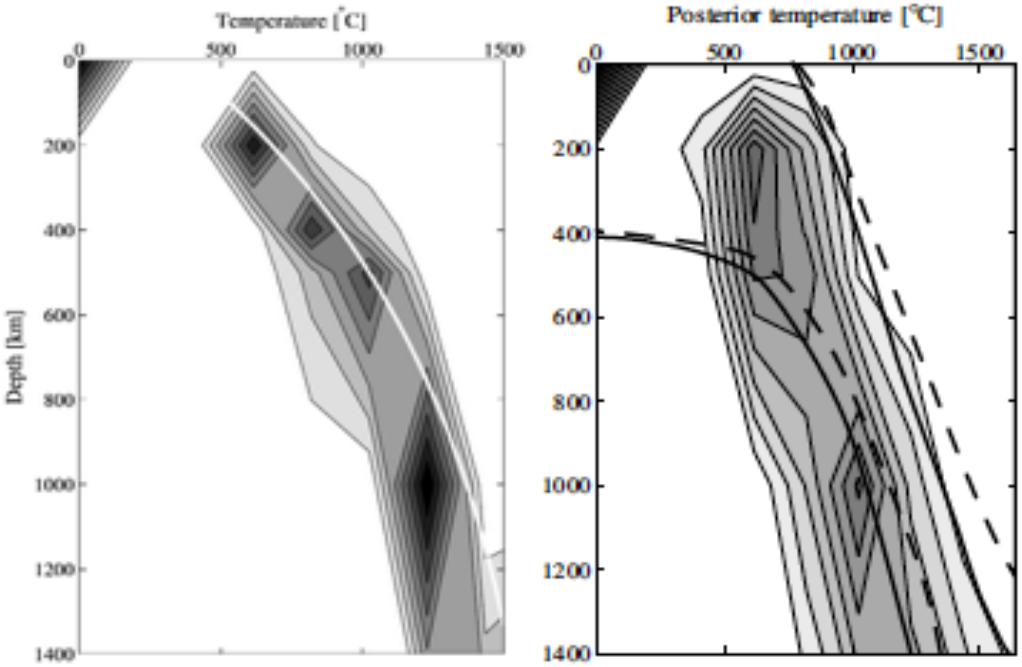
Seismic discovery of the core (2/2)





Weber et al, 2011

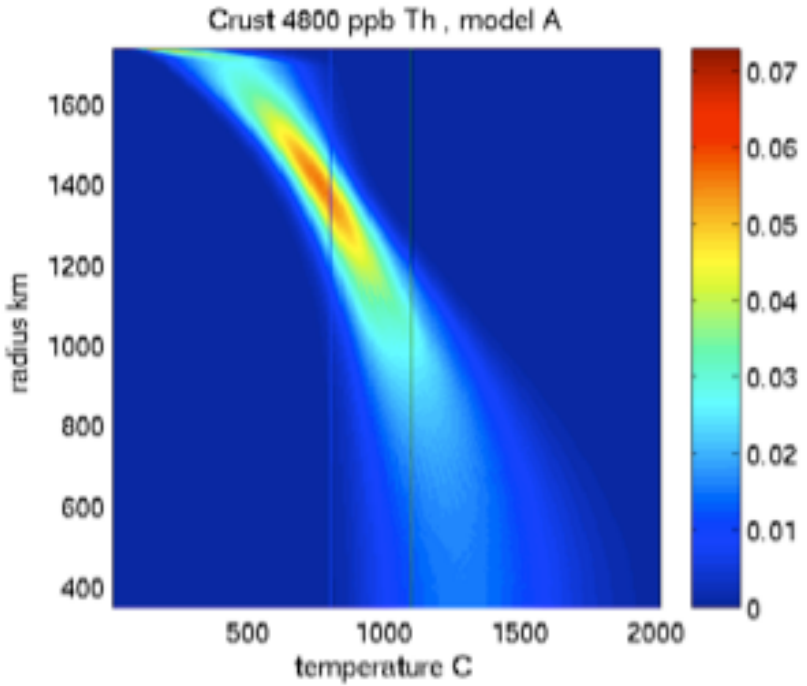
Core temperature and composition (1/2)



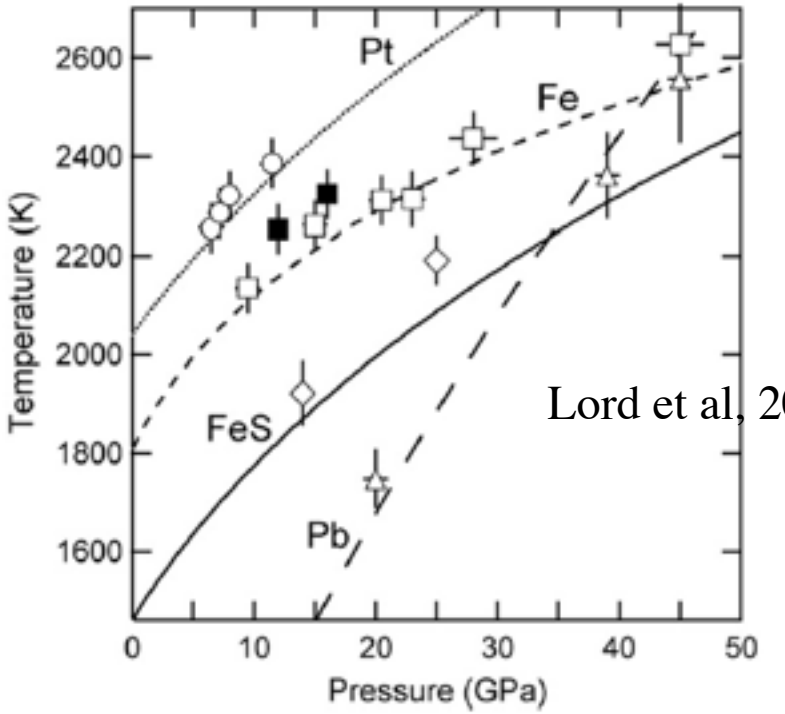
Khan et al, 2006
(direct inversion of seismic data)

Khan et al, 2007
(direct inversion of magnetic data)

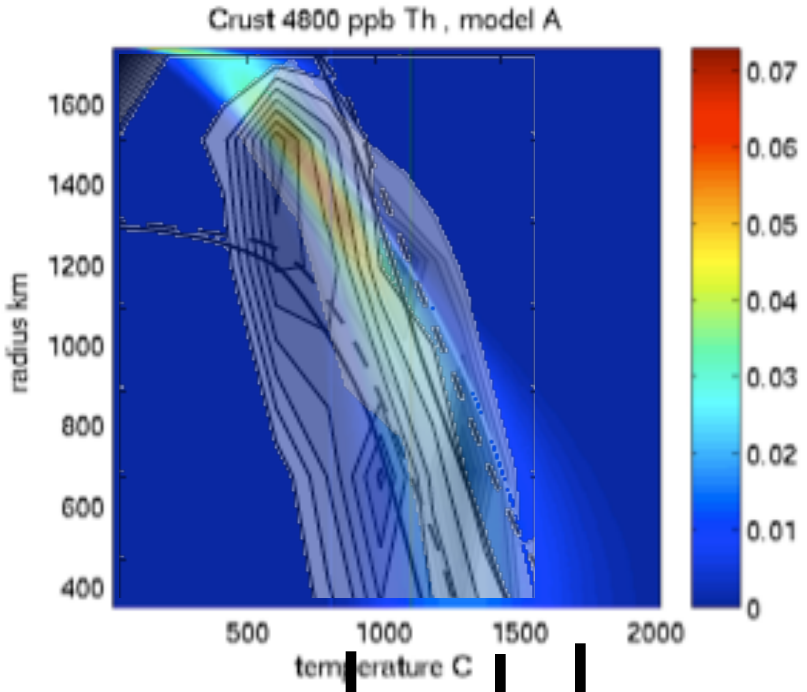
Gagnepain-Beyneix et al, EPSL, 2006



Core temperature and composition (2/2)



Lord et al, 2010

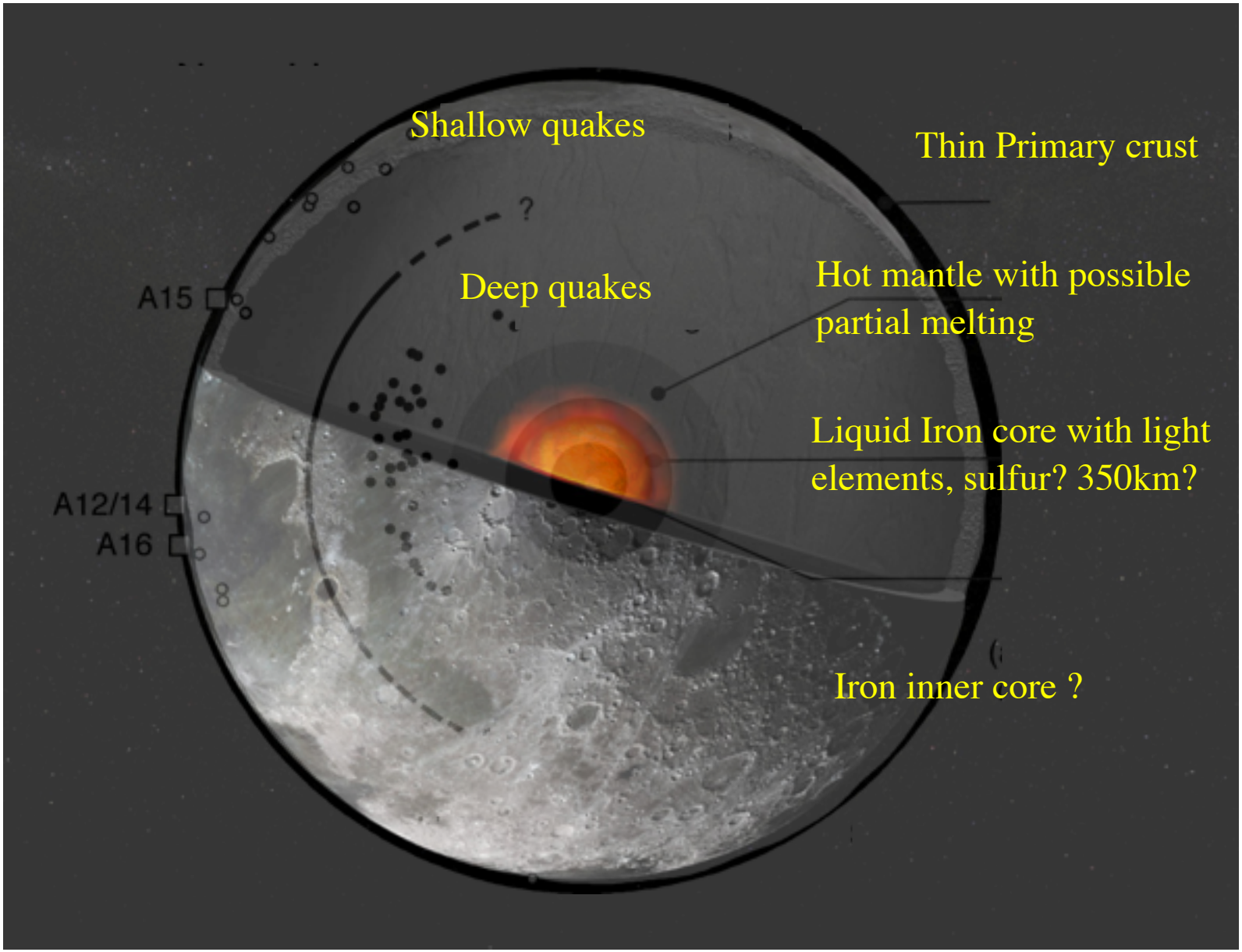


1620°C (Fe, Anderson and Isaak, 2000)

1490°C (29° Ilmenite, 71% clinopyroxene, Wyatt, 1977)

950°C (Fe-S Eutectic, Fei et al, 1997)

Our view of the Moon

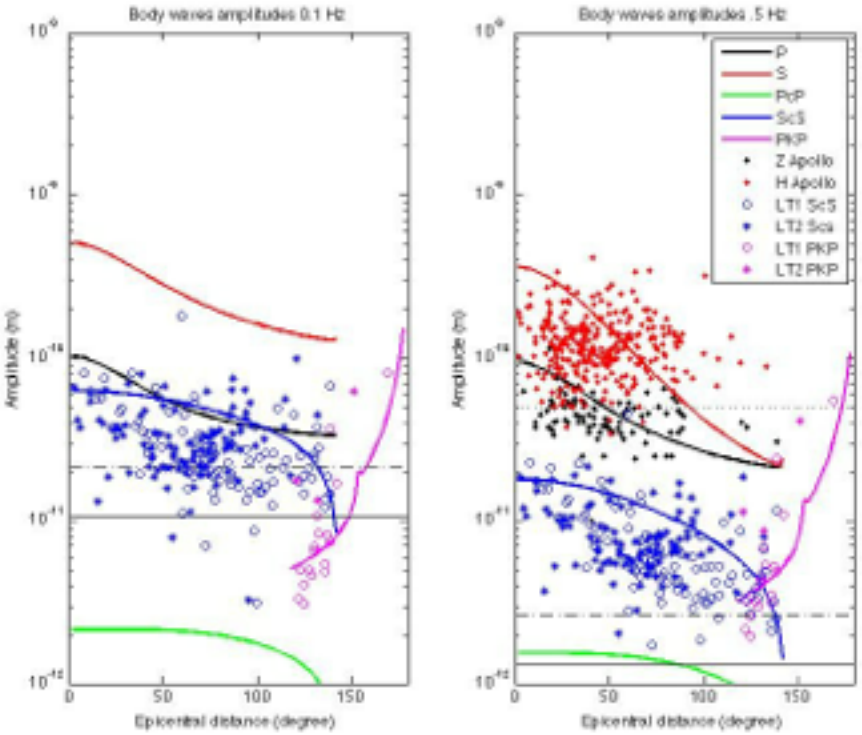


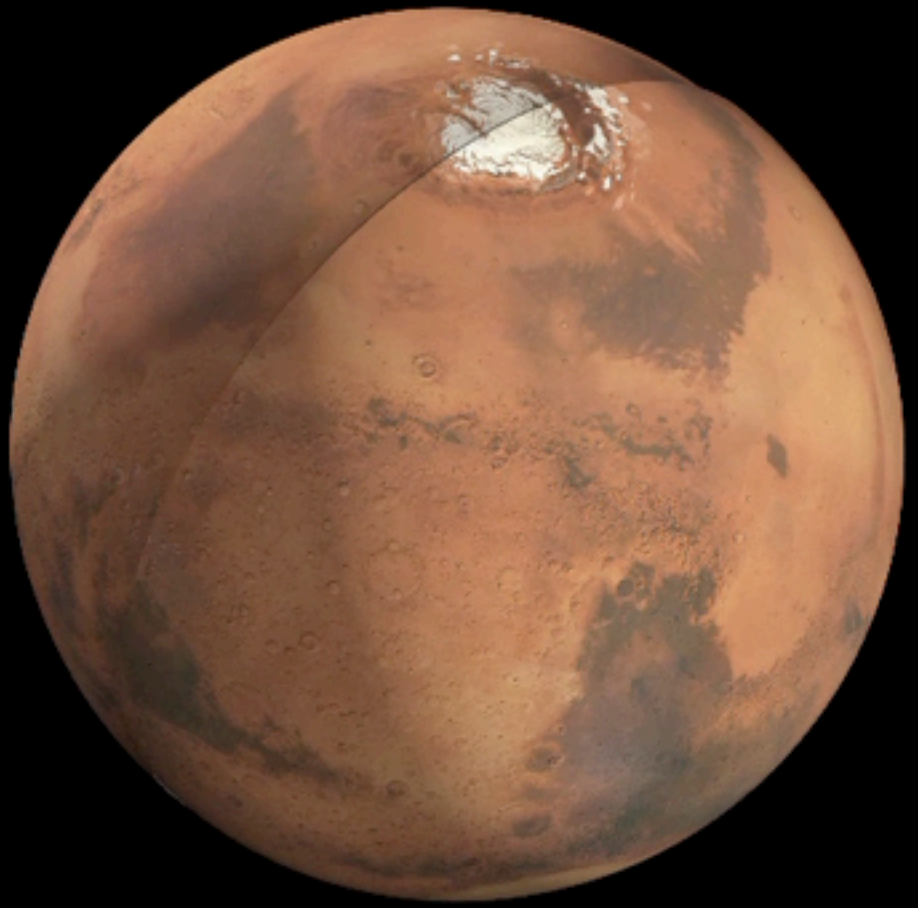
Moon Future directions…

- SELENE2 (JAXA)
- NF Lunar Network (NASA)

- Core: Better sensitivity will allow the detection of core phases on single seismograms

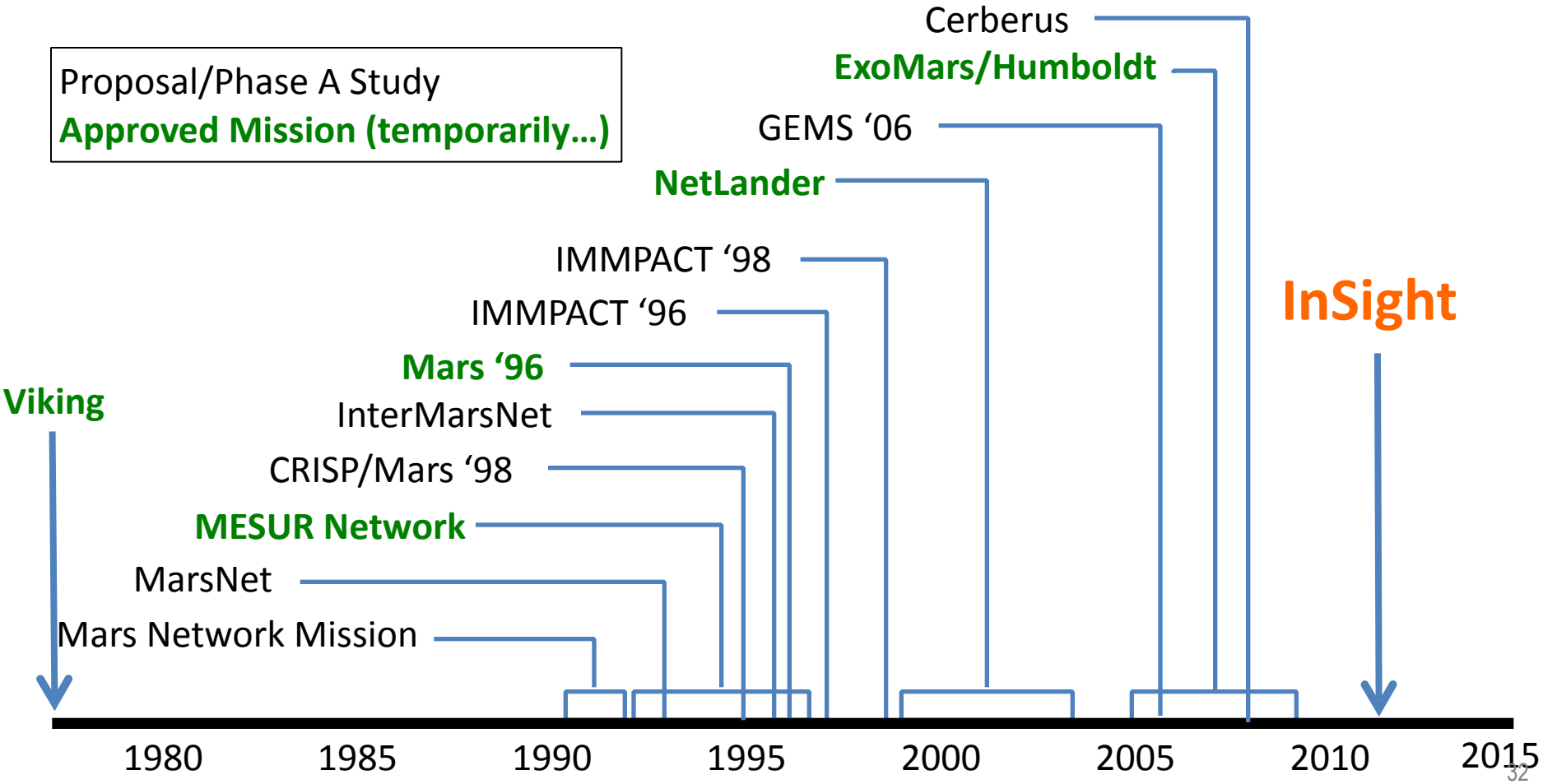
- Impacts: Can now be observed also from Earth and will therefore provide free active seismic experiments with 100th of sources…





1977 – Present

- Over the 35 years since Viking and Apollo, despite many proposals and several mission starts, there have been no further seismic investigations of the interior of any planet… until now!



1977 – Present

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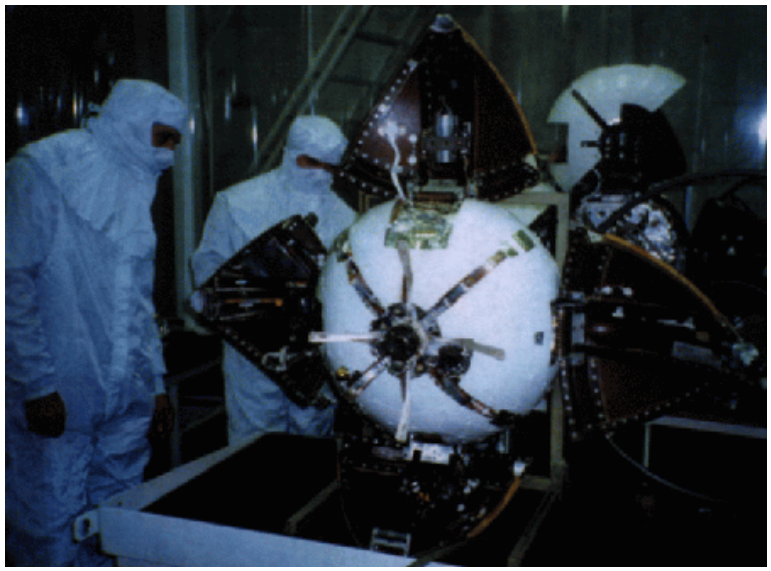
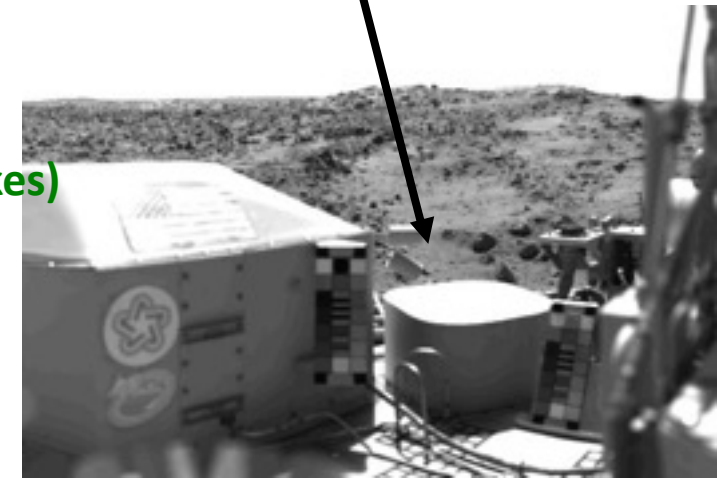


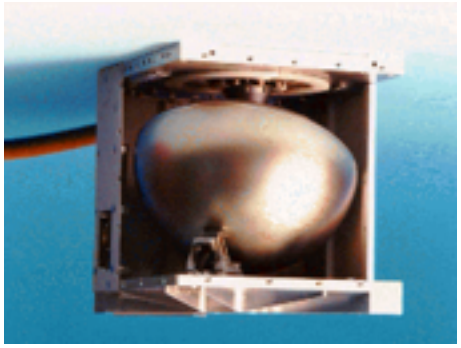
Launched Mission

Mars '96 (lost)

Seismometer



Viking (no quakes)



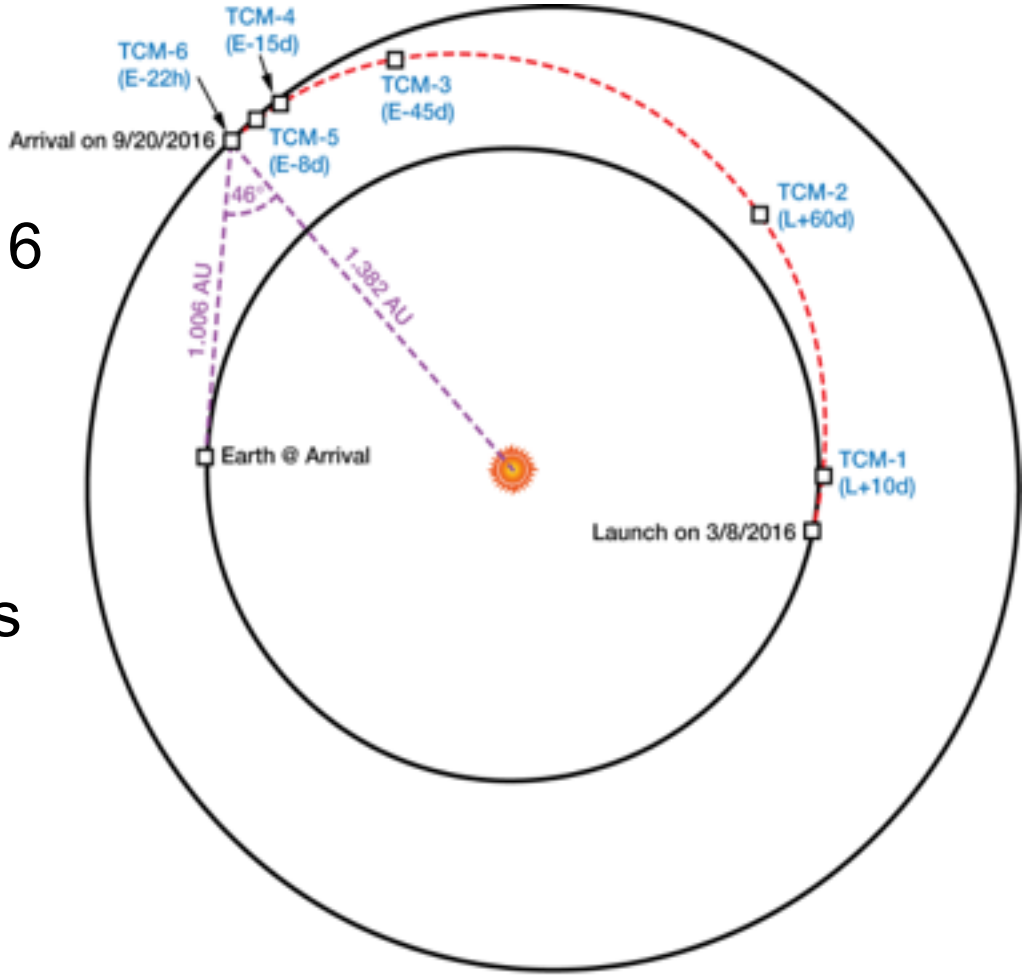
InSight

1980 1985 1990 1995 2000 2005 2010 2015

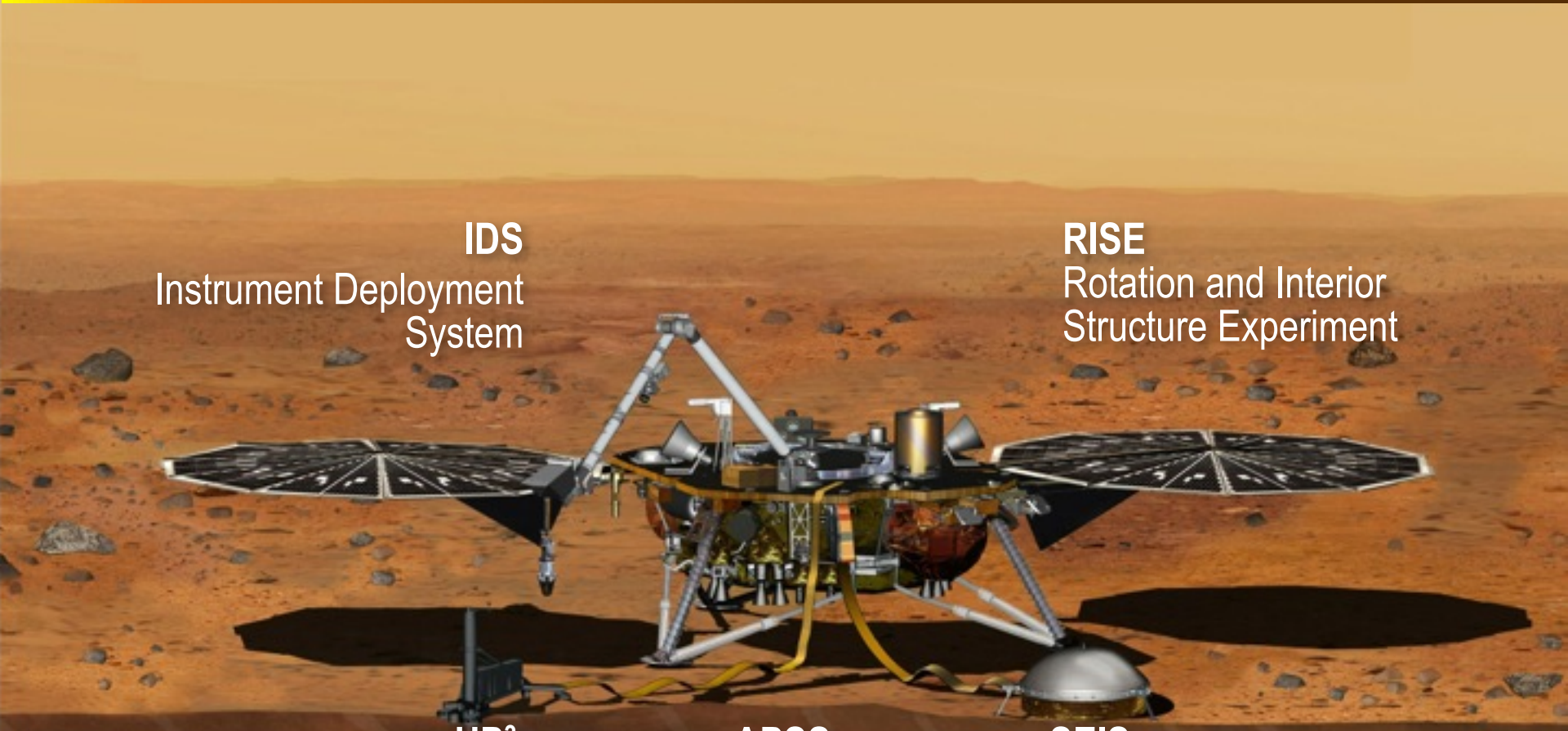
InSight Mission Design Summary

Only 1 year, 9 months,
-1 days from now!

- Launch: March 4, 2016
- Fast, type-1 trajectory, 6.5 month cruise to Mars
- Landing: September 28, 2016
- 67-sol deployment phase
- One Mars year (two years) science operations on the surface; repetitive operations
- Nominal end-of-mission: October 6, 2018



Payload Elements



IDS
Instrument Deployment System

RISE
Rotation and Interior Structure Experiment

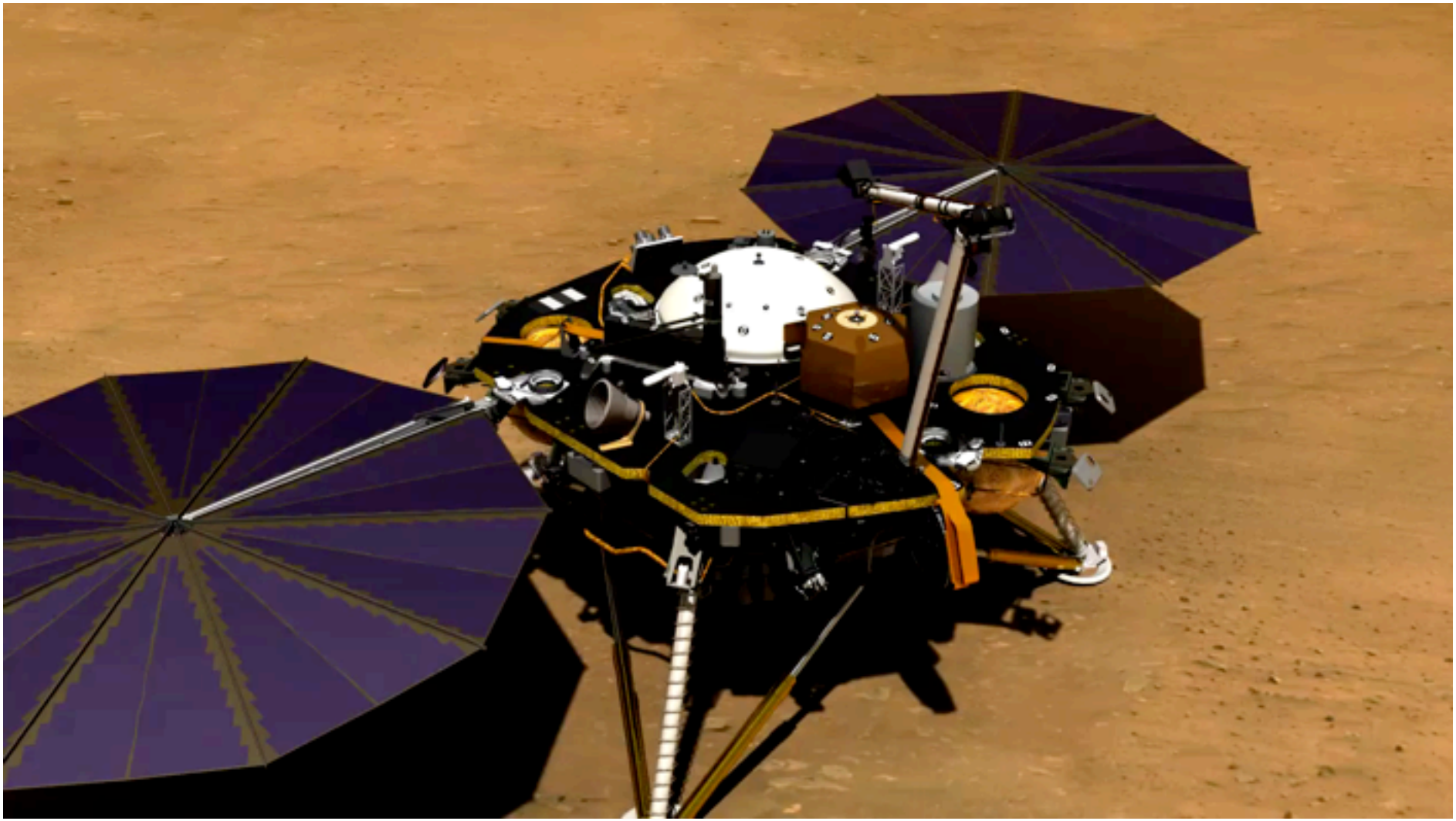
HP^3
Heat-Flow and Physical Properties Probe

APSS
Auxiliary Payload Sensor Suite

SEIS
Seismic Experiment for Interior Structure

Payload Elements Deployment challenge: Apollo

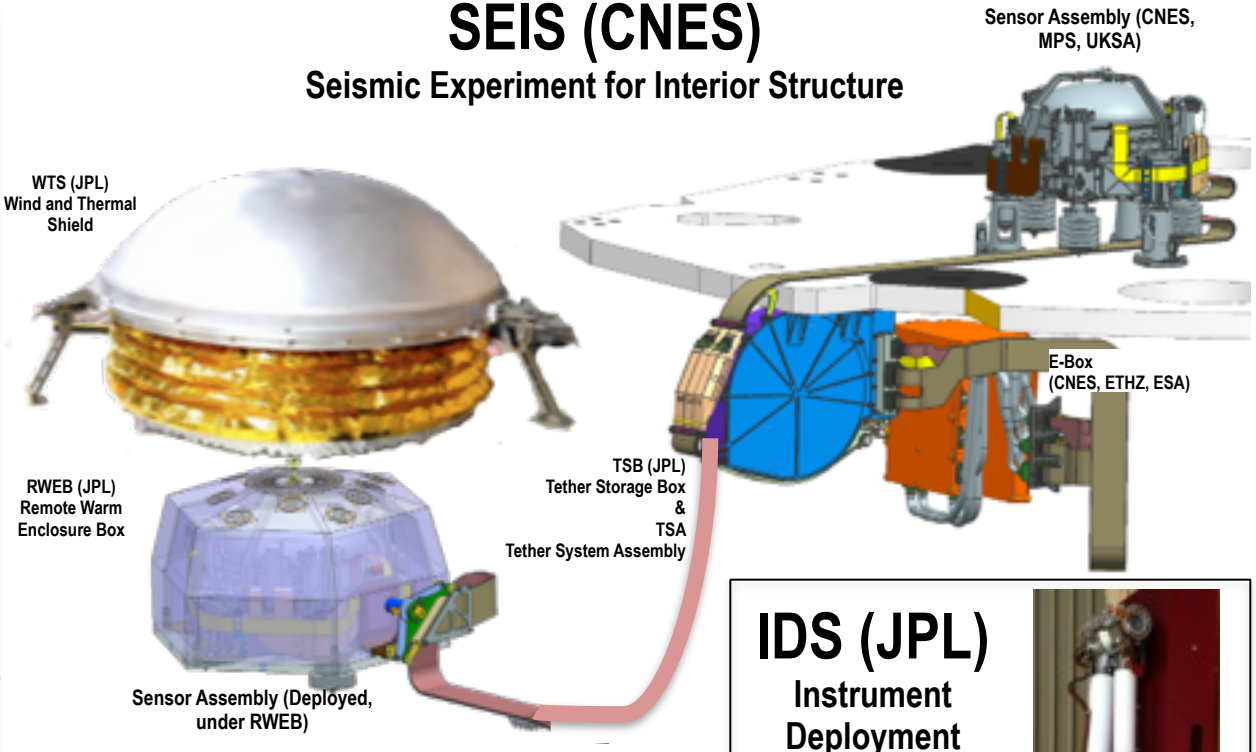
Payload Elements Deployment challenge: InSight



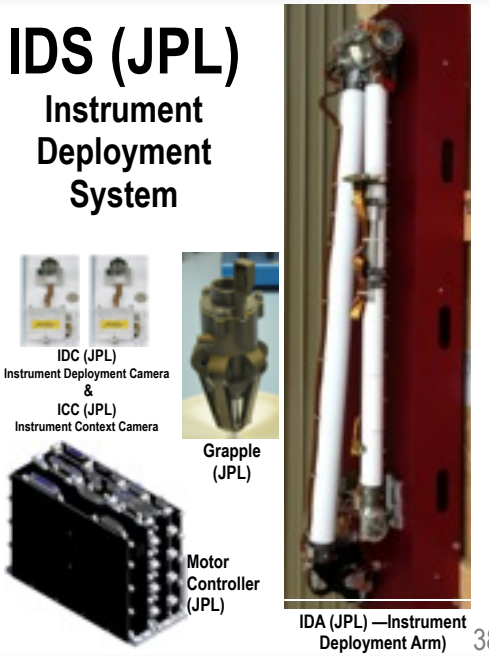
The InSight Payload

HP³ (DLR)
Heat-Flow and Physical Properties Probe

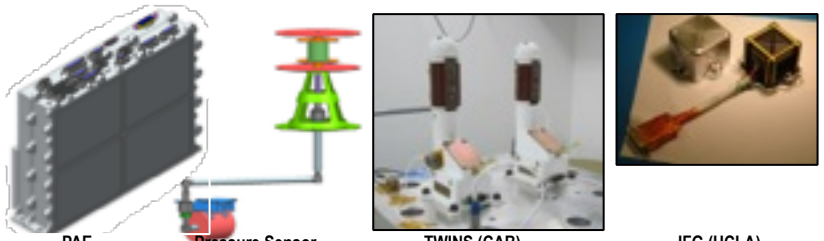
SEIS (CNES)
Seismic Experiment for Interior Structure



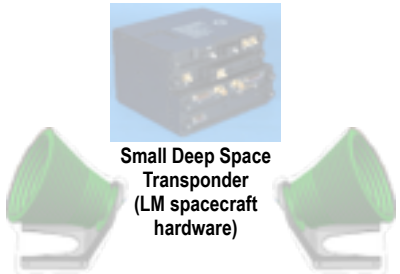
IDS (JPL)
Instrument Deployment System



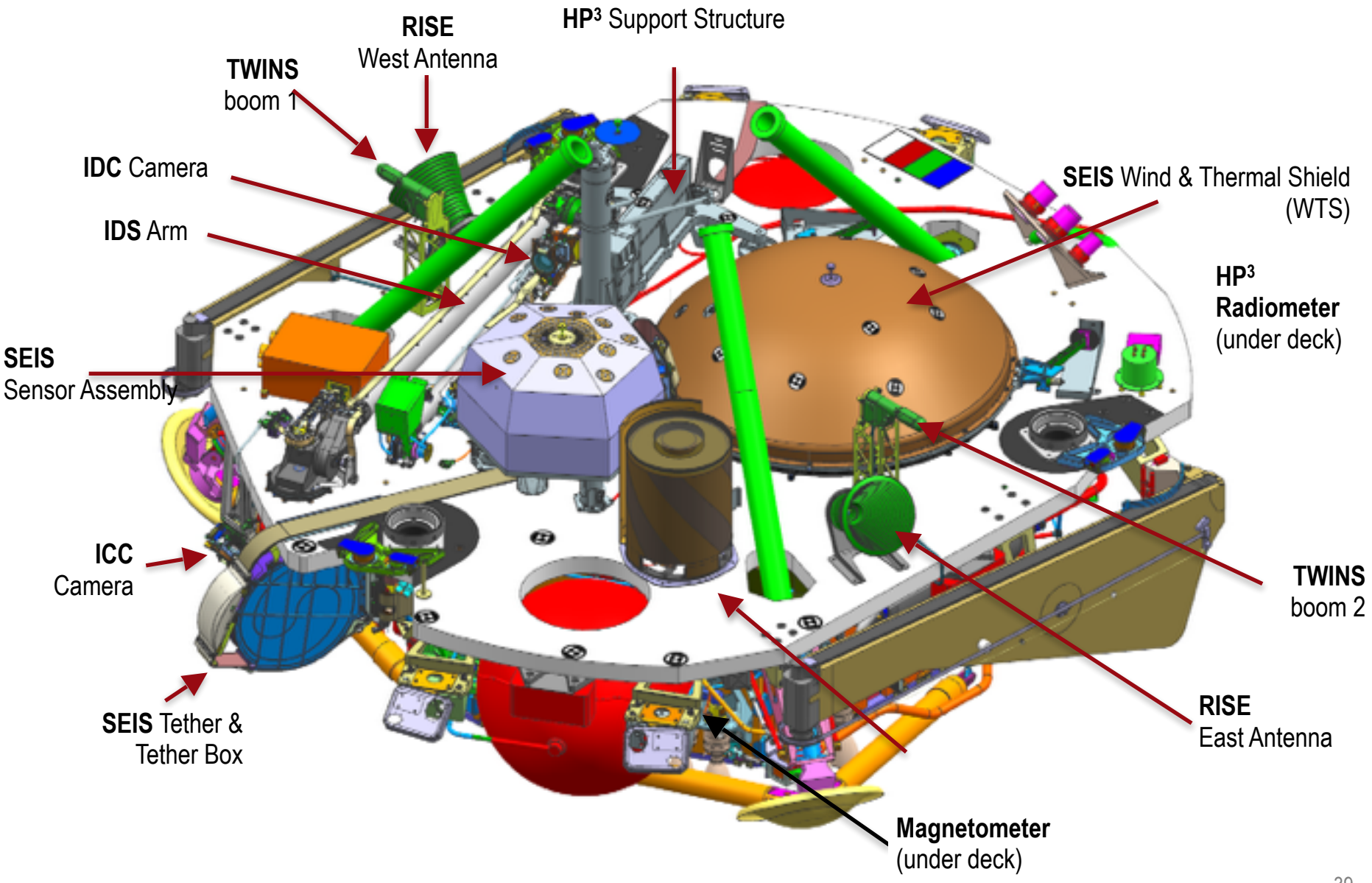
APSS (JPL)
Auxiliary Payload Sensor Suite



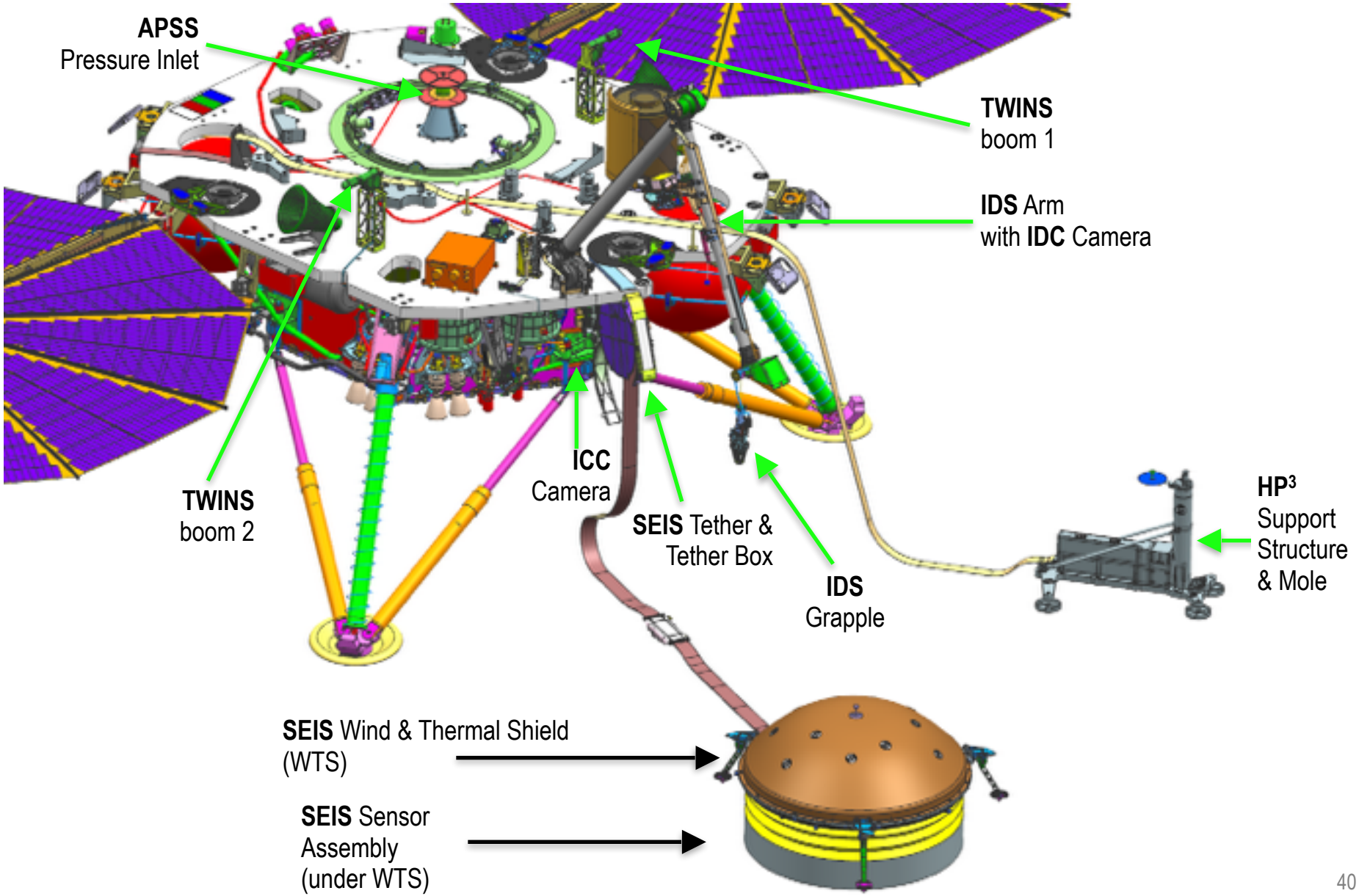
RISE (S/C)
Rotation and Interior Structure Experiment



Payload Configuration on Deck—Stowed

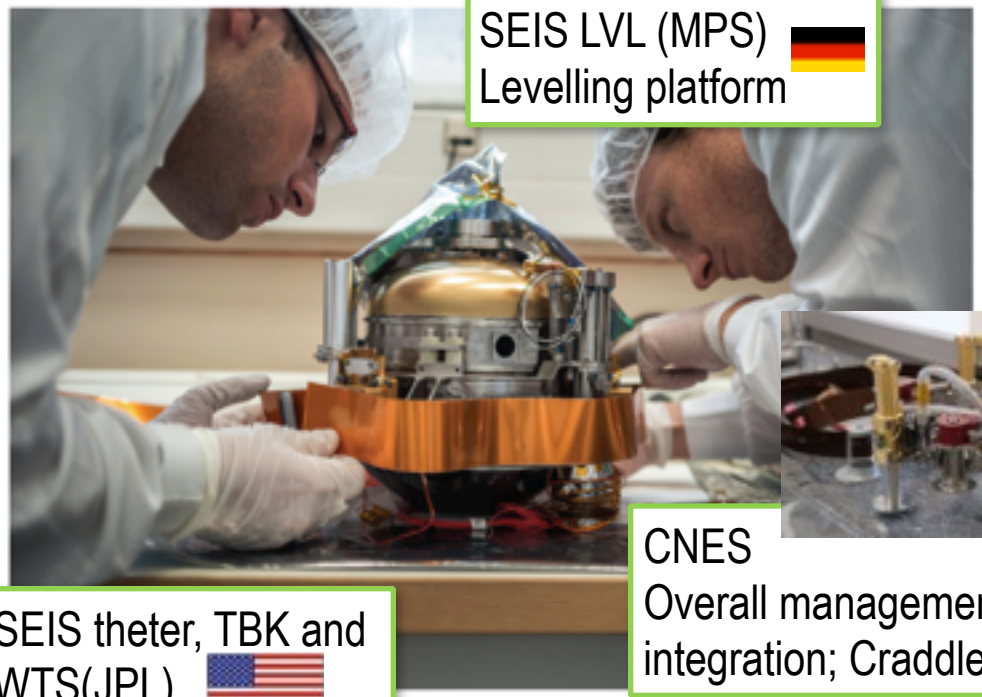


Payload Configuration on Deck—Deployed



SEIS Overview/Description

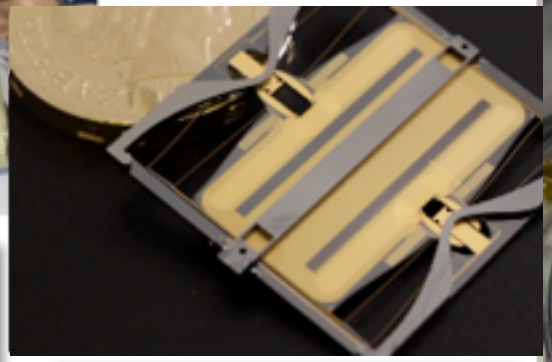
SEIS Electronics (ETHZ)
10x24 vits + 72x12 bits data logger



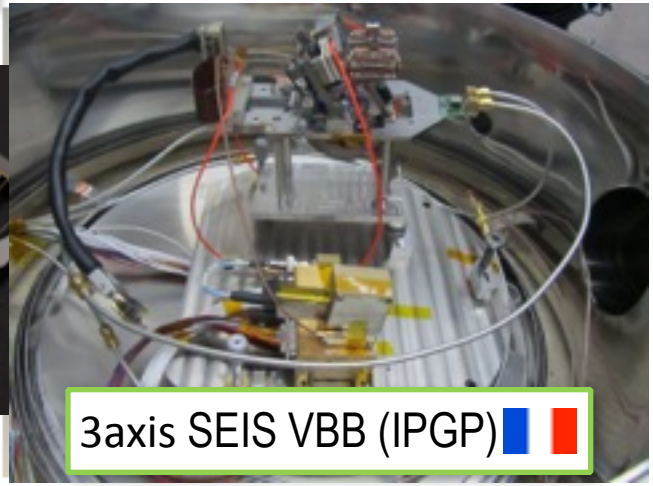
SEIS LVL (MPS)
Levelling platform

CNES
Overall management and integration; Craddle

SEIS theter, TBK and WTS(JPL)

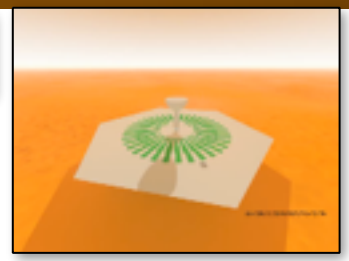


3 axis SEIS SP (IC)



3axis SEIS VBB (IPGP)

SEIS Sensors head Overview/Description



Sundial for azimuth

Tether Service Loop

Tether

SEIS with RWEB

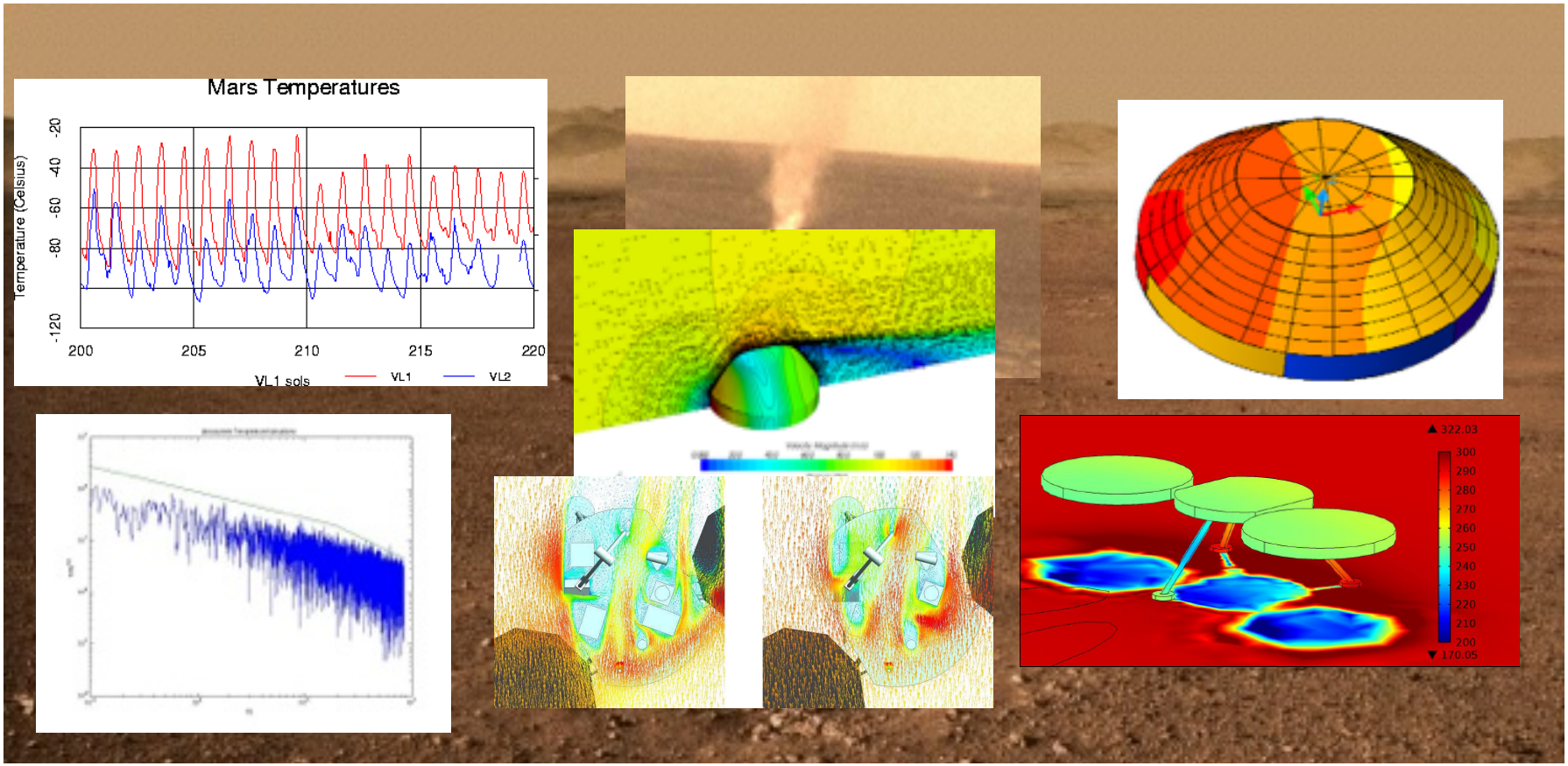
Tether Load Shunt

Tether Pinning Mass

This document contains export-restricted data.

Environmental noise

- We are here……



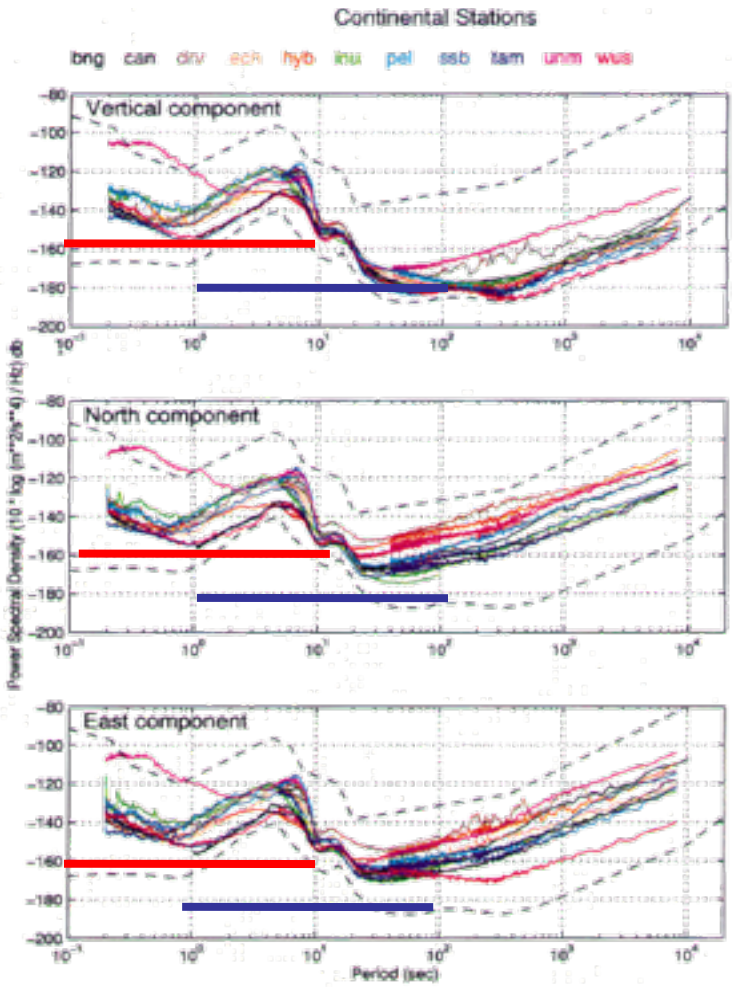
Environmental noise

- but would like to be there……

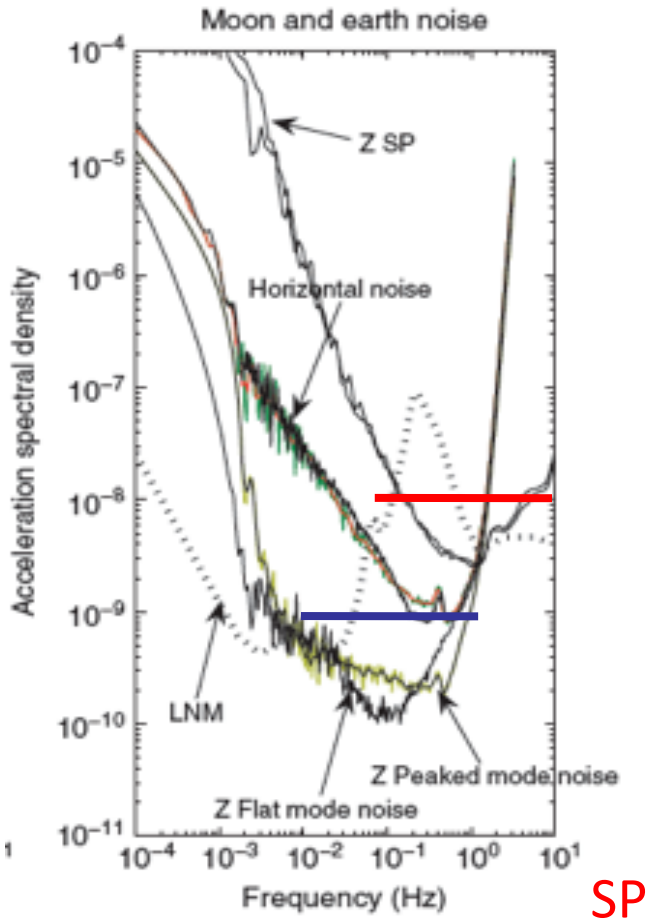
Seismic vault

Environmental noise: installation goals

Planet with Ocean and Atmosphere



Planet without atmosphere and ocean

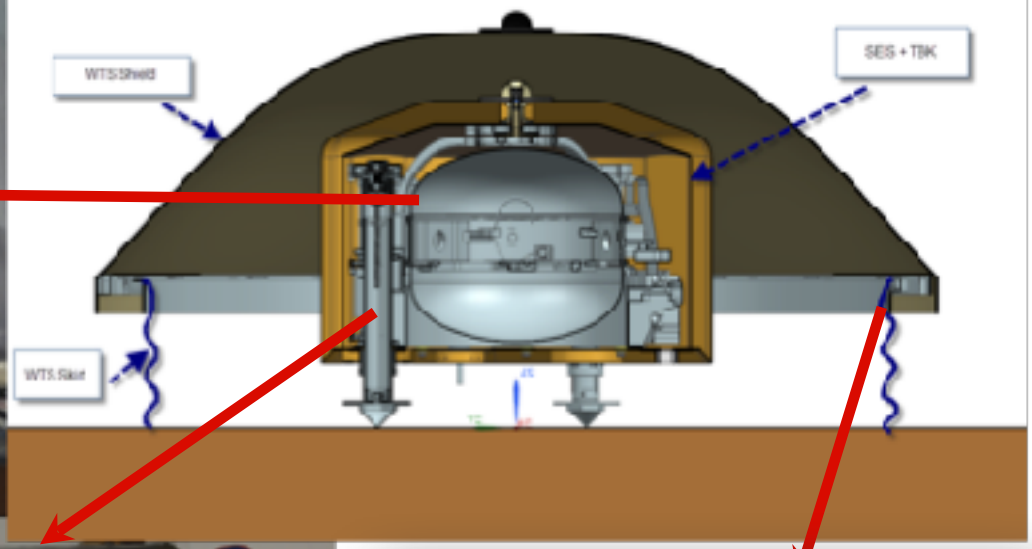


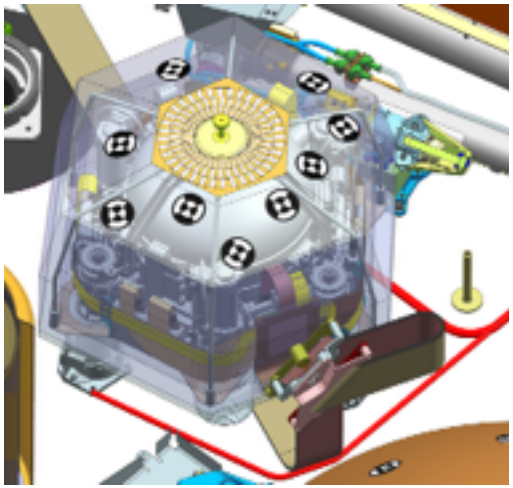
SP VBB

Temperature and wind protection

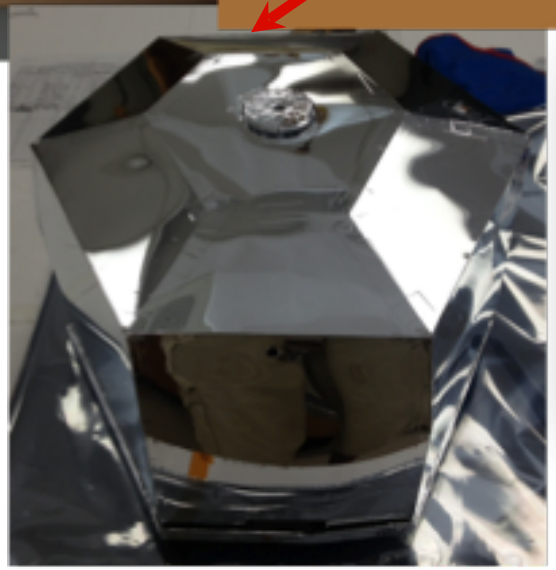
Evacuated sphere

Wind protection

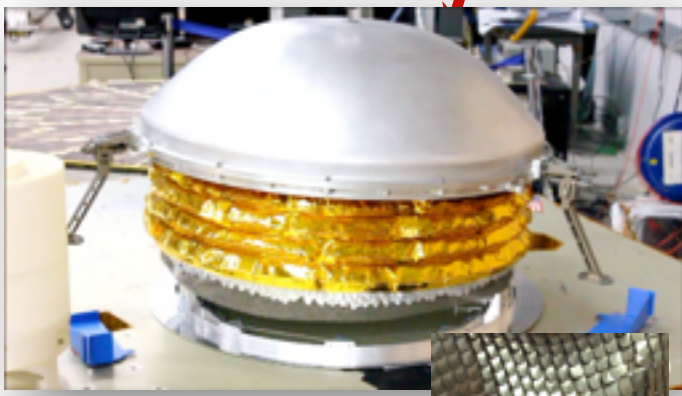


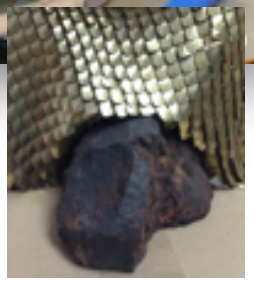


Thermo-elastic service loop



Thermal shield

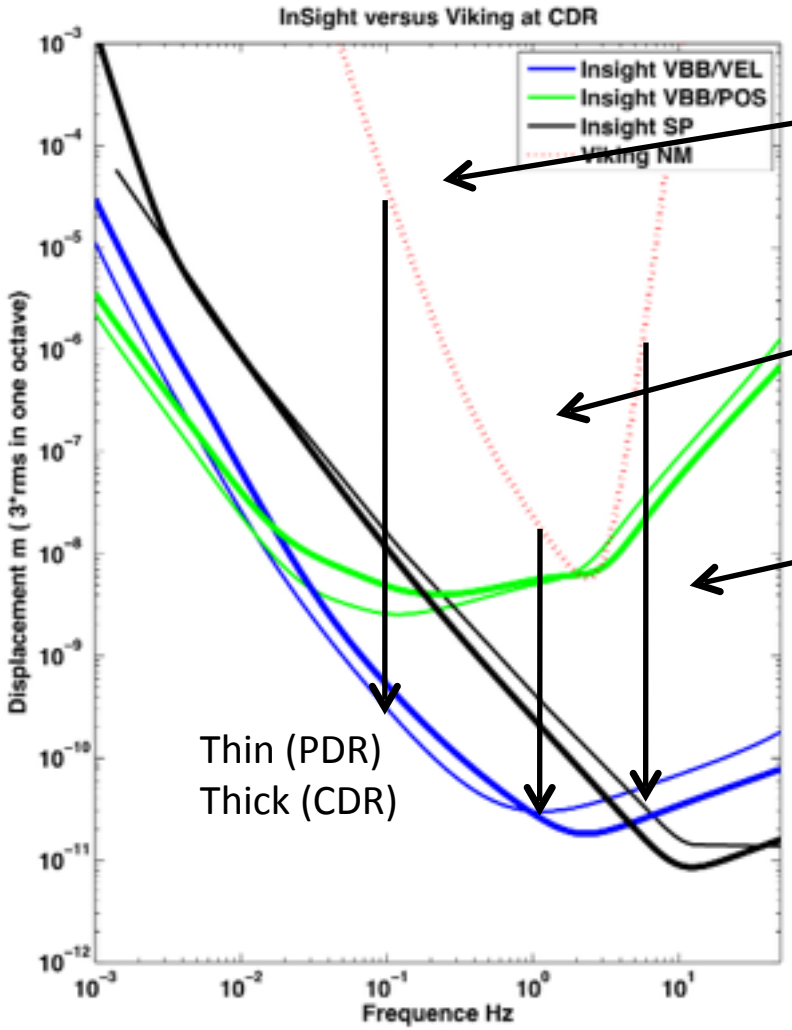




Sealing skirt

InSight/SEIS performances at CDR (4/2014)

• 40 yrs after Viking, SEIS will perform modern Earth seismology, with sensitivity 10^3 to 10^5 larger than Viking NM and with **almost Earth standard** for data products



7.5 10^4 better for regional 10 sec surface waves (and 5 x10^5 ≥20sec)

>10^3 better for remote body waves

>10^4 better for small quakes

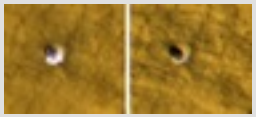
+better installation and 24 bits waveform instead of envelop

SEIS Expected Natural signals

M~5.5 1-2/yr
Global

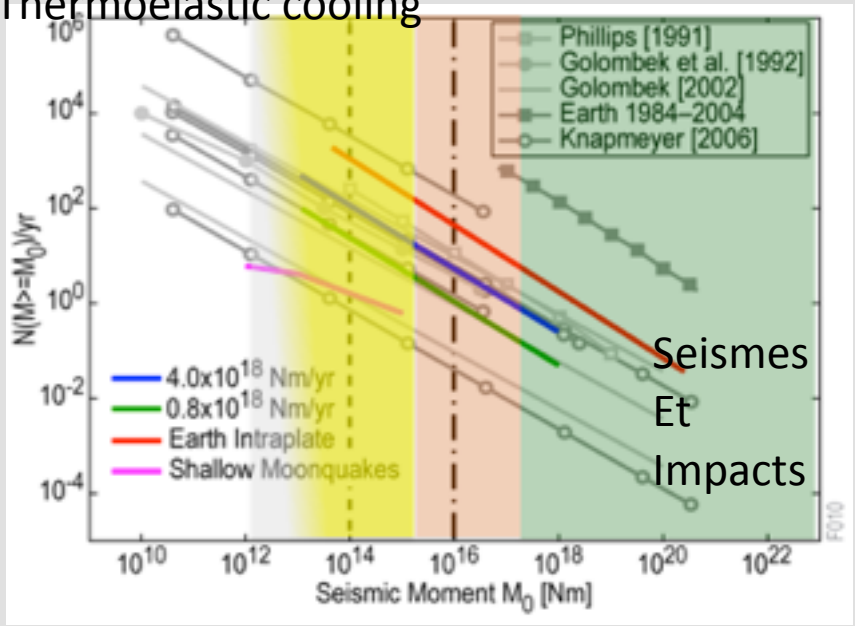
M~4.5 ~ 10/yr
Global to regional

M~3.5 ~100/yr
regional

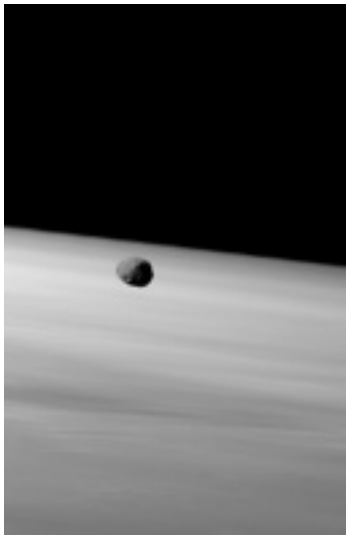


Impacts
10-15/yr

Thermoelastic cooling

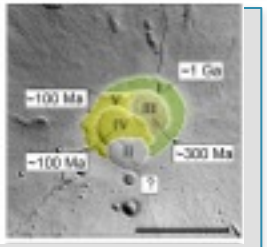


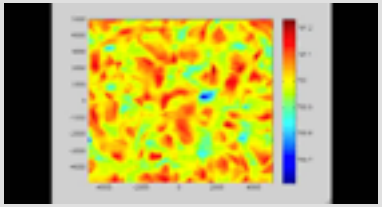
Seismes
Et
Impacts



Phobos tide

Bonus:
Tectonic
activity





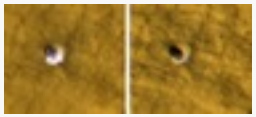
Atmospheric loading
Atmospheric generated seismic noise

SEIS Expected Natural signals

M~5.5 1-2/yr
Global

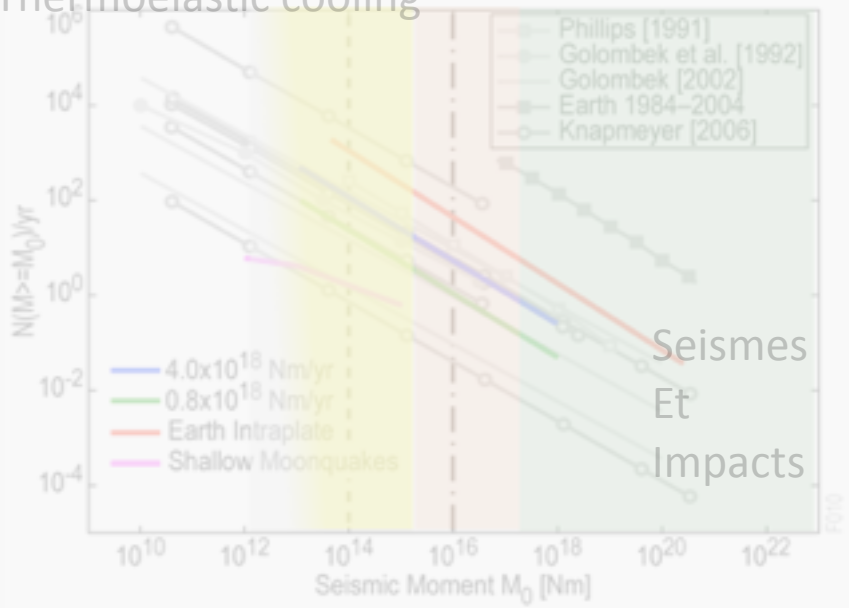
M~4.5 ~ 10/
Global to regional

M~3.5 ~100/
regional



Impacts
10-15/yr

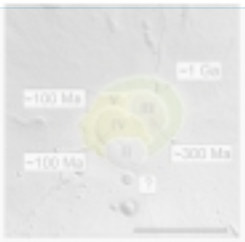
Thermoelastic cooling

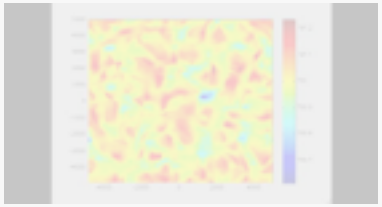


Seismes
Et
Impacts

Phobos tide

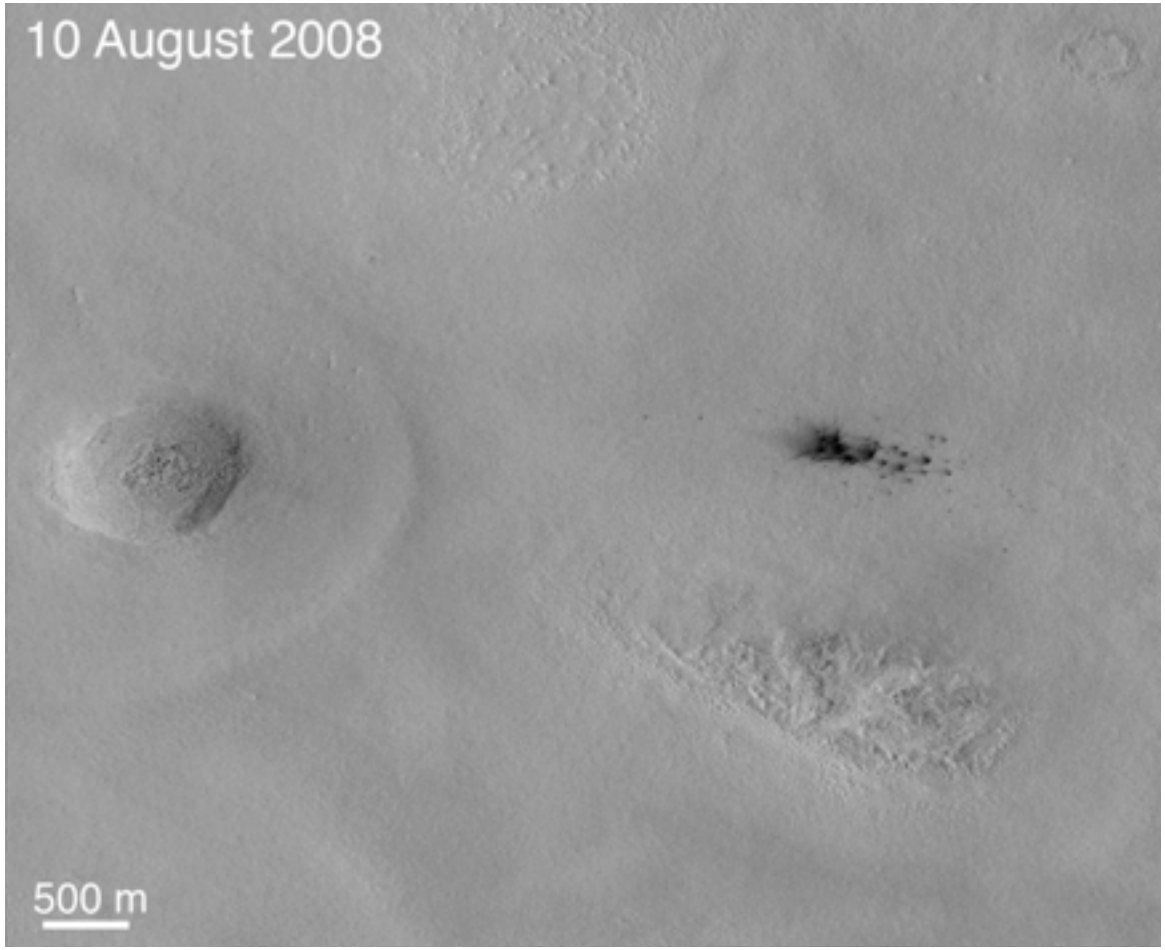
Bonus:
Tectonic
activity





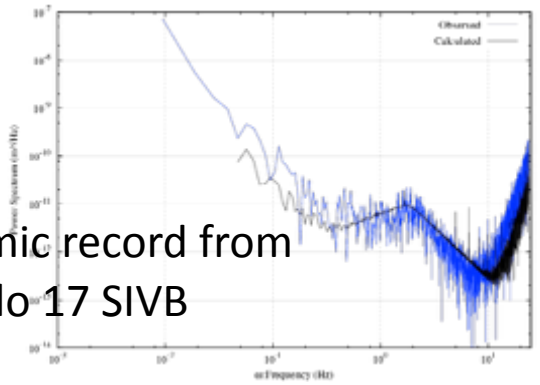
Atmospheric loading
Atmospheric generated seismic noise

Mars impacts (1/2)

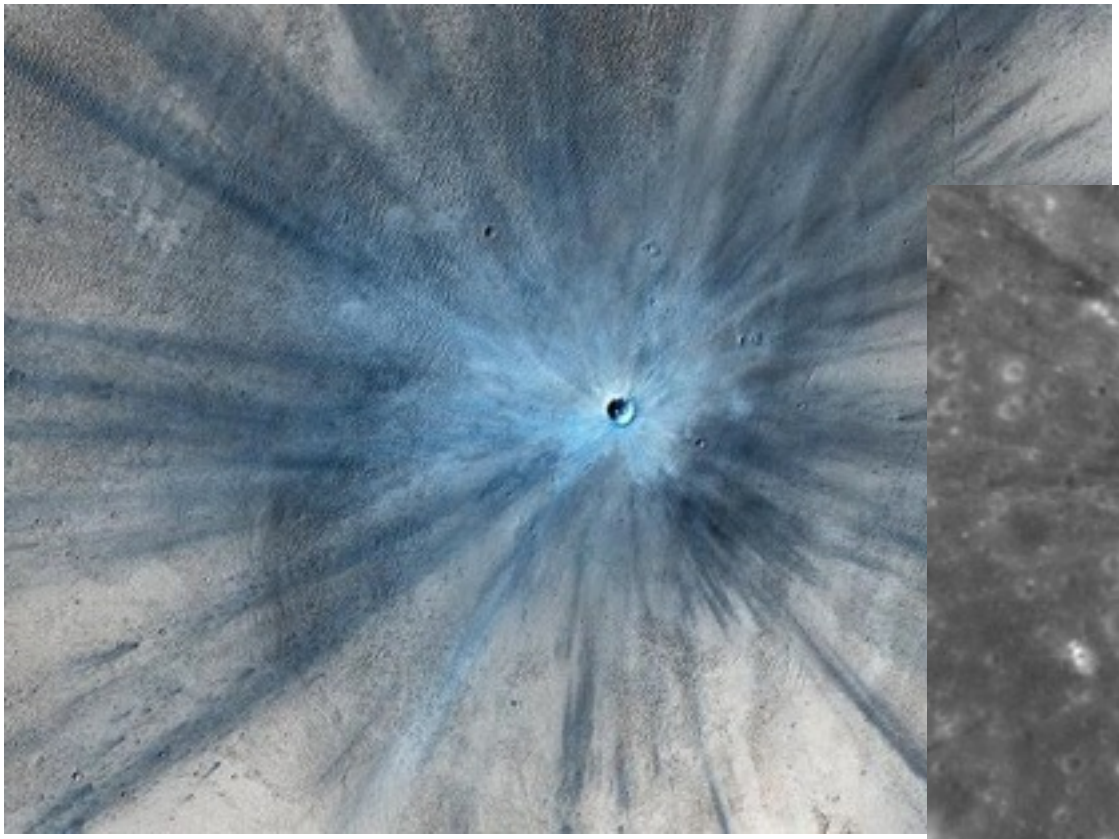


Mars impacts (2/2)

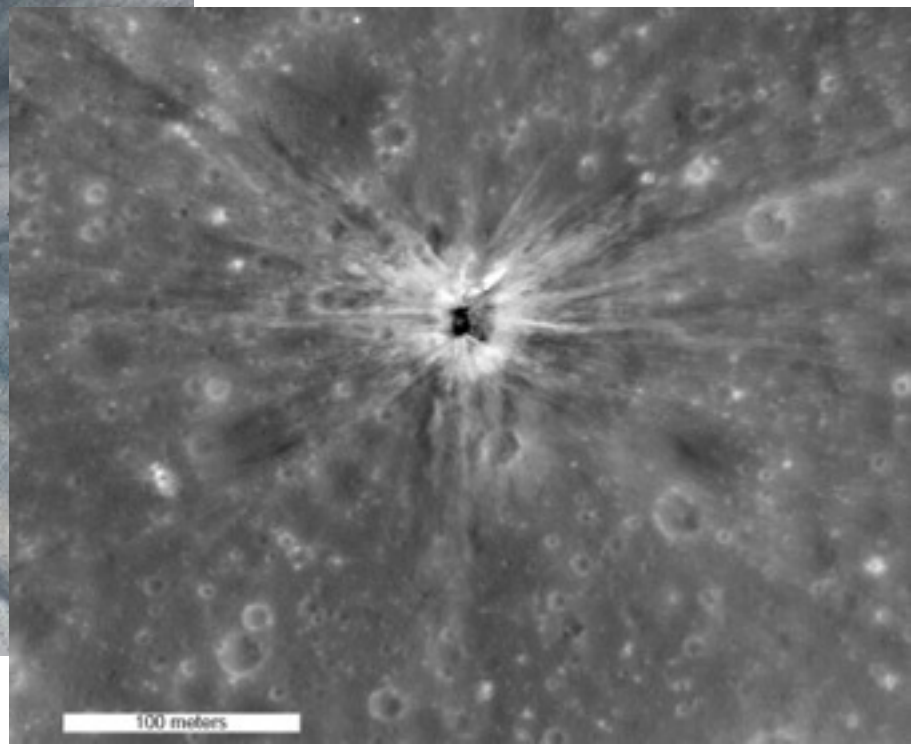
Estimation ~_5.3tons at 10 km/s => 5 10^7 Ns,
plus ejecta effects ~ 10^8 Ns



Seismic record from
Apollo 17 SIVB



Apollo 13 SIVB



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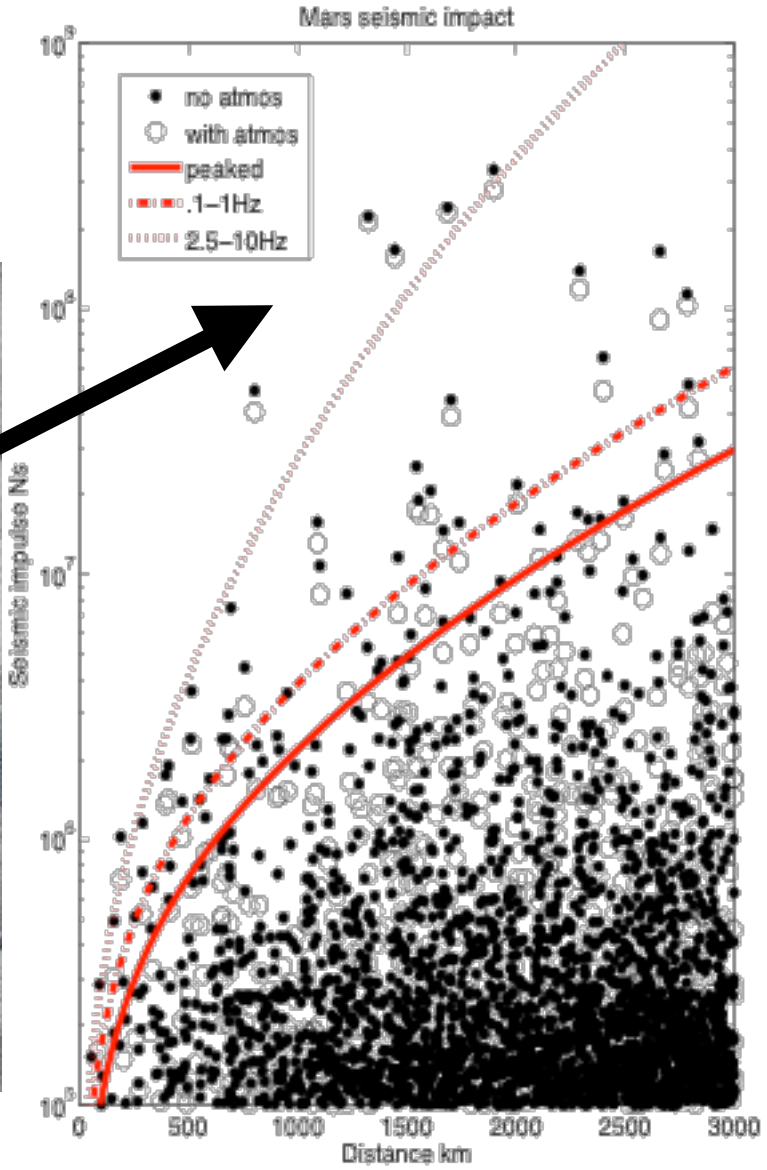

SEIS Expected Natural signals

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Global to regional

M~3.5 ~100/
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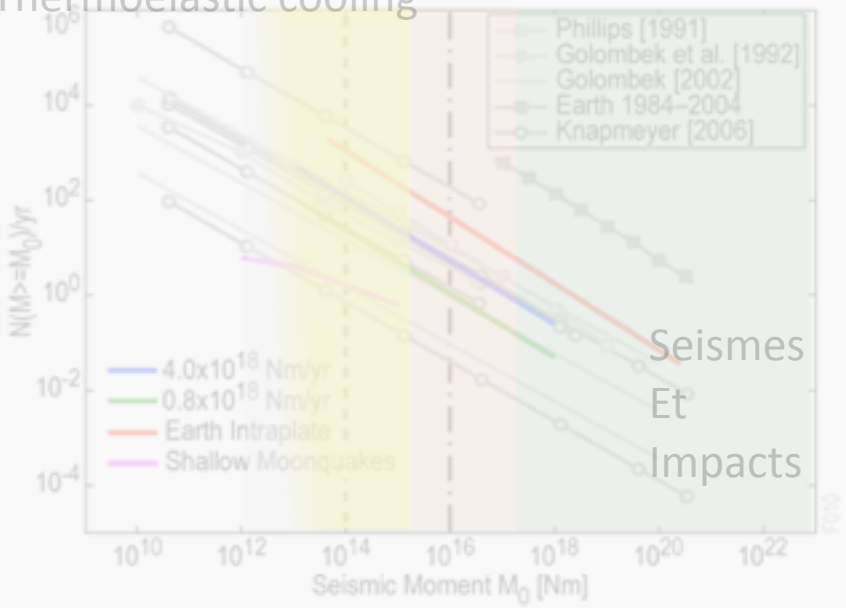
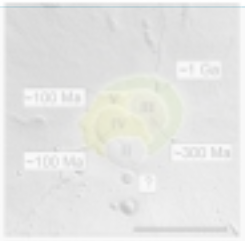
Thermoelastic cooling

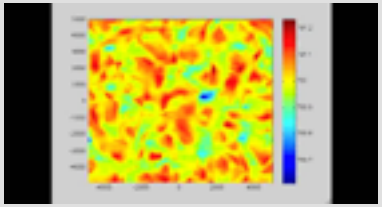


Seismes
Et
Impacts

Phobos tide

Bonus:
Tectonic
activity





Atmospheric loading
Atmospheric generated seismic noise

Wind/pressure generated seismic waves and static loading

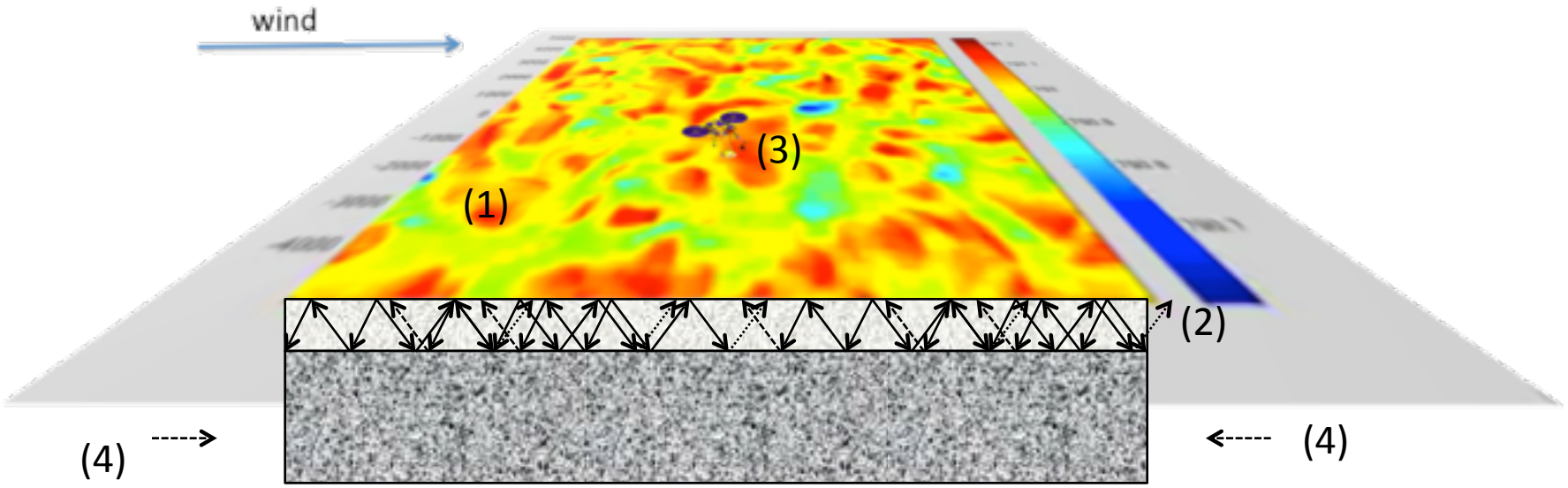
The atmosphere and wind/pressure fluctuations will be a major source of ground displacement for frequencies > 0.02 Hz with:

(1) At long period, static deformations of the surface, associated to wind generated pressure waves **(static loading)**

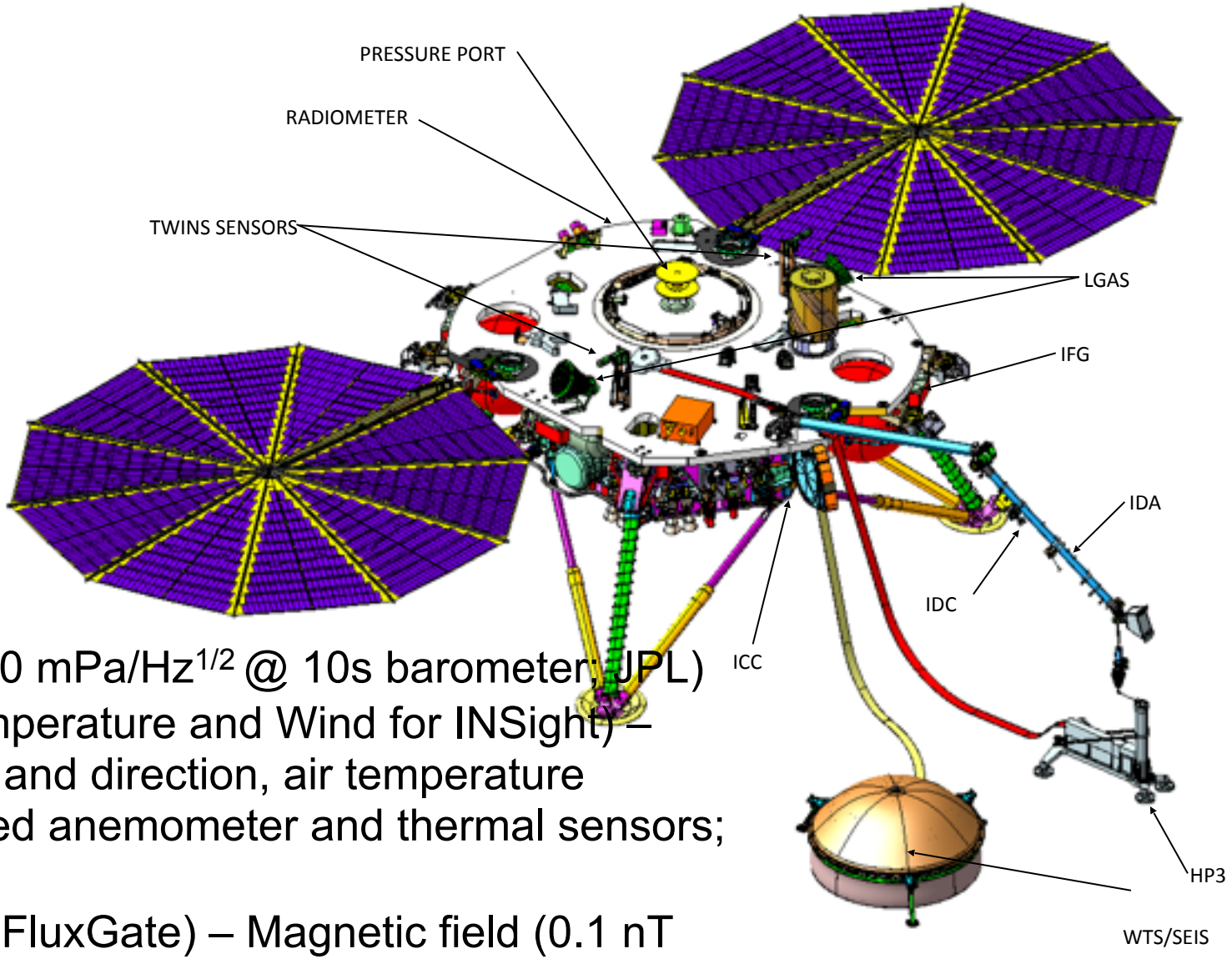
(2) At short period, dynamic ground acceleration, associated to local and possibly regional subsurface trapped surface waves excited by wind dynamic pressure **(short period seismic waves)**

(3) again at short period, wind interaction with the shield and the lander **(seismic noise)**

(4) on the global scale and at long period, surface waves excited by the global weather pressure fluctuations **(long period seismic waves, called hum)**

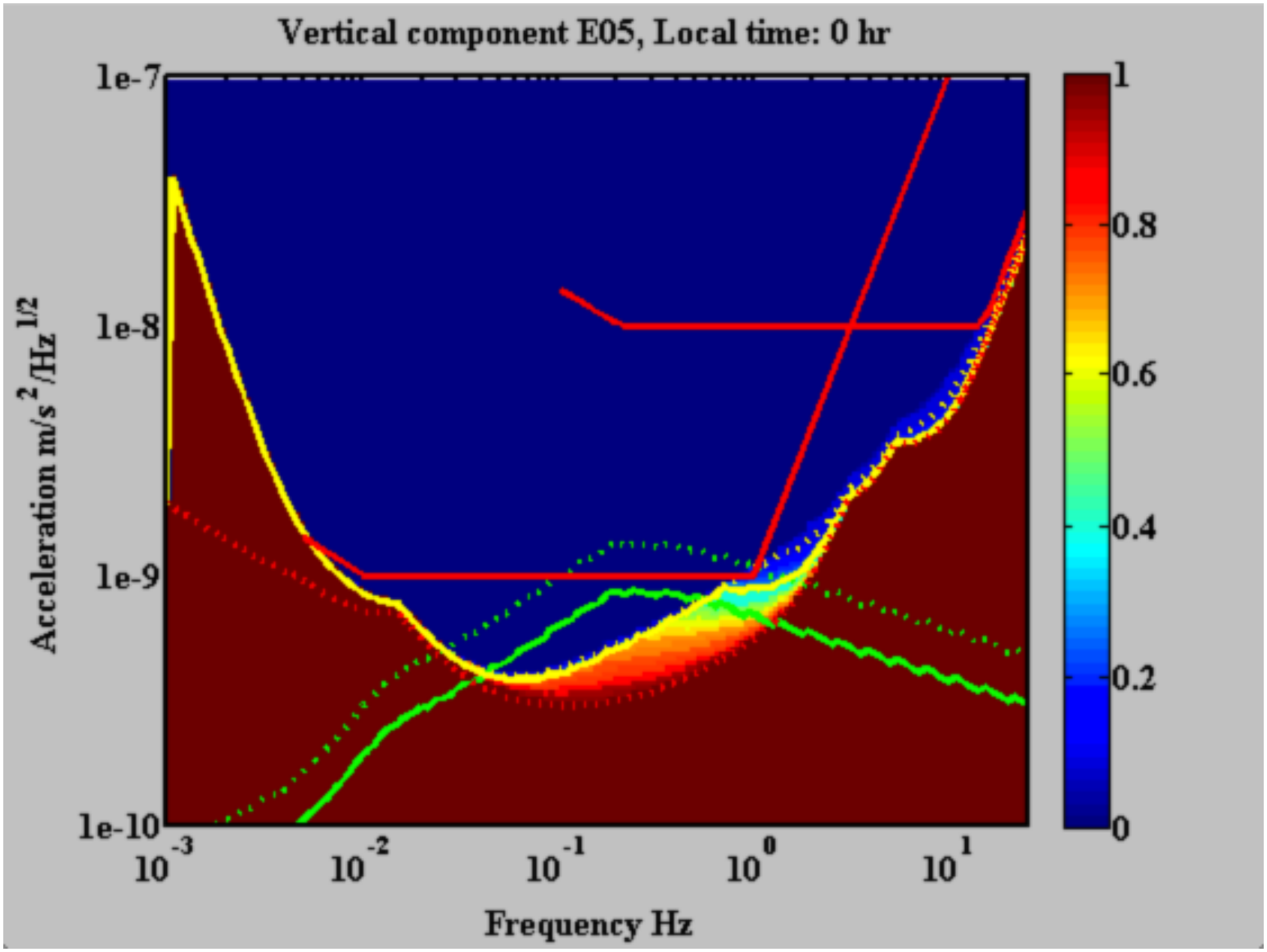


Environmental sensors for SEIS support



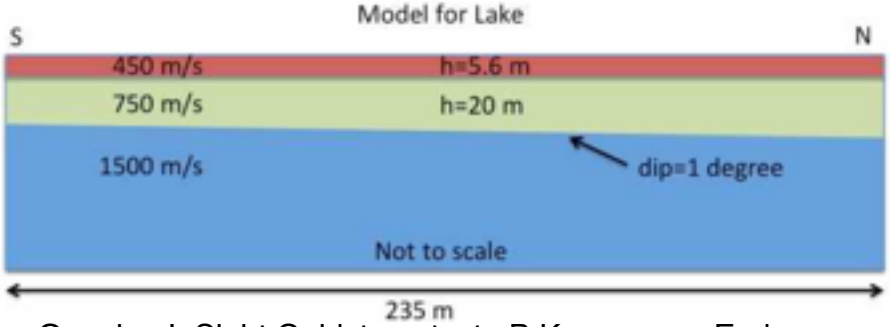
- **Pressure** (10 mPa/Hz$^{1/2}$ @ 10s barometer; JPL)
- **TWINS** (Temperature and Wind for INSight) – Wind speed and direction, air temperature (REMS-based anemometer and thermal sensors; CAB, Spain)
- **IFG** (Insight FluxGate) – Magnetic field (0.1 nT

Planet breathing estimation

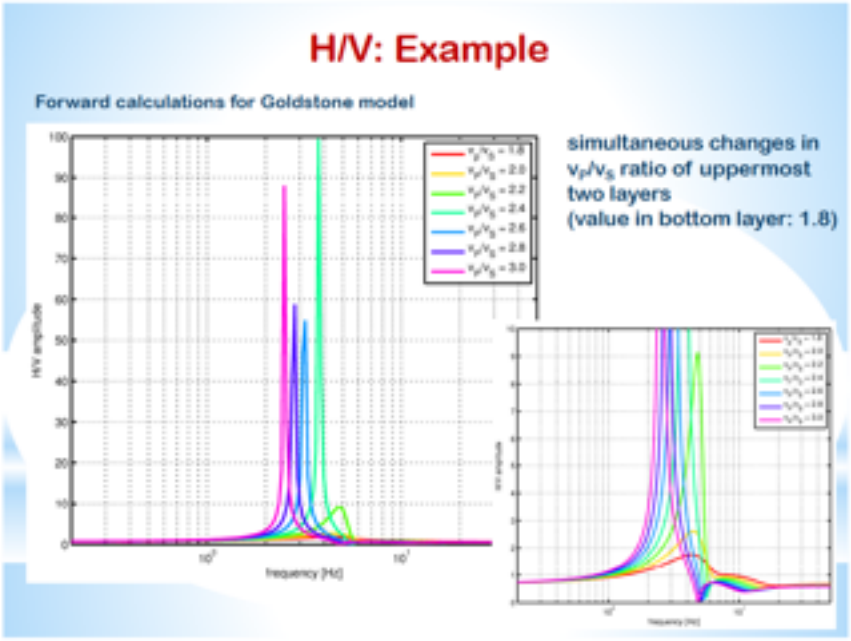


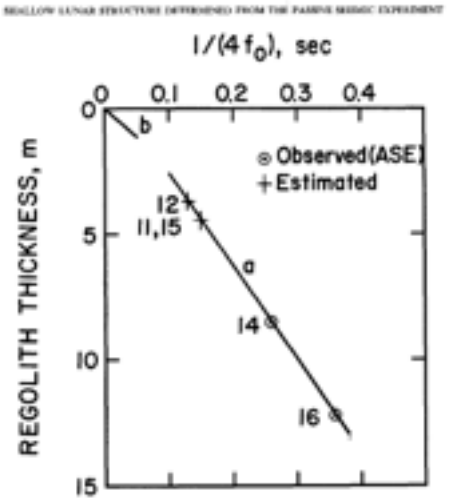
Short period surface waves: H/V structure inversion

- Based on the ratio of Horizontal versus vertical noise spectrum
- Find the waves resonances

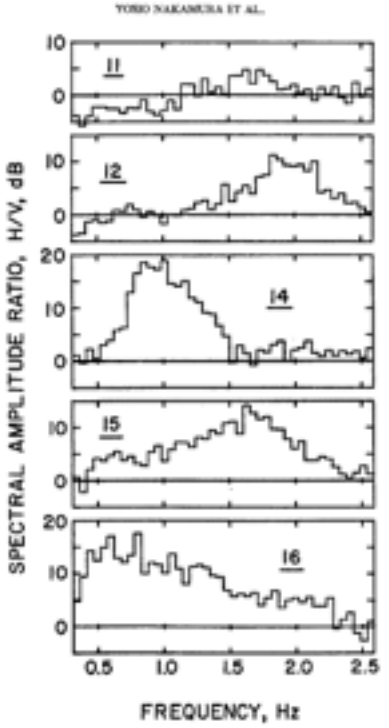


Ongoing InSight Goldstone test: B.Knapmayer-Endrun and S.Kedar





Moon example: Nakamura et al, 1975



SEIS Expected Quakes…

M~5.5 1-2/yr

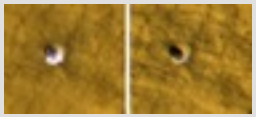
Global

M~4.5 ~ 10/yr

Global to regional

M~3.5 ~100/yr

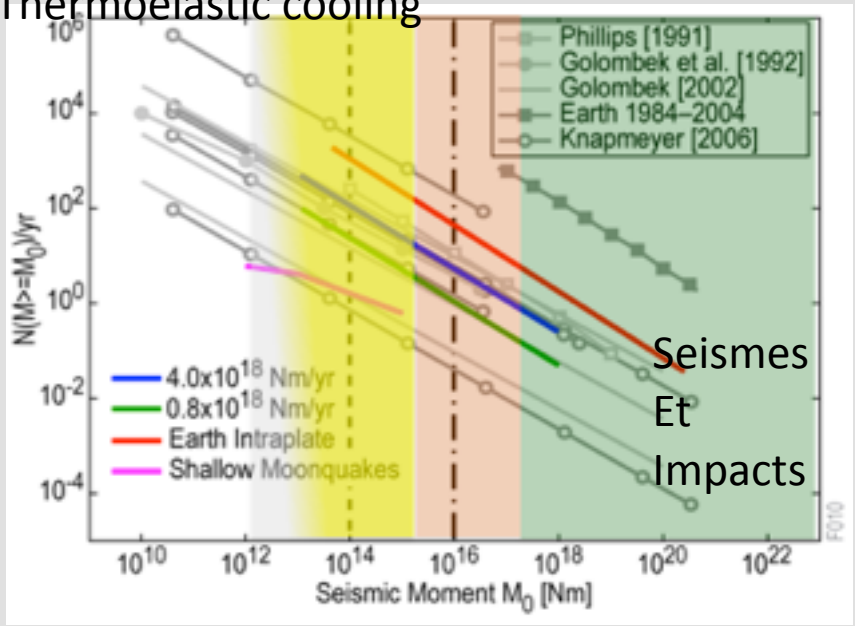
regional



Impacts

10-15/yr

Thermoelastic cooling

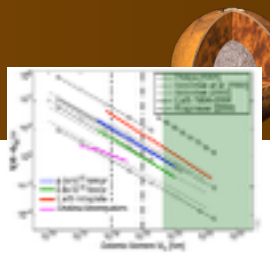


Phobos tide

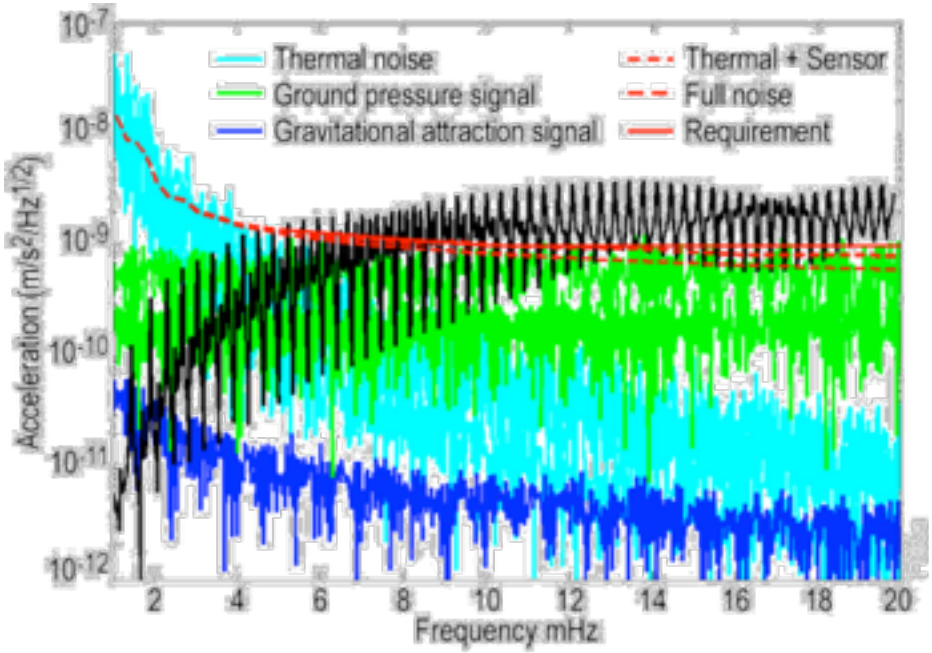
Bonus:
Tectonic
activity

Atmospheric loading
Atmospheric generated seismic noise

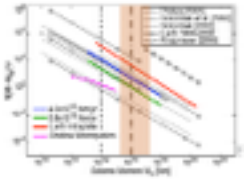
Largest quakes: Normal modes



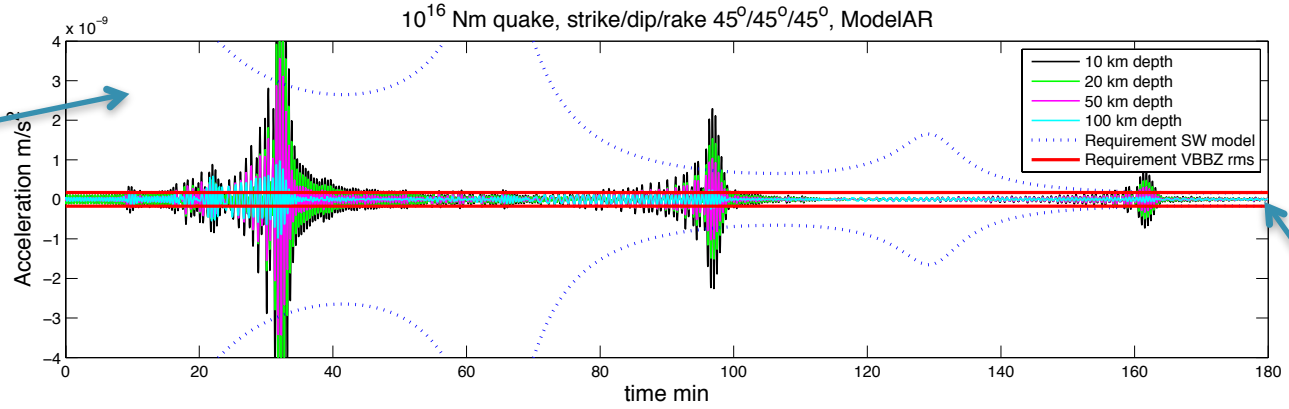
- Normal modes of a 2×10^{17} Nm quake
- « spectroscopy » seismology: does not need the knowledge of the source location
- will constrain the upper mantle with the normal modes frequency inversion (e.g. PREM on Earth)
- Might also be excited by the atmospheric turbulences



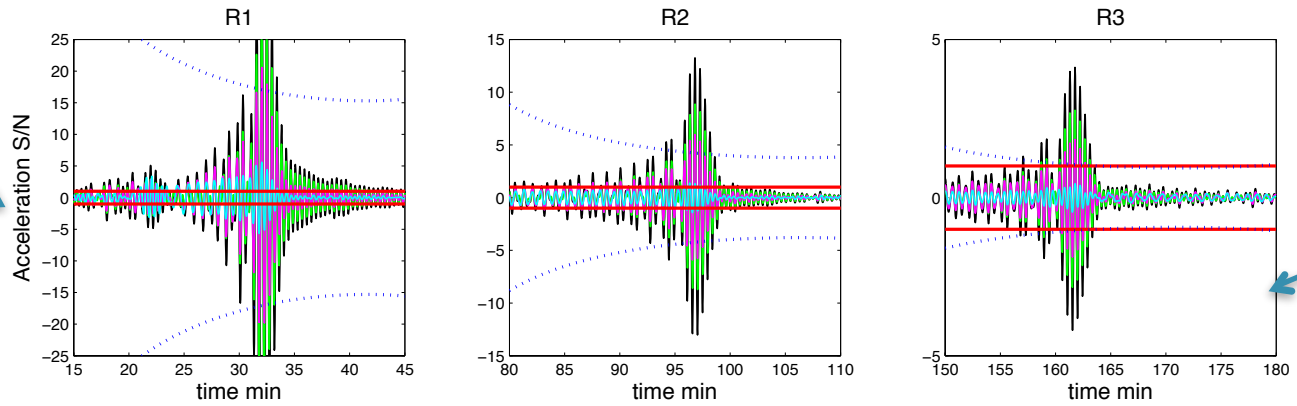
Moderate quakes: Turning waves



Rayleigh



Overtones



t_{R1} t_{R2} t_{R3}

Rms Noise in bandwidth

$$t_{R1} - t_0 = \frac{\Delta}{v_R}$$

$$t_{R2} - t_0 = \frac{2\pi a - \Delta}{v_R}$$

$$t_{R3} - t_{R1} = \frac{2\pi a}{v_R}$$

$$\frac{\Delta}{\pi a} = 1 - \frac{t_{R2} - t_{R1}}{T_R}$$

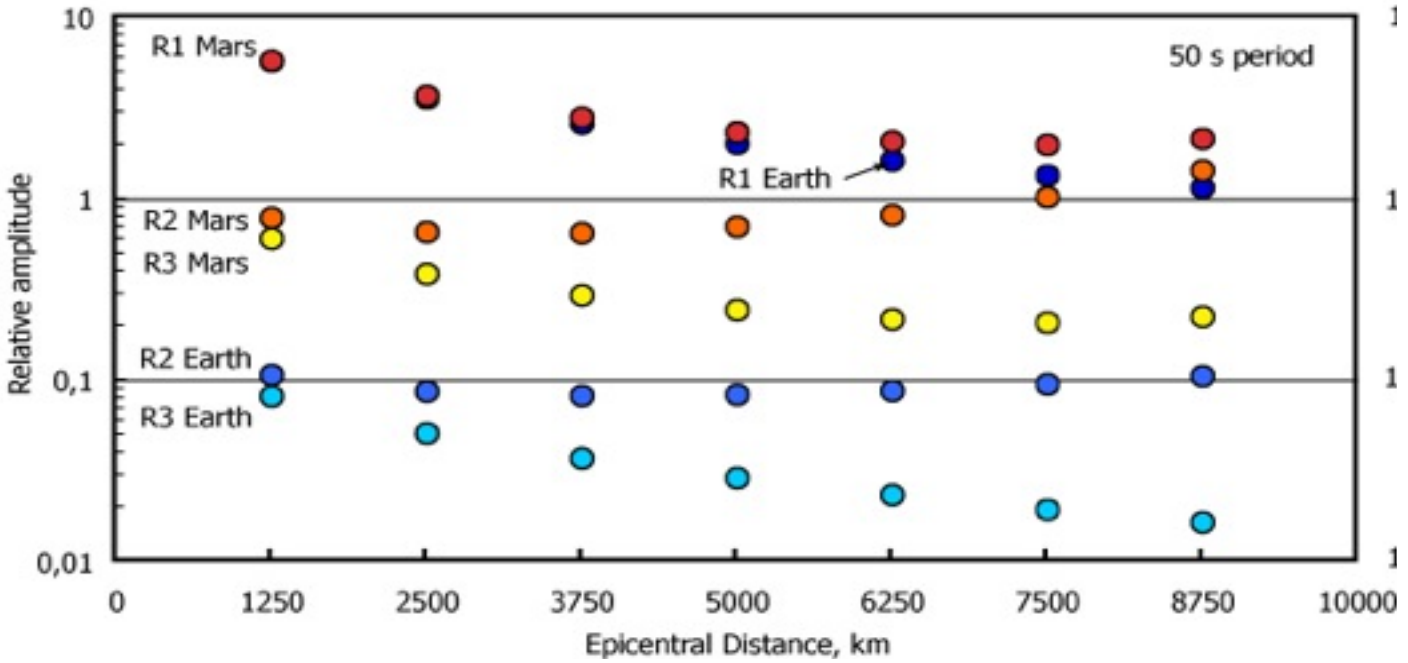
$$t_S - t_P = f_1(\Delta, v_s, v_p)$$

$$t_R - t_P = f_2(\Delta, v_s, v_p)$$

$$T_R = f_3(f, v_s, v_p)$$

Model

Mars-Earth comparison

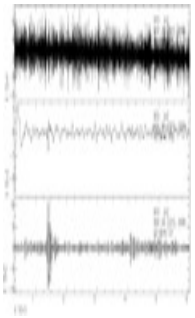


Amplitude of Rayleigh wave trains normalized by R1 amplitude at an epicentral distance of 10,000 km on Earth

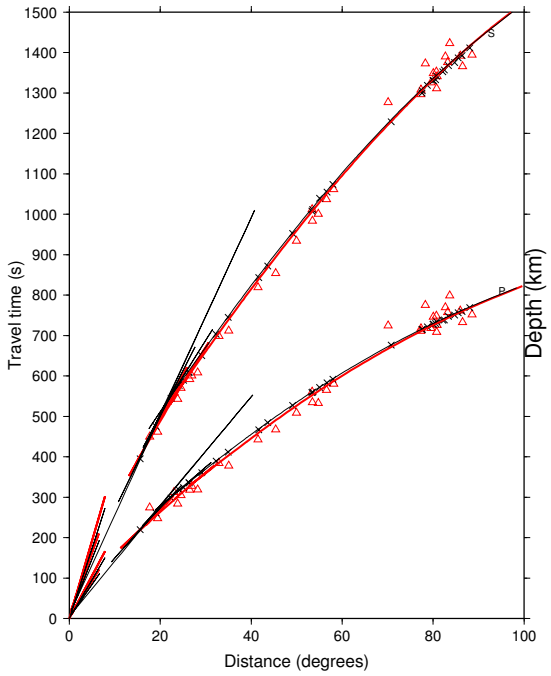
Surface waves are one order of magnitude larger on Mars for R2 and R3

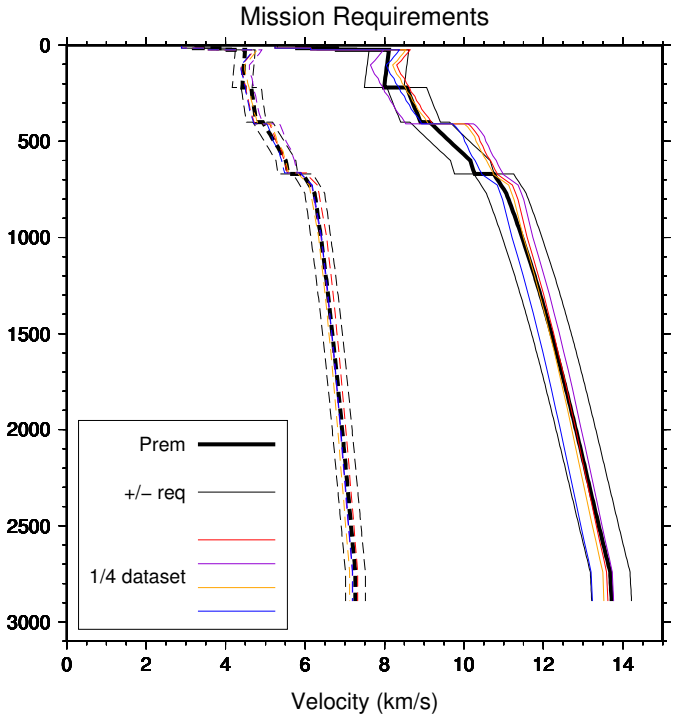
Expected Mantle model

- Inversion strategy has been validated with Earth data
- Results demonstrate that the PREM model can be retrieved within the INSIGHT error bars



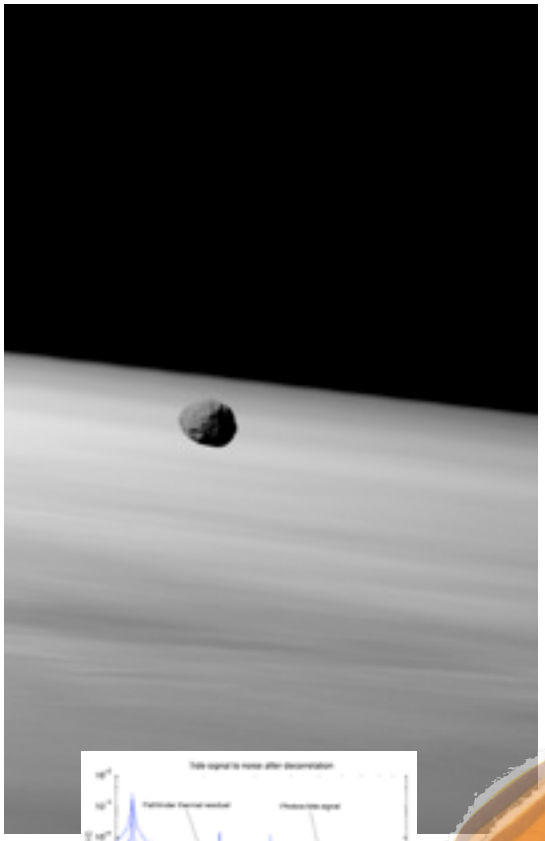
Earth data



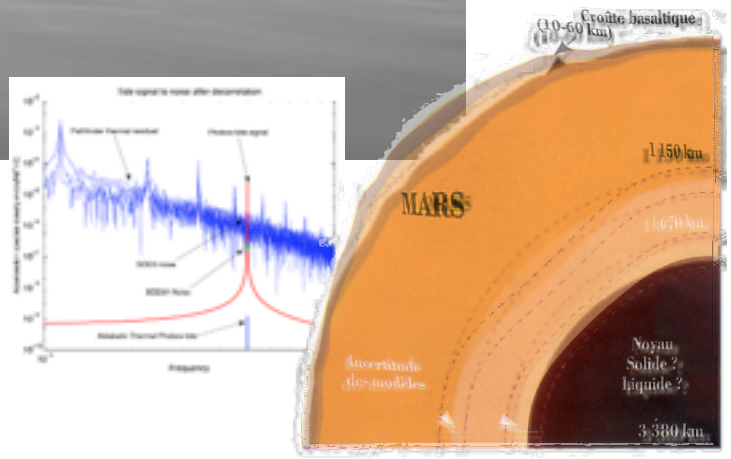


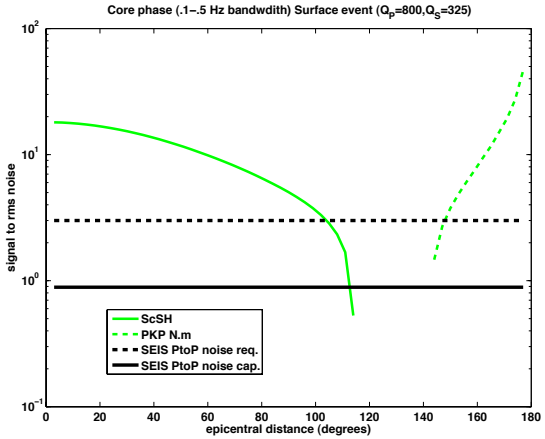
M.Panning, A.Mocquet, E.Beucler et al., 2014

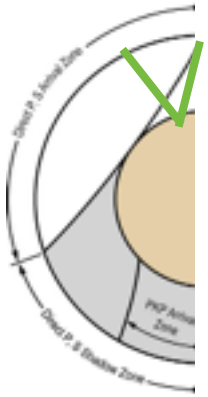
And …. the core



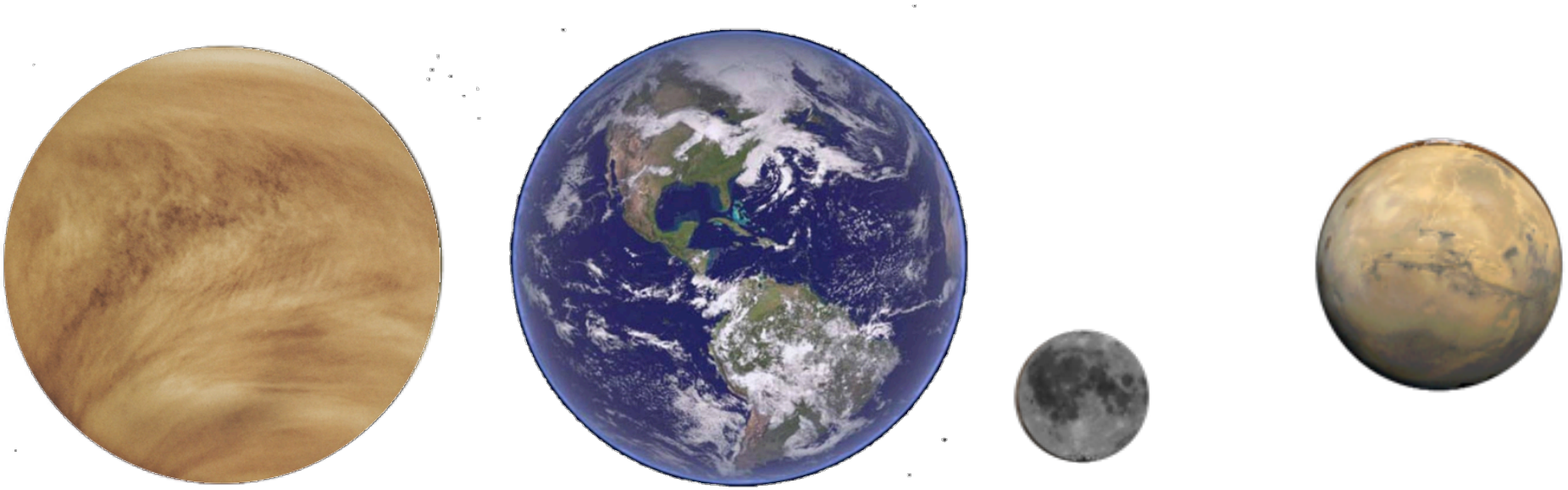
- Two ways investigation:
  - non-seismic by detection of the Phobos solid tide (~mm) and interpretation of the amplitude in term of core size
  - seismic by detection of the core reflected waves (ScS) similar Earth and Moon



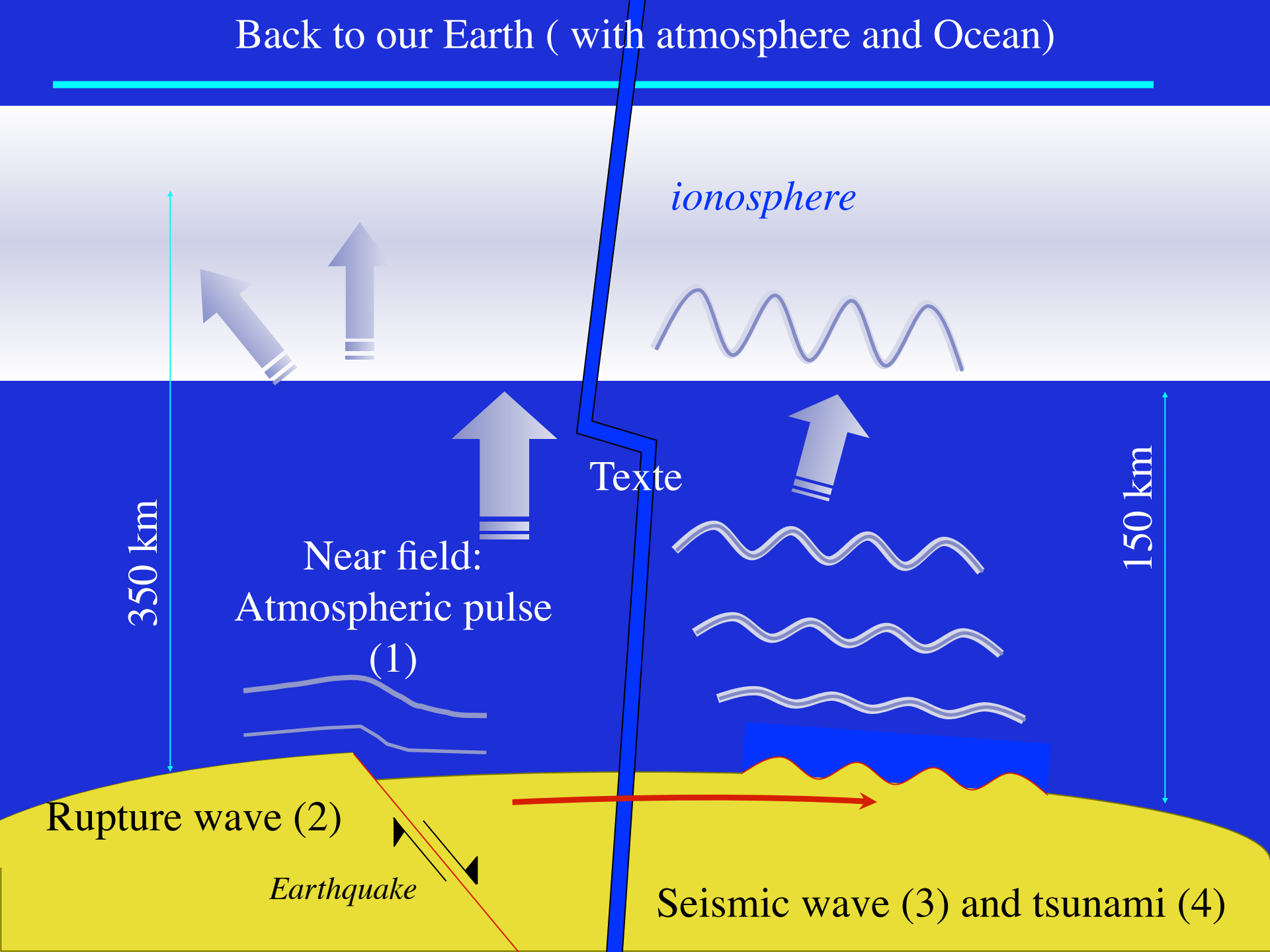




New frontiers of Planetary seismology

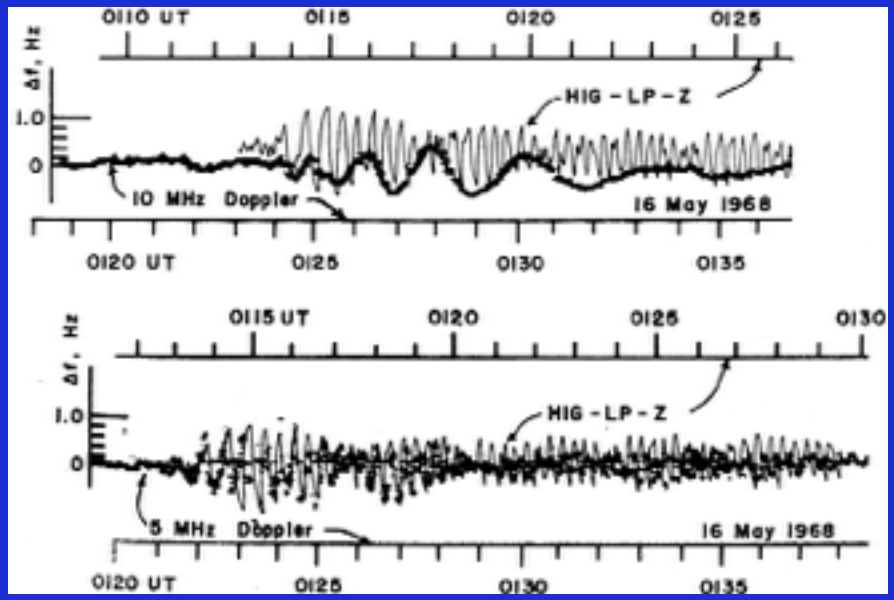


The ultimate challenge…


Back to our Earth (with atmosphere and Ocean)
ionosphere
350 km
Texte
150 km
Near field:
Atmospheric pulse
(1)
Rupture wave (2)
Earthquake
Seismic wave (3) and tsunami (4)

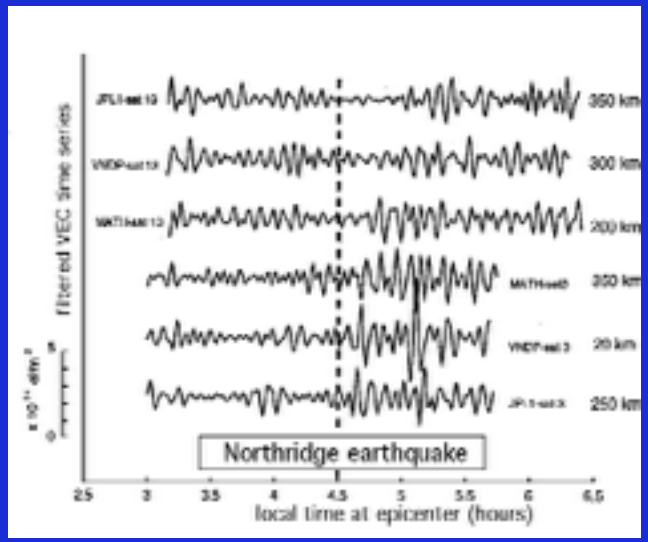
Some pionnier works

- 1960/ 1964: Chili and Alsaska quakes (M ~9)
  - Many observations performed by ionosonde.
  - *Yuen et al., 1969*: Doppler observation after the Hachinohe (Japan) quake, M=8,3



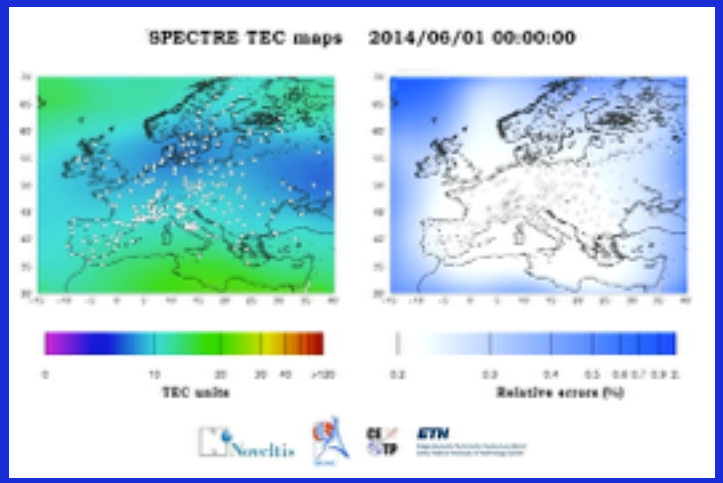
- 1994: Northridge quake (Mw=6,7)
  - *Calais et Minster, 1995* detection of signal on the GPS ionospheric data

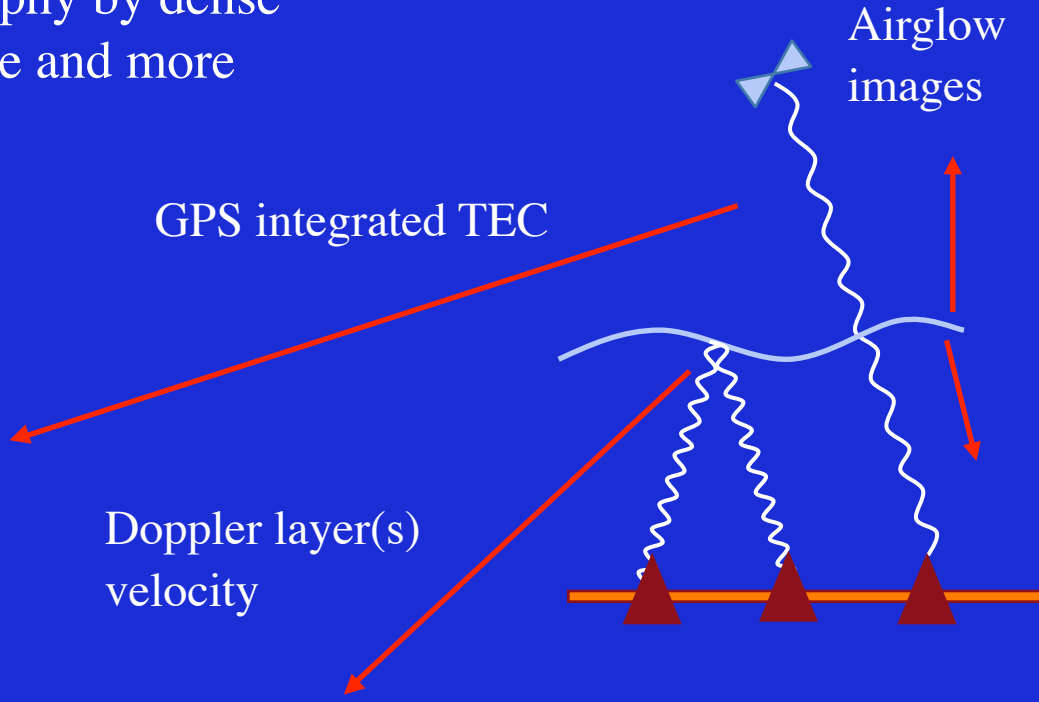
(blast, rocket launch, etc are also detected)



Detection tools and instruments

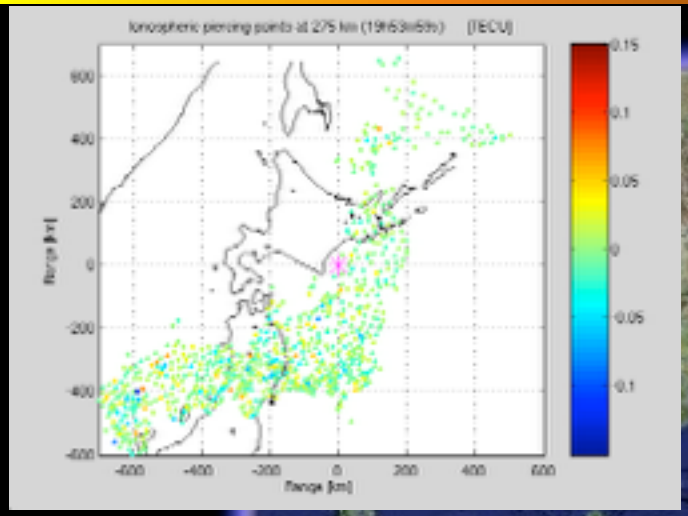
- Measure based on the TEC tomography by dense Networks: Dense Networks are more and more available in USA, Japan, Europe



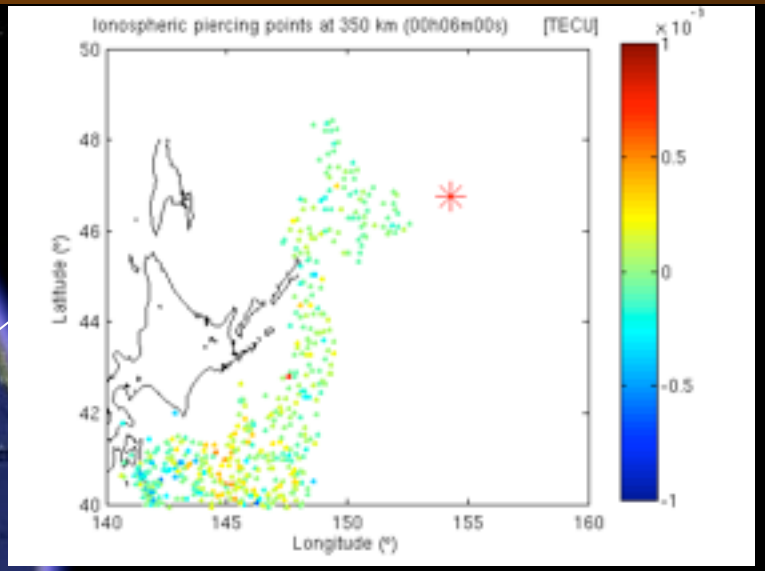


- CEA sounder: Operation since 1999 with observation of all quakes with magnitude greater than Ms=6.5 (during day time)
- ONERA OTHR: 96 antenna in 3 lines with 120°

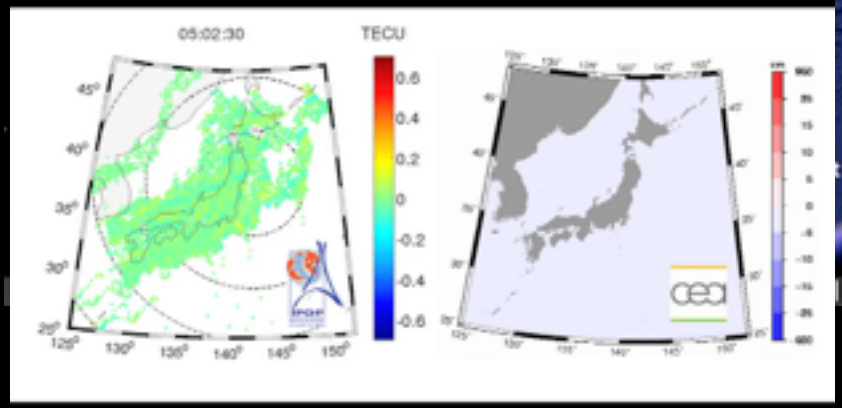
Ionospheric seismic acoustic wave



Tokacho-Oki 9/25/2003 M~8.3

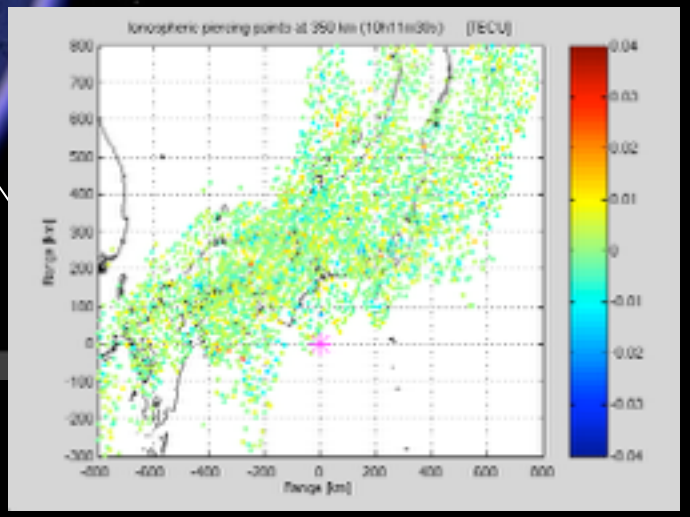


Kurils 13/1/2007 M~8.1



Tohoku 3/11/2003 M~9

Rolland et al., 2011



Kii 9/5/2004 M~7.4

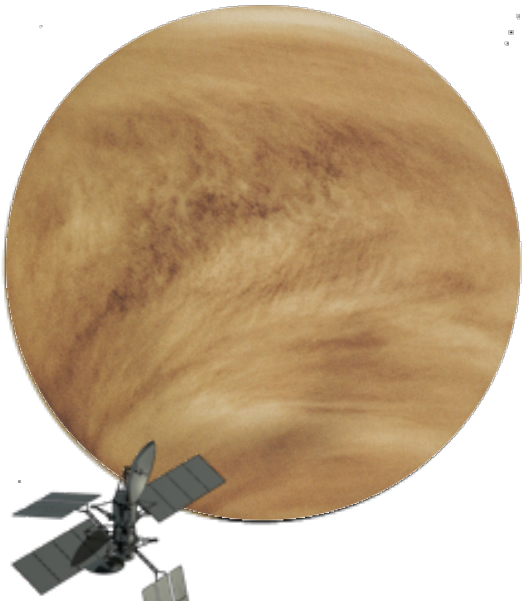
Airglow: OI red line

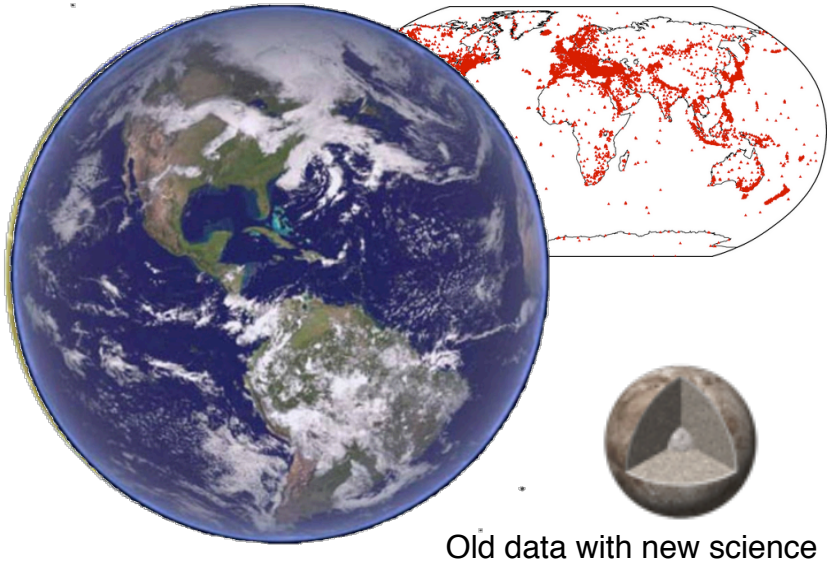
$$
\begin{aligned}
O_2 + O^+ &\rightarrow O_2^+ + O \\
O_2^+ + e^- &\rightarrow O + O(^1D) \\
O\,(^1D) &\rightarrow O\,(^3P) + h\nu
\end{aligned}
$$

- 630 nm
- Emission peak at 250-300 km
- quiet night 50-100 Rayleigh
- about 12.5-25 mWatt/km^2 of light power.. and a seismic signals of 100-100 microWatt/km^2

New frontiers of Planetary seismology

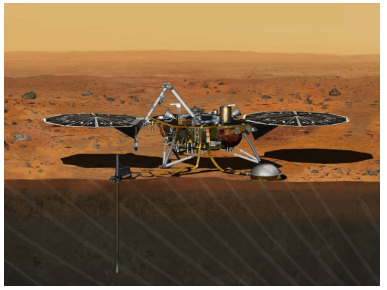
More and more data from denser seismic networks





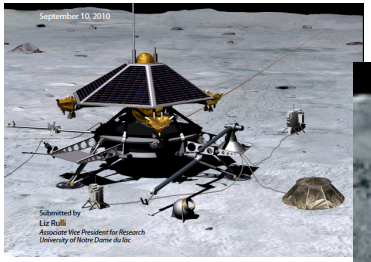
Old data with new science

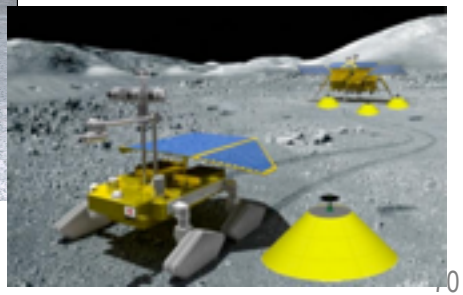
New data : end 2016



?

Possible First tsunami space data : 2020 -2025





Possible return: 2020-25