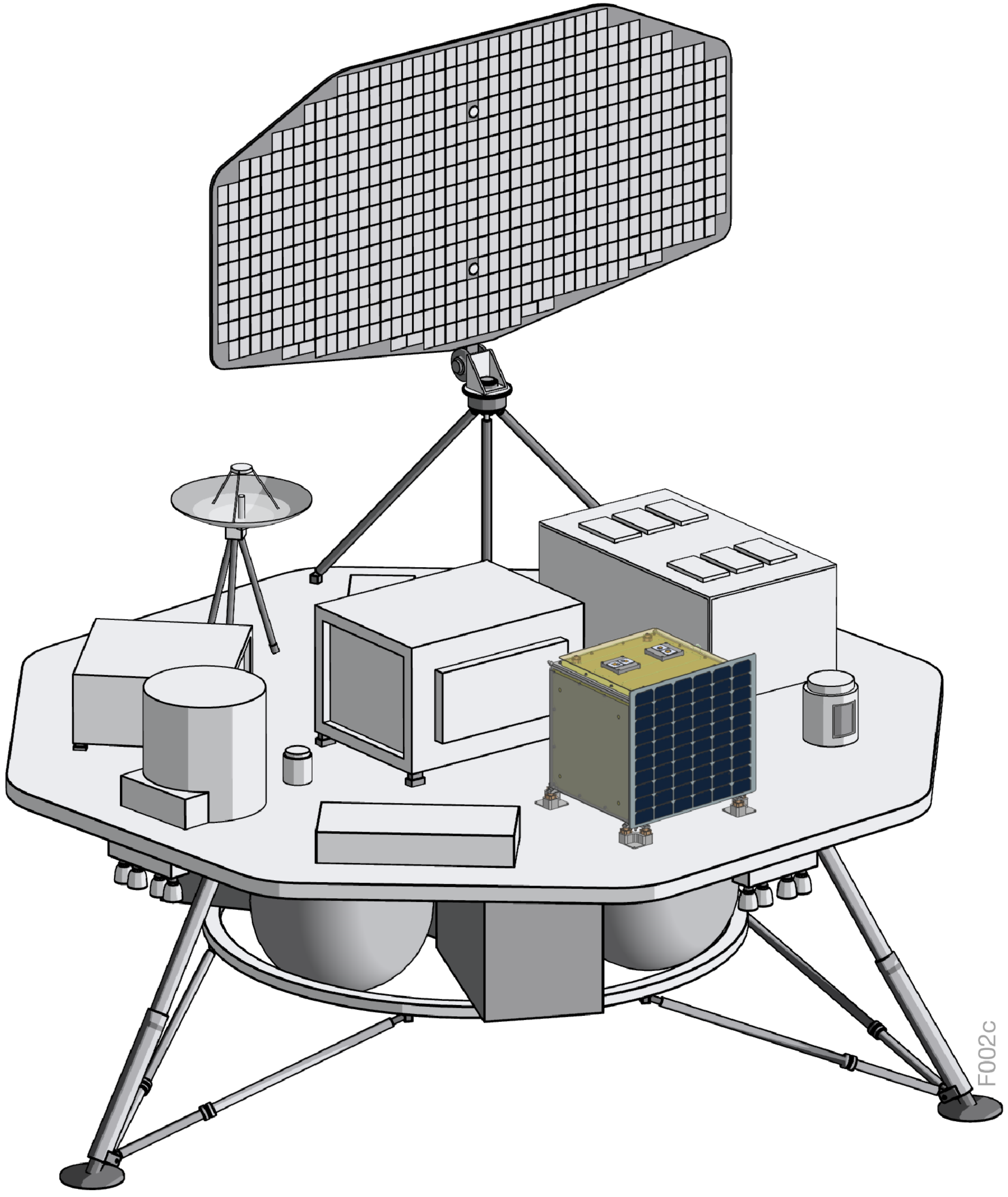


Farside Seismic Suite

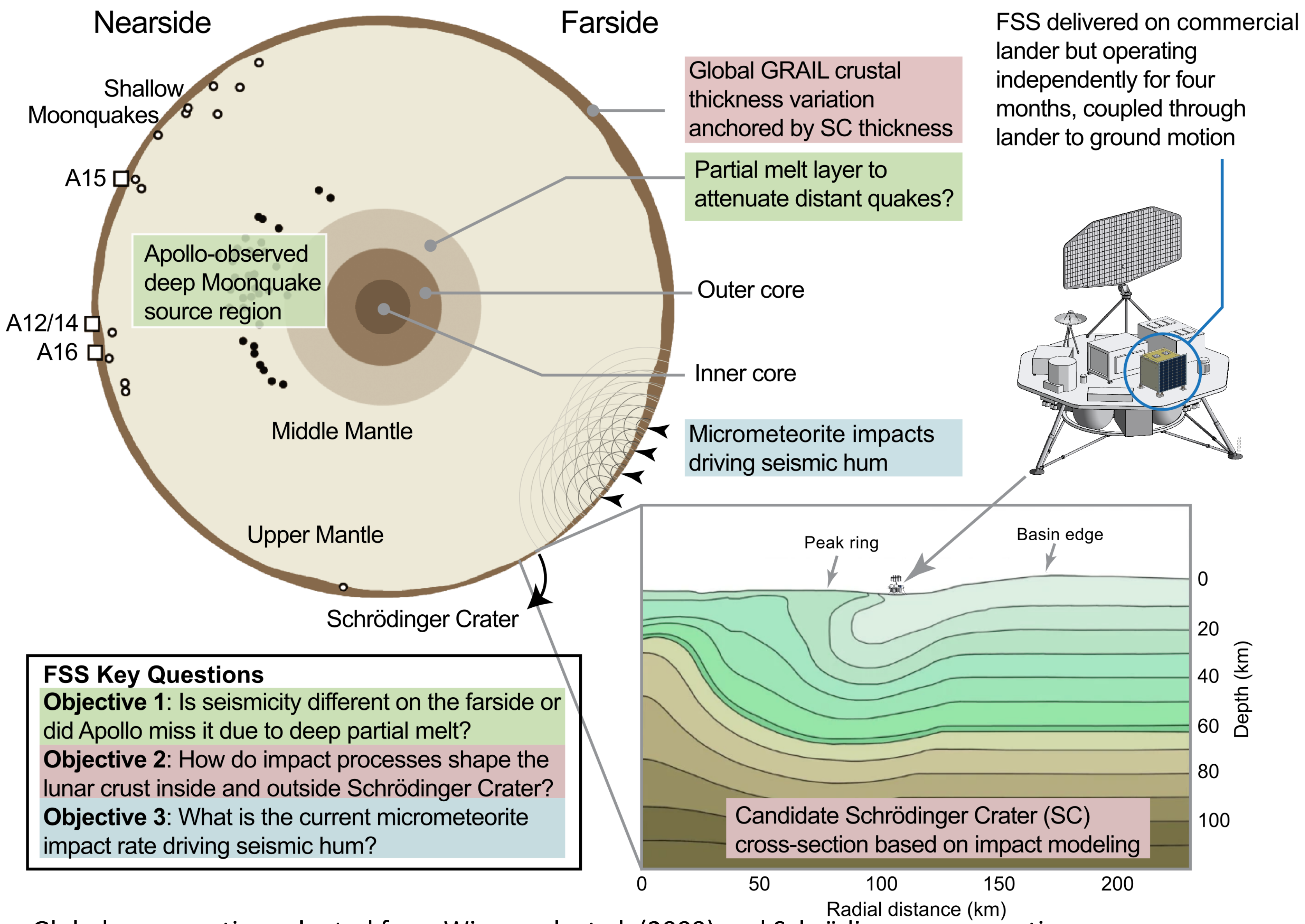
P.Lognonné

Institut de physique du globe de Paris, Université de Paris

And the FSS team: Mark Panning[1], Sharon Kedar[1], Neil Bowles[2], David Bugby[1], Simon Calcutt[2], James Cutler[3], John Elliott[1], Raphael Garcia[4], Taichi Kawamura[5],, Ceri Nunn[1], W. Tom Pike[6], Gabriel Pont[7], Sebastien de Raucourt[5], Ian Standley[8], William Walsh[1], Renee Weber[9], Charles Yana[7]

1. Jet Propulsion Lab, California Institute of Technology, 2. University of Oxford, 3. University of Michigan, 4. ISAE Supaero, 5. Institut de Physique du Globe, Paris, 6. Imperial College, London, 7. CNES, 8. Kinemetrics, Inc., 9. NASA Marshall Space Flight Center

The Concept (Selected by NASA for 2024/2025 launch)

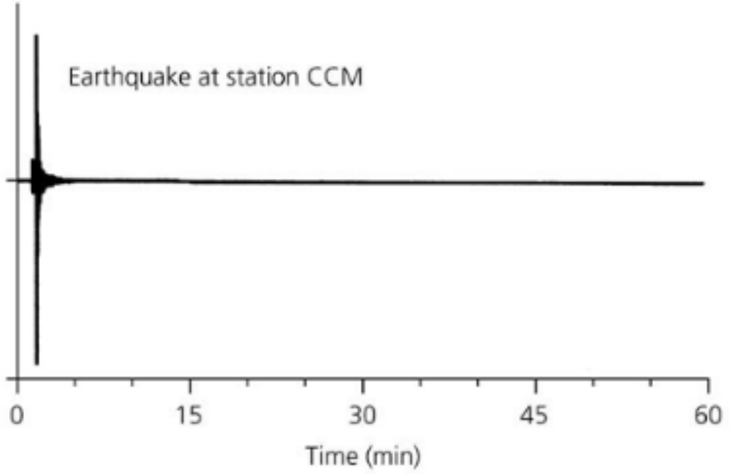


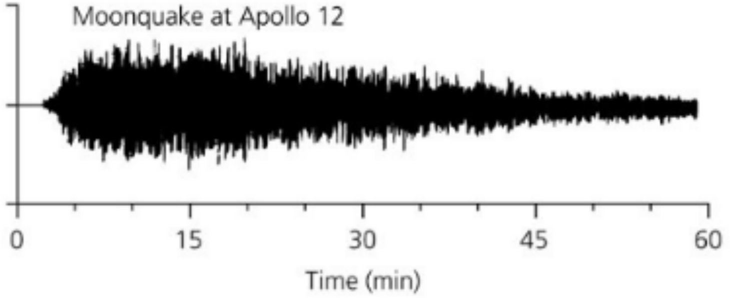
Global cross-section adapted from Wieczorek et al. (2009) and Schrödinger cross-section from Kring et al. (2016)

FSS delivers a vertical component Very Broad Band seismometer (VBBZ), the most sensitive seismometer to fly on a planetary mission, and a very capable and compact 3-component SP seismometer, both based on the instrumentation of the currently-operating InSight Mars mission.

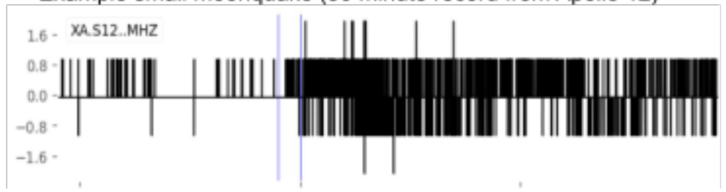
These instruments are delivered inside a thermal enclosure incorporating independent command, power, and communications systems to outlive the commercial lander and deliver continuous day and night seismic data for months.

Lunar Seismology





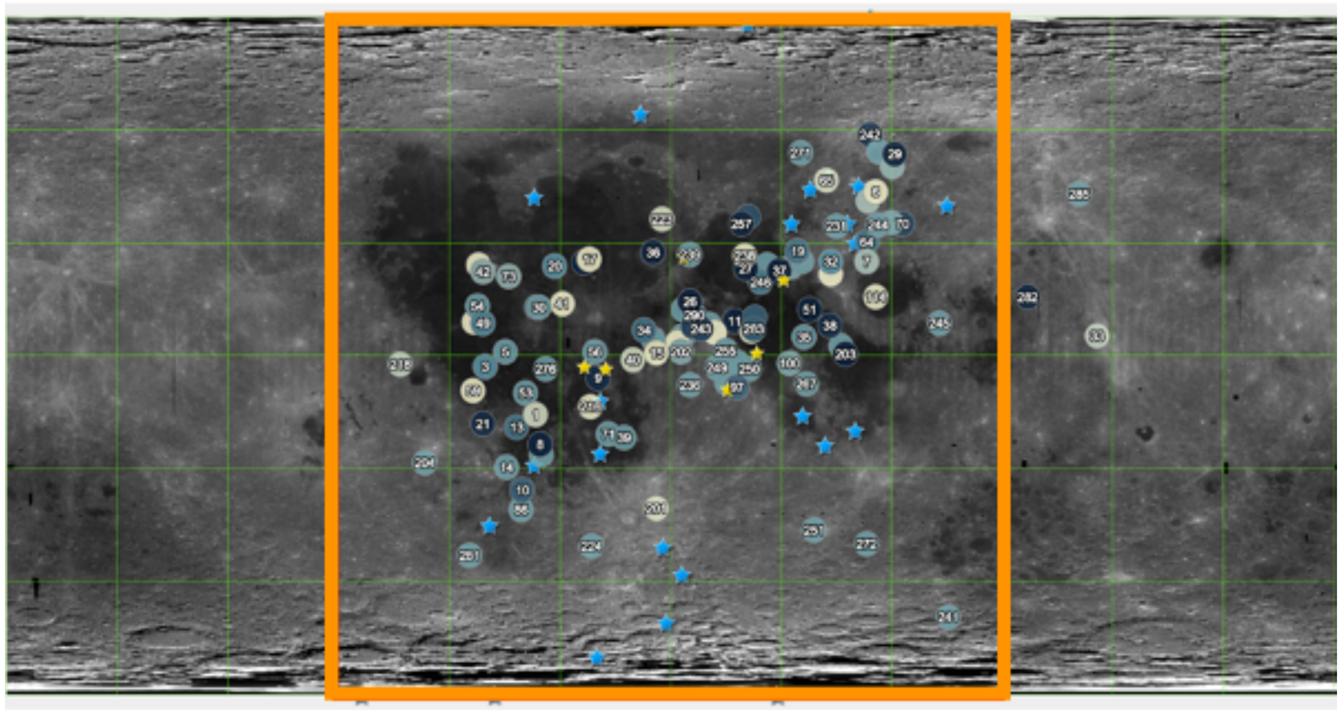
Example small moonquake (30 minute record from Apollo 12)



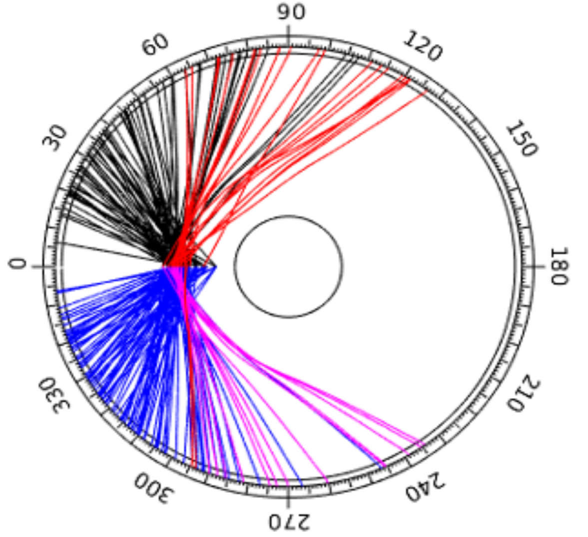
- Lunar seismology is very different than Earth seismology with unique challenges
- The Apollo instruments were extremely sensitive instruments, but were limited by very coarse digitization
- Apollo measurements were only made at the nearside landing locations
- Landing modern, sensitive instruments (on the far side of the Moon!) with 24-bit modern digitization opens up new opportunities beyond what was possible with Apollo

Farside Seismicity

- Nearly all located deep moonquake clusters and shallow moonquake locations are on the nearside of the Moon
- How much of this is due to attenuation in the deep lunar mantle and how much is due to fundamental differences in seismicity?
- Paths from known repeating deep moonquake locations to Schrödinger pass through the deep mantle constraining that structure, while recording of new sites on the far side will directly constrain farside activity rates



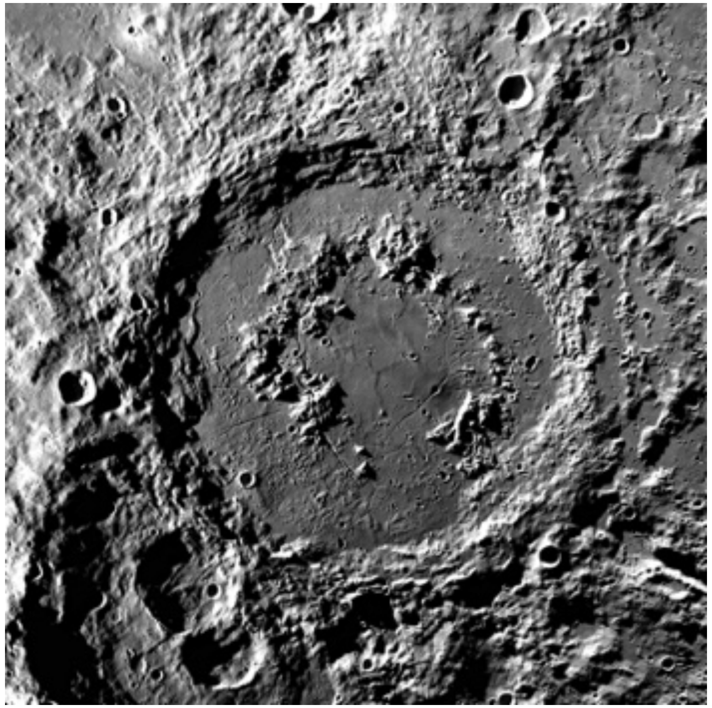
Ray paths in Garcia et al. (2019) M1 model from known deep moonquakes



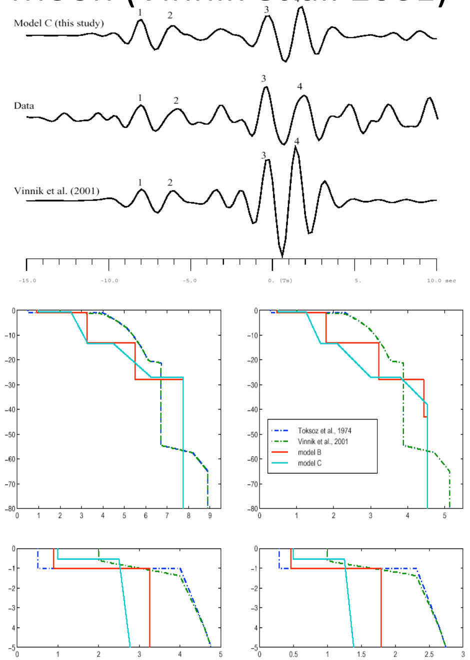
Black (P), Blue (S) from Apollo
Red(P), Purple (S) with FSS

Local structure at Schrödinger

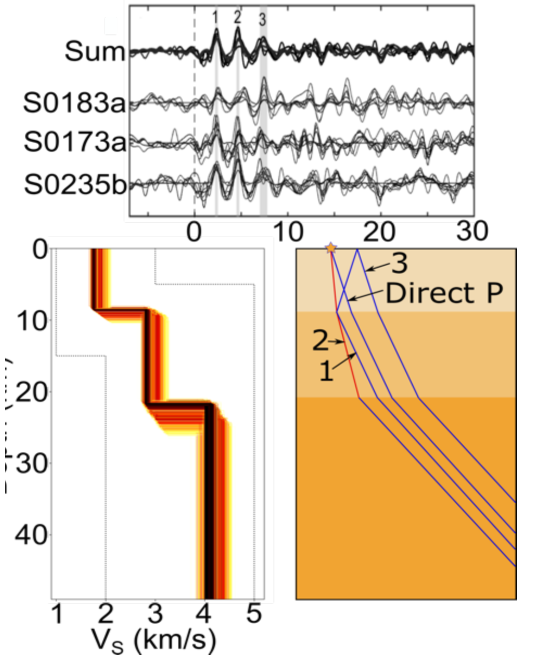
- Schrödinger Crater is well-preserved impact crater with a peak ring and smooth floors interpreted as impact melts
- 3-component seismic records present the potential for resolving crustal thickness and layering through a receiver function approach
- Continuous noise records can be autocorrelated to obtain the seismic reflectivity response below the landing site
- Local crustal structure can be used to anchor global gravity-derived models



Moon (Vinnik et al. 2001)

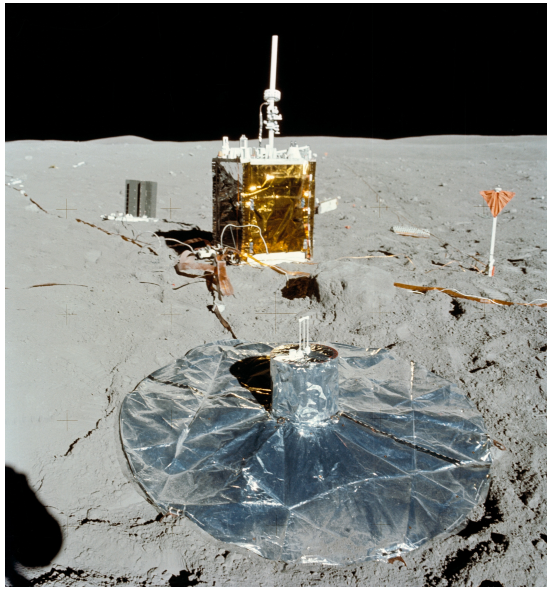


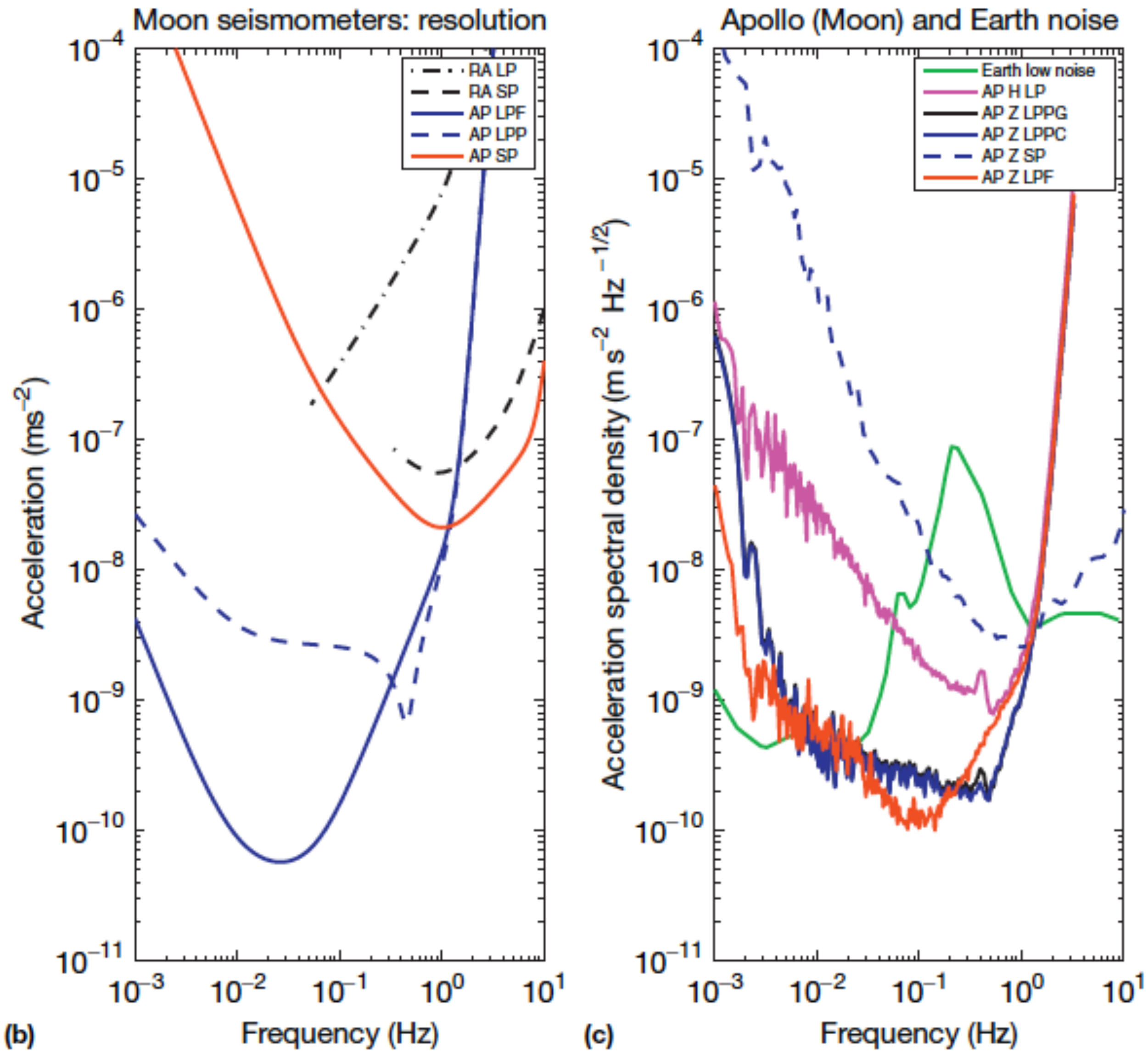
Mars (Knapmeyer et al. 2021)



The lunar background hum

- The background seismic noise on the Moon is expected to be driven by the regular impacts of micrometeorites (Lognonné et al. 2009) and micro-moonquakes
- Apollo seismometers were not able to record the level of this background noise due to the sensitivity of the instruments and the digitization noise

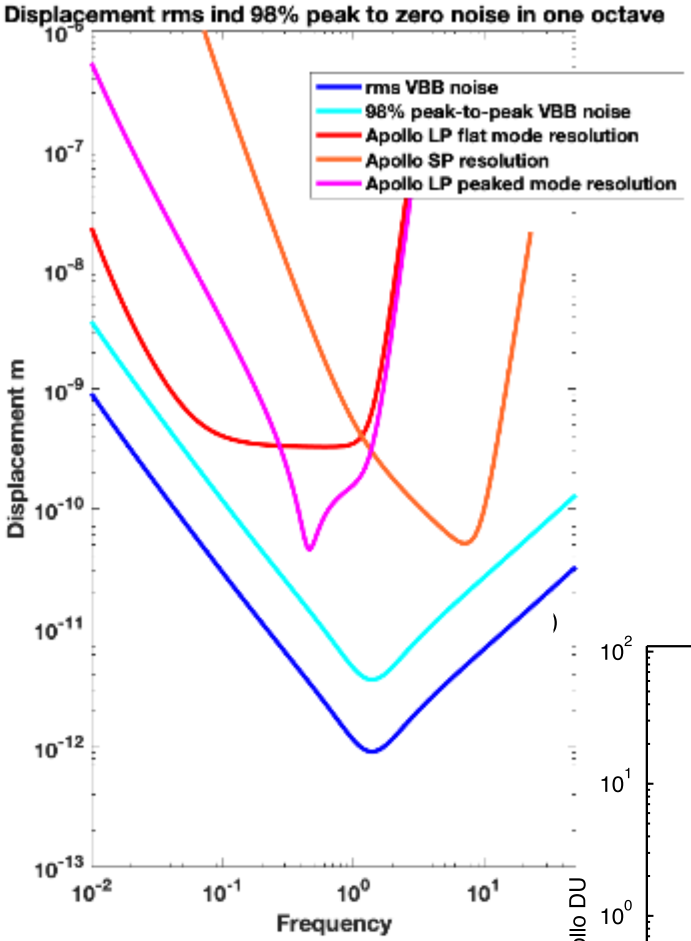


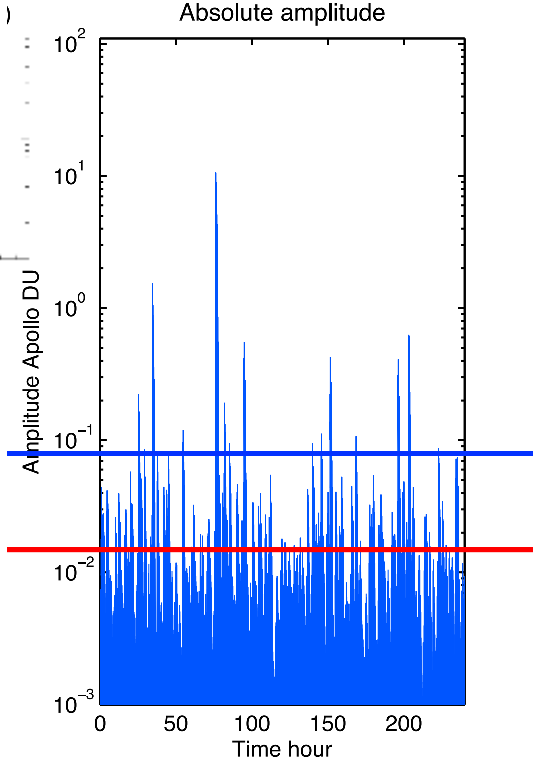


From Lognonné & Johnson (2015)

The lunar background hum

- The background seismic noise on the Moon is expected to be driven by the regular impacts of micrometeorites (Lognonné et al. 2009) and micro-moonquakes
- Apollo seismometers were not able to record the level of this background noise due to the sensitivity of the instruments and the digitization noise
- VBBZ will record at a lower noise level than Apollo and either directly constrain the lunar background noise, or lower the upper bound of that noise level
- This can be used to better constrain the impact rate of the smallest micrometeorites, an important goal for long term human safety



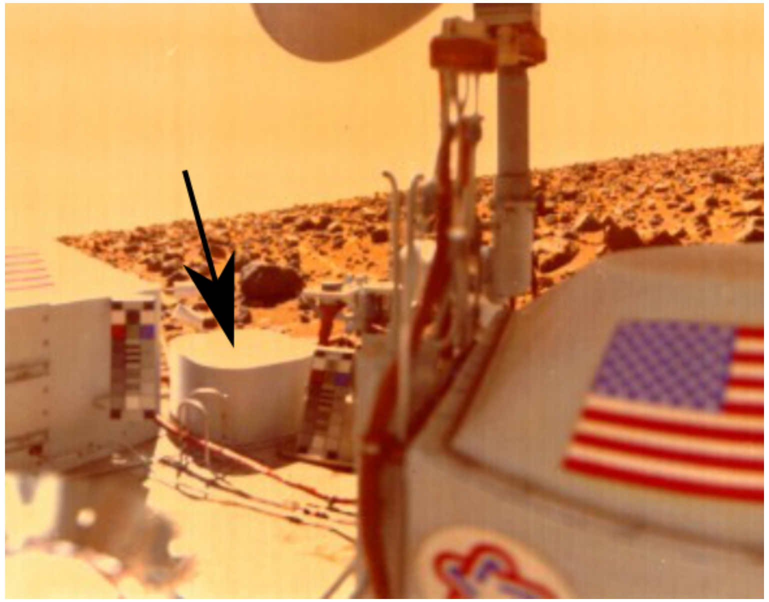


From Lognonné et al (2009)

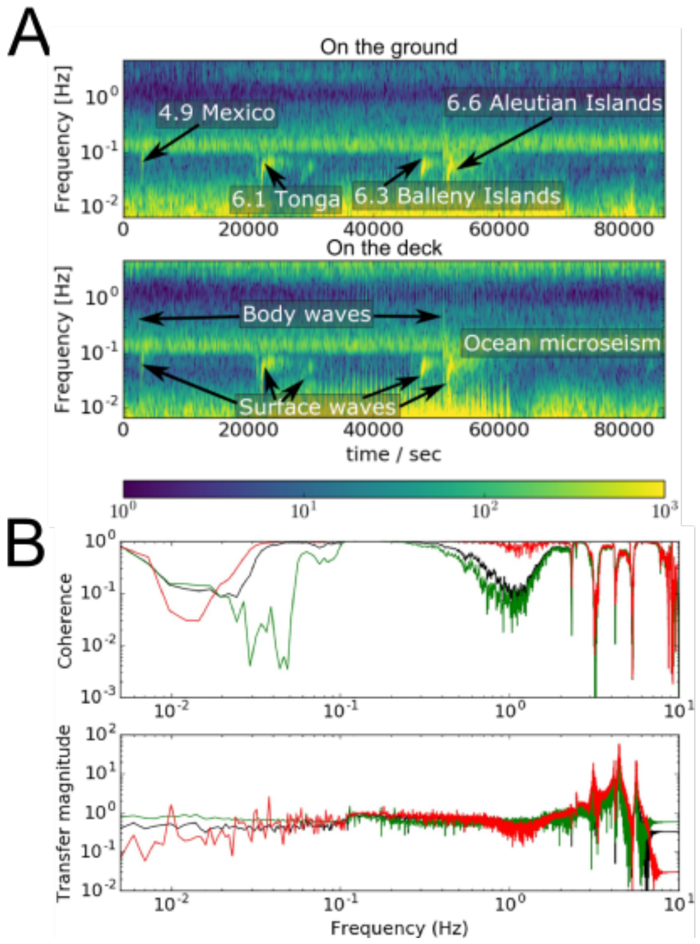
Science Traceability

Decadal Survey Questions	Science Goals	Science Questions	Investigation Objective Requirements			Mission Top Level Requirements
			Measurement	Requirement	Projected Performance	
• How do the structure and composition of each planetary body vary with respect to location, depth, and time? • What are the major heat-loss mechanisms and associated dynamics of their cores and mantles?	**Objective 1**: Investigate deep lunar structure and the difference between near and farside activity	What is the rate of farside seismicity?	**1A**: Detect >50 farside events	VBB: $2x10^{-10}$ m/s^2/Hz$^{1/2}$ from 0.1-1 Hz	$1.5x10^{-10}$ m/s^2/Hz$^{1/2}$ or better over required frequency band	1 month (threshold mission)
		What is the deep mantle seismic attenuation?	**1B**: Detect >10 nearside events (known clusters or impact flashes)	VBB: $2x10^{-10}$ m/s^2/Hz$^{1/2}$ from 0.1-1 Hz	$1.5x10^{-10}$ m/s^2/Hz$^{1/2}$ or better over required frequency band	4 months (baseline mission)
• What are the major surface features and modification processes on each of the inner planets? • What were the sources and timing of the early and recent impact flux of the inner solar system?	**Objective 2**: Understand how the lunar crust is affected by the development of an impact melt basin	What is the crustal thickness and layering beneath Schrodinger Crater?	**2A**: Detect >3 events at SNR > 3 on 3 components to create receiver functions	SP: $5x10^{-9}$ m/s^2/Hz$^{1/2}$ from 0.3-1 Hz	$3x10^{-9}$ m/s^2/Hz$^{1/2}$ over required frequency band	4 months (baseline mission)
			2B: VBBZ autocorrelation of seismic noise	VBB: $2x10^{-10}$ m/s^2/Hz$^{1/2}$ from 0.1-1 Hz	$1.5x10^{-10}$ m/s^2/Hz$^{1/2}$ or better over required frequency band	1 month (threshold mission)
• What were the sources and timing of the early and recent impact flux of the inner solar system?	**Objective 3**: Assess the current micrometeorite impact rate and local tectonic activity	What is the micro-seismic noise 10x below Apollo level?	**3A**: Seismic noise over at least one lunar day/night cycle	VBB: $2x10^{-10}$ m/s^2/Hz$^{1/2}$ from 0.1-1 Hz	$1.5x10^{-10}$ m/s^2/Hz$^{1/2}$ or better over required frequency band	1 month (threshold mission)

Can we record without deploying to the surface?

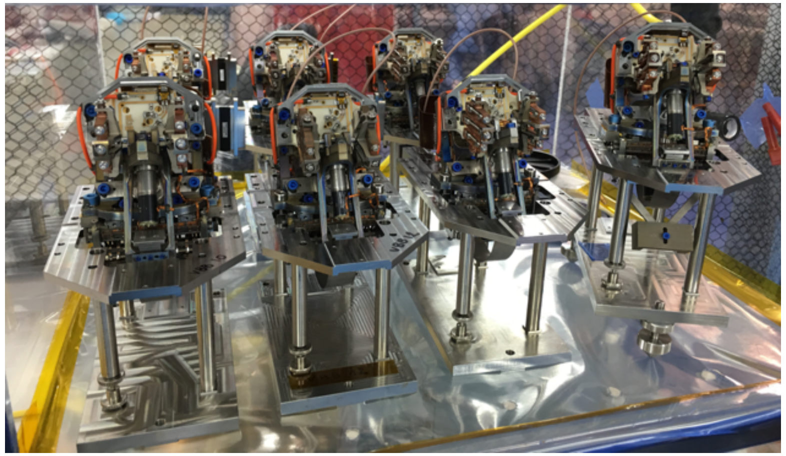


- The Viking mission (and InSight prior deployment) taught us that a deck-mounted seismometer faces difficulties.
- But experiments on the engineering model of the MSL Curiosity rover show ground motion can be well-coupled through the structure of a spacecraft below the resonant frequency
- On the Moon, there will be no wind noise, and thermal noise is expected to be concentrated near dawn and dusk (as demonstrated by thermal moonquakes measured by Apollo instruments)

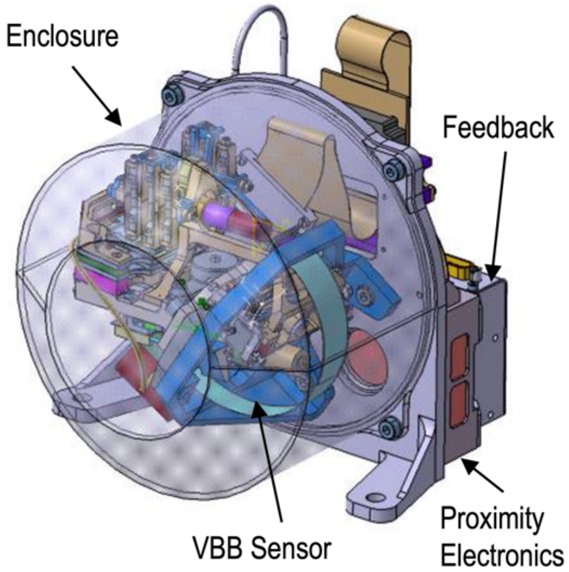


From Panning and Kedar (2019)

The VBBZ seismometer

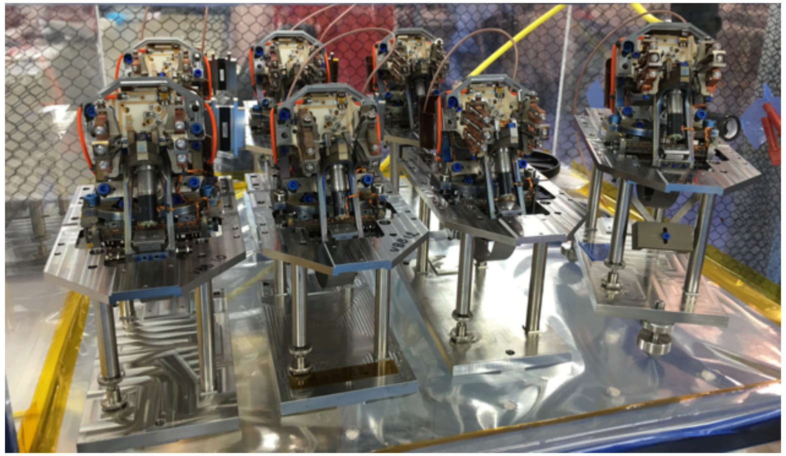


3 FM on Mars but 3 spare FMs + 2 QMs available forthe Moon !



- Uses a flight spare VBB seismometer from the InSight mission
- Spring needs to be replaced to account for lunar gravity and rotated to sense vertical motions (rather than 3 tilted components as in InSight)
- Packaged in enclosure which allows venting to attain vacuum on the Moon
- Contributed by partnership between Institut de physique du globe de Paris/Université de Paris and CNES with support from ISAE and APC

The VBBZ seismometer

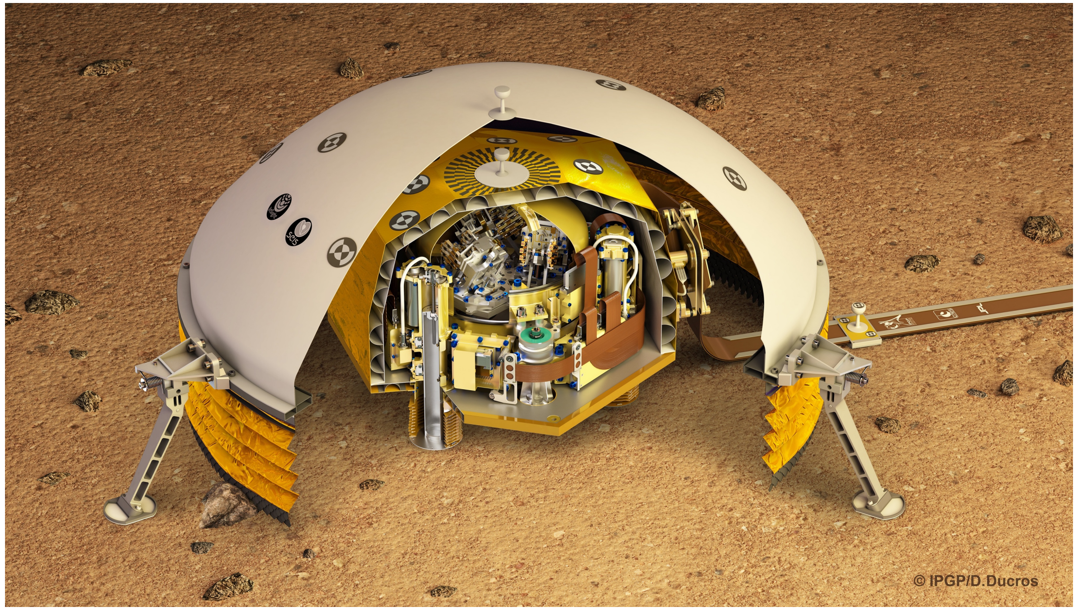


3 FM on Mars but 3 spare FMs + 2 QMs available forthe Moon !

- Uses a flight spare VBB seismometer from the InSight mission

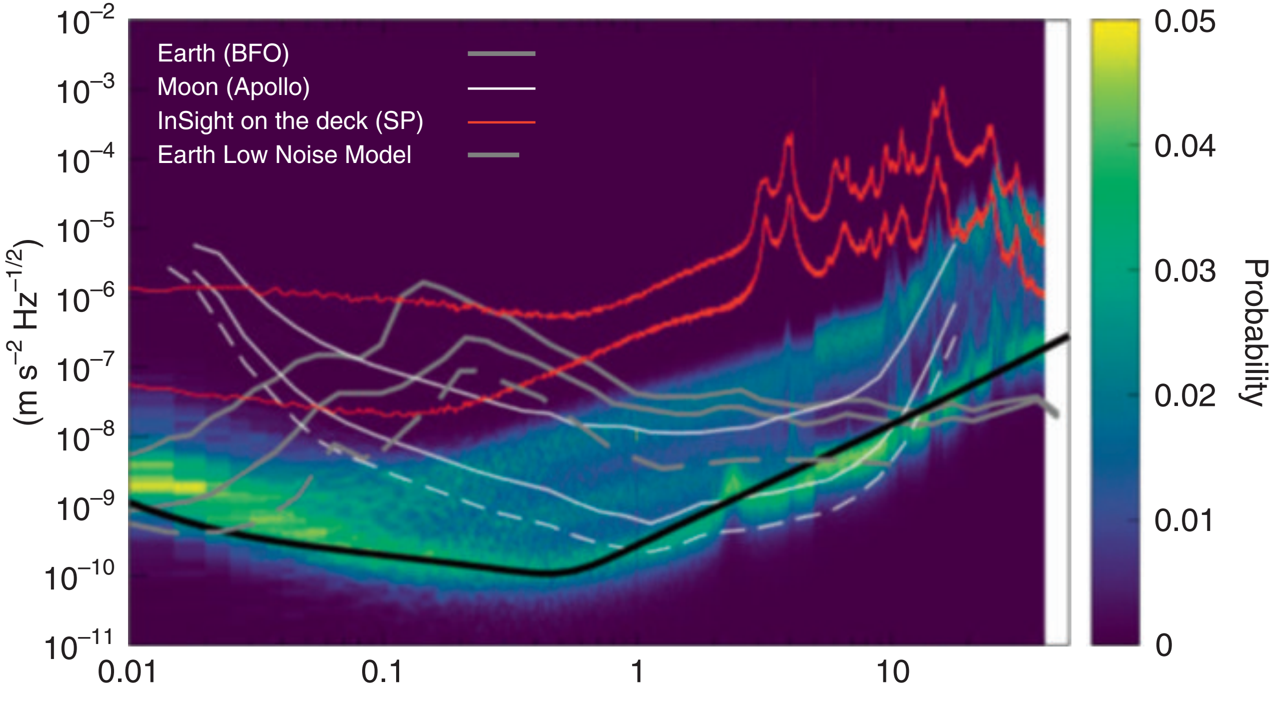
From Lognonné et al. (2020)

Mars InSight configuration

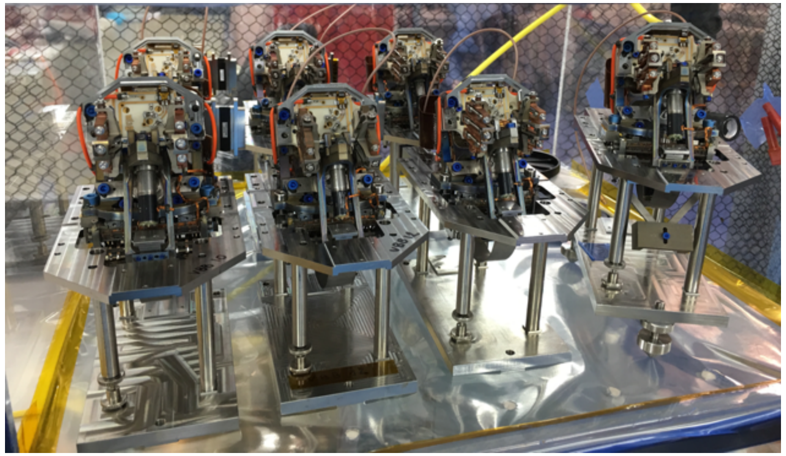


From Lognonné et al. (2019)

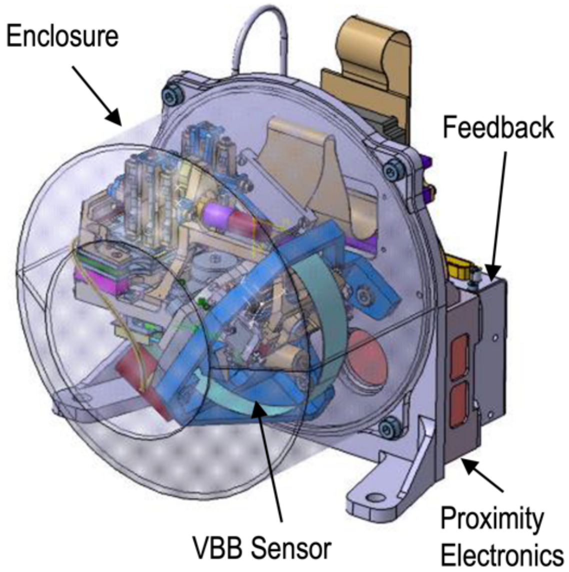
Mars Recorded noise



The VBBZ seismometer



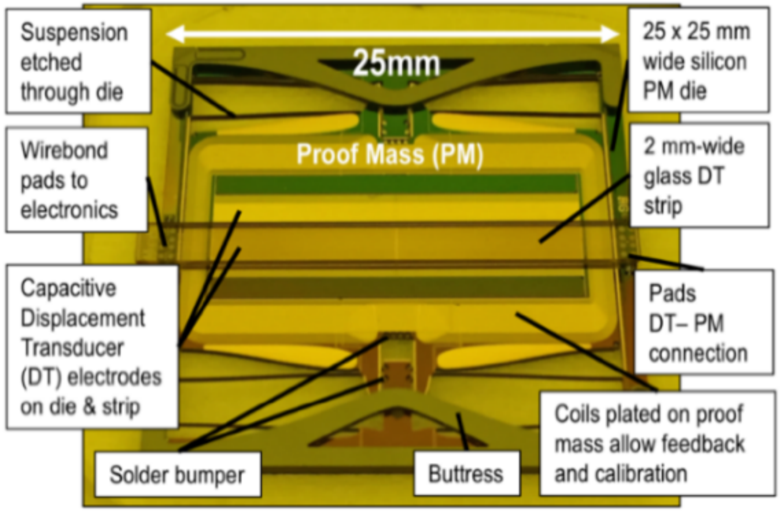
3 FM on Mars but 3 spare FMs + 2 QMs available forthe Moon !

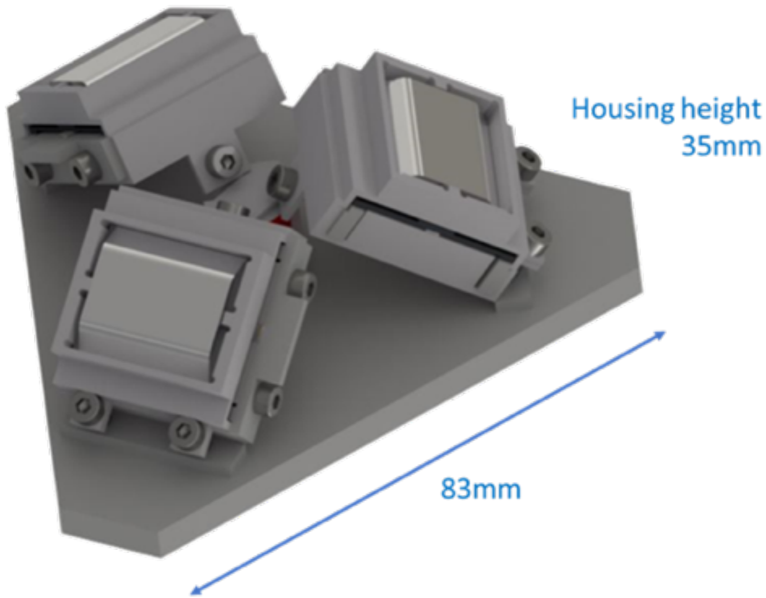


- Uses a flight spare VBB seismometer from the InSight mission
- Spring needs to be replaced to account for lunar gravity and rotated to sense vertical motions (rather than 3 tilted components as in InSight)
- Packaged in enclosure which allows venting to attain vacuum on the Moon
- Contributed by partnership between Institut de physique du globe de Paris/Université de Paris and CNES with support from ISAE and APC

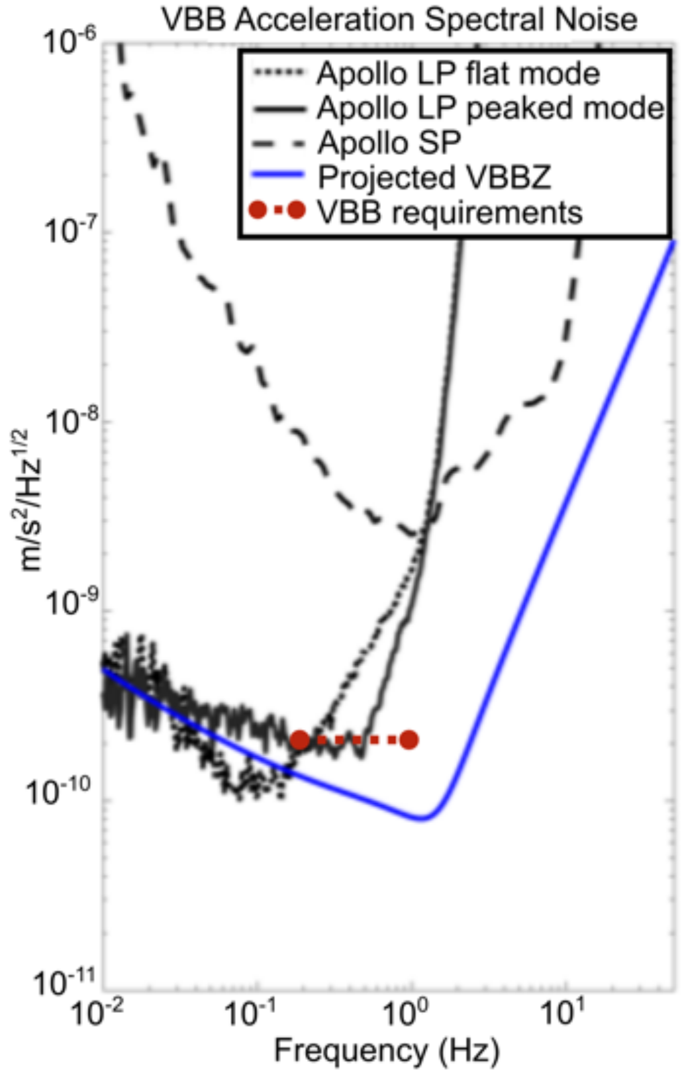
The SP seismometer

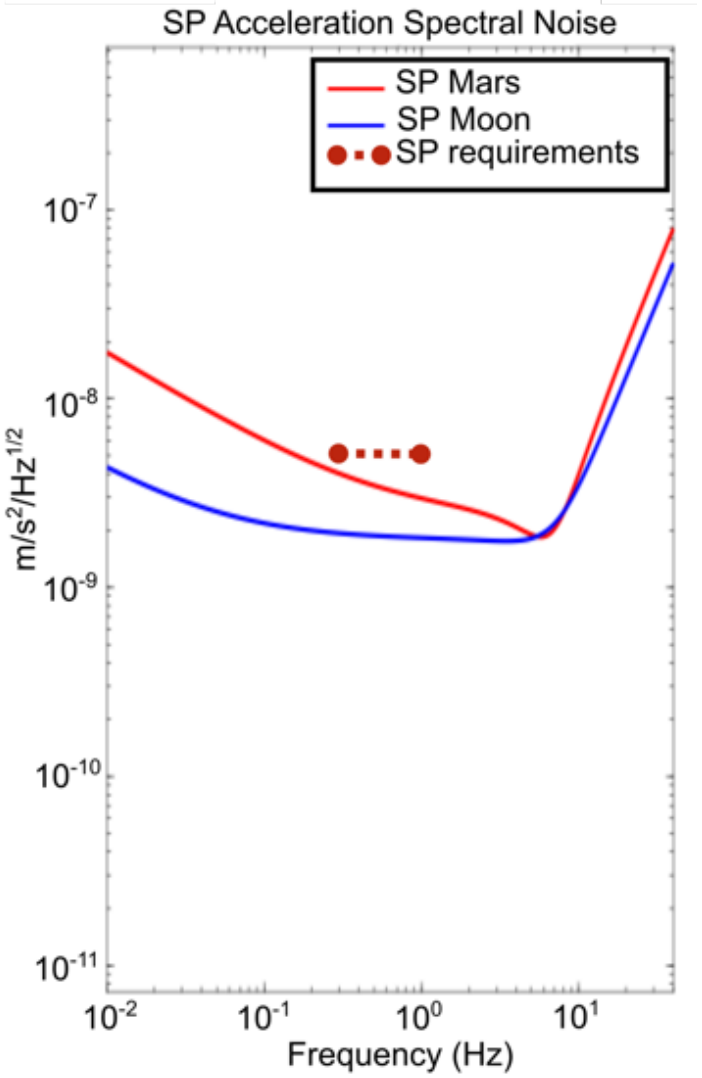
- Micromachined silicon system
- New build based on InSight heritage
- Spring adjusted for lunar gravity and changed to Galperin configuration (3 tilted components) rather than 1 vertical and 2 horizontal sensors as on InSight
- Delivered by Kinemetrics, Inc. in collaboration with Oxford University and Imperial College, London





Instrument sensitivity

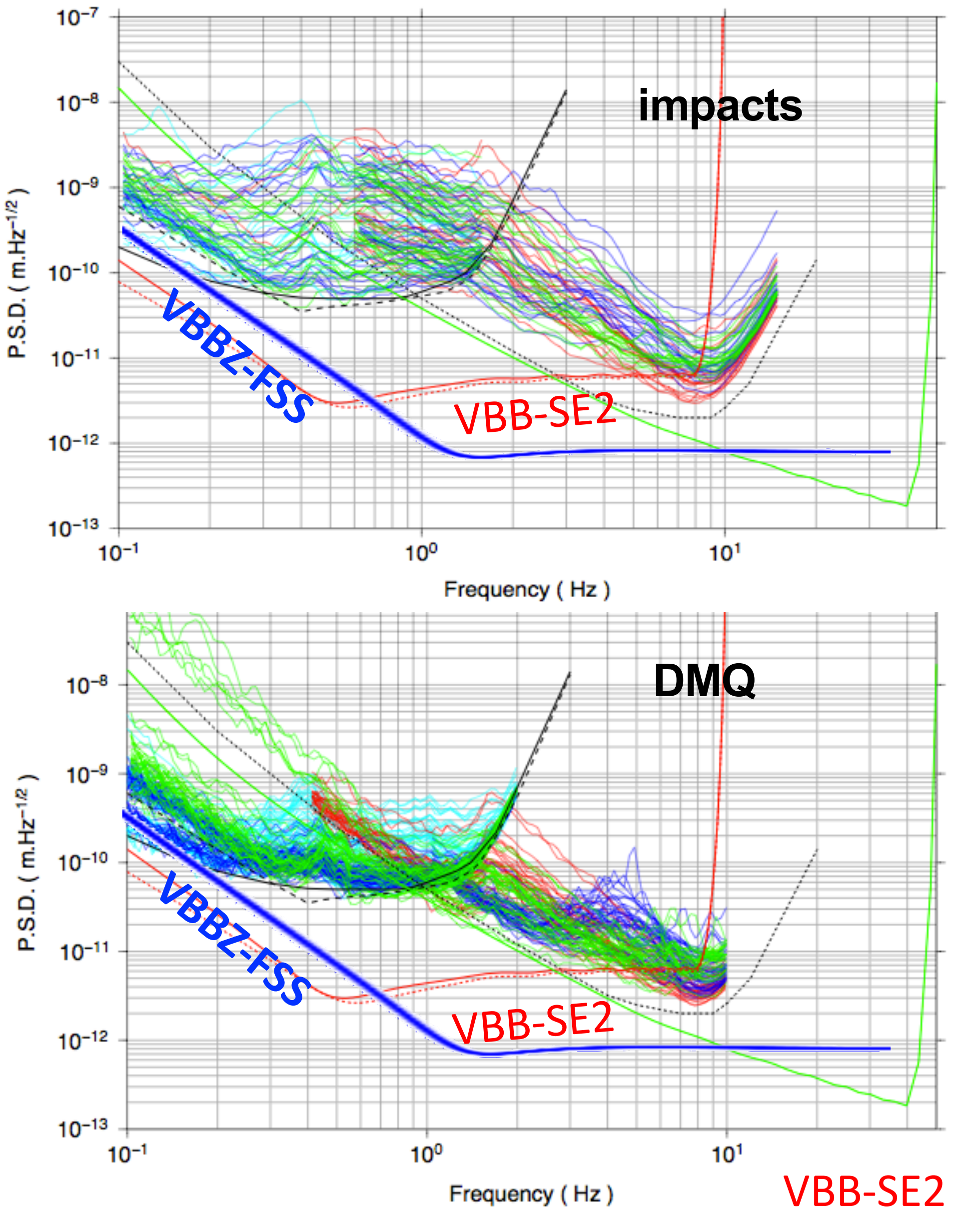




- VBBZ will be the most sensitive seismometer to land on the Moon after Apollo
- SP delivers compact and capable 3-component measurement
- Both are projected to meet the performance requirements of FSS

Instrument sensitivity: comparison with signals

- The FSS –VBBZ will explore with unprecedent sensitivity seismic waves down to 0.1 Hz
- It will however NOT be sensitive enough for exploring the long period seismic noise and signals below 0.1 Hz
- STEPS to be done by future missions, including
  - LGN with Optical VBBs
  - Future GW oriented missions…



VBB-SE2
(considered for JAXA Selen

Expected event frequency

Unknown: saturation of low events
- lower seismic efficiency (impacts)
- fault aspericities (quakes)

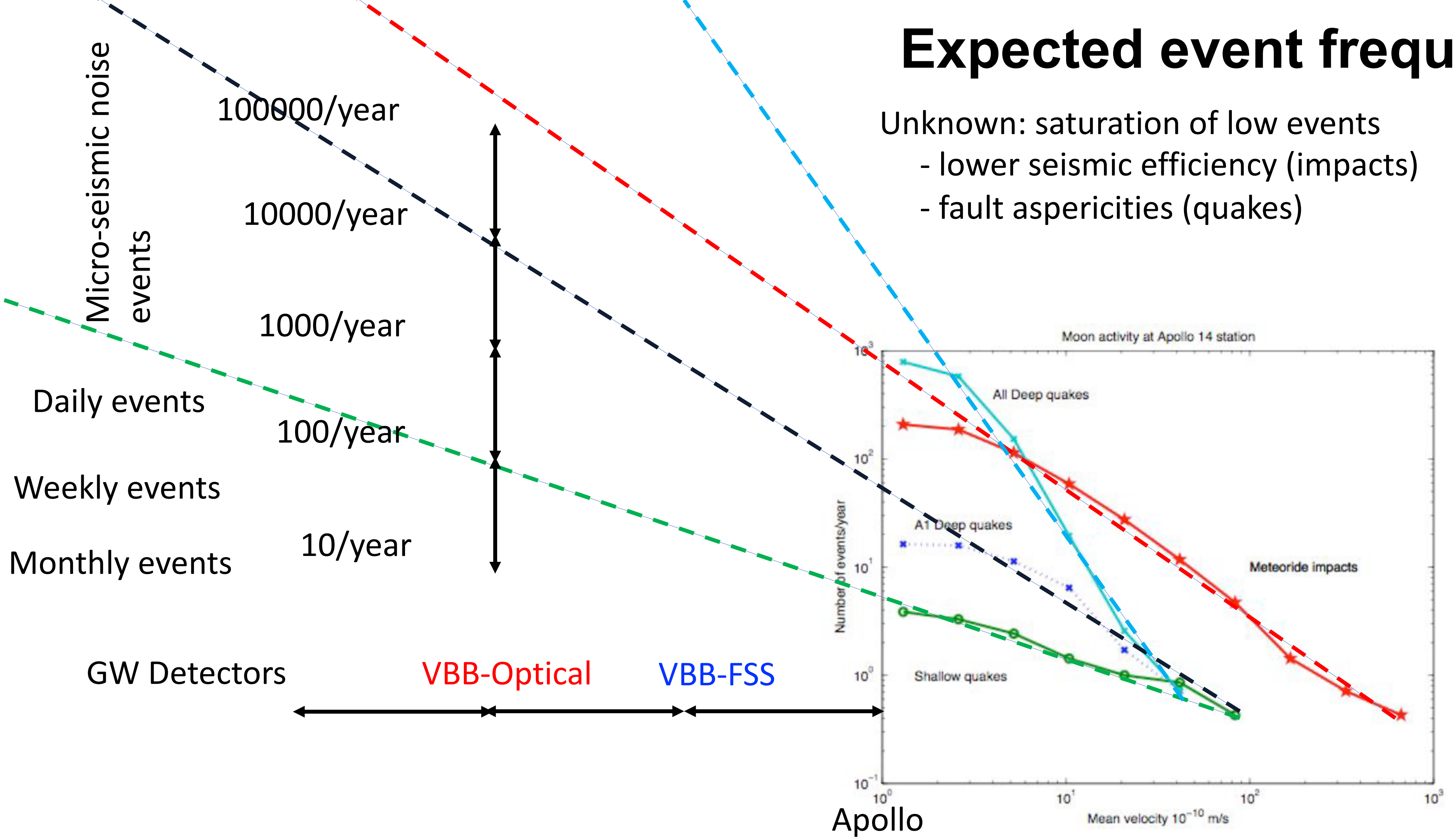
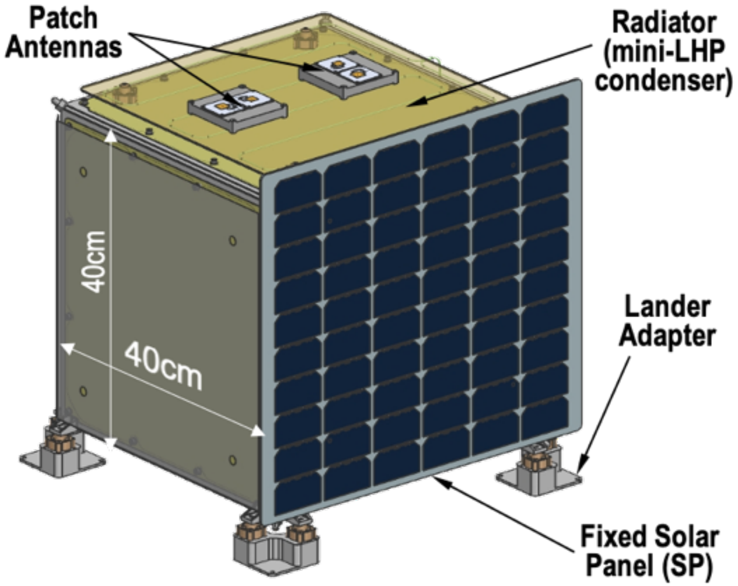


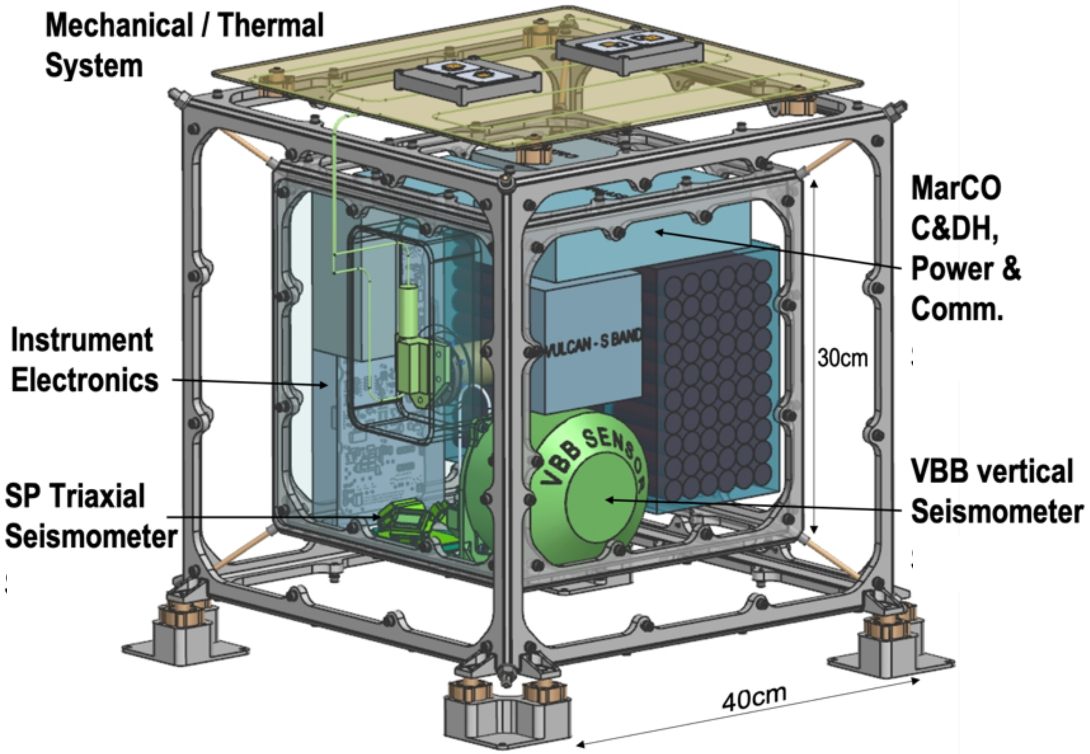
Figure 10: Number of events/year detected on the Apollo 14 station versus amplitude. Amplitudes are from the Nakamura (2004) catalogue and converted approximately as mean velocity, assuming a recording by the long-period horizontal component on the peaked mode and peaked frequency. Note the very high number of events detected, despite their very low amplitudes (See Figure 1 for seismometer sensitivity)

From Lognonné & Johnson (2015)

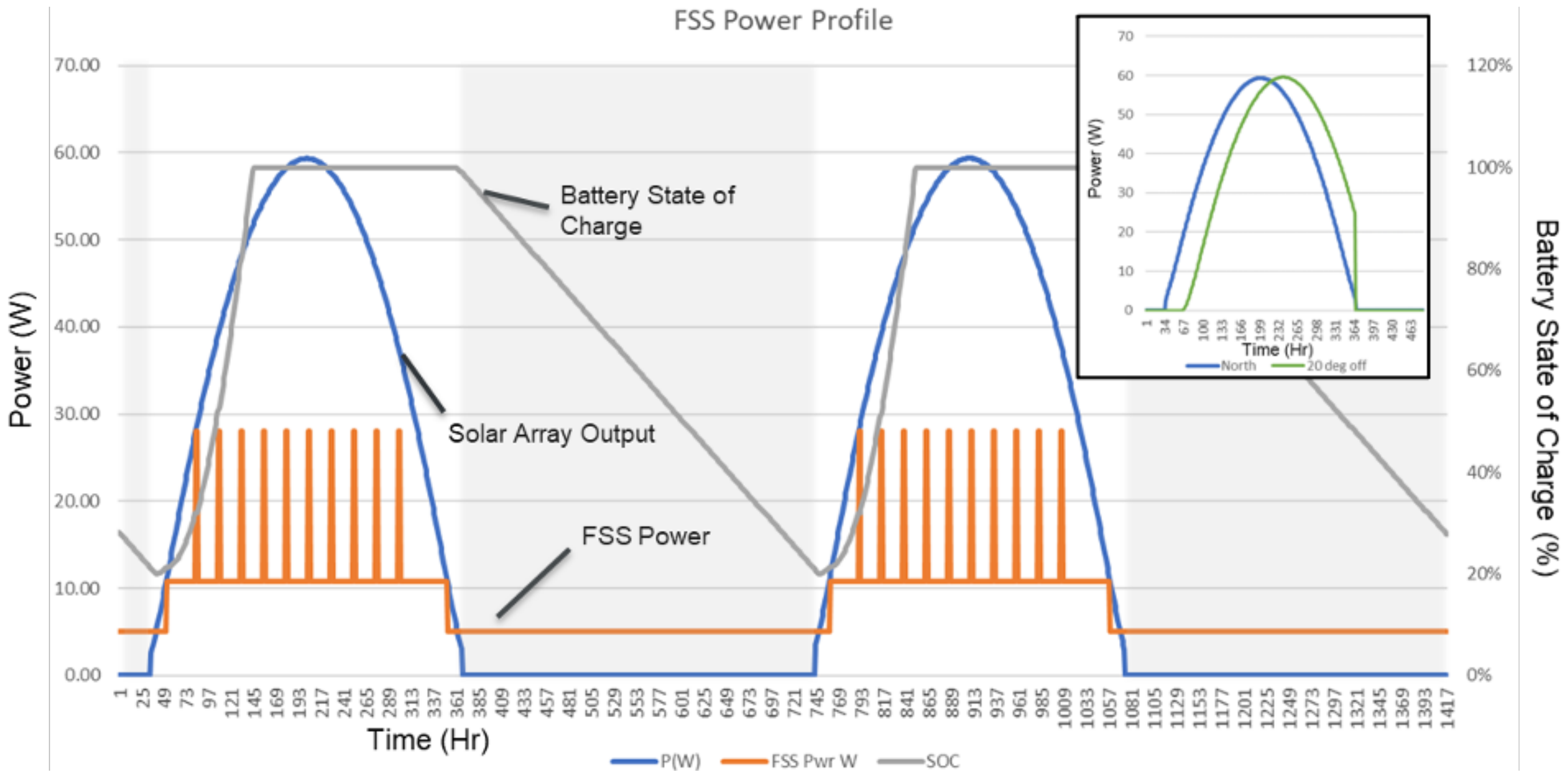
The package design

- Powered by solar panel with sufficient batteries to operate through the night
- Thermal system relies on cube within cube separated by spacerless multi-layer insulation
- Command, communications and power systems based on MarCO flight spares delivered by University of Michigan





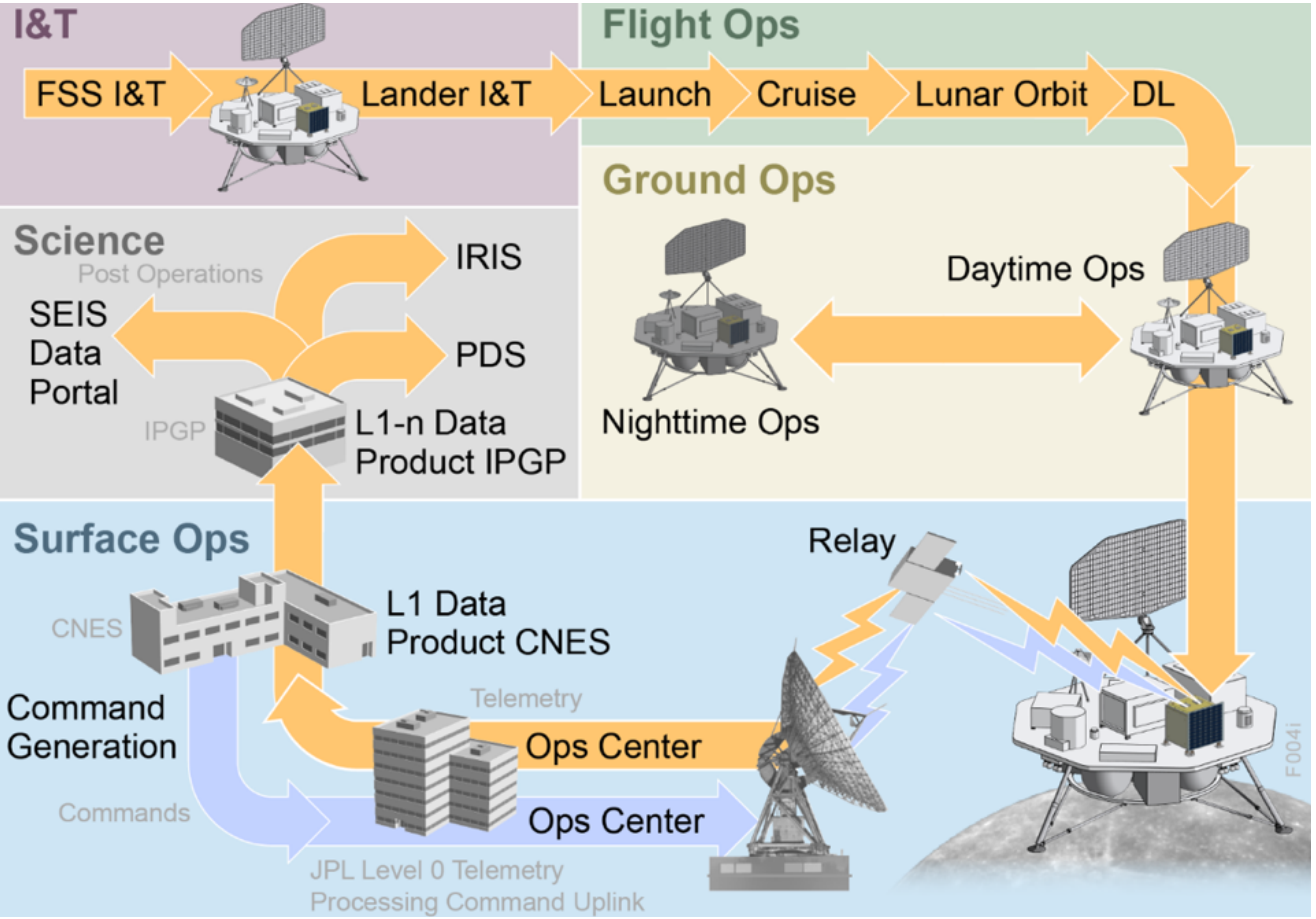
FSS Power profile



- Solar panel charges battery during the day (enough power even if misaligned by 20 degrees)
- Communications only performed during the day
- Seismometers operate continuously through the night

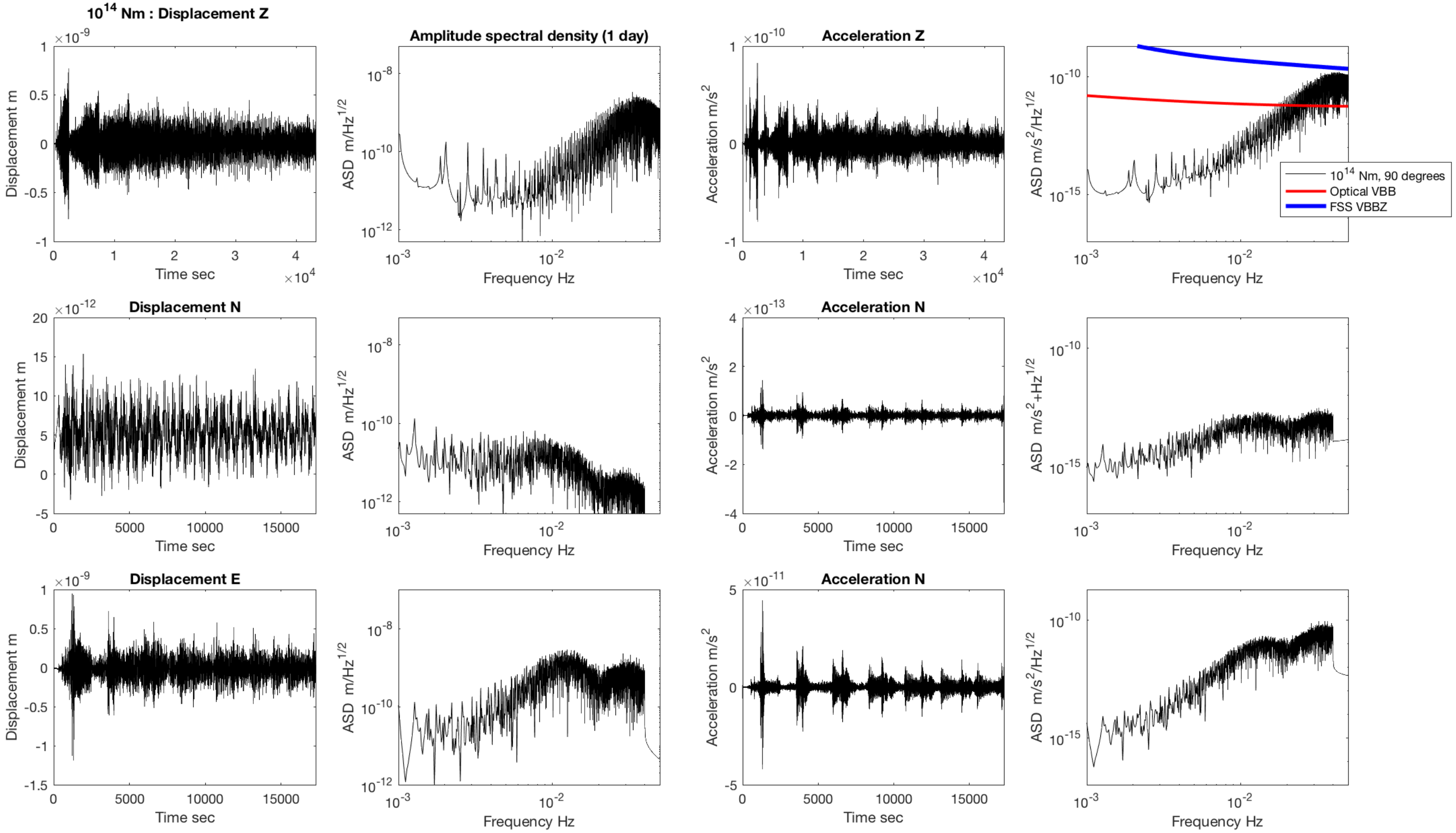
FSS Operations profile

- Operations are a joint effort between CNES/IPGP and JPL
- Communication during the day
- Nighttime data is collected and stored in data acquisition system while Command system sleeps
- Data will be distributed to community following NASA guidelines, in a similar way as SEIS on InSight

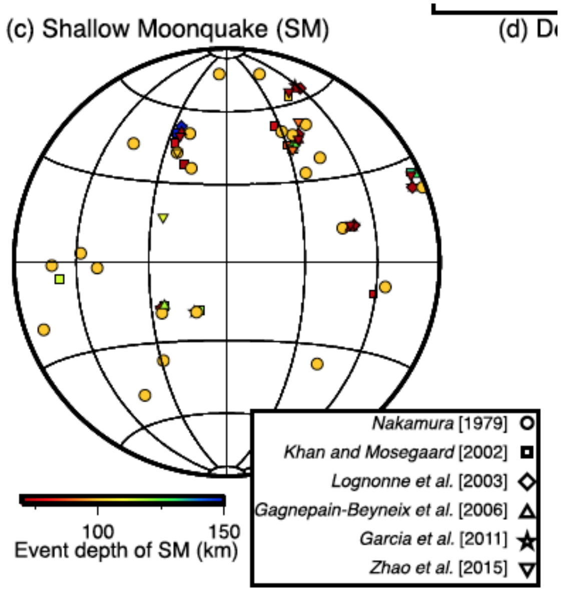


What FSS will not do: Exploring long period seismic signals

Shallow moonquake: 10^{14} Nm, 30 km prof, Δ=90°

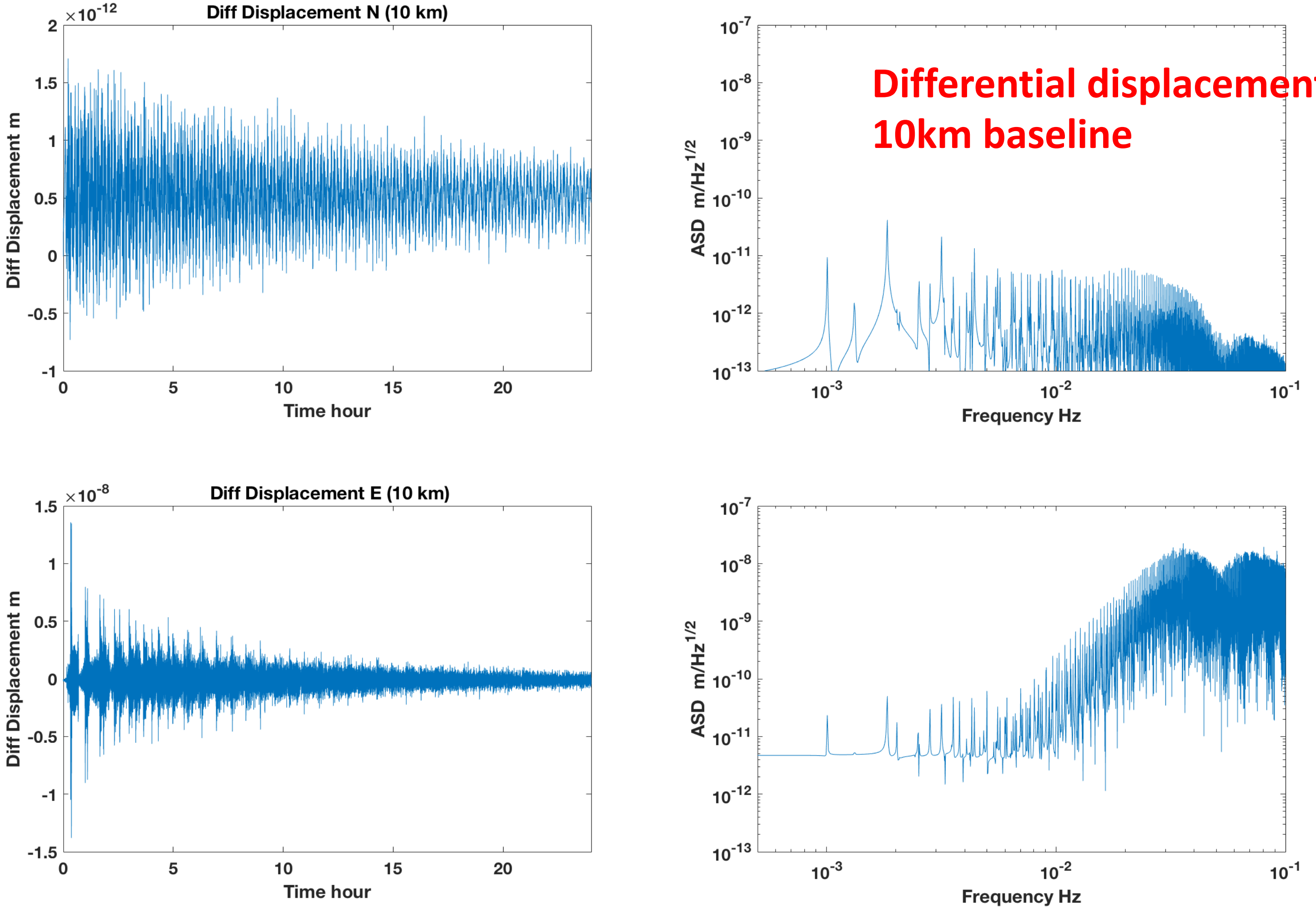


Seismic Moment Nm	Number
2.5 10^{13}	18
5 10^{13}	13
10^{14}	**9**
2 10^{14}	6
4 10^{14}	3

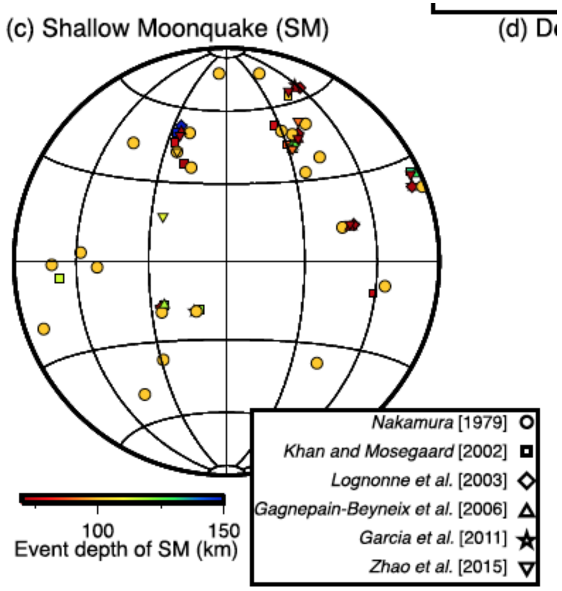


Exploring long period seismic signals: requirements

Shallow moonquake: 10^{14} Nm, 30 km prof, Δ=90°

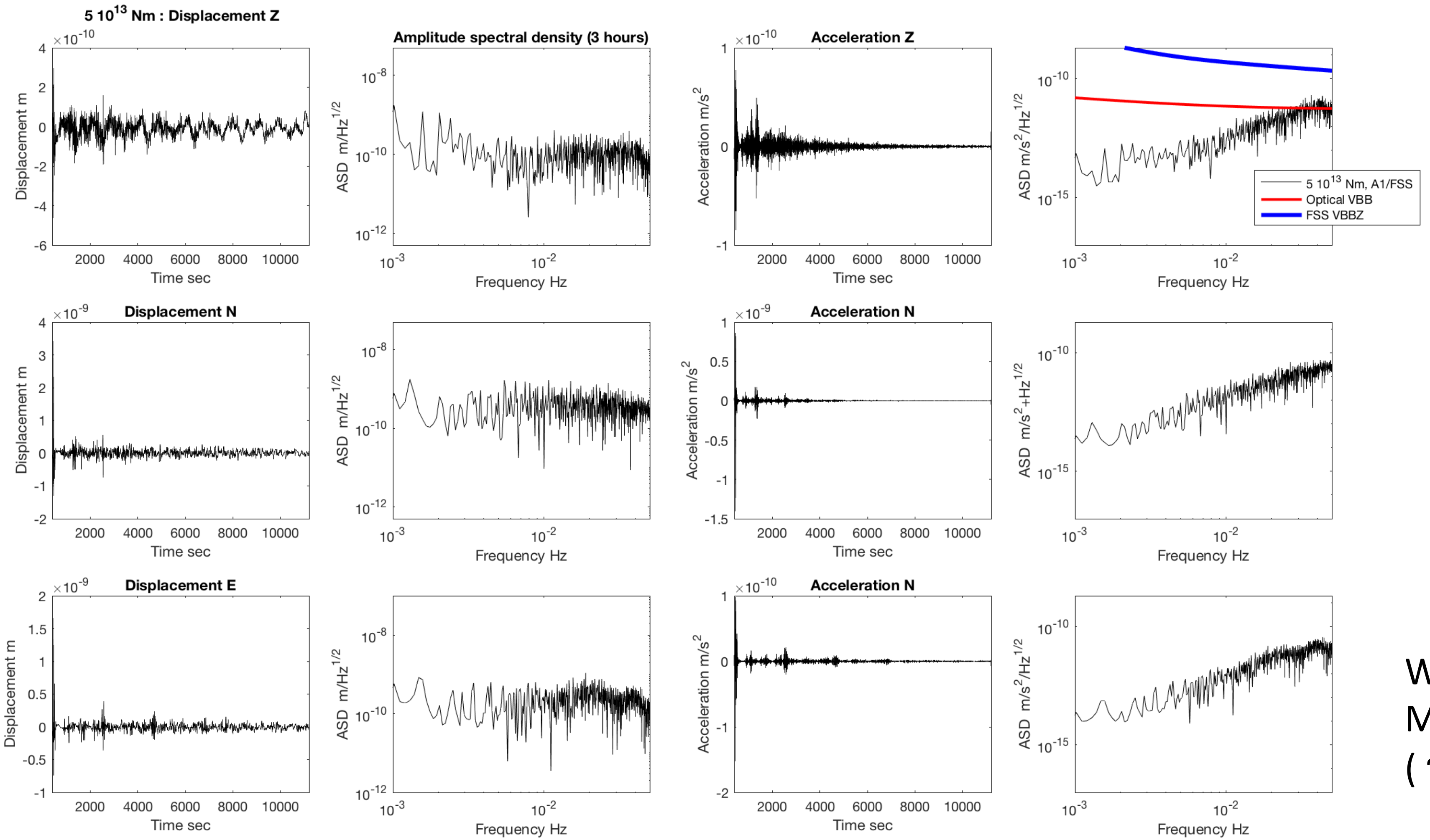


Seismic Moment Nm	Number
2.5 10^{13}	18
5 10^{13}	13
10^{14}	**9**
2 10^{14}	6
4 10^{14}	3

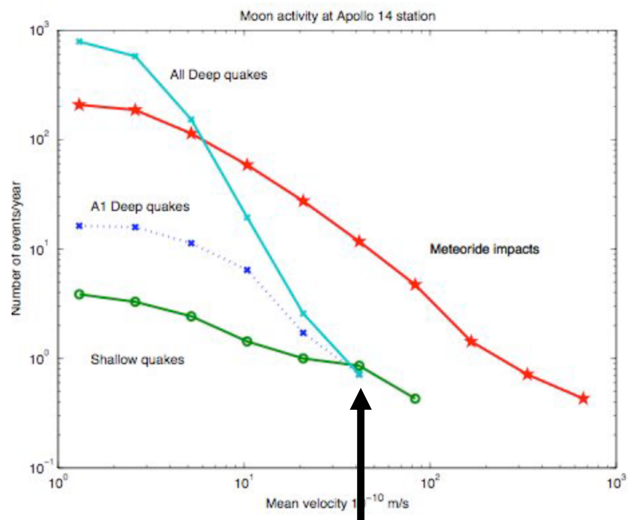


Exploring long period seismic signals: requirements

Deep moonquake: 5 10^{13} Nm, A1, FSS



Amplitude of Apollo signals



Weak A1
M ~ 5 10^{11} Nm
(~ daily event)

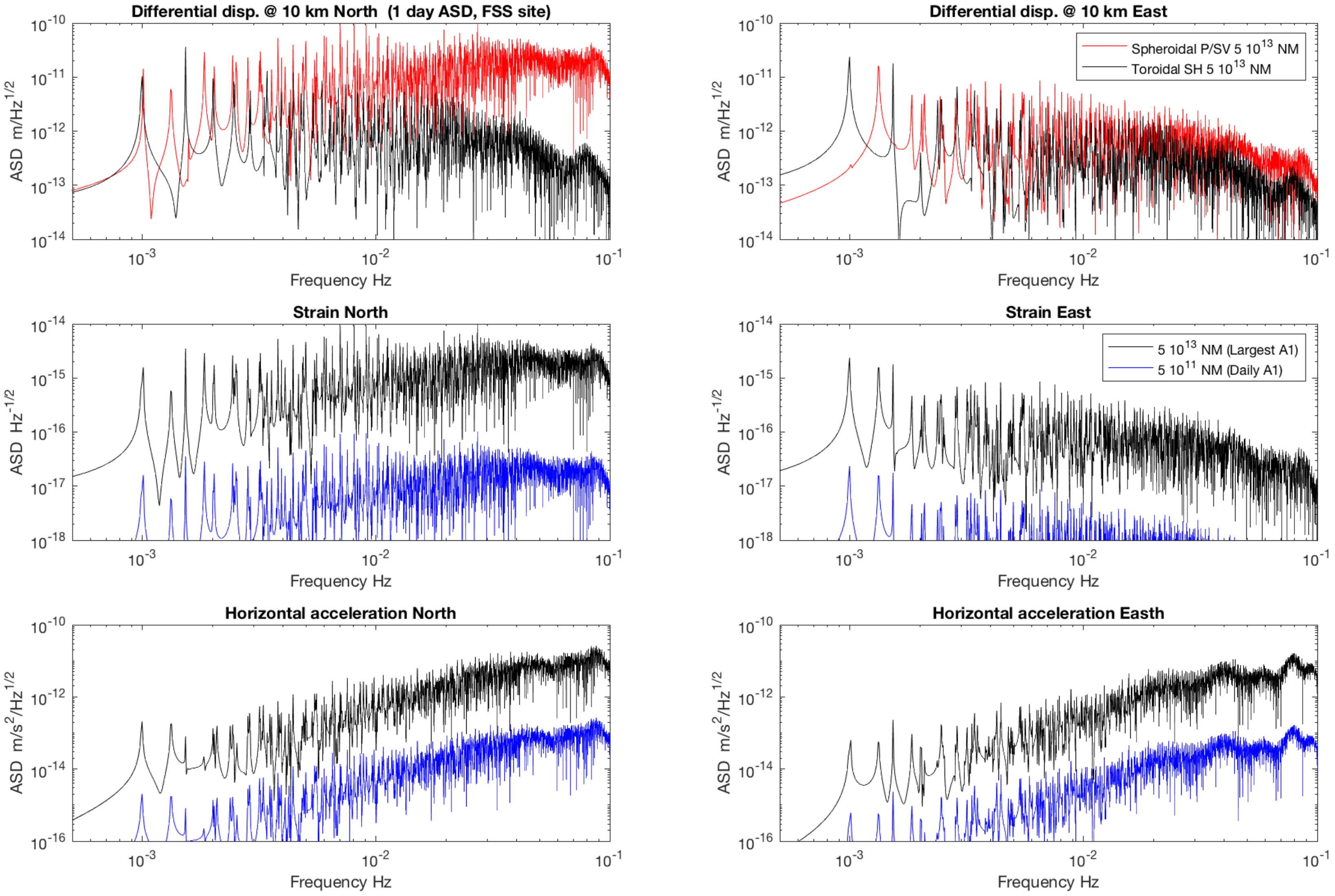
Largest A1
M ~ 7 10^{13} Nm

Exploring long period seismic signals: requirements for GW DMQ noise corrections…

Differential Displacement 510^{13} Nm
(e.g. Laser strainmeter)
Spheroidal/Toroidals

Strain 510^{13} Nm / 5 10^{11} Nm
(e.g. any strainmeter)
Full signal (Spheroidal+Toroidals)

Horizontal acceleration
510^{13} Nm / 5 10^{11} Nm
Full signal (Spheroidal+Toroidals)



Summary

- FSS will deploy in 2024-2025 an autonomous seismic package on the Moon with a VBBZ
- Performances will be more than 10x better than Apollo for body waves detection, with new findings on the internal structure and far side lunar seismicity
- Steps after FSS must integrate
  - Better performances on 3 axis instead of only vertical axis (Optical VBB, Candidate for LGN and EL3 seismic station among other)
  - Even much better performances will be required for detecting Normal modes

Summary for GW requirements

- DMQ will generate likely a noise close to 10^{-14} m/s^2/Hz$^{1/2}$ x 100f, which will be a superposition of many 10s of small DMQs
- Even if each DMQ will have a known pattern, determining the amplitude (and start time) of all these superimposing patterns might be challenging
- Geophysical science return of seismic systems compatible with GW will therefore be extremely large and will include the determination of the Lunar free oscillation spectrums