Medium and long-term perspectives of seismology for the study and characterization of planetary and satellite interiors

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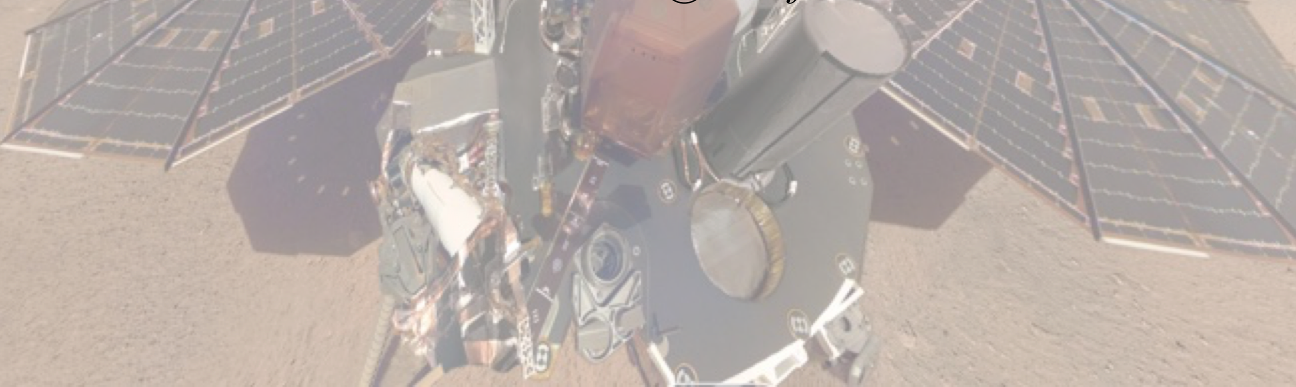
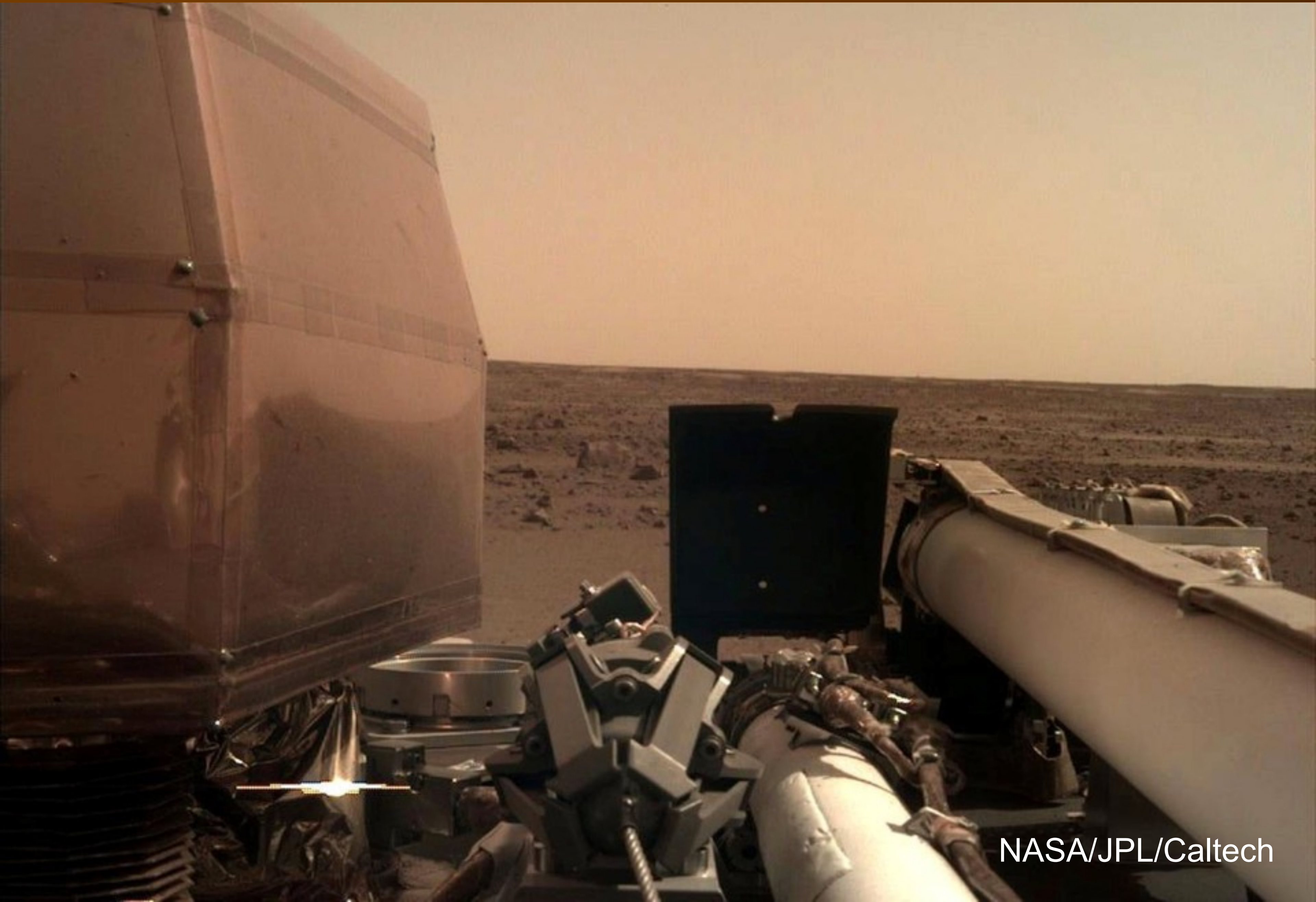


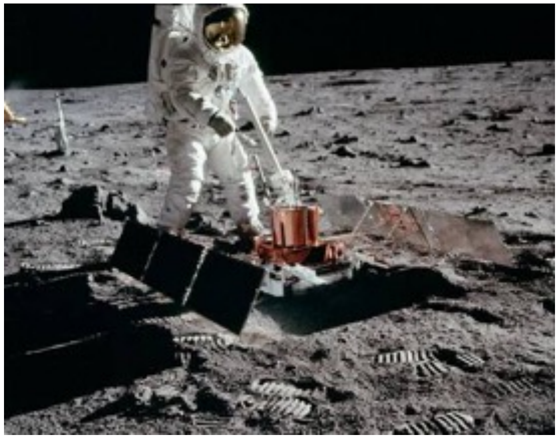
Sept 12th, 2019

May 5th 2018 : Start of a new era for planetary seismology

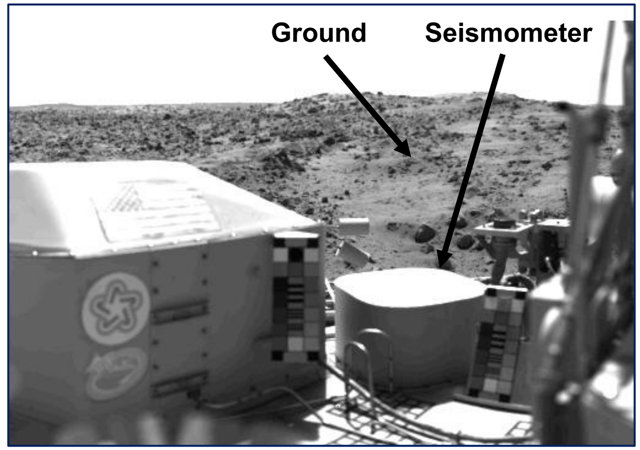
Nov 26th 2018 : Start of a new era for planetary seismology



2018 : Start of a new era for seismology



NASA



NASA/JPL/Caltech

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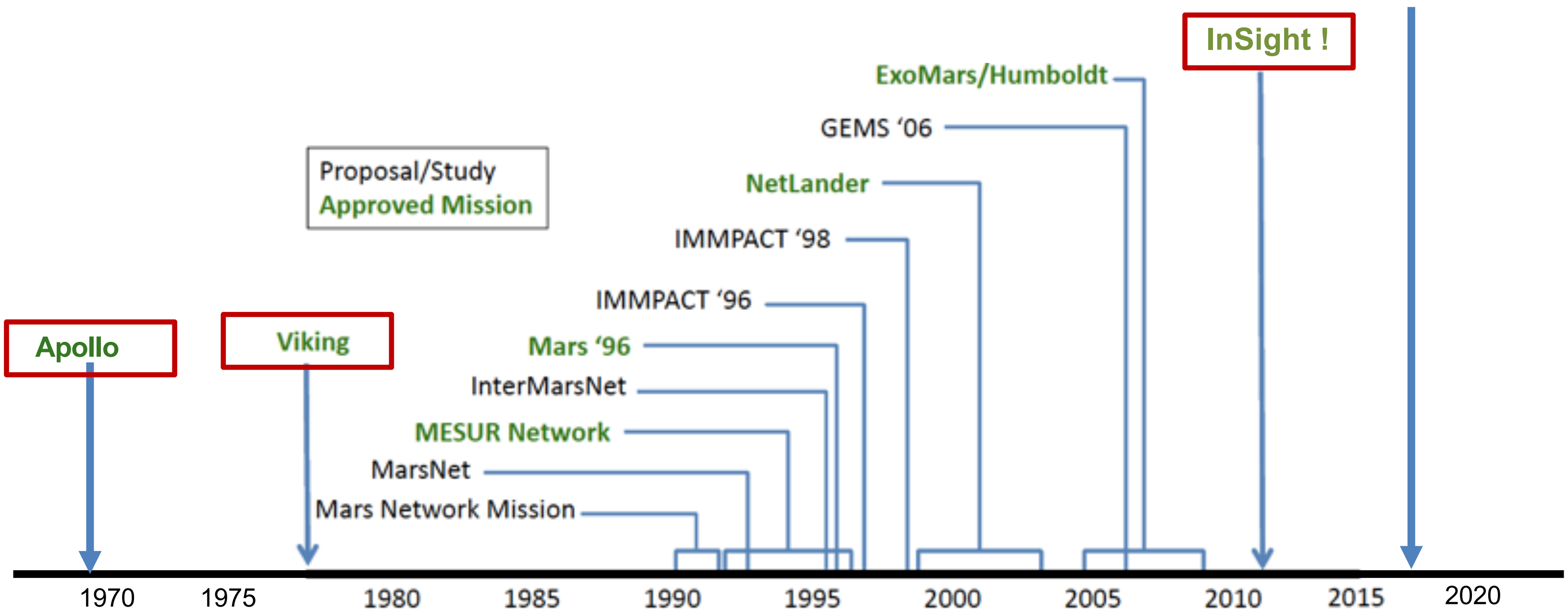
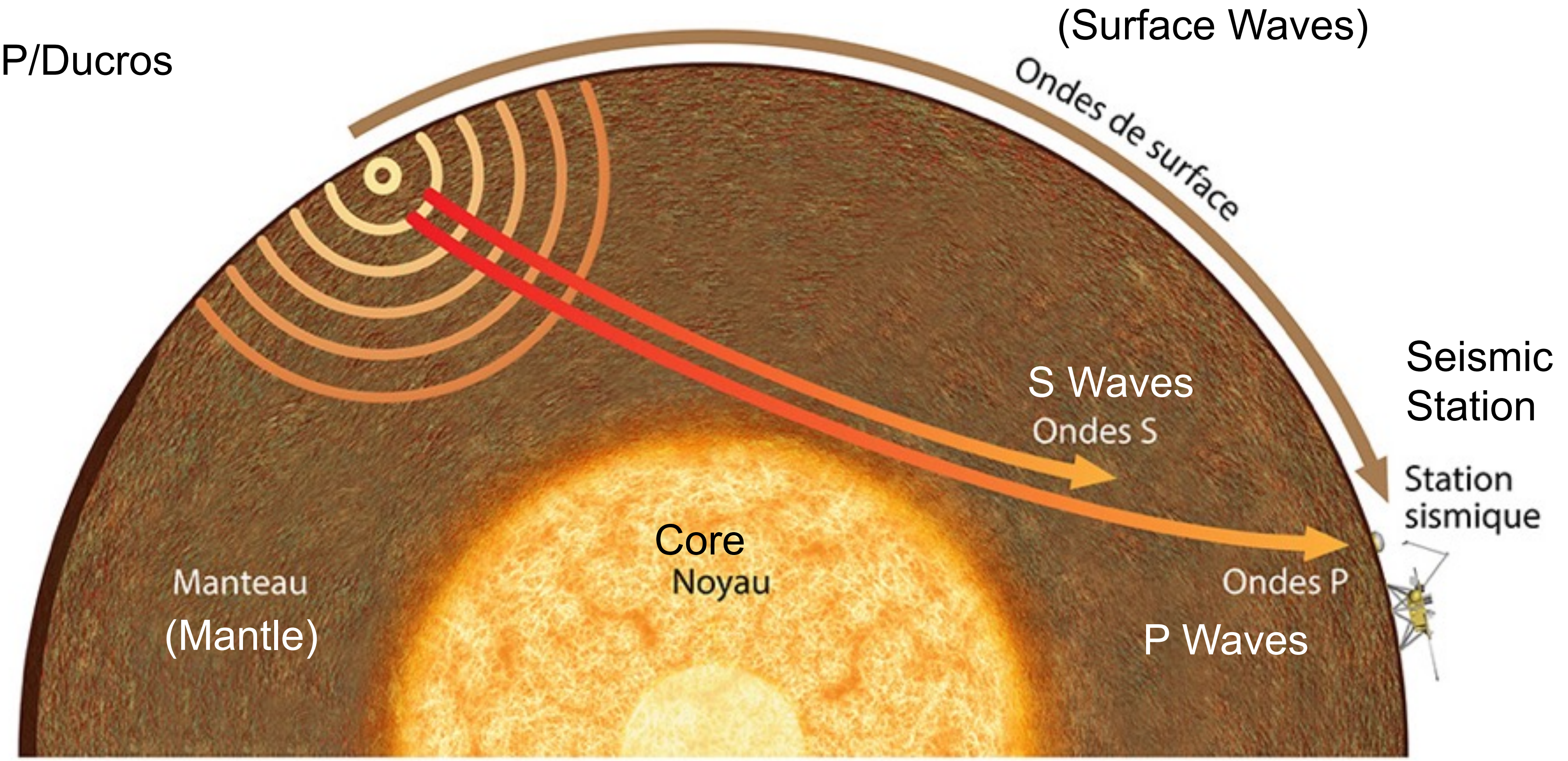


Summary of Past Missions Involving Seismology

MISSION	Launch	Major mission events	Instrument description	Seismometer deployment	Reference
Ranger 3	1962-01-26	Failure due to the booster. Moon missed	Vertical axis seismometer, with a free frequency of 1 Hz. (Mass: 3.36 kg)	Seismometer in a lunar capsule designed for a 130-160 km h^{-1} landing. Batteries powered for 30 days of operations	Lehner *et al.* (1962)
Ranger 4	1962-04-23	Failure of spacecraft central processor. Moon crash.			
Ranger 5	1962-10-18	Failure in the spacecraft power system. Moon missed.			
Surveyor	1966-1968	The seismometer was finally deselected from the payload of the Surveyor missions	Single short period vertical axis seismometer (mass: 3.8 kg, power: 0.75 W)	Fixed to the lander.	Sutton and Steinbacher (1967).
Apollo 11	1969-7-16	Successful installation. Powered by solar panel, worked during the first lunation and stopped after 21 days	Passive seismic experiment (PSE). Triaxis Long Period seismometer (LP) and one vertical Short Period (SP) seismometer, with resonance periods of 15 sec and 1 s respectively. (mass: 11.5 kg , power: 4.3 -7.4 W)	Installation performed by crew. Seismometers were manually leveled and oriented with bubble level and sun compass. A sun protection/thermal shroud was covering the instruments. Power was delivered by a Plutonium thermal generator for A12-14-15-16	Latham *et al.* (1969, 1970a, 1970b).
Apollo 12 **Apollo 14** **Apollo 15** **Apollo 16**	1969-11-14 1971-01-31 1971-07-26 1972-04-16	Successful installation of a network of 4 stations. For all but the Apollo 12 SP seismometer and Apollo 14 vertical LP seismometer operated until the end of September 1977, when all were turned off after command from the Earth. 26.18 active station years of data collected.			
Apollo 13	1970-4-11	Moon landing aborted. No installation of the PSE experiment but lunar crash of the Apollo 13 Saturn-IV upper stage recorded by the A12 PSE.			
Apollo 14 **Apollo 16** **Apollo 17**	1971-01-31 1972-04-16 1972-12-07	Successful installation and operation of the active seismic experiments. Seismic sources were thumper devices containing 21 small explosive sources and a rocket grenade launcher with 4 sources exploding up to 1500 m on A-14 and A-16. 8 sources were used containing up to 2722 g of explosive and deployed at 3500 m by astronauts	String of 3 geophones on A-14 and A16 and on 4 geophones on A-17. Frequency was 3Hz-250 Hz.	Geophones were anchored into the surface by short spikes as they were unreeled from the thumper/geophone assembly.	Watkins and Kovach (1972) Kovach and Watkins (1973a)
Apollo 17	1972-12-07	Deployment of the Lunar Surface Gravimeter. The gravimeter was unable to operate properly due to an error in the design of the proof mass.	Gravimeter designed for gravity waves detection. Additionnal long period vertical seismic output (10^{-11} lunar g resolution) for free oscillation detection, with a 16 Hz sampling.	Installation performed by crew.	Weber (1971)
Viking Lander 1	1975-08-20	Successful landing but instrument failure.	Short period instrument, with an undamped natural period of 0.25 s, a mass of 2.2 kg, a size of 12x15x12 cm and a nominal power consumption of 3.5 W.	The seismometer was installed on the Lander platform. No recentering was necessary since the 3 axis seismometer had been designed to function even when tilted to up to 23 degrees.	Anderson *et al.* (1977a, 1977b)
Viking Lander 2	1975-09-09	Successful landing and 19 months of nearly continuous operation. Too high wind sensitivity associated to the elastic recovery of the Viking landing legs to the loading of the station by pressure fluctuations induced by the wind.			
Phobos 1-2	1988-07-07 1988-07-12	Respecivelly:Lost during transfer to Mars and Phobos ; Contact lost just before the final phase of lander deployment, after Mars orbit insertion		Instrument onboard the long-service lander.	Surkov (1990)
Mars 96-Small surface stations	1996-11-16	Failure of the Block-D propulsion system in parking orbit. Earth re-entry. 2 small stations and 2 penetrators lost.	Long period vertical axis seismometer (0.1-4Hz, 0,405kg for the sensor) combined to a magnetometer. 55 mW of power	Seismometer in the small surface station. Semi-hard landing (200g-20 ms). Nominal operations of one Martian year with 90th first days of nearly continuous mode with internal batteries	Lognonné *et al.* (1998a)
Mars 96 Penetrators			High frequency seismometer (10-100Hz, 0.3kg, 20 mW)	Seismometer in the penetrator. Hard landing. Nominal operations of one Martian year.	Kravroshkin and Tsyplakov (1996)
Rosetta	2004-03-04	Landing on the comet 67P/Churyumov-Gerasimenko planned a few months after rendez-vous, expected on 22-05-2014	CASSE/SESAME experiment: High frequency accelerometer covering the frequency bandwidth ~10 Hz-20 kHz.	Instrument mounted on the lander	(Kochan *et al.* 2000)

Lognonné et al, 2007

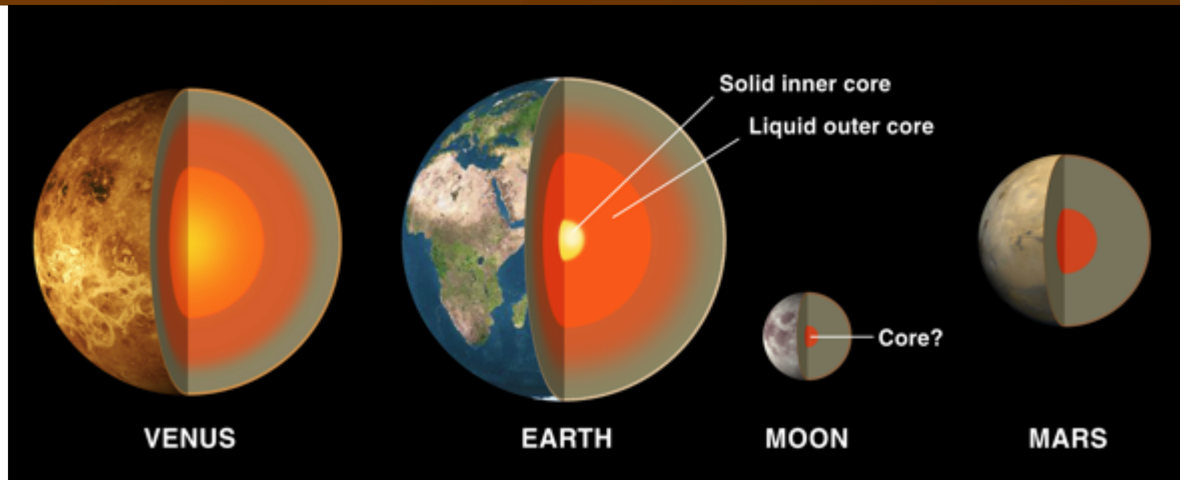
Why Seismology ?



Seismology is the best (if not the only) only way to investigate the internal structure of a telluric planet

It can help with Oceans Worlds, too !

Planetary Seismology : current status



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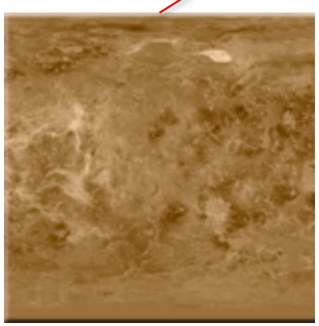

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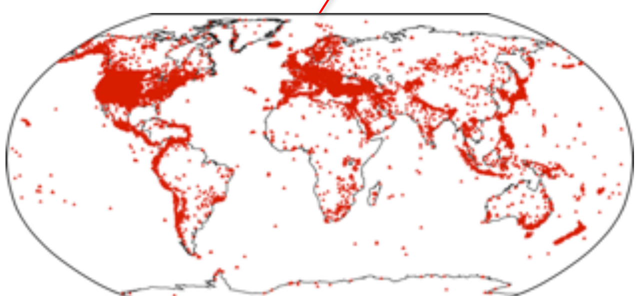
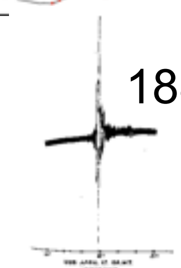
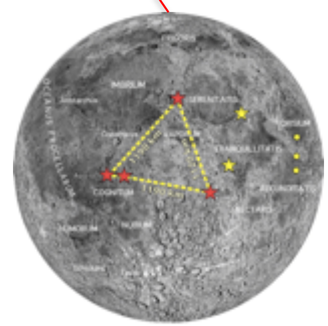


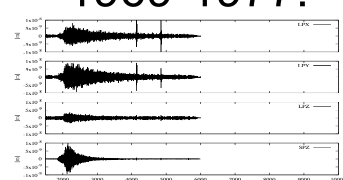
1889-1910



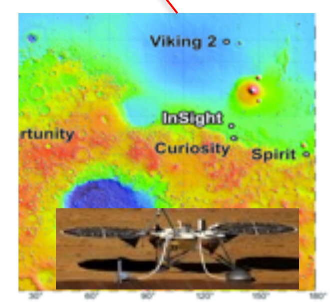
3 (1970's)



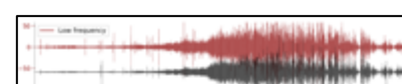
1969-1977:



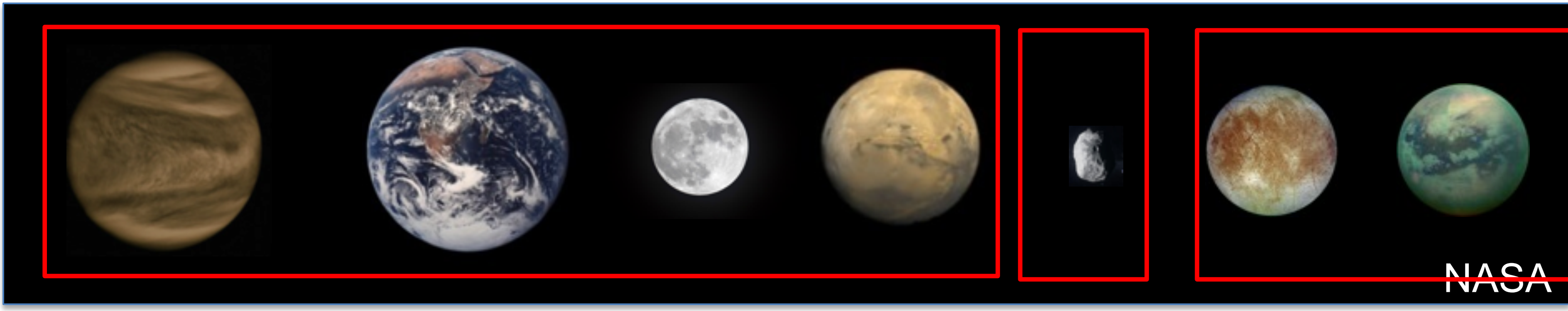
1 (2018)



2019- …

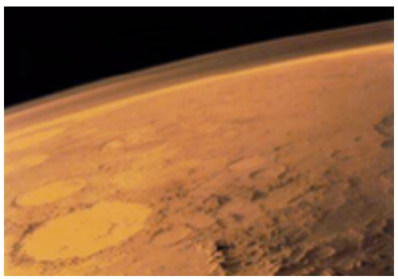


Science Questions ?



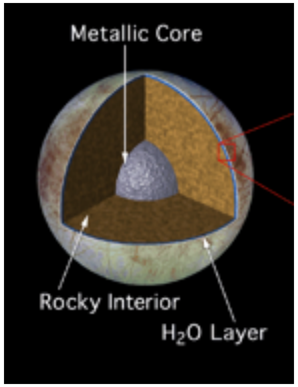
400°C, 90 atm

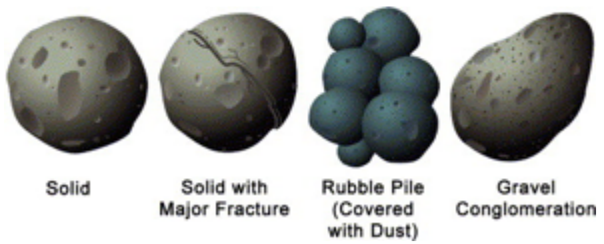
15°C, 1 atm



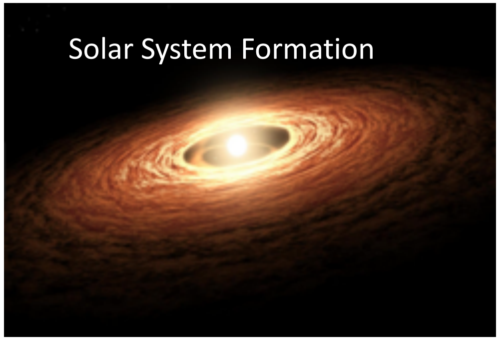
-50°C, 0.005 atm

JPL/Caltech





Walkers et al. 2006



Science Questions ?

Planetary Body	Main Associated Science Question	Seismometer Type	Main Instrument Constraint	Reference
Moon	Core size, Earth Moon history,	Long Period, High sensitivity	Lunar night	(Mimoun et al 2012)
Mars	Formation, history, habitability	Long Period, High sensitivity Network ?	Instrument sensitivity to environment	(Mimoun et al 2017)
Mercury	Formation process	Long Period, High sensitivity	Strong temperature variations	
Venus	Formation processes, coupling with atmosphere, habitability	Long Period, High sensitivity	Extremely harsh environment	(Cutts, Mimoun et al, 2015)
Small Boday	Internal structure “Planetary defense”	Short period, autonomy	Size and mass, low gravity, coupling	(Murdoch et al, 2017)
Oceans Worlds	Internal Structure Ice sheet width Ocen depth	Short period	Radiations, temperature	(Lee et al, 2003)

STEP 1 : New generation of ALSEP and Seismology as a tool for ISRU

- The Moon holds a particular place on this prospective exercise, including with the context of human mission.
- **Establishing a seismic network operating several years on the Moon must be the first priority**, with the development of a **new generation of Artemis Lunar Surface module**.
- Beside of the completion of the Moon structure understanding, which may be done in the next few years thanks to the effort of US and (or) China we expect the seismology to become also (as it is on Earth) a standard tool for In Situ Resources Utilization (ISRU), for mining water ice of other minerals of interest.

Science Objectives

Crust

- Confirm the GRAIL lunar crustal models and better anchor it with seismic data ?
- What is the vertical & lateral structure of the lunar crust interior and how did it develop?
- What is the nature of the Moon's crustal asymmetry, what caused it ?

Mantle

- What is the composition, structure, and variability of the lunar mantle?
- Is there an undifferentiated lower mantle ; if so, what was its role in lunar magmatism?

Core

- Precise the radius of central metallic (molten) core, and if it does, how large is it and what is its composition?
- Discovery of the inner core remains to be done…

Preparing for human occupation

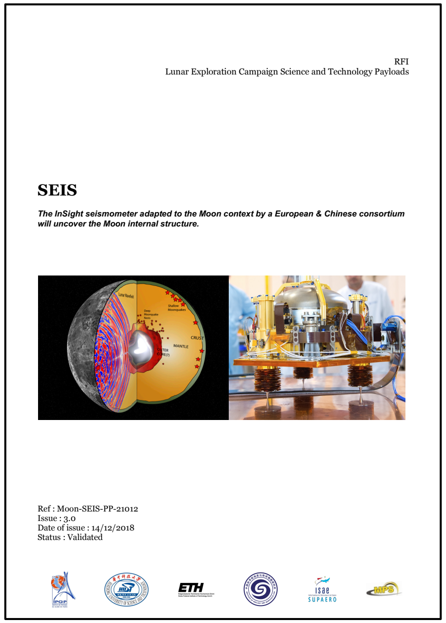
Water

Find sustainable sources of water in the subsurface

Minerals

Find Minerals in the subsurface

Step 1 : New generation of ALSEP and Seismology as a tool for ISRU

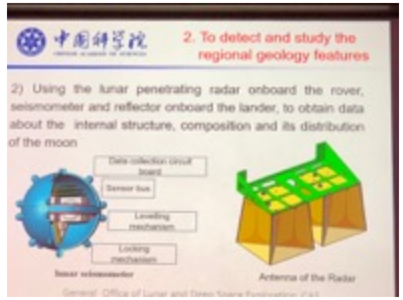


RFI
Lunar Exploration Campaign Science and Technology Payloads

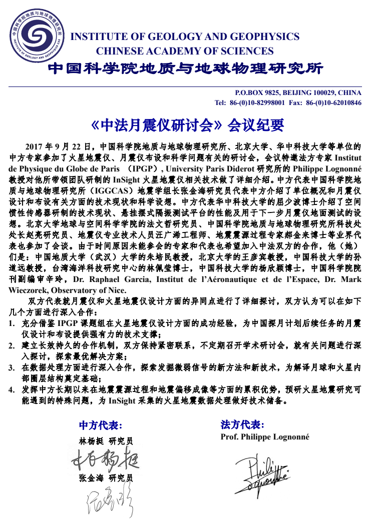
SEIS

The InSight seismometer adapted to the Moon context by a European & Chinese consortium will uncover the Moon internal structure.

Ref : Moon-SEIS-PP-21012
Issue : 3.0
Date of issue : 14/12/2018
Status : Validated



Chang’E 7 workshop



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《中法月震仪研讨会》会议纪要

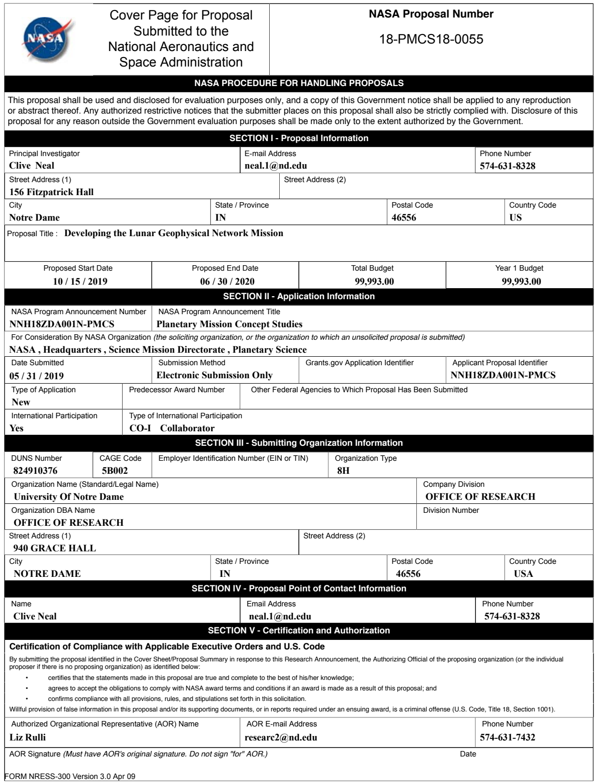
2017年9月22日，中国科学院地质与地球物理研究所、北京大学、华中科技大学等单位的中方专家参加了火星地震仪、月震仪布设和科学问题有关的研讨会，会议特邀法方专家 Institut de Physique du Globe de Paris （IPGP）, University Paris Diderot 研究所的 Philippe Lognonné 教授对他所带领团队研制的 InSight 火星地震仪相关技术做了详细介绍。中方代表中国科学院地质与地球物理研究所（IGGCAS）地震学组长张金海研究员代表中方介绍了单位概况和月震仪设计和布设有关方面的技术现状和科学设想。中方代表华中科技大学的屈少波博士介绍了空间惯性传感器研制的技术现状、悬挂摆式隔振测试平台的性能及用于下一步月震仪地面测试的设想。北京大学地球与空间科学学院的法文哲研究员、中国科学院地质与地球物理研究所科技处处长赵亮研究员、地震仪专业技术人员汪广浠工程师、地震震源过程专家郝金来博士等业界代表也参加了会谈。由于时间原因未能参会的专家和代表也希望加入中法双方的合作，他（她）们是：中国地质大学（武汉）大学的朱培民教授，北京大学的王彦宾教授，中国科技大学的孙道远教授，台湾海洋科技研究中心的林佩莹博士，中国科技大学的杨欣颖博士，中国科学院院刊副编审辛玲，Dr. Raphael Garcia, Institut de l’Aéronautique et de l’Espace, Dr. Mark Wieczorek, Observatory of Nice.

双方代表就月震仪和火星地震仪设计方面的异同点进行了详细探讨，双方认为可以在如下几个方面进行深入合作：

1. 充分借鉴 IPGP 课题组在火星地震仪设计方面的成功经验，为中国探月计划后续任务的月震仪设计和布设提供强有力的技术支撑；
2. 建立长效持久的合作机制，双方保持紧密联系，不定期召开学术研讨会，就有关问题进行深入探讨，探索最优解决方案；
3. 在数据处理方面进行深入合作，探索发掘微弱信号的新方法和新技术，为解译月球和火星内部圈层结构奠定基础；
4. 发挥中方长期以来在地震震源过程和地震偏移成像等方面的累积优势，预研火星地震研究可能遇到的特殊问题，为 InSight 采集的火星地震数据处理做好技术储备。

中方代表：
林杨挺 研究员
张金海 研究员

法方代表：
Prof. Philippe Lognonné



Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number
18-PMCS18-0055

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This proposal shall be used and disclosed for evaluation purposes only, and a copy of this Government notice shall be applied to any reproduction or abstract thereof. Any authorized restrictive notices that the submitter places on this proposal shall also be strictly complied with. Disclosure of this proposal for any reason outside the Government evaluation purposes shall be made only to the extent authorized by the Government.

SECTION I - Proposal Information

Principal Investigator: Clive Neal | E-mail Address: neal.1@nd.edu | Phone Number: 574-631-8328
Street Address (1): 156 Fitzpatrick Hall | Street Address (2):
City: Notre Dame | State / Province: IN | Postal Code: 46556 | Country Code: US
Proposal Title : Developing the Lunar Geophysical Network Mission

Proposed Start Date	Proposed End Date	Total Budget	Year 1 Budget
10 / 15 / 2019	06 / 30 / 2020	99,993.00	99,993.00

SECTION II - Application Information

NASA Program Announcement Number: NNH18ZDA001N-PMCS | NASA Program Announcement Title: Planetary Mission Concept Studies
For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*: NASA , Headquarters , Science Mission Directorate , Planetary Science
Date Submitted: 05 / 31 / 2019 | Submission Method: Electronic Submission Only | Grants.gov Application Identifier: | Applicant Proposal Identifier: NNH18ZDA001N-PMCS
Type of Application: New | Predecessor Award Number: | Other Federal Agencies to Which Proposal Has Been Submitted:
International Participation: Yes | Type of International Participation: CO-I Collaborator

SECTION III - Submitting Organization Information

DUNS Number: 824910376 | CAGE Code: 5B002 | Employer Identification Number (EIN or TIN): | Organization Type: 8H
Organization Name (Standard/Legal Name): University Of Notre Dame | Company Division: OFFICE OF RESEARCH
Organization DBA Name: OFFICE OF RESEARCH | Division Number:
Street Address (1): 940 GRACE HALL | Street Address (2):
City: NOTRE DAME | State / Province: IN | Postal Code: 46556 | Country Code: USA

SECTION IV - Proposal Point of Contact Information

Name: Clive Neal | Email Address: neal.1@nd.edu | Phone Number: 574-631-8328

SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in this solicitation.

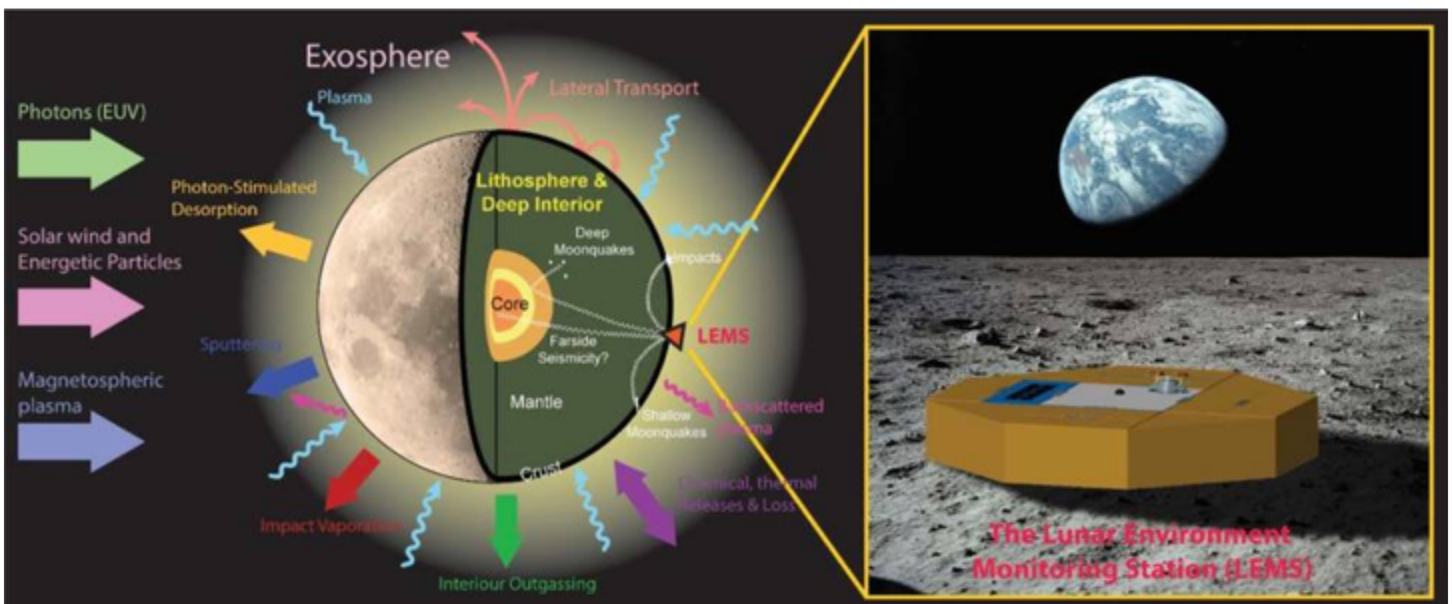
Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name: Liz Rulli | AOR E-mail Address: researc2@nd.edu | Phone Number: 574-631-7432
AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)* | Date

FORM NRESS-300 Version 3.0 Apr 09

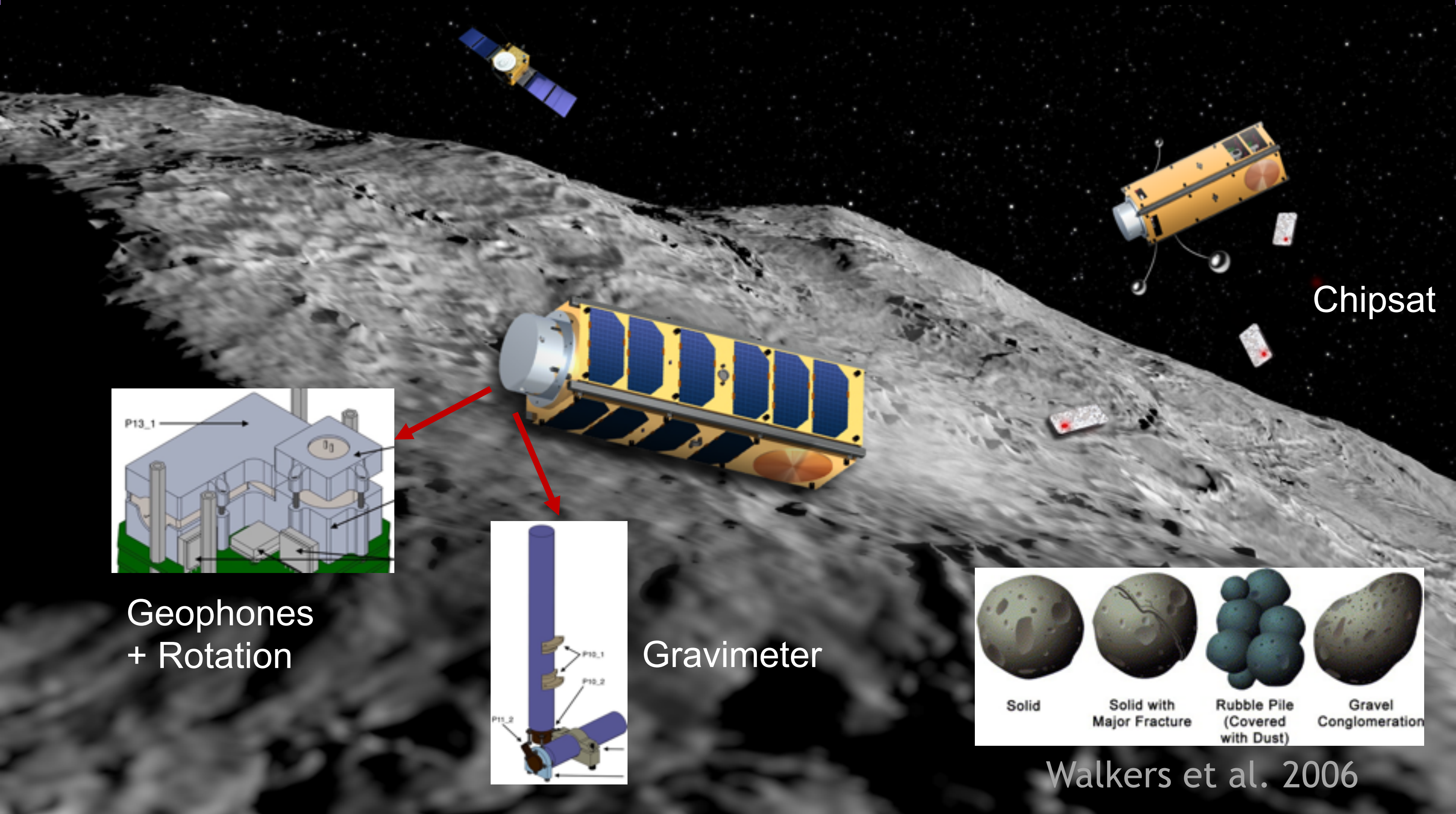
With the Chinese and American community

Commercial Missions : Seismology as a tool for ISRU

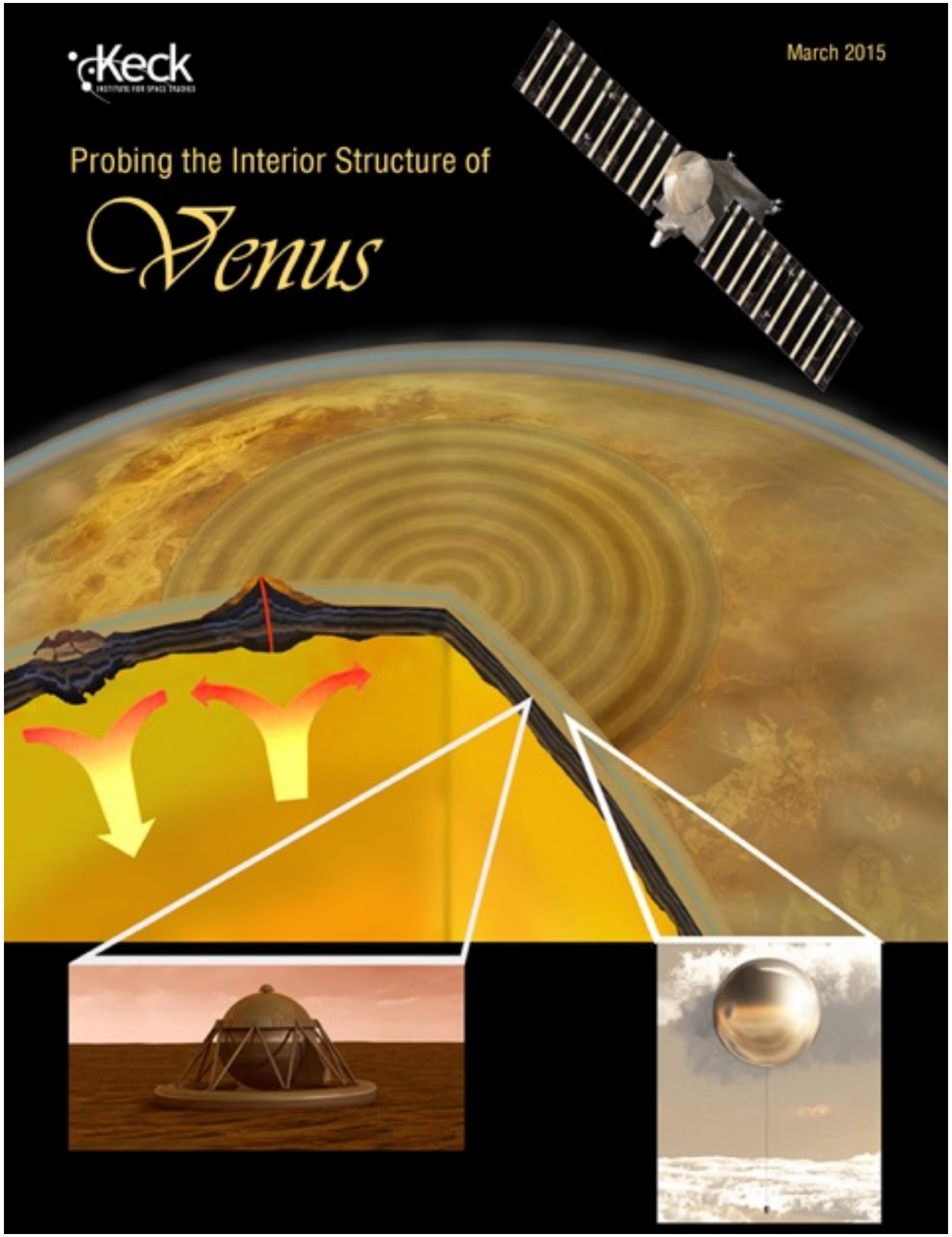


Step 1 : Exploration of Small Bodies with seismometers

- Several studies : AGEX, SEISCube … for AIM/AIDA, HERA, MMX
- Objective : determination of Asteroid internal structure
- Origins, Planetary Defense



STEP 2: “finish the job” and reveal the solar systems rocky planets interior structure.

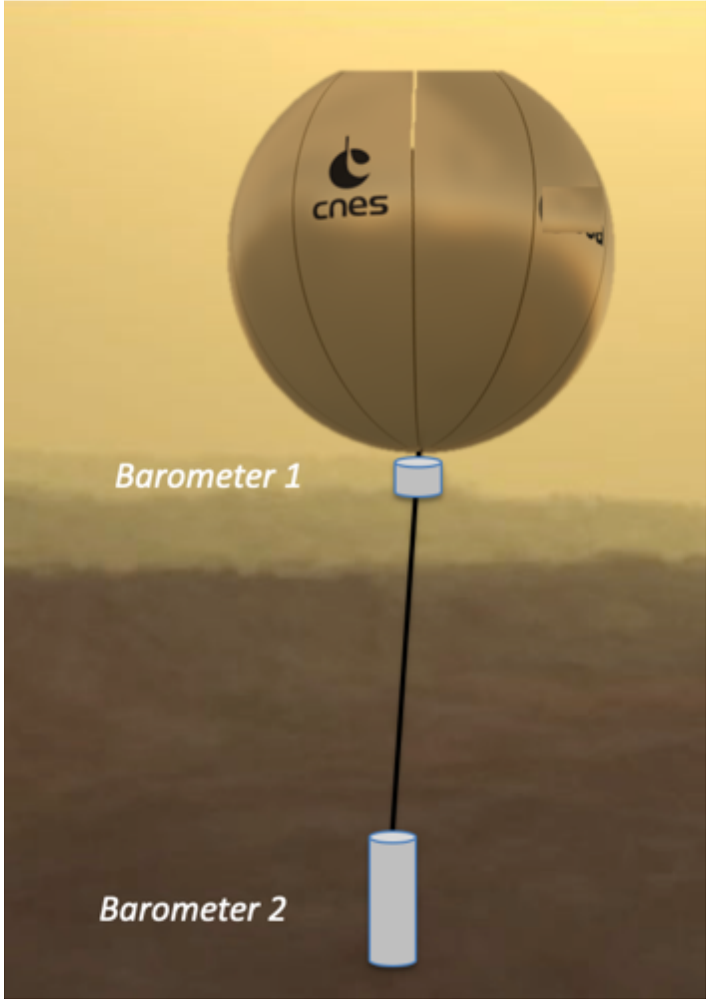


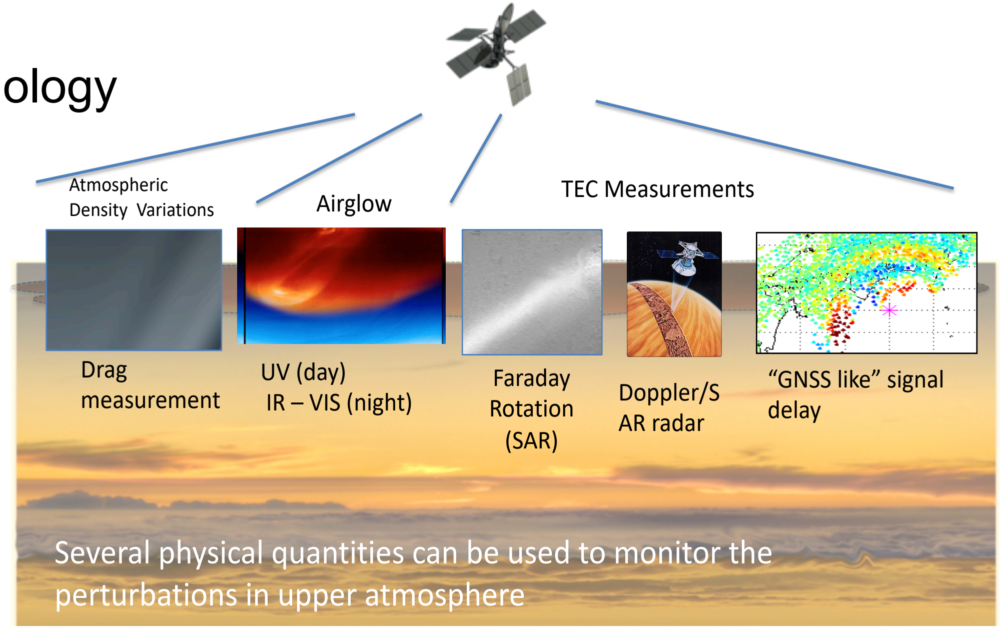
- Formidable questions but formidable difficulties
- Knowledge of its interior may hold the key to the understanding of its unique properties, such as its dense and hot carbon dioxide atmosphere and apparent lack of plate tectonics
- However, the temperature (400°C) and pressure (90 atm) at the Venus surface are not compatible with the state of the art of planetary seismometer
- Several options are open

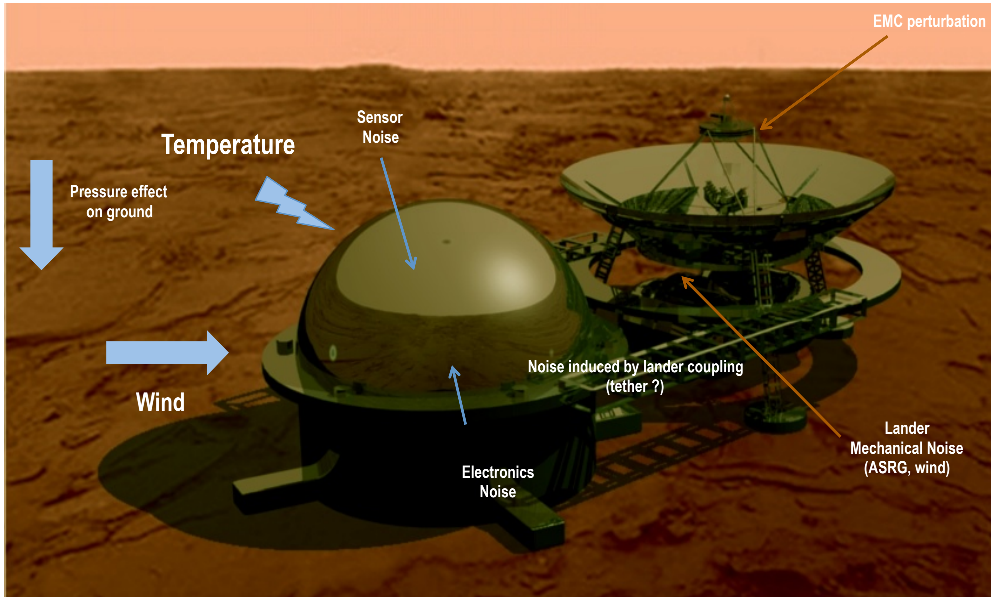
(Cutts, Mimoun et al, 2015)

Step 2: "finish the job" and reveal the solar systems rocky planets interior structure.

- Possible options for Venus Seismology



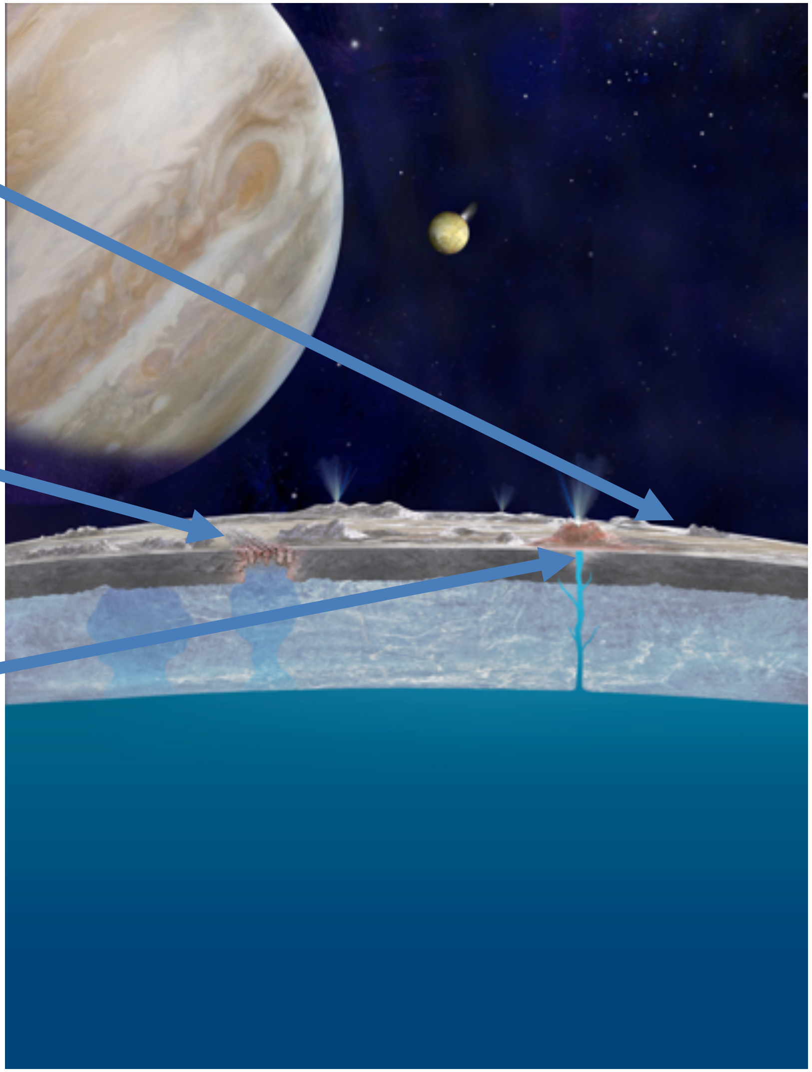




(Cutts, Mimoun et al, 2015)

Step 3: Ocean worlds internal structure

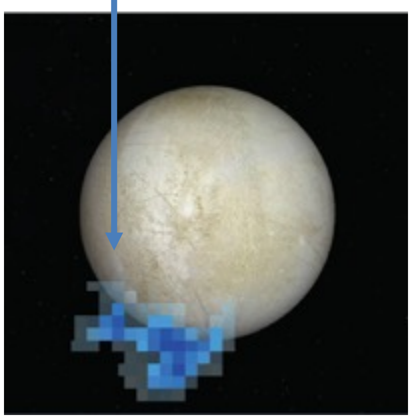
- Determination of ice shell thickness
- Tectonics-related activity ?
- Plume / cryovolcano events ?
- Asteroid Impact Rates

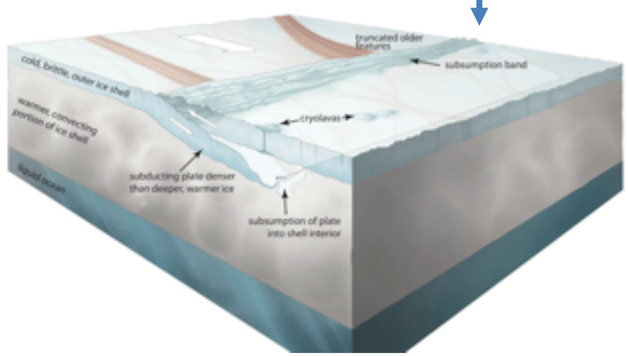


(Image via Slate)

Step 3: Ocean worlds internal structure

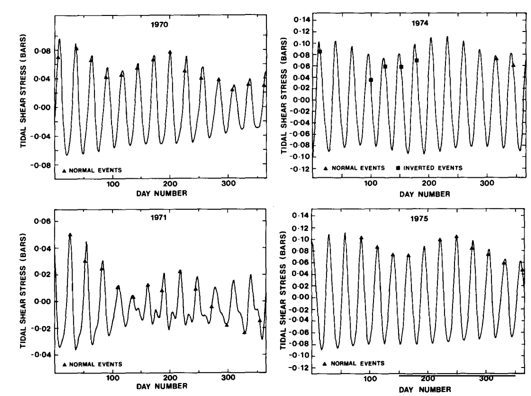
- Several signals sources are expected to be measured by geophones
  - Ice crack signals related to excentricity tidal stresses
  - Ice crack signals related to plate tectonics
  - Signal related to cryovolcanoes/plumes
  - Meteoritic impacts





Kattenhorn et al, 2014

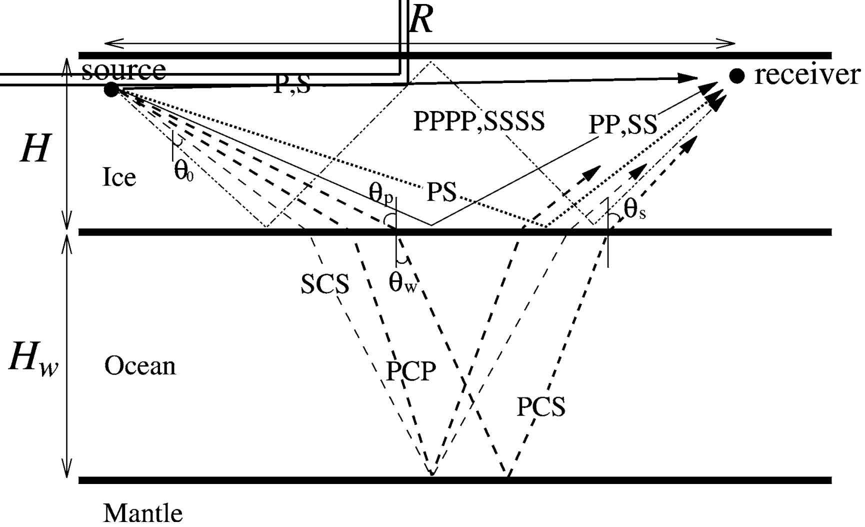
Moonquakes vs tidal stresses

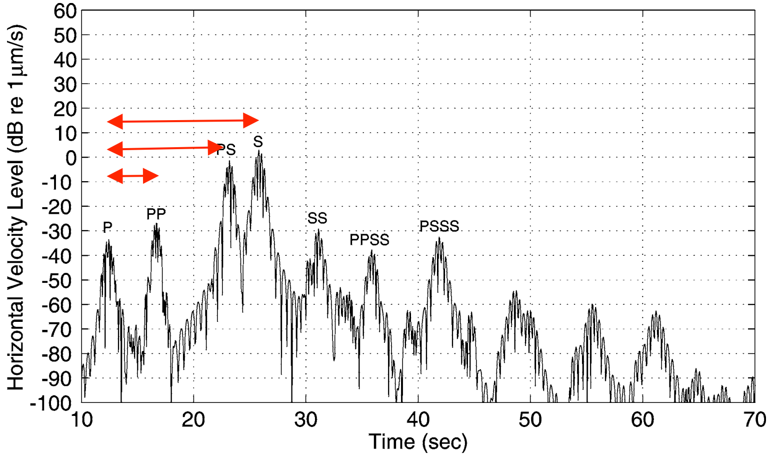


T.A. Minshull et al, 1987

Nous ne pouvons pas afficher l'image.

Step 3: Ocean worlds internal structure

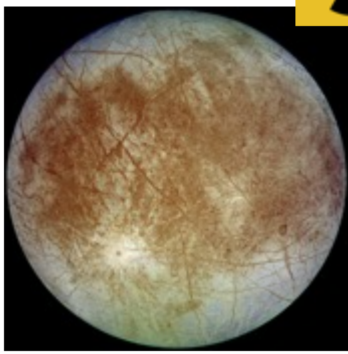


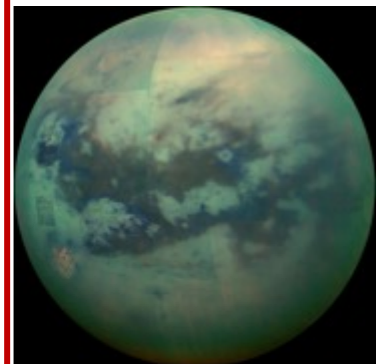


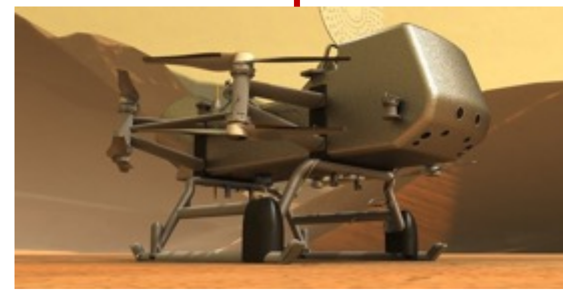
(Lee et al, 2003)

- Distance between P,PP,PS and S waves arrivals depends on ice shell width
- Only requirement is to have « seismic » events big enough to be detected by the geophones
- PCP and PCS arrivals could also in principle sound the sug-surface ocean (likely very big, close events only)

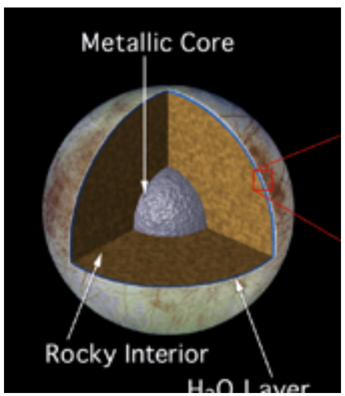
Step 3: Ocean worlds internal structure

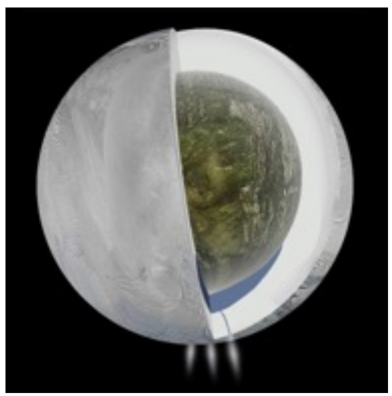


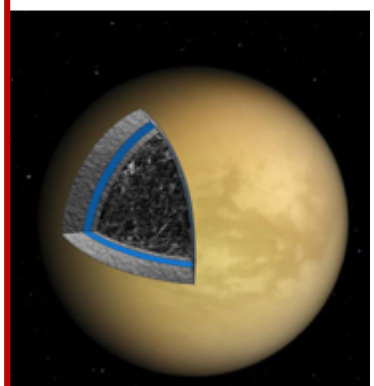




Lorenz et al 2009





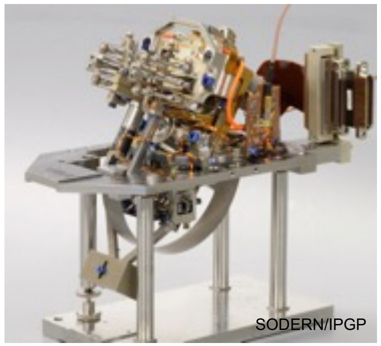


- Temperature
- The radiation challenge for galilean satellites (MRad level !)
- 3 seismometers on DragonFly !

Oceans Worlds	Internal Structure Ice sheet width Ocen depth	Short period	Radiations, temperature	(Lee et al, 2003)

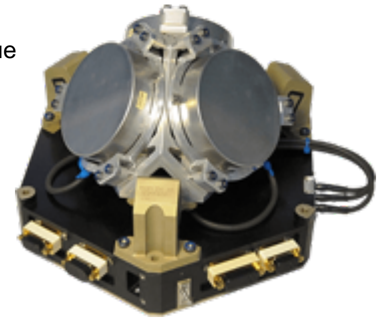
PIONEERS : the next generation of planetary seismometers

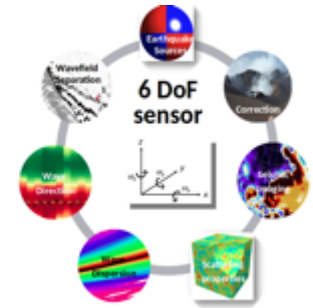
- **SEIS : an outstanding achievement**
- **…. but 1990's technologies**



- **Use of optical technologies**
- Displacement transducer : x100 perf. improvement
- Fiber Optics Gyrolaser : translation & rotation

Airbus/ixBlue





- **PIONEERS** is the acronym of **P**lanetary **I**nstruments based on **O**ptical technologies for an i**N**novative **E**uropean **E**xploration using **R**otational **S**eismology
- It is about developing the new generation of planetary seismometers which will fly on the next missions of exploration of the solar system
- A project of 4 years and 3 millions Euros

- **Two instruments are developped**

- « Small » CubeSat size Instrument
  - Small bodies
  - Ocean worlds
- Planetary size Instruments:
  - Moon Missions
  - Mars Missions

isae SUPAERO Institut Supérieur de l'Aéronautique et de l'Espace · ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich · iXblue · LMU Ludwig-Maximilians-Universität München · IPGP

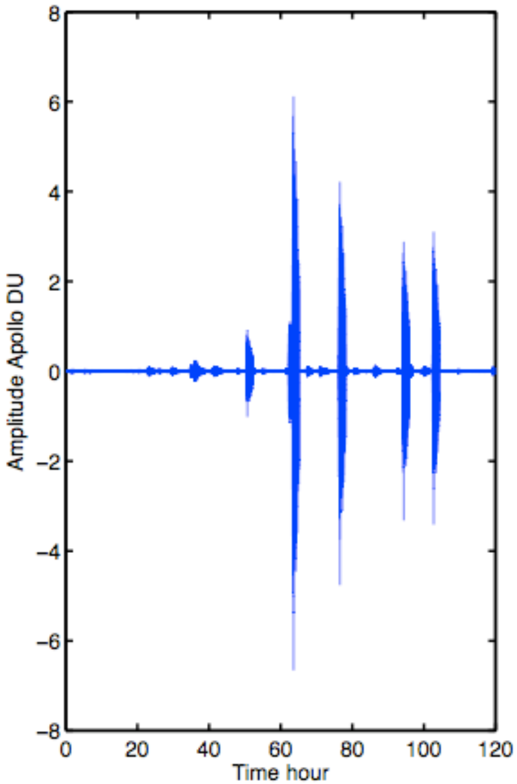
PIONEERS : a breakthrough for the performance level

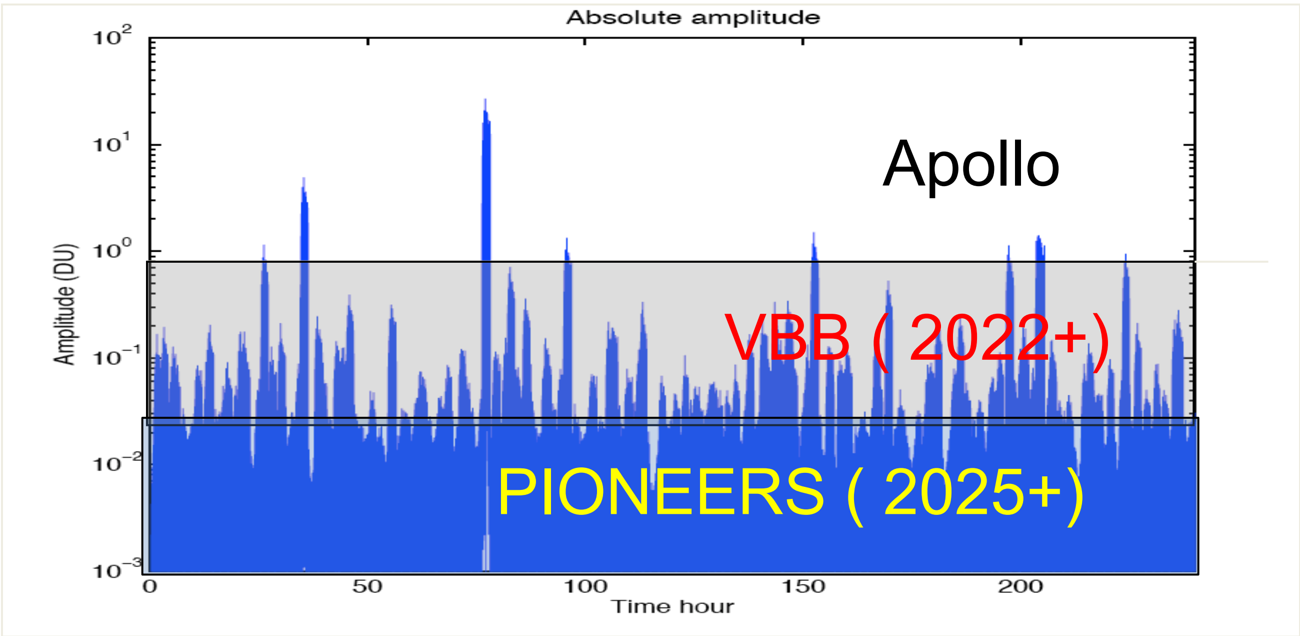
Impacts with Apollo

Impacts with VBB and PIONEERS

DU= 5 x 10^{-10} ms^{-2}

RMS= $5x10^{-11}$ ms^{-2}

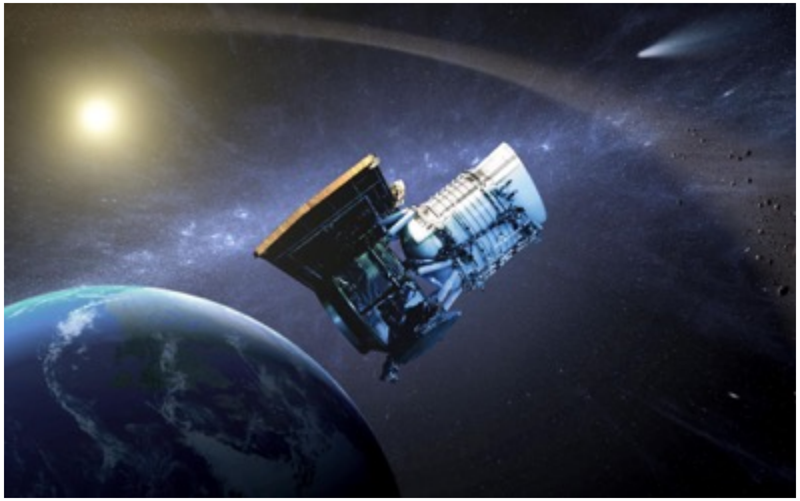




Summary of Present / Future Missions Involving Seismology

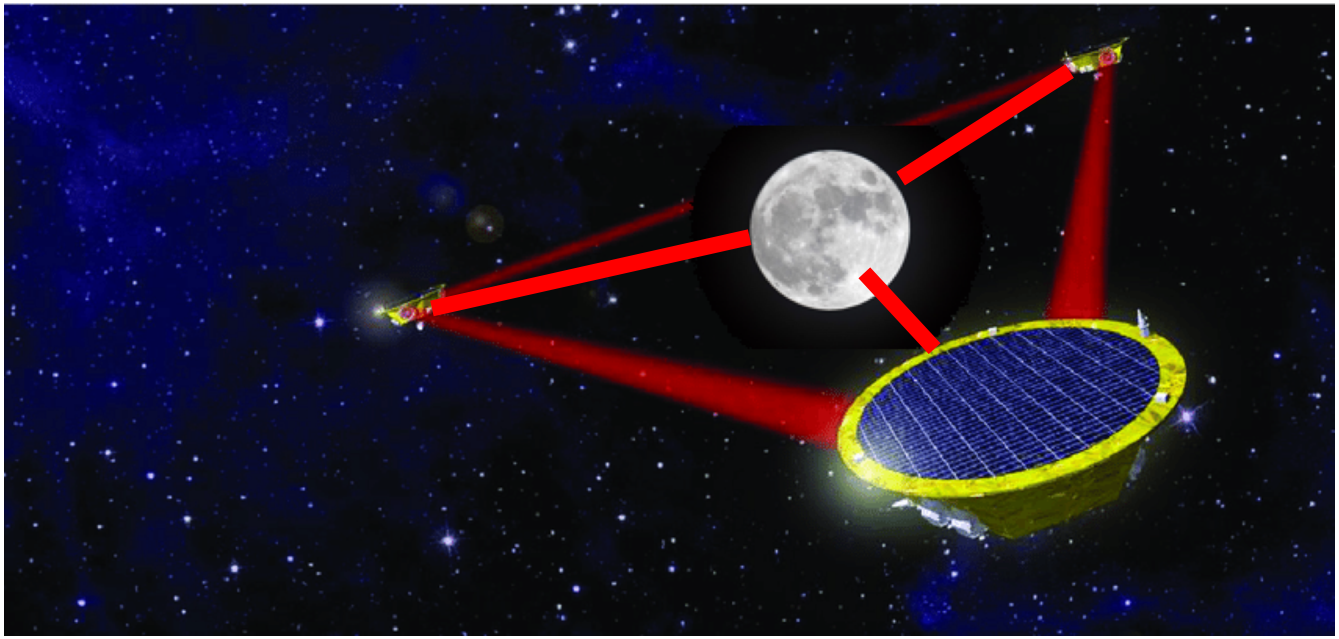
Mission	Launch	Major Mission event	Instrument description	Seismometer deployment	Reference
SEIS (Mars)	May 5th 2018	Arrival on Mars November 26th 2018. First Marsquake detection	Hybrid 6- axis instrument VBB and SP. [0.01 1 Hz] Noise floor < 0.5 10^{-9} m/s^2/√Hz - about 30 kg all included	Instrument deployed on the ground by robotic arm. Protected from environment by Wind and Thermal shield	Lognonné et al (2019)
DragonFly (Titan)	launch in 2026	Arrival foreseen in 2034	Lunar-A vertical seismometer (see Yamada paper) lowered with a windshield. Mass 0.4 kg Two small (10Hz) geophones .	Seismometer lowered with a windshield underneath UAV. Geophones implemented on both skid	Lorenz et al, 2009
MMX Rover (Phobos)	Sept 2024	Rover landing foreseen March 2025	PIONEERS PFM instrument. High sensitivity accelerometer plus fiber optics gyro.	Used as an IMU by the Rover	Mimoun et al, 2019
LGN Chang'E 7 (Moon)	TBD	Launch 2025-2030 ?	Lunar Version of SEIS or Silicon Audio (SiA) Ultra Low Noise optical/mechanical sensor is a force feedback accelerometer that allows for very broadband detection and uses a laser interferometer	Deployed by robotic arm or lowered below lander.	Neal et al, 2019
Europa Lander (Europa)	TBD	Mission candidate for NF5	Instrument derived from SP seismometer	Instrument in the lander warm box (radiation, temperatures …)	(Pike et al, 2016)
SEM ExoMars (Mars)	Mars 2021	Arrival October 2021	3-axis trihedron seismometer based on bronze-beryllium moving mass	Instrument in the lander warm box (temperatures …)	Manoukian et al
Chandrayiian-2 Seismometer (Moon)	22 juillet 2019		ILSA is a triple axis, MEMS-based seismometer that can detect minute ground displacement, velocity, or acceleration caused by lunar quakes. Its primary objective is to characterize the seismicity around the landing site. ILSA has been designed to identify acceleration as low as 100 ng /√Hz with a dynamic range of ±0.5 g and a bandwidth of 40 Hz. The dynamic range is met by using two sensors — a coarse-range sensor and a fine-range sensor.	Instrument in the lander warm box (temperatures …)	https://www.isro.gov.in/chandrayaan2-payloads
Venus Climate Geophysics (Venus)	2025-2030	Mission candidate for NF5	Microbarometer netwok to detect seismo-gravity waves	Two barometers deployed below a balloon gondola.	

Step 4 : Long term : planetary defense system



- Deriving from small bodies exploration
- Another use of the understanding of small bodies seismology is planetary defense;
- By helping to determine the internal structure of potentially hazardous asteroids (PHAs), seismic techniques can help evaluate the threat and the potential efficiency of a planned mitigation action
- A systematic survey of PHAs (as soon as they are discovered) with small CubeSat size probes including a seismometer a gyroscopic payload and a beacon to precisely track their location would definitely be a part of a planetary wide defense system.

Step 4 : Long, long term : planetary wide sensors



- In the previous discussion, we have considered the use of seismic techniques with a performance level close to what has already been achieved for Apollo or Insight (typically 10^{-10} m/s^2/Hz). Improving the detector performance by several orders of magnitude -which is technically possible with optical interferometry techniques - would enable the measurement of gravitational waves – on a planetary scale.

- All planets without atmosphere can be the place of remote sensing long period seismology, if very precise ranging (below nm) can be made between slow orbiting S/C and surface reflectors.