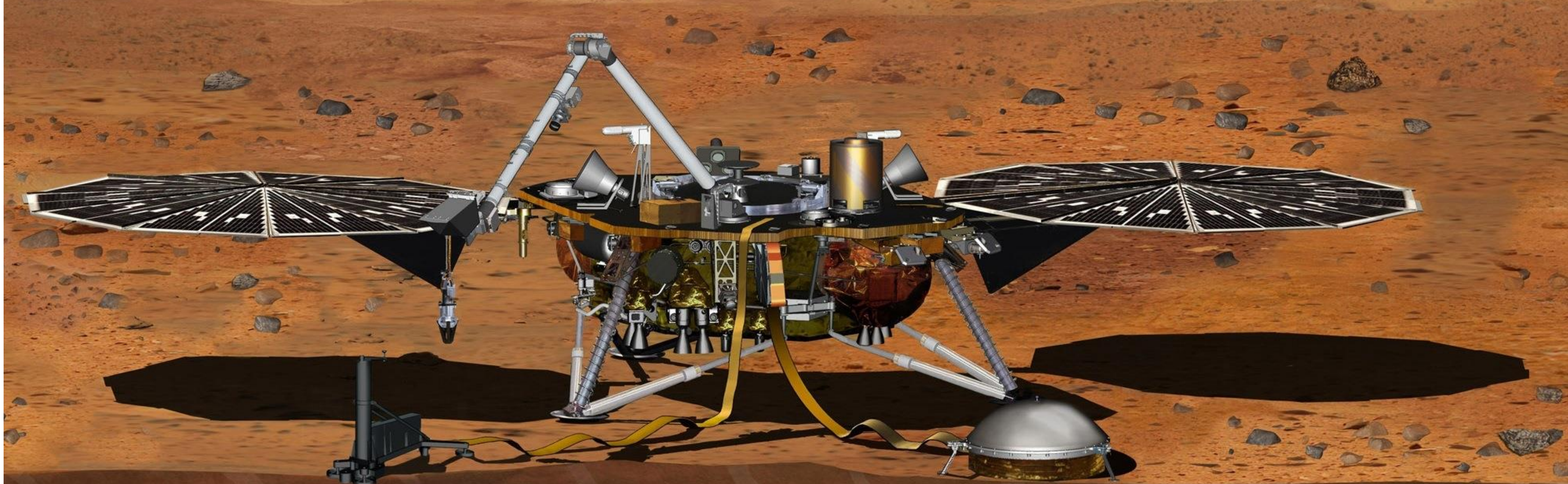
Seismometers and seismic detection techniques



P. Lognonné (1) with inputs from Bruce Banerdt (2), Tom Pike (3), David Mimoun (3), S. de Raucourt (1), H. Igel (5), J. Makela (6) and the InSight/SEIS Team.

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(6) Univ. Illinois, USA.

Seismometers and seismic detection techniques

- Planetary seismometers: From Apollo to InSigh
- Noise and signal of a seismometer
- Building a seismic station: The InSight SEIS Requirement flow
- The next generation to the Moon: How sensitive?
- Alternatives to ground seismometers
  - Venus Seismology Airglow imaging
  - Lunar Seismology from orbit

Principle of a seismometer

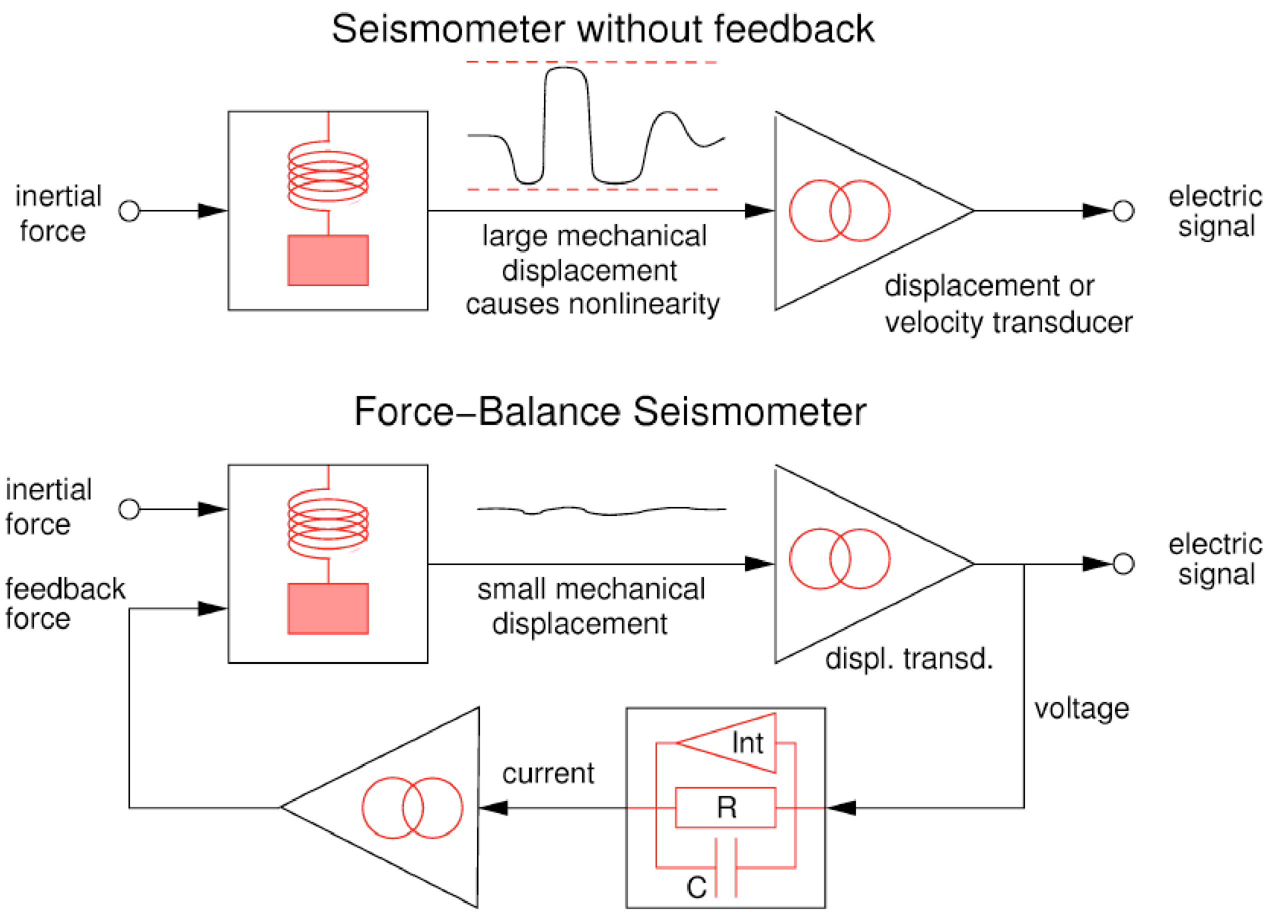


Figure 1: Block diagrams of conventional and feedback seismometers. Ideally, in the feedback configuration, the mechanical suspension and the displacement transducer “don’t see” the full amplitude of the ground motion, which is present only in the feedback path..

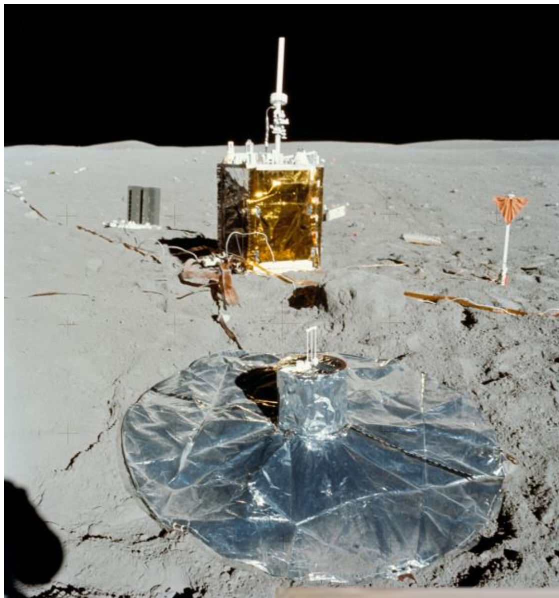
Geophone:
Ranger
Apollo ALSEP SP
Viking
OPT (Mars96)
Lunar A

Force Feedback:
Apollo LP
InSight SP
InSight VBB

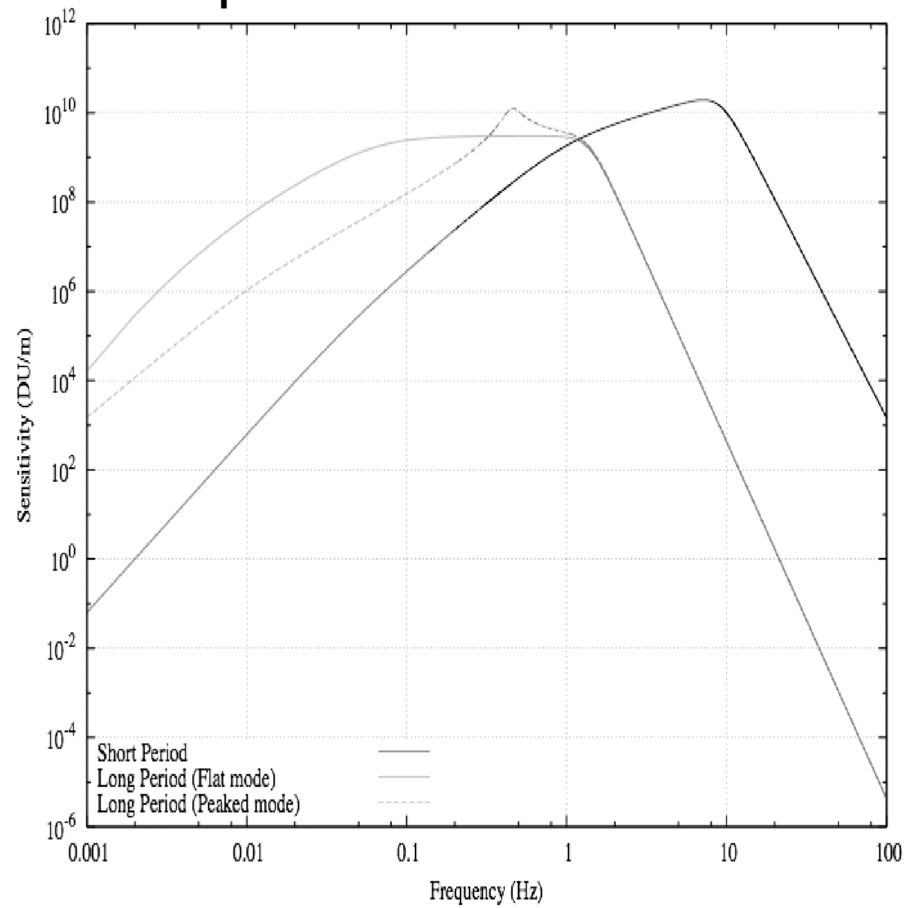
after E.Wielandt

Apollo ALSEP

- Apollo ALSEP seismometers, likely more advanced than those working on Earth in the 70th

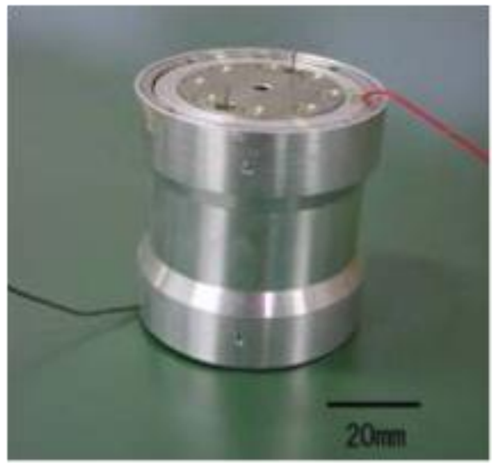


- ~11.5 kg (sensors, made mostly in Beryllium
- Many feature simple due to man installation



Lunar A: example of Modern Geophone

- Lunar A Geophone
- A very robust geophone designed for Lunar penetrators
- Very low power due to simple electronics



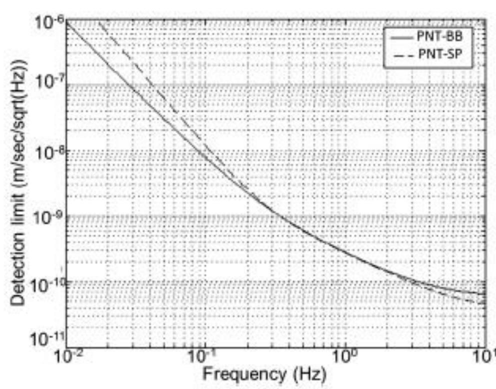


Fig. 8. Detection limits of the PNT-SP and the PNT-BB in terms of velocity as amplitude spectral density (ASD).

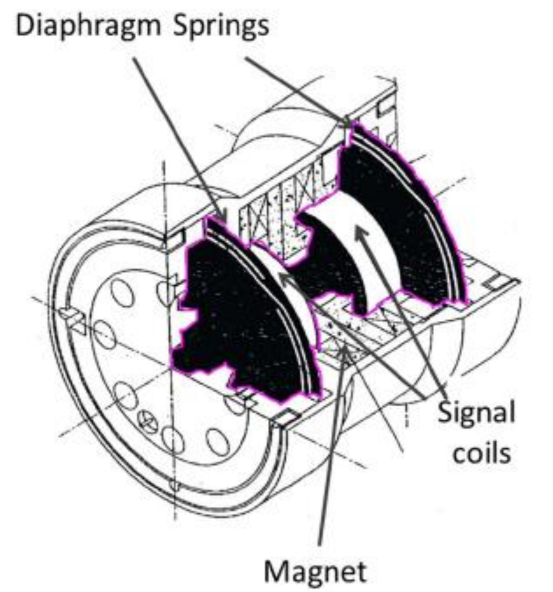


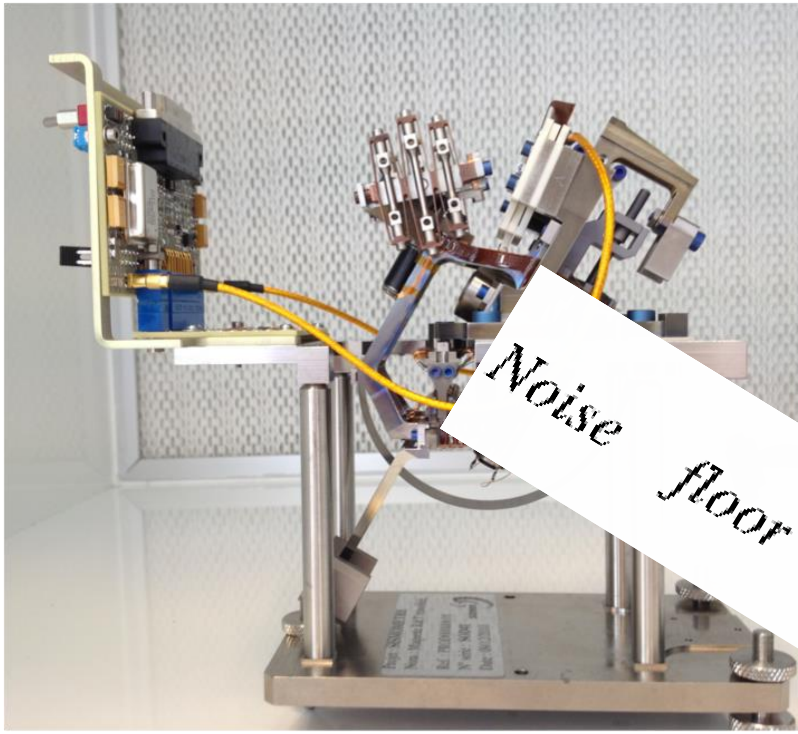
Fig. 2. A perspective view of the short-period seismometer for the penetrator.

Table 2
Specification of the short-period sensor for the penetrator.

Sensor Type	Electromagnetic sensor
Resonant frequency	1.0–1.2 (Hz)
Damping constant	0.6–0.7
Generator constant	1050–1100 (Volt/(m/s))
Size	Diameter: 5 (cm) × height: 5 (cm)
Mass	0.350 (kg) (Pendulum 0.046 (kg))

Yamada et al, 2015

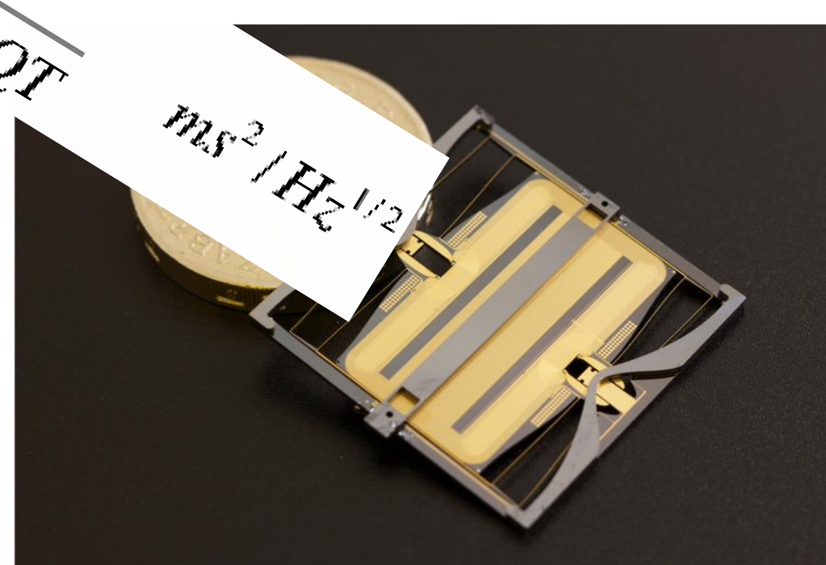
InSIght sensor heads : example of Feedback seismometers



- InSIght VBB (LP) instrument
- 190 gr of proof mass
- Period of 2 sec
- Noise floor of 2 x 10^{-10} m/s^2/Hz$^{1/2}$
- ~3 kg for the 3 axis Sphere
- Q > 100 in vacuum

$$\text{Noise floor} = \sqrt{\frac{10^{-19}}{mQT}}\ ms^{-2}/Hz^{1/2}$$

- InSIght SP instrument
- ~0.85 gr of proof mass
- Period of ~0.2 sec
- Noise floor of 3 x 10^{-9} m/s^2/Hz$^{1/2}$
- ~ 450 gr for the 3 axis boxes
- Q ~100



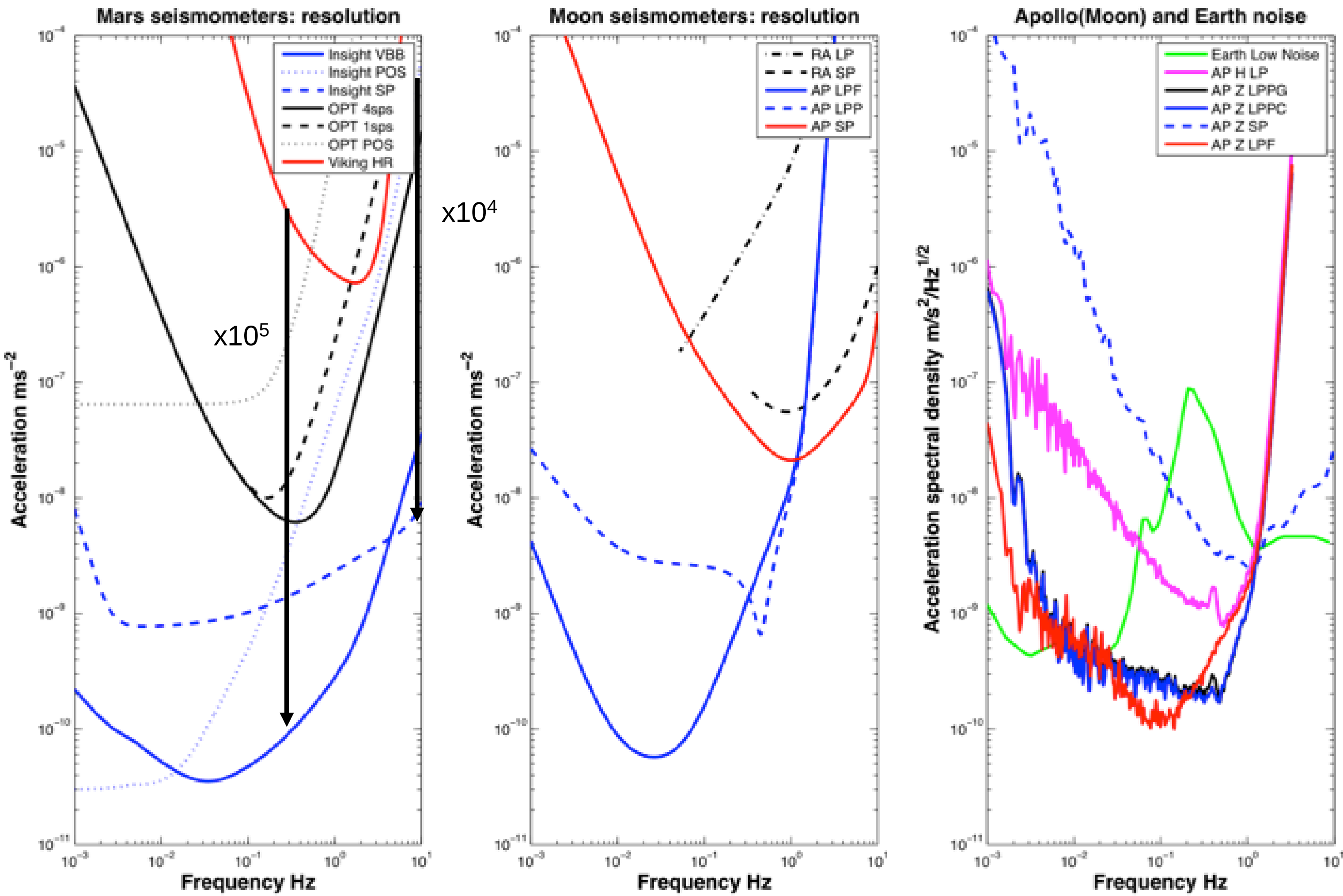
Lognonné & Pike, 2015

Seismometer performances evolution

Resolution for InSight =
rms in 1/6 bandwidth
A/D resolution smaller due to 24 bits…

Resolution for Apollo =
A/D resolution due to 11 bits
rms noise smaller in peaked mode

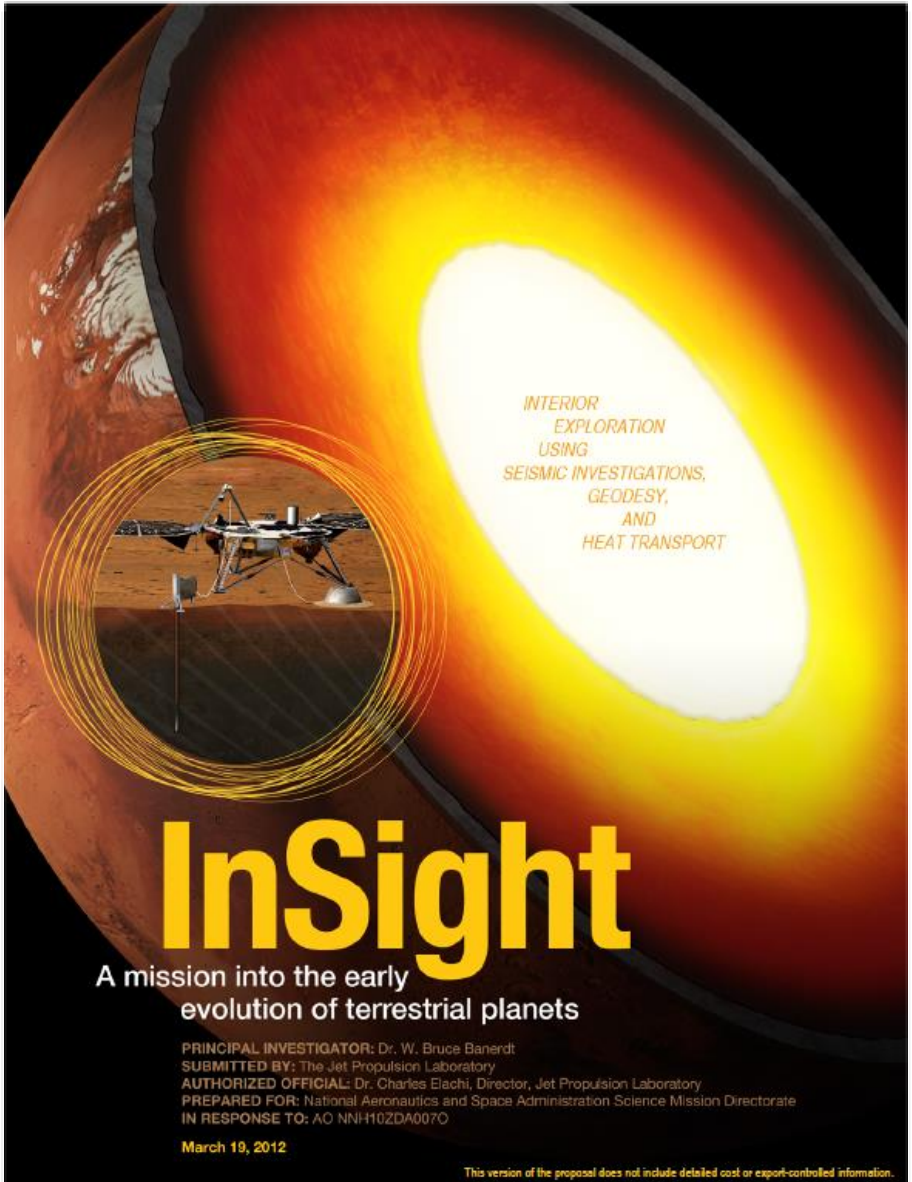
Lognonné & Pike, 2015



Presentation outline: Seismometers and seismic detection techniques

- Planetary seismometers: From Apollo to InSigh
- Noise and signal of a seismometer
- How sensitive ?
- **Building a seismic station: The InSight SEIS Requirement flow**
- Alternatives to ground seismometers
  - Seismology Airglow imaging
  - Seismology from orbit

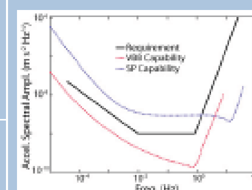
InSight… Birth of the mission



- **Mission**
  - selected by NASA as mission discovery 12 (August 2012)
  - Big proposal ~800 pages in step II
  - Launch initially planned in March 2016 for an arrival in late September 2016
  - Leak detected in the Flight model Evacuated Sphere in summer 2015
  - Repair path was unable to fix the leak, leading to the postponement of the launch to 2018
  - Mission confirmed by NASA by end of August, 2016
  - Launch planned in May 2018 for an arrival in November 2018

High Level Science Goals in words and numbers

Table FO1-1. Science traceability matrix (AO Table B1).

Science Goals	Science Objectives	Scientific Measurement Requirements: Observables	Scientific Measurement Requirements: Physical Parameters	Instrument Performance Requirements		Projected Performance	Mission Requirements (Top Level)	Instrument
Understand the formation and evolution of the terrestrial planets through investigation of the interior structure and processes of Mars	Determine the size, composition and physical state of the core	Time variation of planetary rotation vector magnitude and orientation	Radial distribution of mass and shear modulus (indicating solid vs. liquid)	Two-way Doppler acceleration resolution	0.1 mm/s² with 10-second averaging	< 0.1 mm/s² with 10-second averaging	60 minutes of 2-way X-band DTE tracking per week over at least ½ Mars year = 334 sols	RISE
		Tidally induced displacement of planetary surface	Gravimetric factor γ_2; Radial distribution of mass and shear modulus	Vertical ground acceleration sensitivity at 0.05 mHz	10^{-7} m/s²/Hz$^{1/2}$	0.05 mHz: 10^{-8} m/s²/Hz$^{1/2}$	Near-continuous seismic measurement at 0.1 sps for ≥⅓ Mars year	SEIS
		Seismic phase arrival times (e.g., P, S, PcP, PKP, etc.)	Core radius; mantle and core seismic velocities	3-D ground acceleration sensitivity at 0.1–5 Hz	0.1–1 Hz: 10^{-9} m/s²/Hz$^{1/2}$ 1–5 Hz: $f^2 \times 10^{-9}$ m/s²/Hz$^{1/2}$		Place seismometer on the martian surface. Support near-continuous seismic measurement for one Mars year with selected sampling from 2 to 50 sps (compression acceptable for >2 sps data)	SEIS
	Determine the thickness and structure of the crust	Cross-correlation of vertical and horizontal components of ground displacement	Receiver function; Crust thickness, layering, and seismic velocities					
		Seismic phase arrival times (e.g., P, PmP, S, SmS, etc.)	Crust thickness, layering, and seismic velocities					
		Seismic phase arrival times and event distance (from P–S)	Seismic velocities as a function of depth					
		Arrival time of surface wave energy vs. frequency	Group velocity dispersion; Seismic velocities in crust and upper mantle, depth to crust-mantle boundary	3-D ground acceleration sensitivity at 0.01–0.1 Hz	10^{-9} m/s²/Hz$^{1/2}$			
	Determine the composition and structure of the mantle	Arrival time of surface wave energy vs frequency						
		Seismic phase event distance (from P–S interval)	Seismic velocities as a function of depth	3-D ground acceleration sensitivity at 0.1–5 Hz	0.1–1 Hz: 10^{-9} m/s²/Hz$^{1/2}$ 1–5 Hz: $f^2 \times 10^{-9}$ m/s²/Hz$^{1/2}$			
		Normal mode eigenfrequencies from quakes or background	Seismic velocities as a function of depth	Vertical acceleration at 1–10 mHz	$f^{-1/2} \times 10^{-10}$ m/s²/Hz$^{1/2}$			
	Determine the thermal state of the interior	Temperature profile in the near-subsurface Transient thermal response to external heat inputs	Heat flux from the interior Thermal conductivity of near-subsurface	Temperature and depth measurement precision, total depth interval	T: ± 0.05 K Depth: within 5% Depth interval: 2 m	T: ± 0.005 K Depth: within 2% Depth interval: 5 m	Place HP³ on the martian surface. Support periodic (1/hour) thermal measurements for one Mars year	HP³
Determine the present level of tectonic activity and meteorite impact flux on Mars	Measure the rate and geographical distribution of seismic activity	Ground vibration from remote fault displacement (amplitude and P and S arrival times)	Number, size and location of seismic events	3-D ground acceleration sensitivity at 0.1–20 Hz	0.1–1 Hz: 10^{-9} m/s²/Hz$^{1/2}$ 1–20 Hz: $f^2 \times 10^{-9}$ m/s²/Hz$^{1/2}$	See plot above.	Place seismometer on the martian surface. Support near-continuous seismic measurement for one Mars year at 2 to 50 sps (compression and sub-sampling acceptable)	SEIS
	Measure the rate of meteorite impacts on the surface	Ground vibration from meteorite impact (amplitude and P and S arrival times)	Number, size and location of impact events					

High Level Science Goals in requirements

Table E.4.2-1. Instrument capability margins exist to meet all L1 science requirements. Additional, unallocated science margins exist above the L1 requirements relative to answering the fundamental scientific questions ("Science Need;" Table E.4.3.1-1).

L1 Requirement	L2 Requirement	Capability	Margin
L1-SCI-41 Determine the depth of the crust-mantle boundary to within ±10 km	L2-PSRD-191: Measure Rayleigh wave group velocity dispersion to ±5% for at least 2 quakes with SNR≥3 on R3 wavetrains.	13 quakes or SNR=40	550% (quakes) 1200% (SNR)
L1-SCI-42 Detect velocity contrast ≥0.5 km/sec over depth interval ≥5 km within the crust, if it exists.	L2-PSRD-192: Measure group velocity dispersion to ±4% for at least 3 quakes with SNR≥3 on R3 wavetrains.	13 quakes or SNR=35	330% (quakes) 1000% (SNR)
L1-SCI-43 Determine seismic velocities in the upper 600 km of the mantle to within ±0.25 km/sec.	L2-PSRD-193: Measure P and S arrival times to ±2 sec, and R1 and R2 arrival times to ±15 sec for at least 13 quakes.	30 quakes or SNR=16	200% (quakes) 430% (SNR)
L1-SCI-45 Positively distinguish between liquid and solid outer core*	L2-PSRD-205: Measure the Phobos tide amplitude to $\pm 2.5\times10^{-11} m/s^2$.	$\pm 7\times10^{-12} m/s^2$	250%
	L2-PSRD-196: Determine the free core nutation period to ±15 days.	±7 days	115%
L1-SCI-46 Determine the radius of core to within ±200 km†	L2-PSRD-206: Measure the Phobos tide amplitude to $\pm 3.3\times10^{-11} m/s^2$.	$\pm 7\times10^{-12} m/s^2$	370%
	L2-PSRD-195: Determine the core moment of inertia to ±2.0% of the total MOI.	±1.1%	80%
L1-SCI-47 Determine core density to within $\pm 450 kg/m^3$	L2-PSRD-195: Determine the core moment of inertia to ±2.0% of the total MOI.	±1.1%	80%
L1-SCI-49 Determine the heat flux at landing site to within $\pm 5 mW/m^2$	L2-PSRD-197: Measure the thermal gradient to ±35 mK/m.	±20 mK/m	75%
	L2-PSRD-198: Measure the thermal conductivity to ±7.1 mW/m·K.	±4.3 mW/m·K	65%
L1-SCI-50 Determine the rate of seismic activity to within a factor of 2.	L2-PSRD-199: Measure marsquake signals of P-wave amplitude $\geq 6\times10^{-9} m/s^2$ with SNR≥3.	SNR=6 ½ Mars year	100% (SNR) 100% (duration)
L1-SCI-51 Determine epicenter distance to ±25 % and azimuth to ±20 degrees.	L2-PSRD-200: Measure the horizontal components of P-wave signals from 10^{15} Nm quakes with a SNR of ≥20.	SNR=100 @ $10^{-9} m/s^2/Hz^{1/2}$	400%
	L2-PSRD-201: Detect P and S-wave signals from 10^{15} Nm quakes at distances up to 110° with SNR≥3.	5×10^{14} Nm @ $10^{-9} m/s^2/Hz^{1/2}$	100%
L1-SCI-52 Determine the rate of meteorite impacts to within a factor of 2.	L2-PSRD-202: Measure the seismic signals from meteorite impacts of P-wave amplitudes $\geq 3\times10^{-9} m/s^2$ with SNR≥3.	SNR=4 ⅔ Mars year	33% (SNR) 50% (duration)

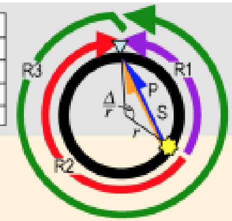
** L1-SCI-45 independently met by L2-PSRD-196 and L2-PSRD-205.* *† L1-SCI-46 independently met by L2-PSRD-195 and L2-PSRD-206.*

Requirements down to the Instruments details…

Discovery 2010, Step 2: AO NNH10ZDA007O InSight F—Science Implementation FOLDOUT 3: Requirements Flow Down: SEI

Driving SEIS L1-L4 Requirements Flow

SEIS L1 requirements for mantle velocity and core state drive the instrument design



Level 1

L1-SCI-45: Liquid vs solid core	
Current Knowledge	Probably liquid
Requirement	Positive determination
Capability	Positive determination
Margin	N/A

L1-SCI-43: Seismic velocities in the upper 600 km of mantle	
Current Knowledge	V_p~8±1 km/s; V_s ~1.5±0.5 km/s
Requirement	∂V_p = ±250 m/s, ∂V_s = ±250 m/s
Capability	∂V_p = ±130 m/s; ∂V_s = ±90 m/s
Margin	90% on velocity

Level 2

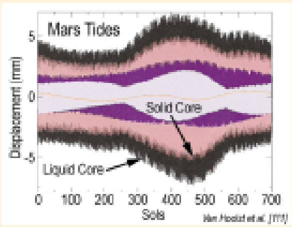
L2-PSRD-205: Measure Phobos Tide Amplitude	
Requirement	Vertical ±2.5x10^{-11} m/s^2 at 0.06 mHz for 1 Mars year of stacking
Capability	7x10^{-12} m/s^2 in 1 Mars year (1.5x10^{-11} m/s^2 in ½ Mars year)
Margin	250% for 1 Mars year (67% for ½ Mars year)

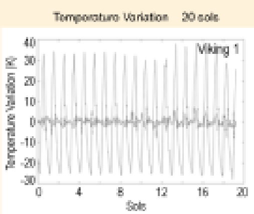
L2-PSRD-193: Measure P, S, R1, R2 arrival times for number of quakes	
Requirement	T_p, T_s to ±2 s; T_{R1}, T_{R2} to ±15 s 13 quakes (SNR3)
Capability	T_p, T_s to ±1 s; T_{R1}, T_{R2} to ±8 s 26 quakes (SNR 3), 1 Mars year (90% conf.) 13 quakes (SNR 16), 0.55 Mars year (90% conf.)
Margin	100% on Arrival Timing 130% on # of quakes, 430% on SNR, 80% on duration

P and S Velocity Determination	
Obtain 4 measurements: T_p, T_s, T_{R1}, T_{R2} • V_R is known from analysis of R3-R1 arrivals (L1-SCI-41) • $V_R = 2\pi r/(T_{R3}-T_{R1})$; $\partial V_R/V_R$ = 0.5%	Determine 4 unknowns: V_p, V_s, Δ, T_0 • $\Delta = \pi r - V_R(T_{R2}-T_{R1})/2$ • $T_0 = T_{R1} - \Delta/V_R$ • $V_p = 2r\sin(\Delta/2r)/(T_p-T_0)$ • $V_s = 2r\sin(\Delta/2r)/(T_s-T_0)$

$$\partial\Delta = 0.5\{(T_{R2}-\partial T_{R1})^2\,\partial V_R^2 + V_R^2(\partial T_{R2}^2+\partial T_{R1}^2)\}^{1/2}$$
$$\partial V_p/V_p = \{(\partial T_p^2+\partial T_0^2)/(T_p-T_0)^2 + \partial\Delta^2/[2r\tan(\Delta/2r)]^2\}^{1/2}$$
$$\partial V_s/V_s = \{(\partial T_s^2+\partial T_0^2)/(T_s-T_0)^2 + \partial\Delta^2/[2r\tan(\Delta/2r)]^2\}^{1/2}$$

Phobos tide is superimposed on the larger solar tide. Solar tide is not observable, as it is swamped by the noise from diurnal temperature variation at 1-sol period. But Phobos period is not synchronous with any diurnal temperature overtones.





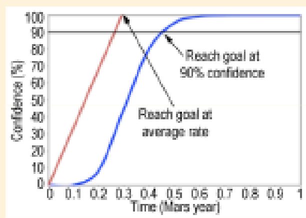
Mars Gravity Tides	
Sun	Amplitude: 5x10^{-8} m/s^2 Frequency: 22.6 μHz
Phobos	Amplitude: 4.5x10^{-9} m/s^2 Frequency: 0.05 mHz
Deimos	Amplitude: 0.5x10^{-9} m/s^2 Frequency: 8.5 μHz

Decrease errors ($N^{-1/2}$) or increase resolution by incorporating more quakes in solution

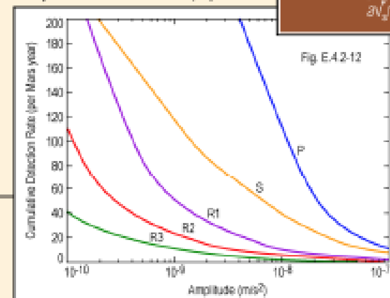
Apply Poisson distribution to determine time for 90% confidence of required number of events in random process

Nominal Values	
V_p	8 km/s
V_s	4.5 km/s
V_R	4 km/s
Δ	60 deg.

Average rate of P, S R1, R2 Detections



Signal detectability based on expected seismic activity and modeled transmission properties



Frequency Bands	
Body Waves	0.1 – 1 Hz
Surface Waves	20 – 40 mHz

Fraction of Time Lost to Noise: <30% for P, S <10% for R1, R2, R3

Noise values given as frequency-band center values for illustration. Full noise analysis considers frequency dependence.

System Noise, SNR

Mars Environment		
Wind Speed	≤3.4 m/s 70% of time ≤5 m/s 90% of time	Max. 60 m/s
Surface Temp Range	Min = 170 K	Max = 270 K
Mean Temp. Amplitude	Diurnal = 55 K	Annual = 20 K
Mean Press. Amplitude	Diurnal - 10-40 Pa	Annual = 120 Pa

Level 3

Residual Thermal Noise at 0.05 mHz	
Requirement	5 mK RMS
Capability	0.5 mK RMS
Margin	900%

Sampling Frequency	
Requirement	2 Hz
Capability	20 Hz
Margin	900%

Vertical Noise (m/s^2/√Hz) from 0.01-1 Hz	
Requirement	1x10^{-9}
Capability	5.6x10^{-10}
Margin	90%

Fig. F.3.1-4b

Fig. F.3.1-4a

Horizontal Noise (m/s^2/√Hz) from 0.1-1 Hz	
Requirement	1x10^{-9}
Capability	6.7x10^{-10}
Margin	50%

Flag compromised data during periods of high environmental noise (i.e., large wind, pressure, or thermal fluctuations).

Driving Level 4

Wind & Thermal Shield / Aerogel Thermal Blanket

Attenuated Thermal Noise from 0.01-1 Hz	
Rqmt.	1x10^{-10}
Cap.	<<1x10^{-12}
Margin	>>1000%

Attenuated Wind Noise from 0.01-1 Hz	
Rqmt.	V: 1x10^{-10}; H: 2x10^{-10}
Cap.	V: 1x10^{-11}; H: 4x10^{-11}
Margin	V: 900%; H: 400%

Thermal Attenuation at 0.05 mHz	
Rqmt.	8x
Cap.	29x
Margin	260%

Survival Wind Speed	
Rqmt.	60 m/s
Cap.	80 m/s
Margin	33%

Environmental Pressure Fluctuations

Pressure Noise from 0.01-1 Hz	
Rqmt.	V: 5x10^{-10}; H: 4x10^{-10}
Cap.	V: 3x10^{-10}; H: 2x10^{-10}
Margin	V: 65%; H: 100%

Seismometer

Clock Stability	
Rqmt.	9x10^{-6} over 3 hr
Cap.	<1x10^{-8}
Margin	92500%

Internal VBB Noise from 0.01-1 Hz	
Rqmt.	9.1x10^{-10}
Cap.	V: 4.7x10^{-10}; H: 6.4x10^{-10}
Margin	V: 95%; H: 45%

Dynamic Range	
Rqmt.	120 dB
Cap.	130 dB
Margin	10 dB

L5

ADC Noise	
Rqmt.	1x10^{-10}
Cap.	7x10^{-11}
Margin	45%

Capacitance Pickup Noise	
Rqmt.	7x10^{-10}
Cap.	4.5x10^{-10}
Margin	55%

Thermoelastic Tilt Noise	
Rqmt.	5x10^{-10}
Cap.	V: 1x10^{-11}; H: 4x10^{-10}
Margin	V: 4900%; H: 25%

Thermal Noise	
Rqmt.	2x10^{-10}
Cap.	7x10^{-11}
Margin	185%

Brownian Motion Noise	
Rqmt.	2x10^{-10}
Cap.	5x10^{-11}
Margin	300%

Context Pressure, Temp, Wind

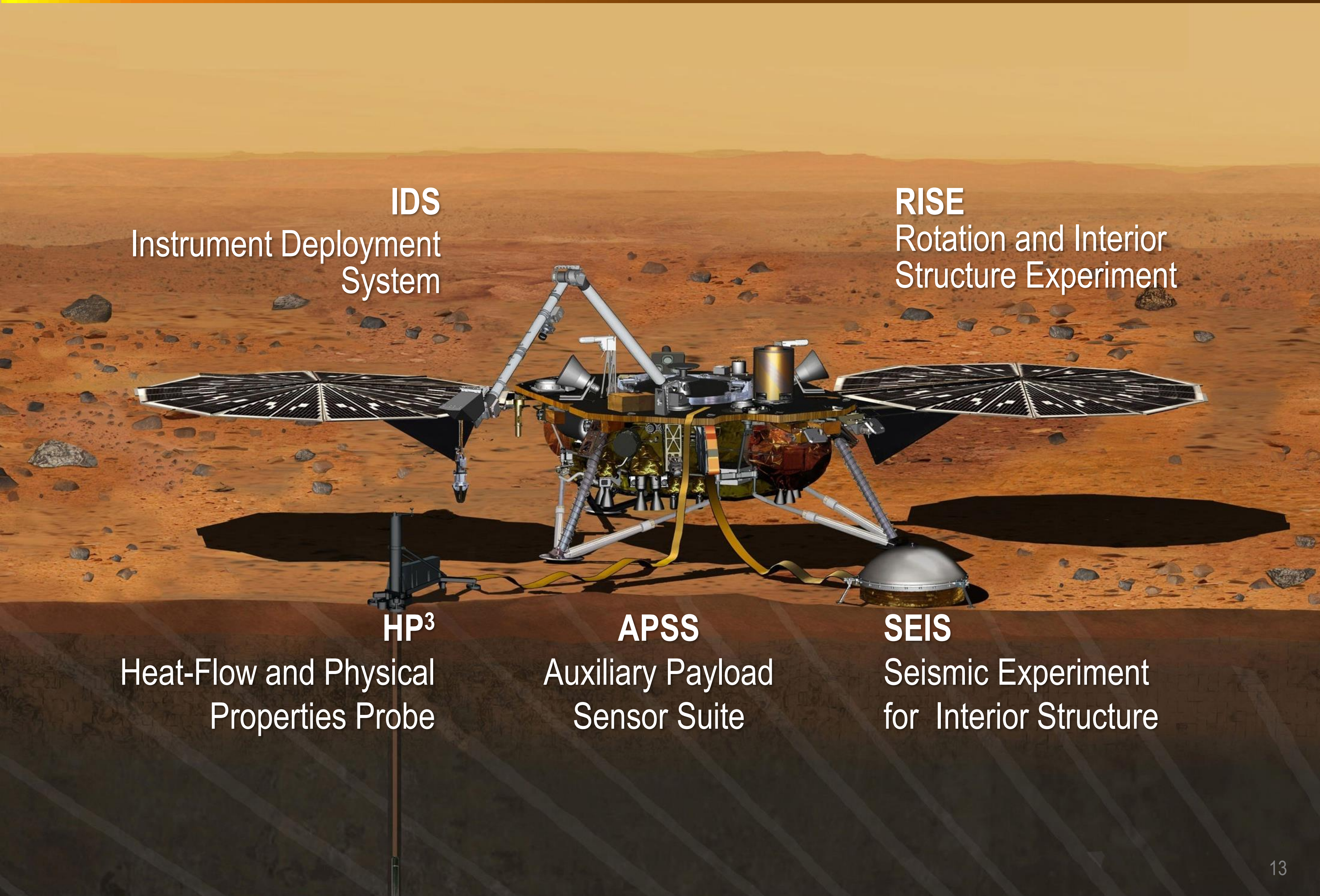
Wind Direction	
Rqmt.	±45°
Cap.	22°
Margin	100%

Wind Speed	
Rqmt.	15% @ 1 Hz
Cap.	10% @ 2 Hz
Margin	50% & 100%

Atmospheric Pressure	
Rqmt.	0.1 Pa @ 1 Hz
Cap.	0.01 Pa @ 1 Hz
Margin	900%

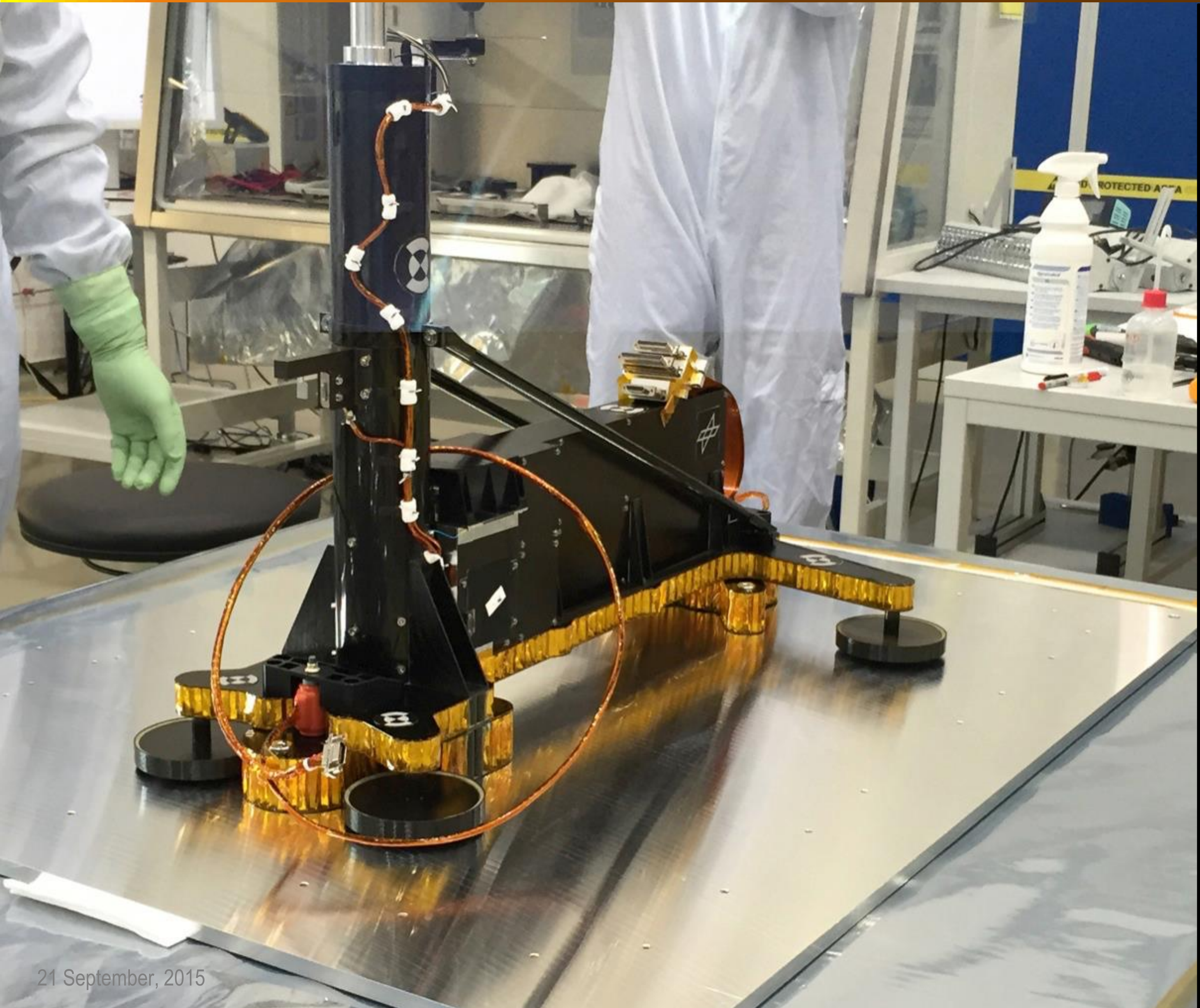
Atmospheric Temperature	
Rqmt.	0.1C
Cap.	0.05C
Margin	100%

Payload Elements

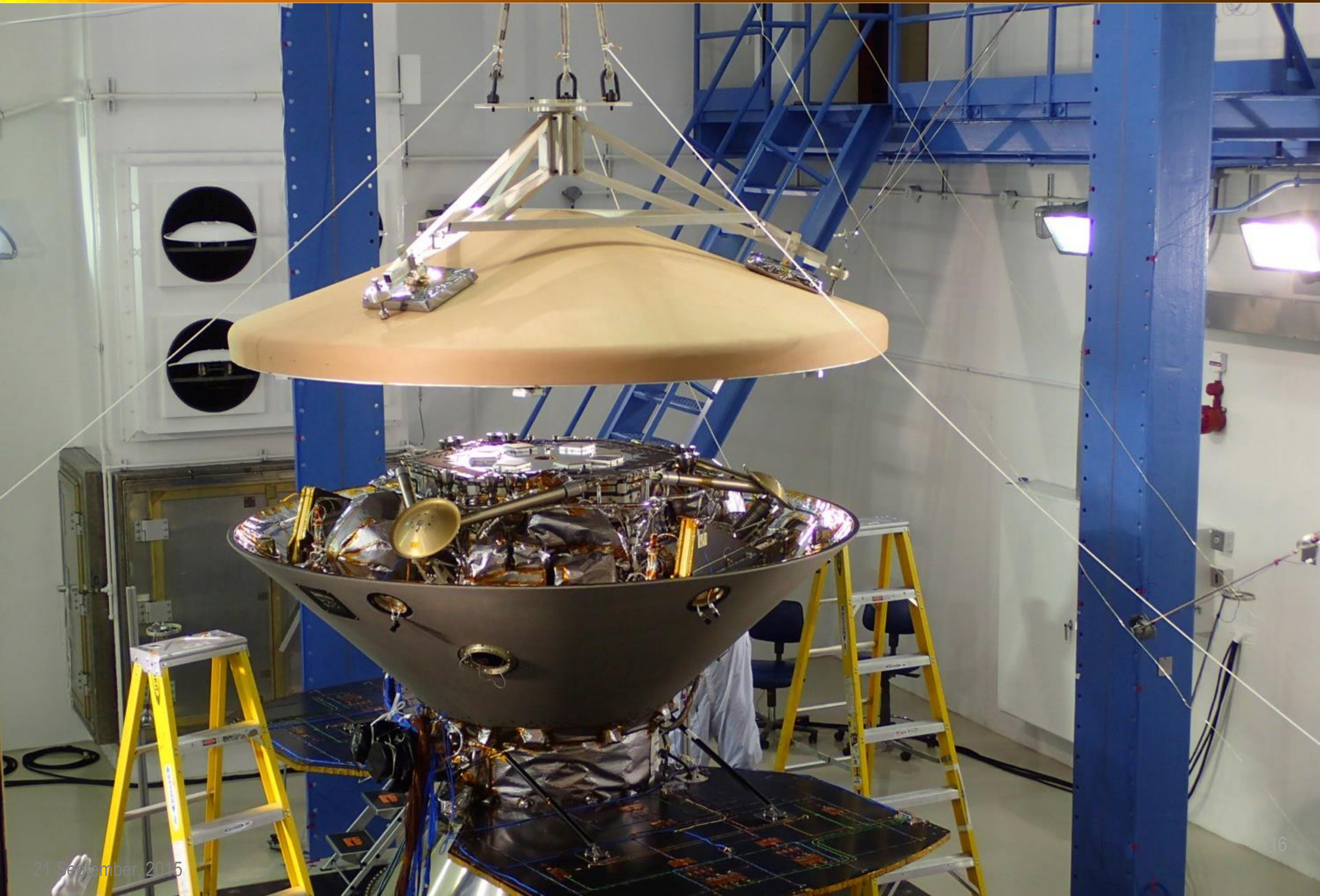


HP3 Instrument

InSight



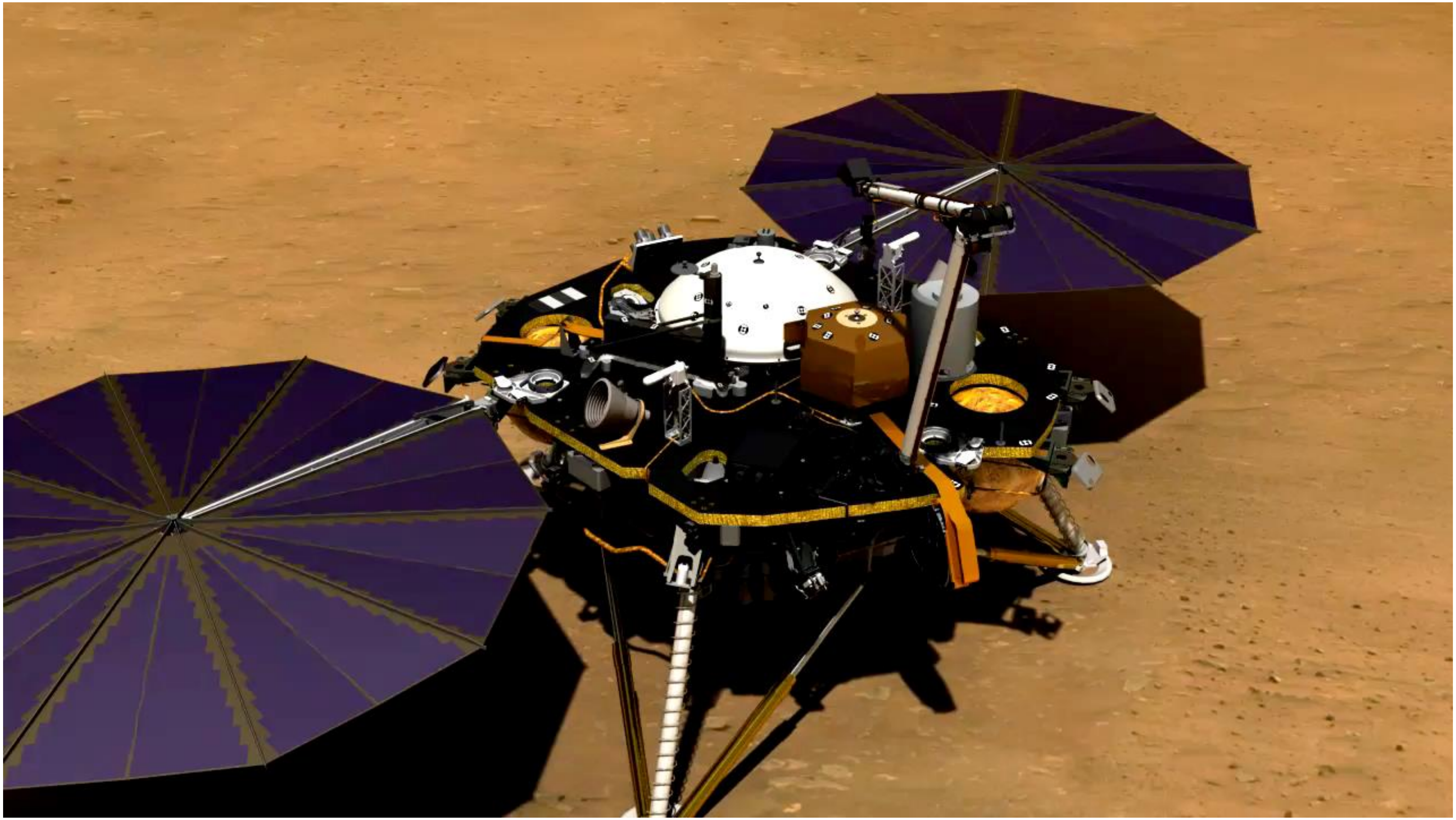
Lander: Heat Shield Installation



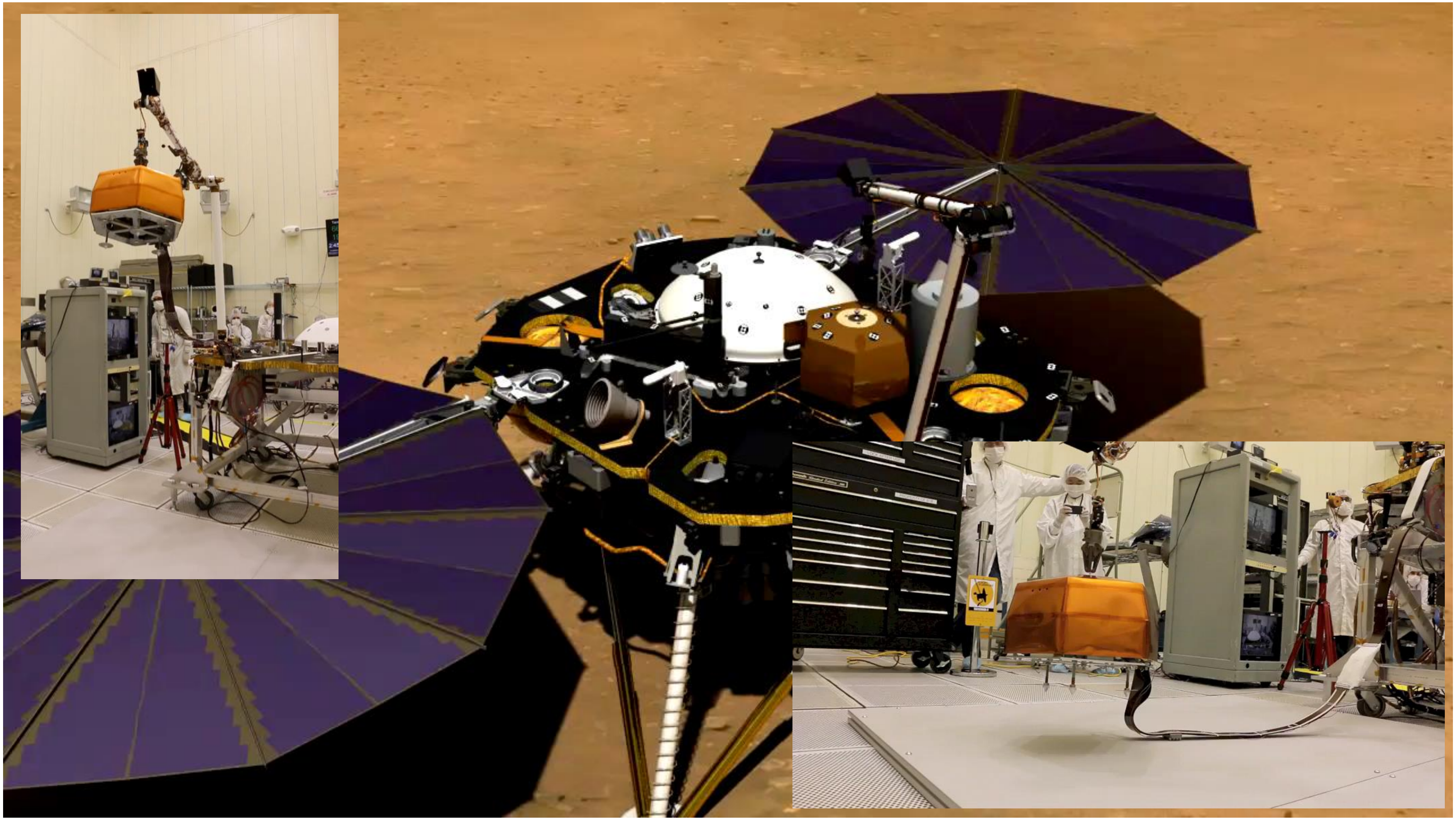
Lander: Cruise Stage Installation

Payload Elements Deployment challenge: Apollo

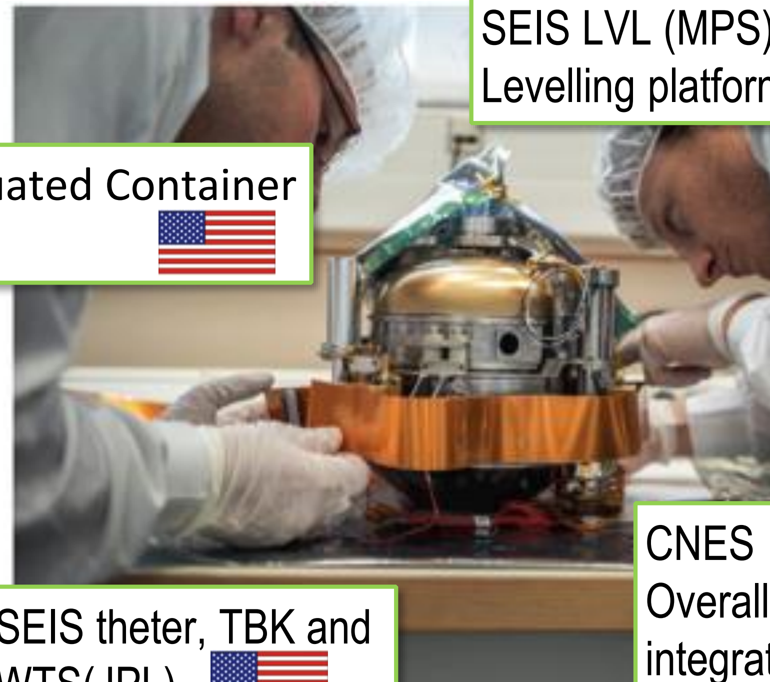
Payload Elements Deployment challenge: InSight

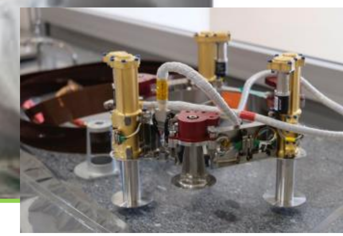


Payload Elements Deployment challenge: InSight



SEIS 2.0 (2018) Overview/Description



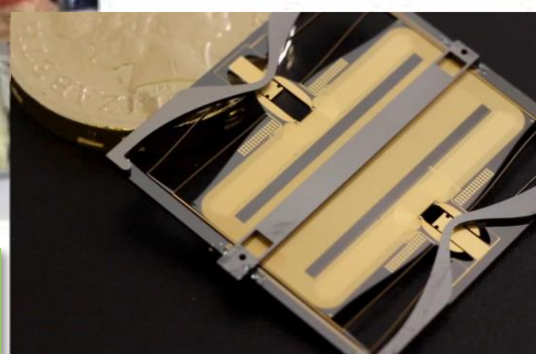


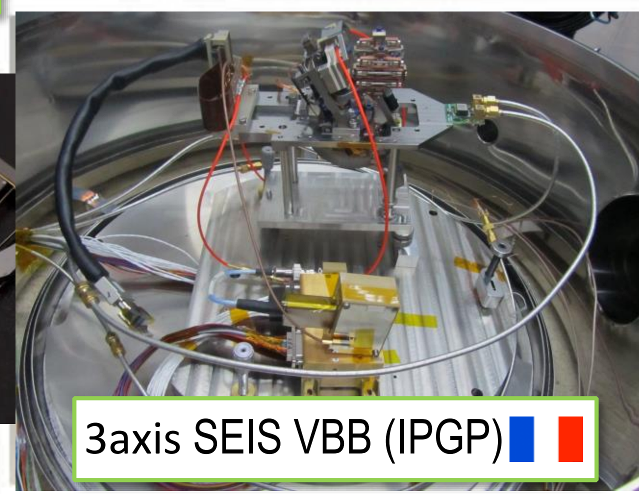
SEIS LVL (MPS)
Levelling platform

Evacuated Container
(JPL)

SEIS theter, TBK and
WTS(JPL)

CNES
Overall management and
integration; Craddle



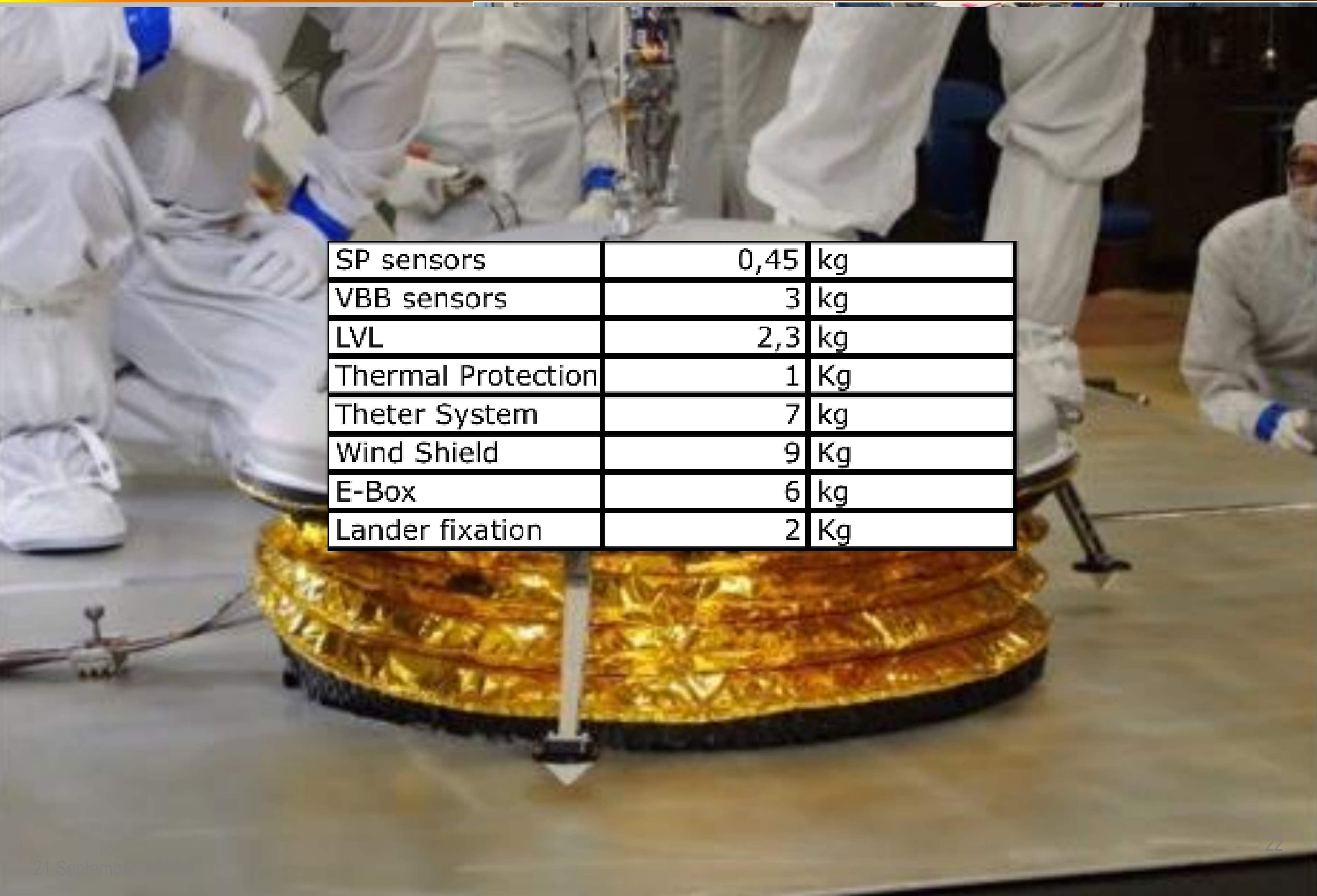


SEIS Electronics (ETHZ)
10x24 bits + 72x12 bits data logger

3 axis SEIS SP (IC)

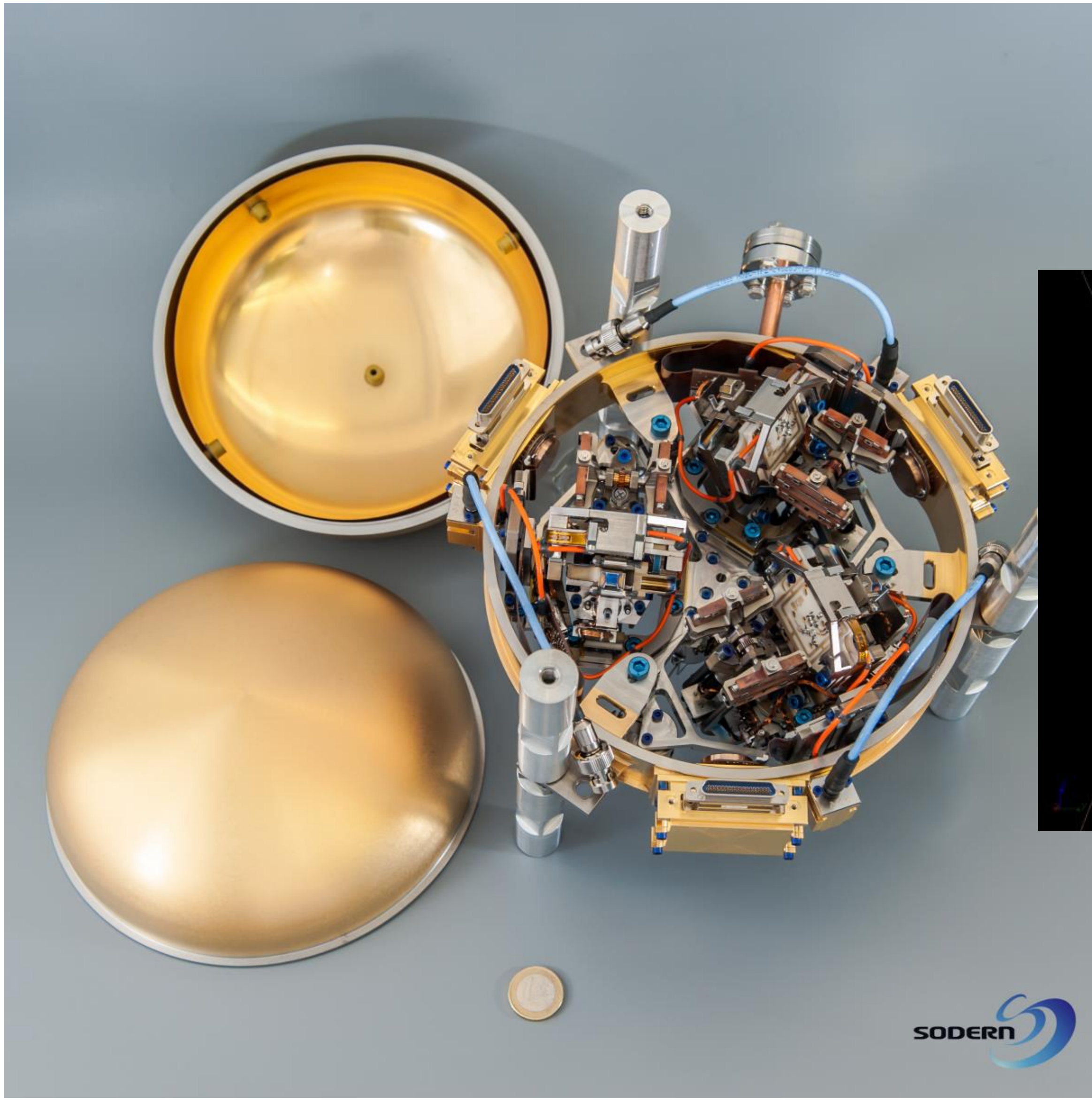
3axis SEIS VBB (IPGP)

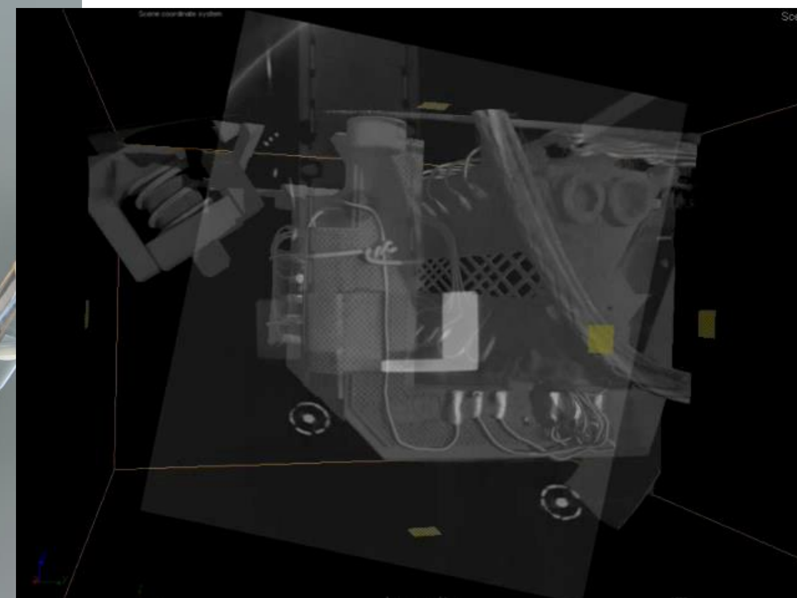
SEIS Instrument



SP sensors	0,45	kg
VBB sensors	3	kg
LVL	2,3	kg
Thermal Protection	1	Kg
Theter System	7	kg
Wind Shield	9	Kg
E-Box	6	kg
Lander fixation	2	Kg

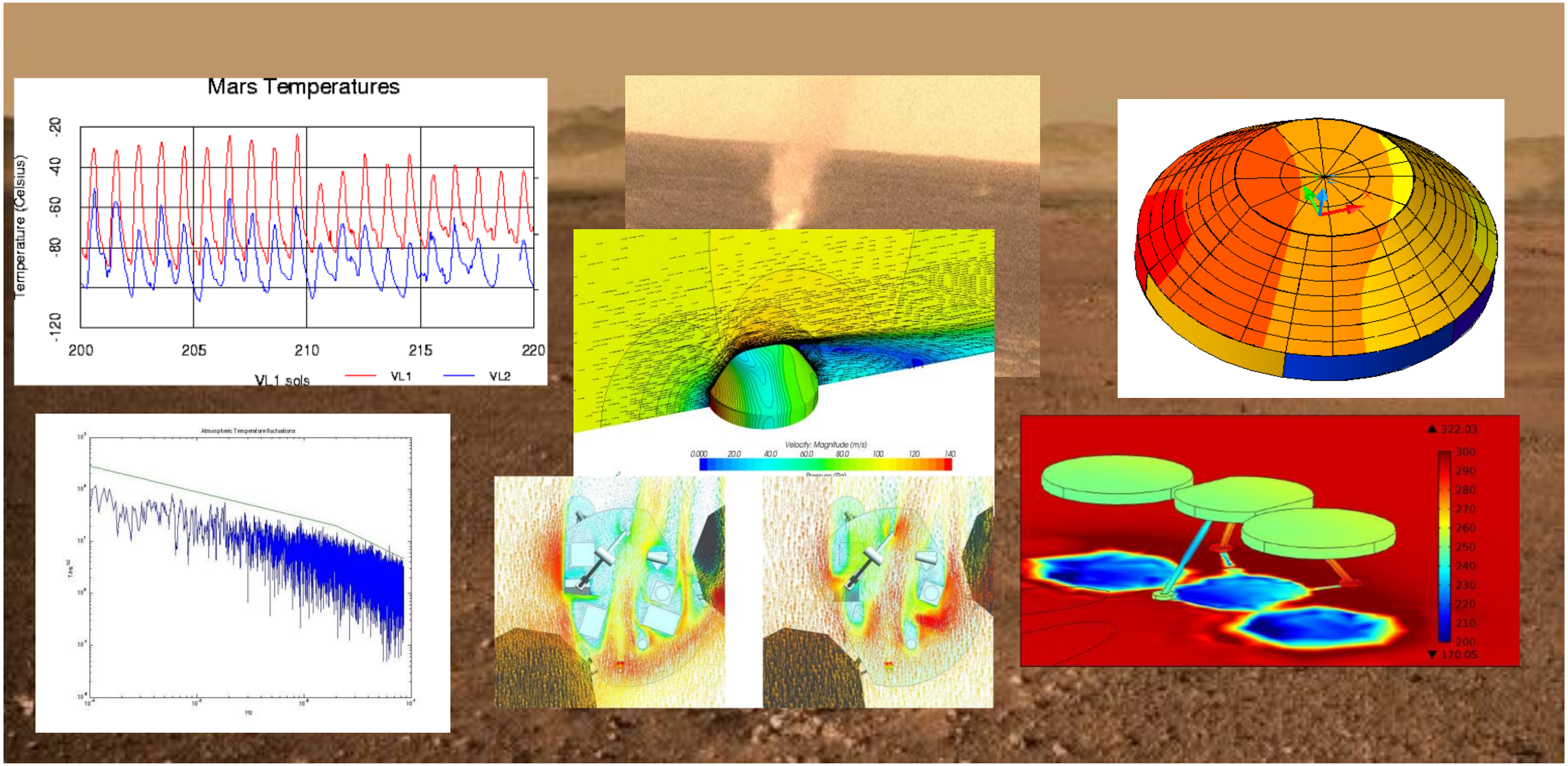
VBB Detail…





Environmental noise

- We are here……



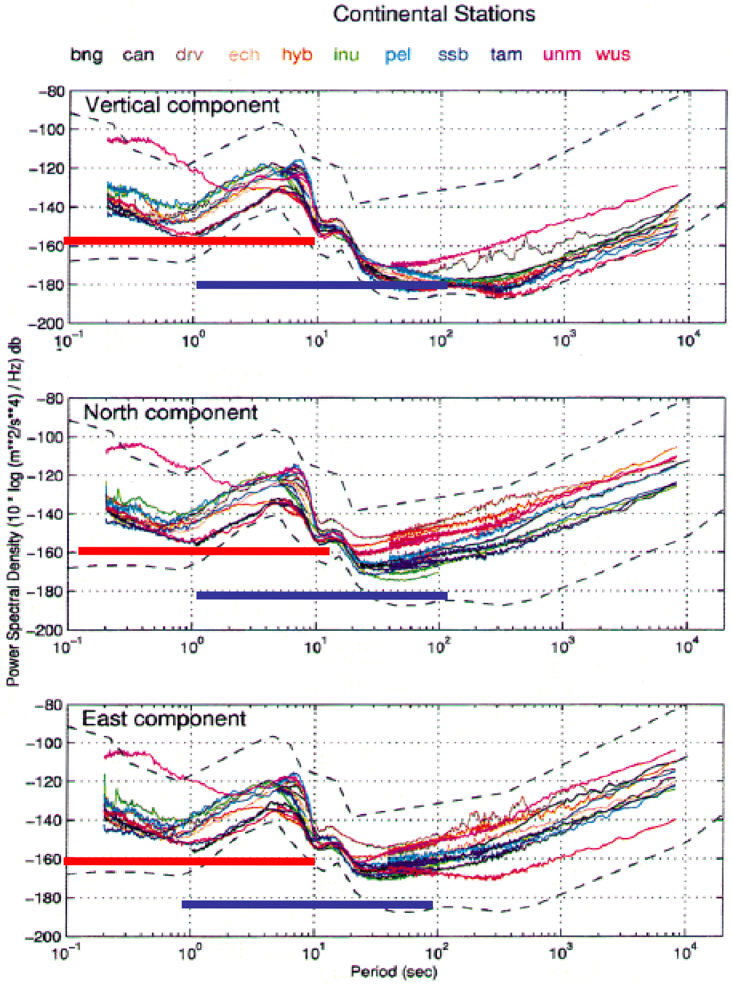
Mimoun et al, InSight Noise model

- but would like to be there……

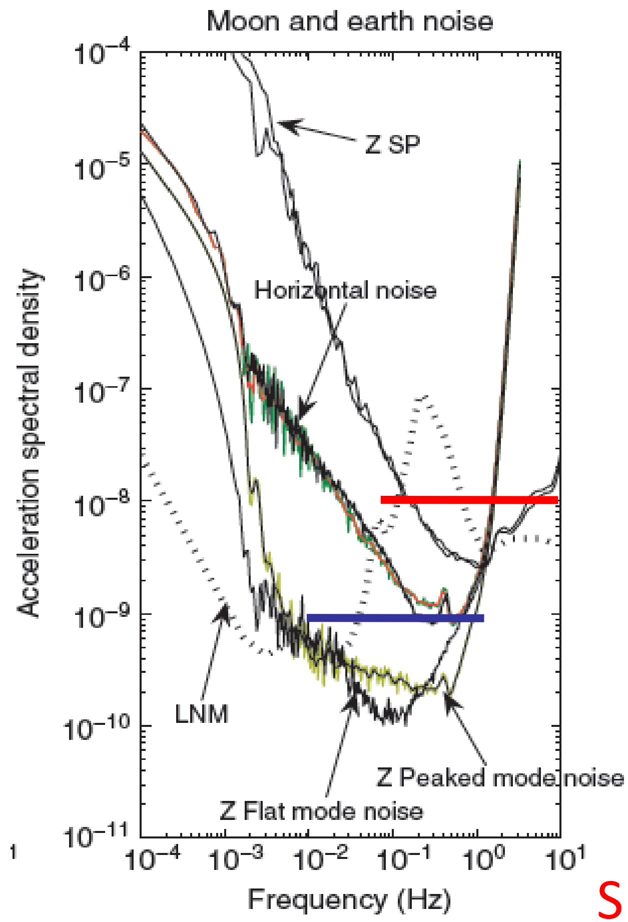
Seismic vault

Environmental noise: installation goals

Planet with Ocean and Atmosphere



Planet without atmosphere and ocean

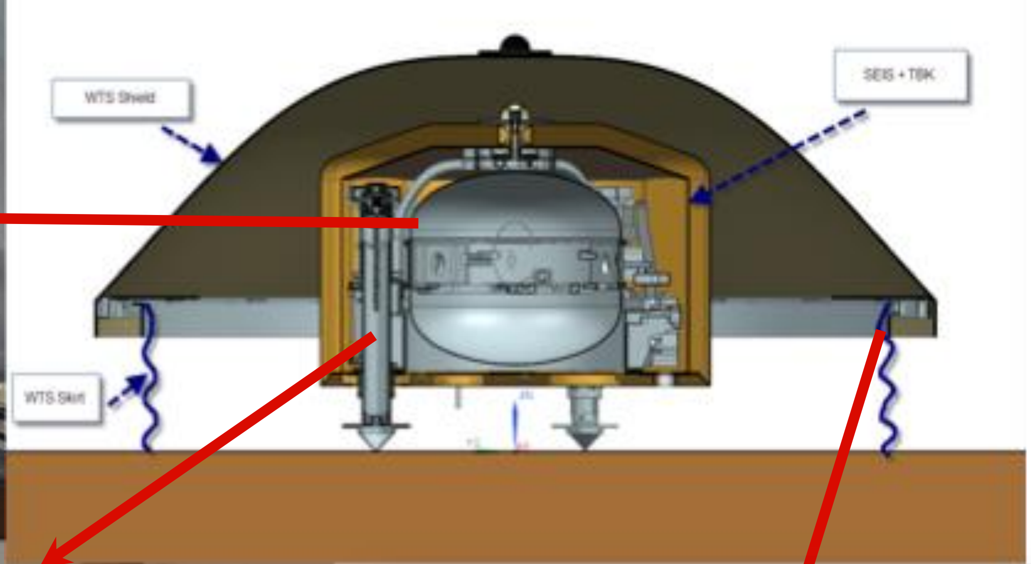


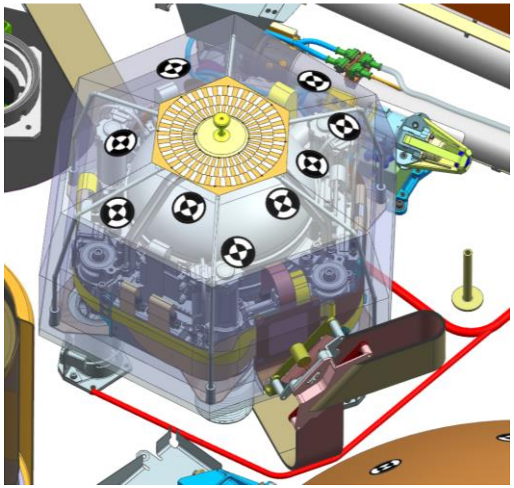
SP VBB

Temperature and wind protection

Evacuated sphere

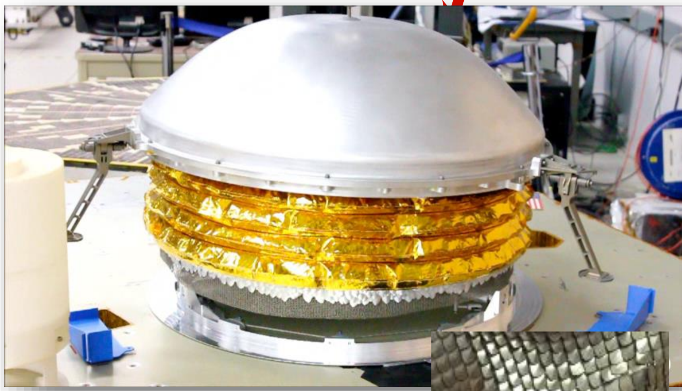
Wind protection





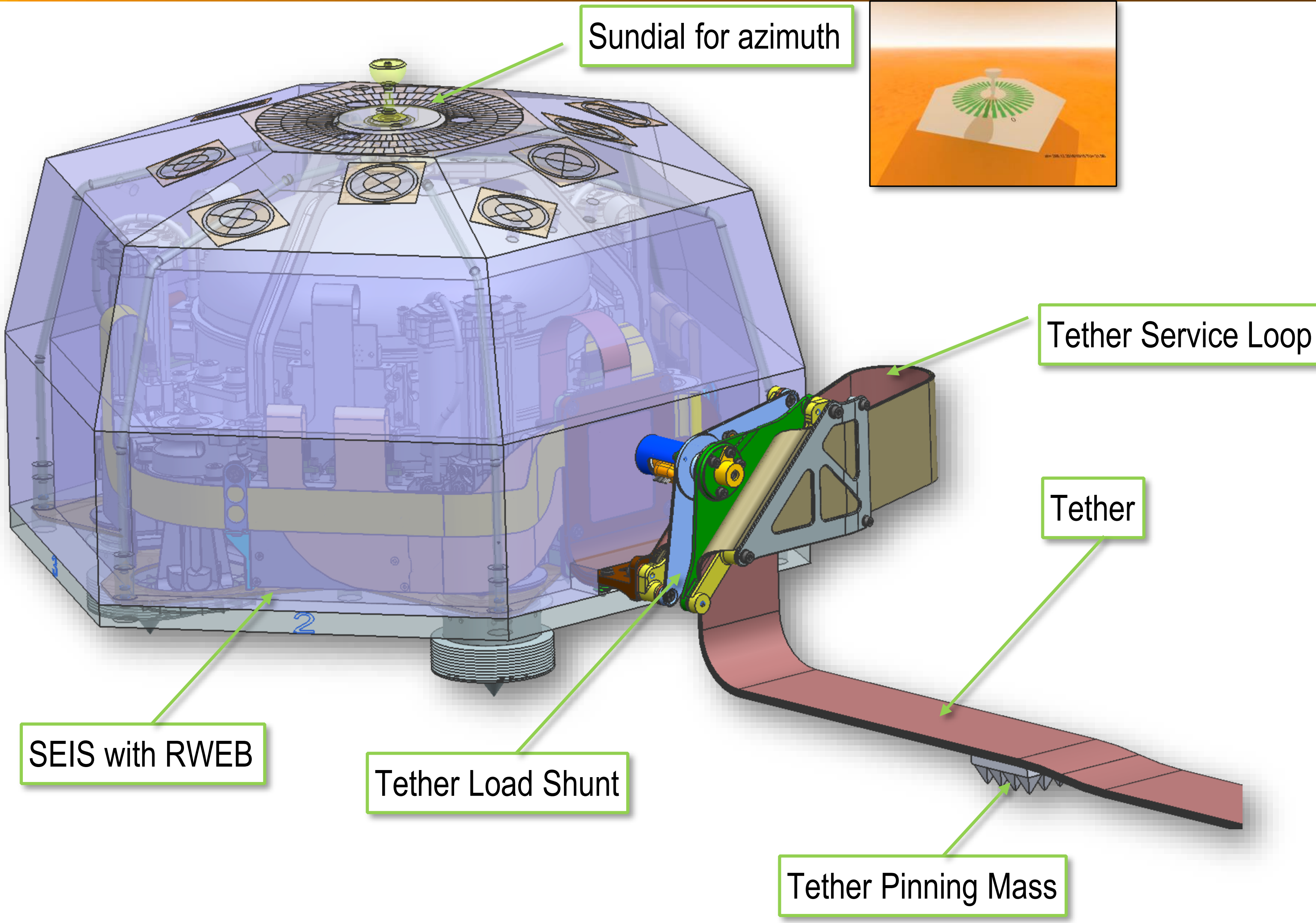
Thermo-elastic service loop

Thermal shield

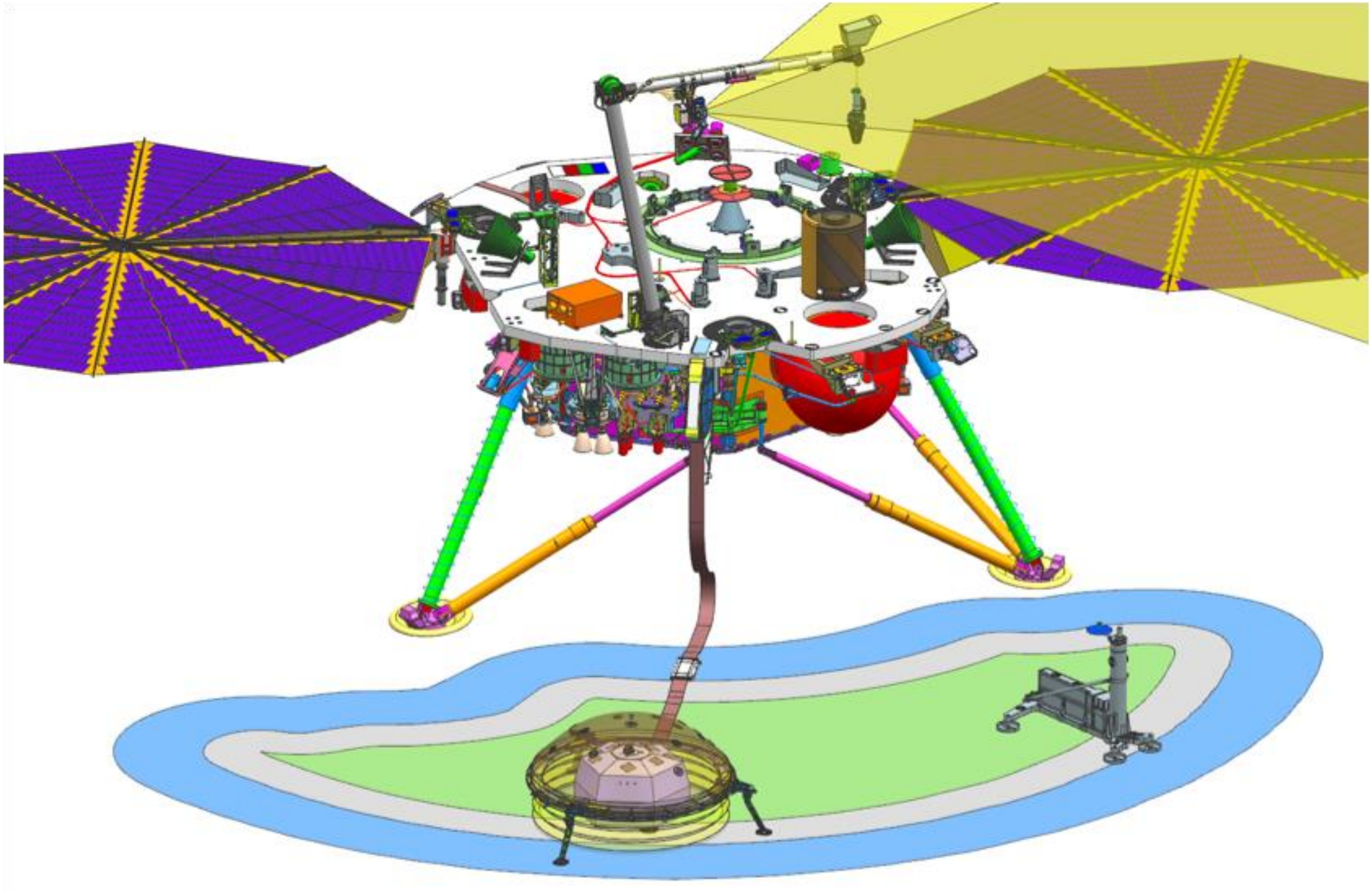


Sealing skirt

SEIS Sensors head Overview/Description



Arm deployment zone



Seismometers and seismic detection techniques

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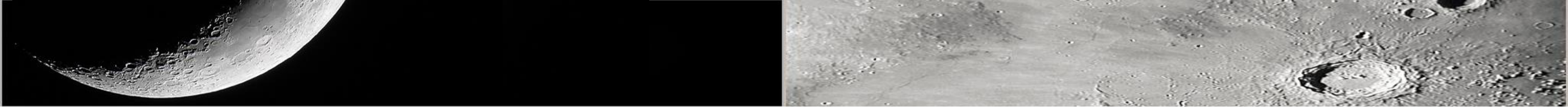
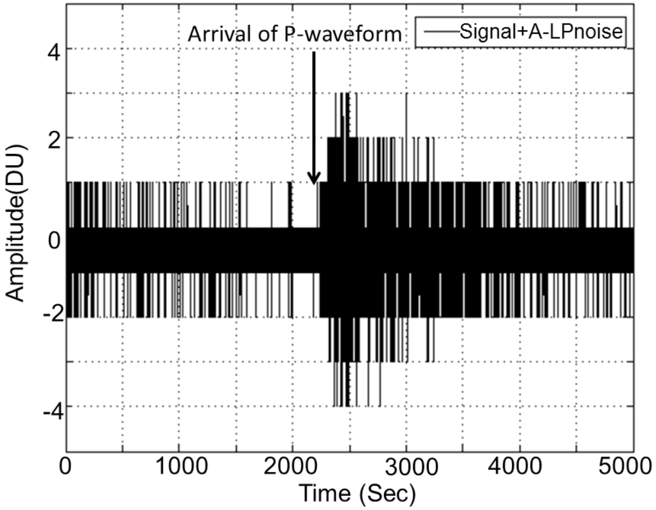


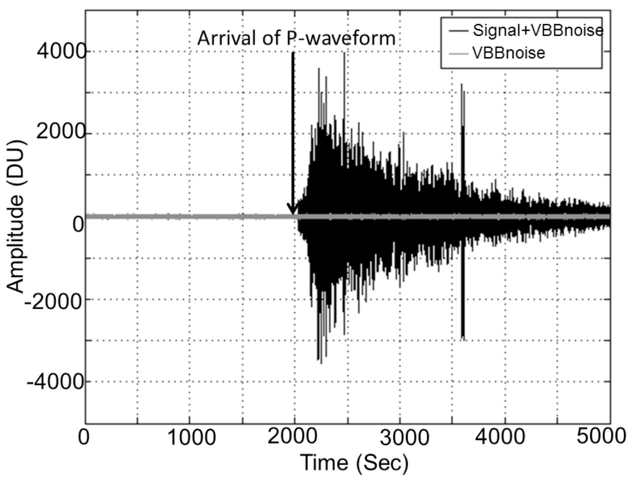
Expected VBB improvement with respect to Apollo will enable new seismic discoveries

- Core phases and core size
- High resolution crustal model from joint Earth/Moon impacts monitoring
- Detailed seismic source dynamics of impacts and DMQ

Apollo LP

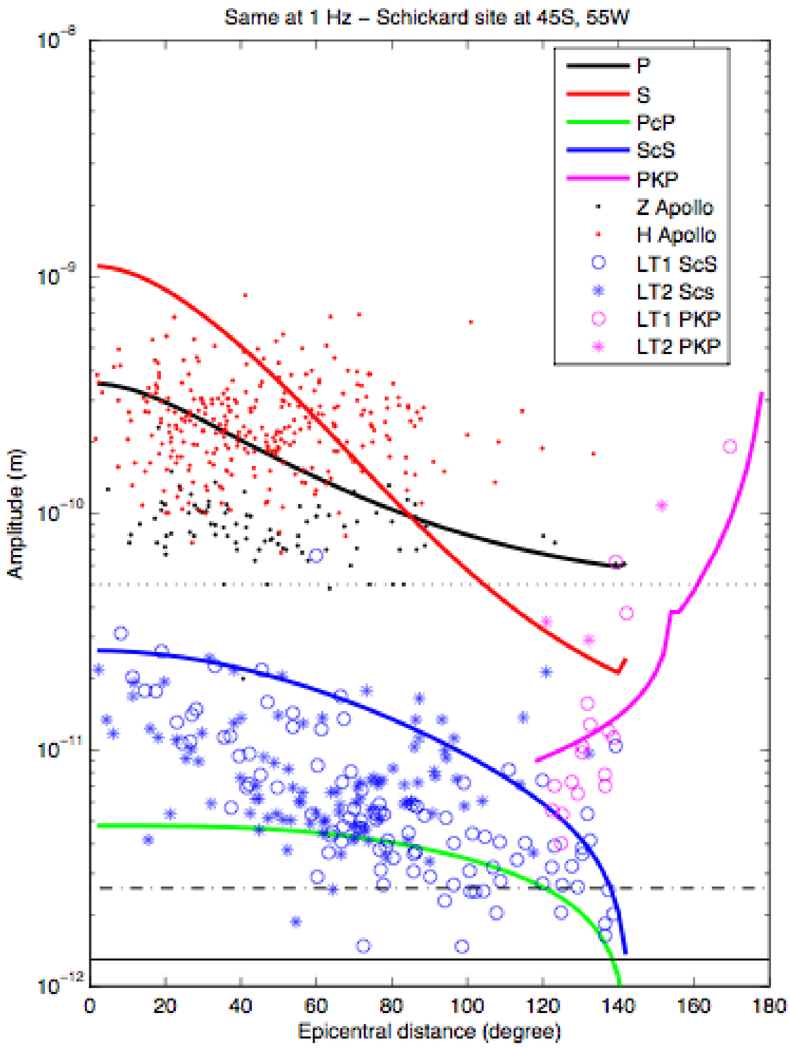


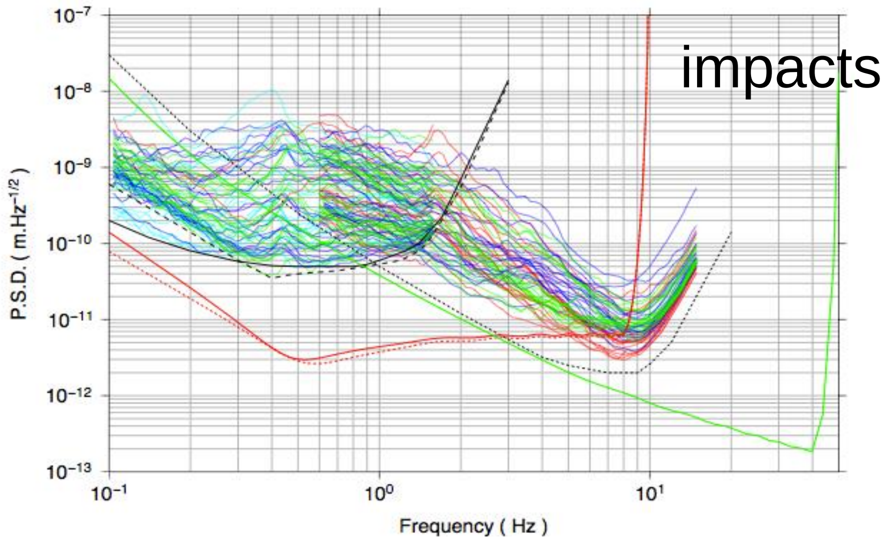
VBB

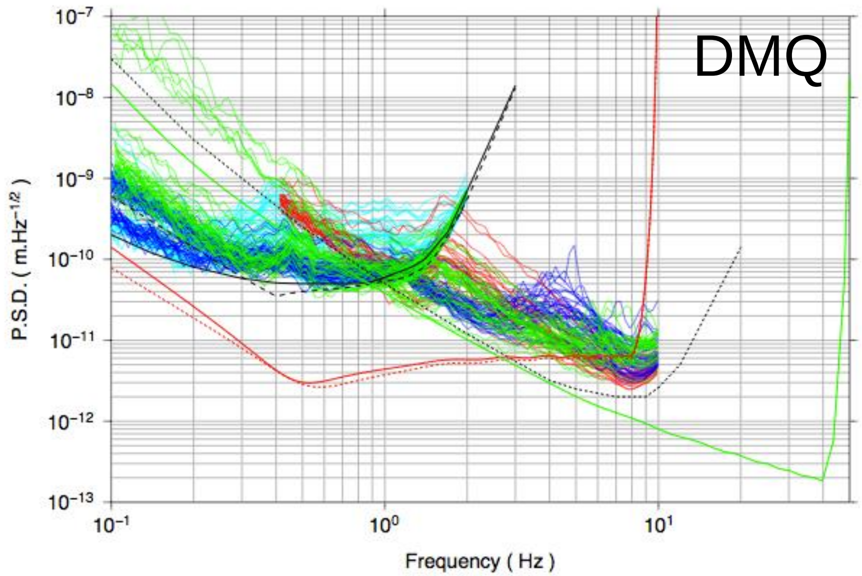


Yamada et al., 2012


Performances improvements…





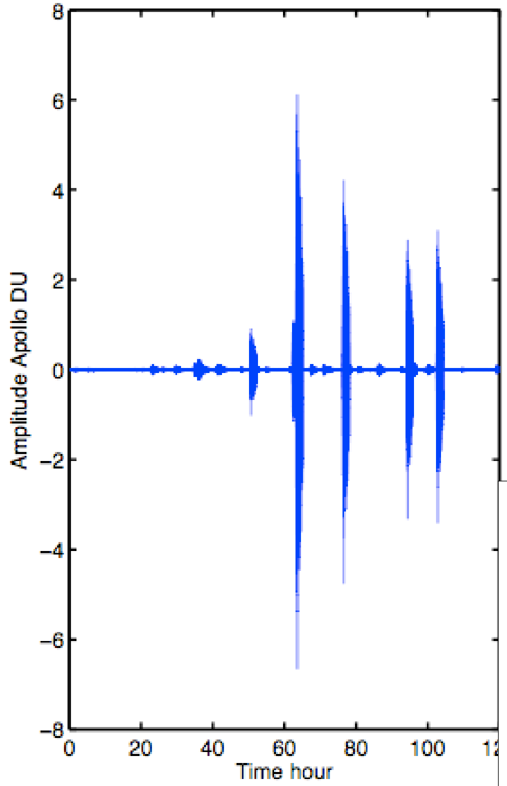


Active seismology using impacts

Impact monitoring gives the source position and time of the seismic event, allowing seismic investigations with a ***single*** station.

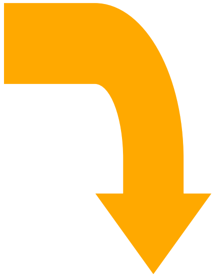
Possible Lunar Limit , i.e. Lunar Seismic noise floor

- Possible noise floor will be the continuous hum associated to all impacts of meteorites (Lognonné et al, 2009)

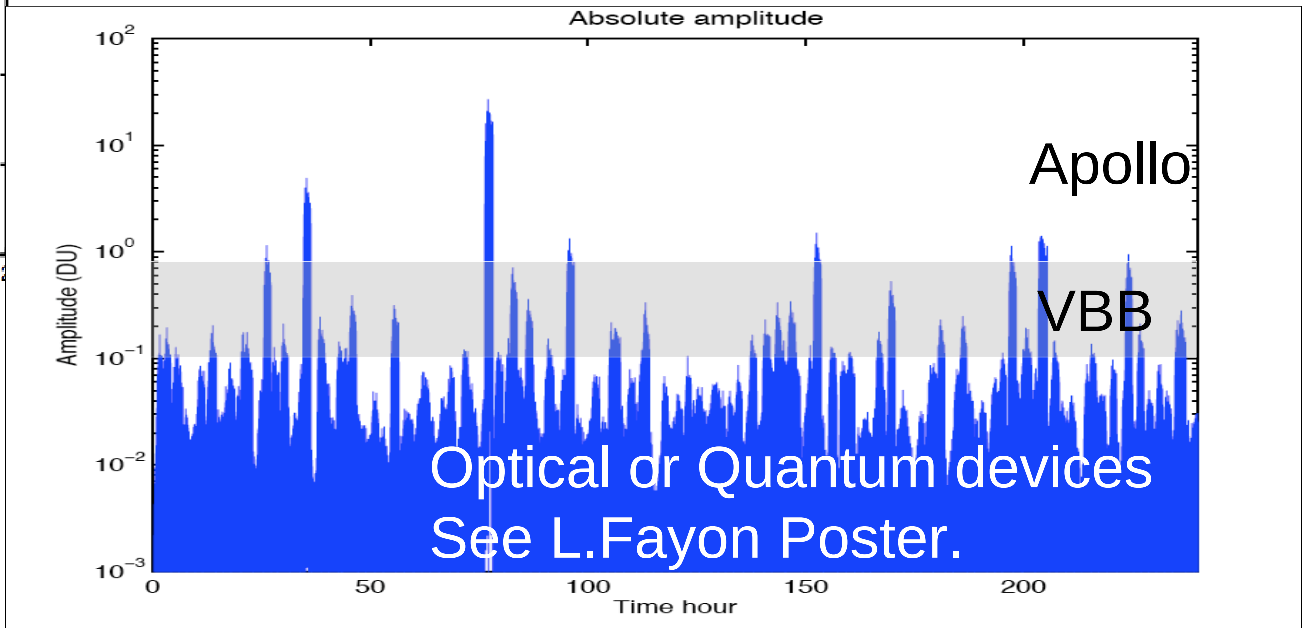


Apollo

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



VBB:
rms= $5x10^{-11}$ ms^{-2}

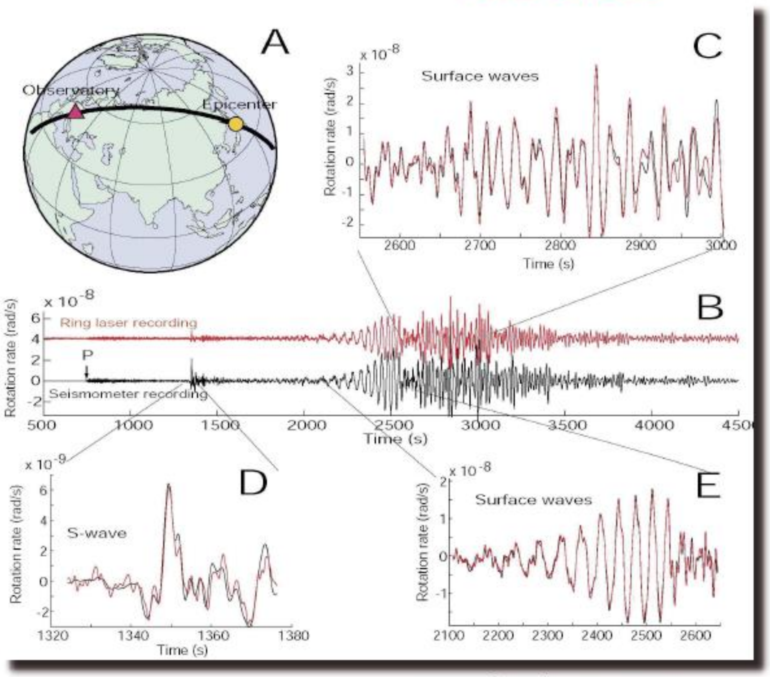


or/and new seismic data with rotational seismology

- Use the fact that the S waves and Surface waves generate ground rotation which depend on the waves phase velocity
- Measuring the rotation gives you the velocity directly !
- Technology is not yet available for the magnitude of Lunar/Mars quake but might be new areas for future instruments…

Mw = 8.3 Tokachi-oki 25.09.2003

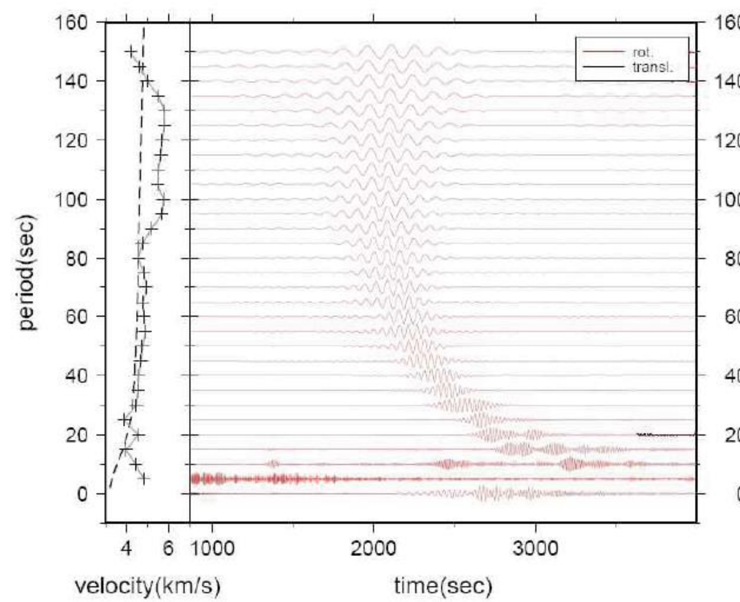
transverse acceleration - rotation rate



From Igel et al., GRL, 2005

… dispersion …

M7.4 Kuril islands, 15/1/09



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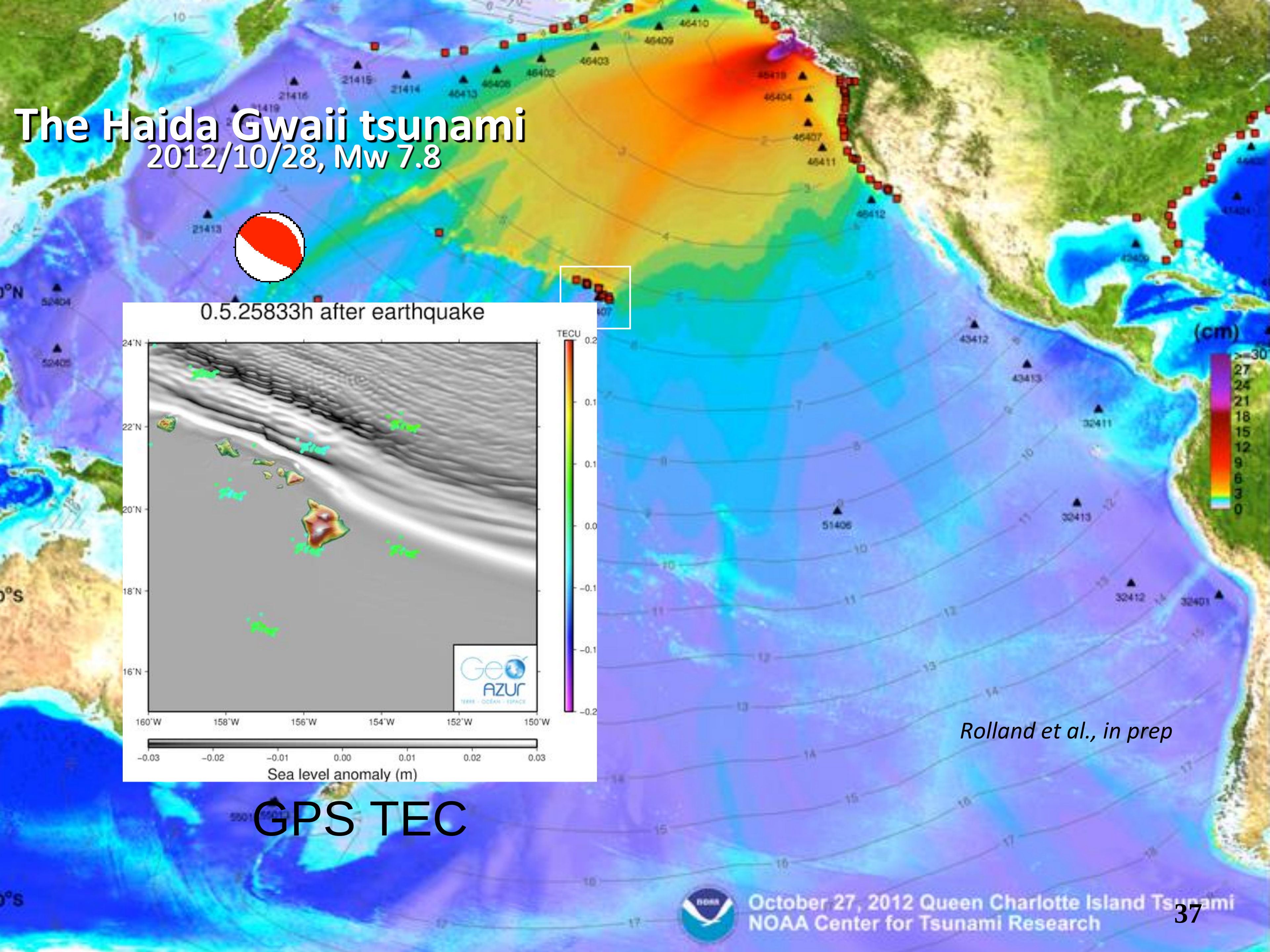
The Haida Gwaii tsunami
2012/10/28, Mw 7.8



GPS TEC

Rolland et al., in prep

Glowing in the Hawaii sky red airglow

- 630 nm
- Emission peak at 250-300 km
- quiet night 50-100 Rayleigh

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

The Haida Gwaii tsunami
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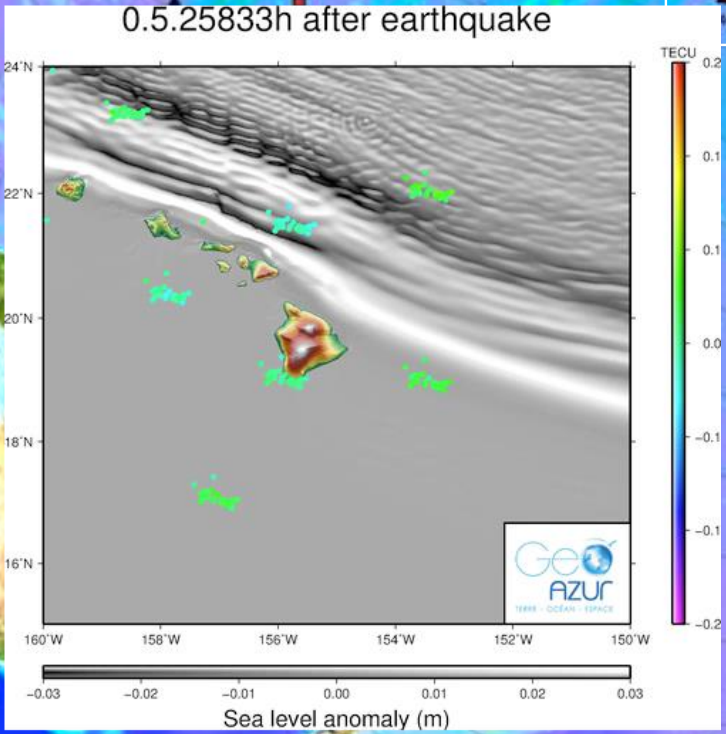
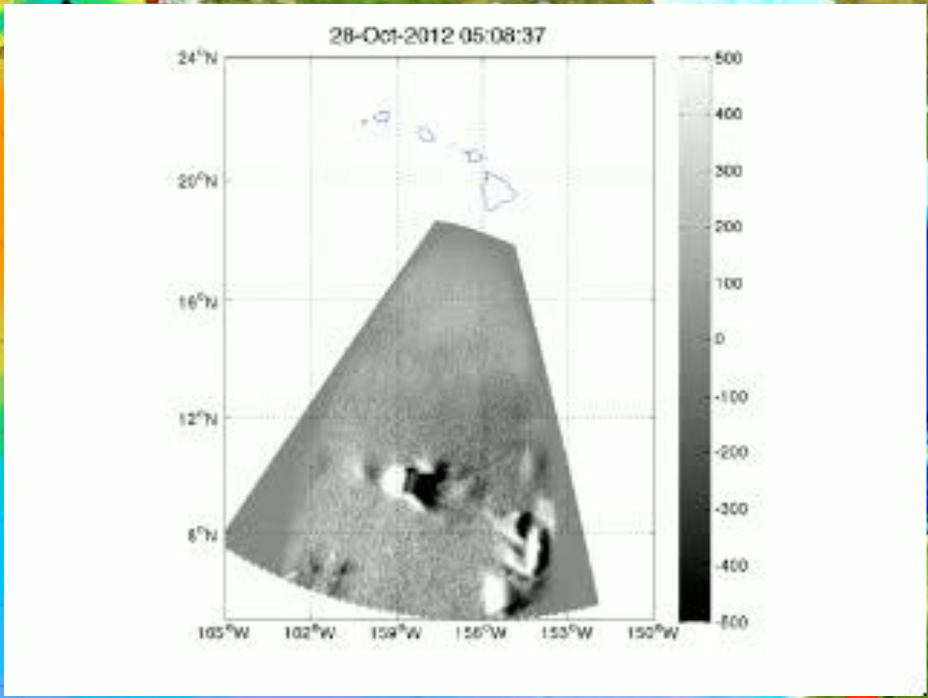


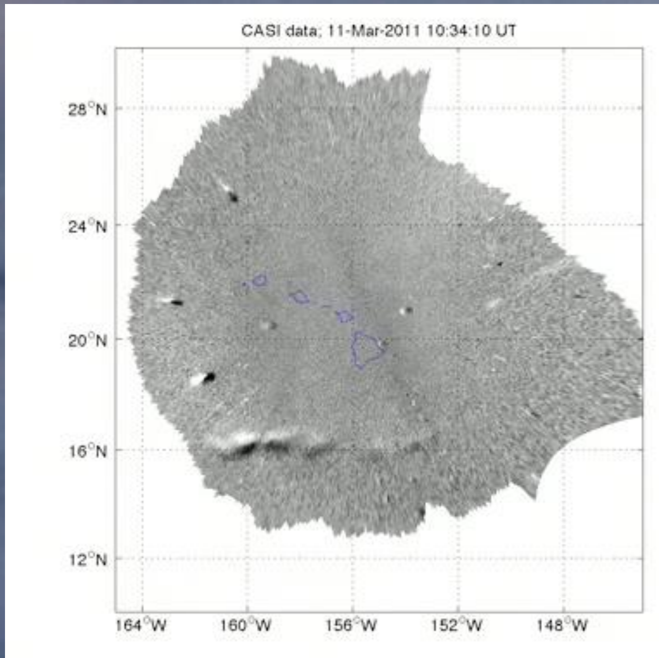
GPS TEC



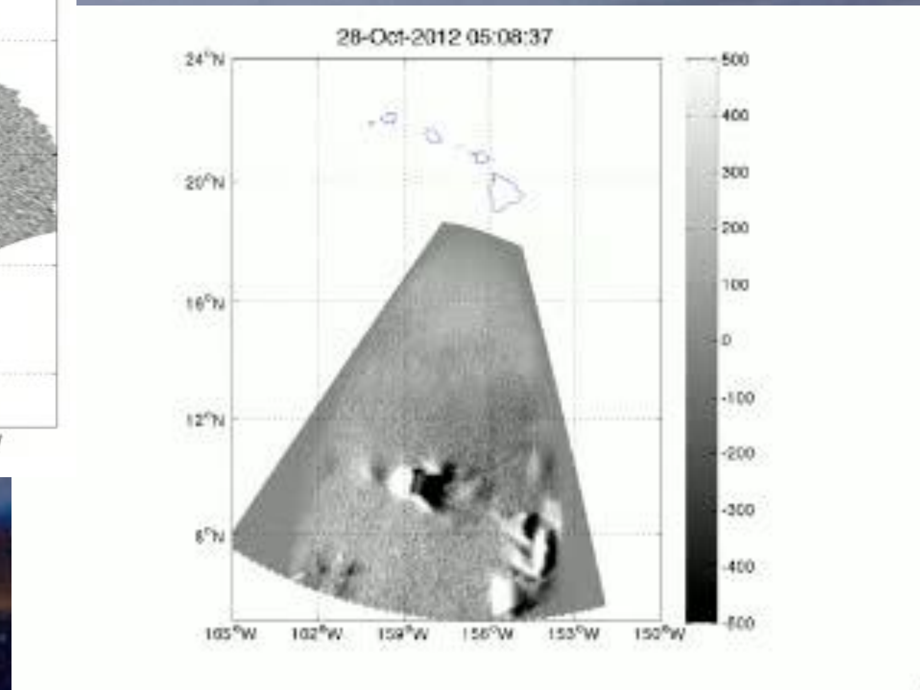
Airglow camera

Makela et al, in prep
Rolland et al., in prep

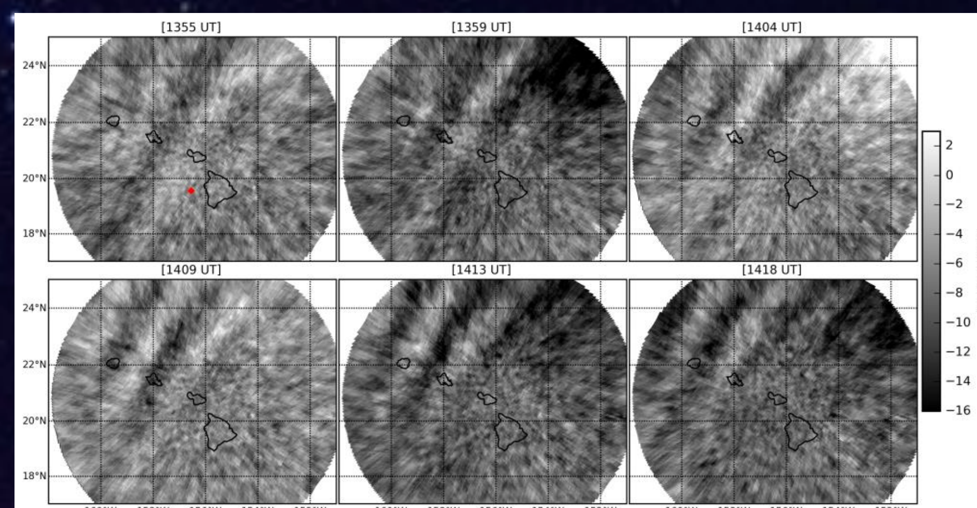
October 27, 2012 Queen Charlotte Island Tsunami
NOAA Center for Tsunami Research



Tohoku, May, 2011 over Hawaii



Queen Charlotte, October, 2012 over Hawaii



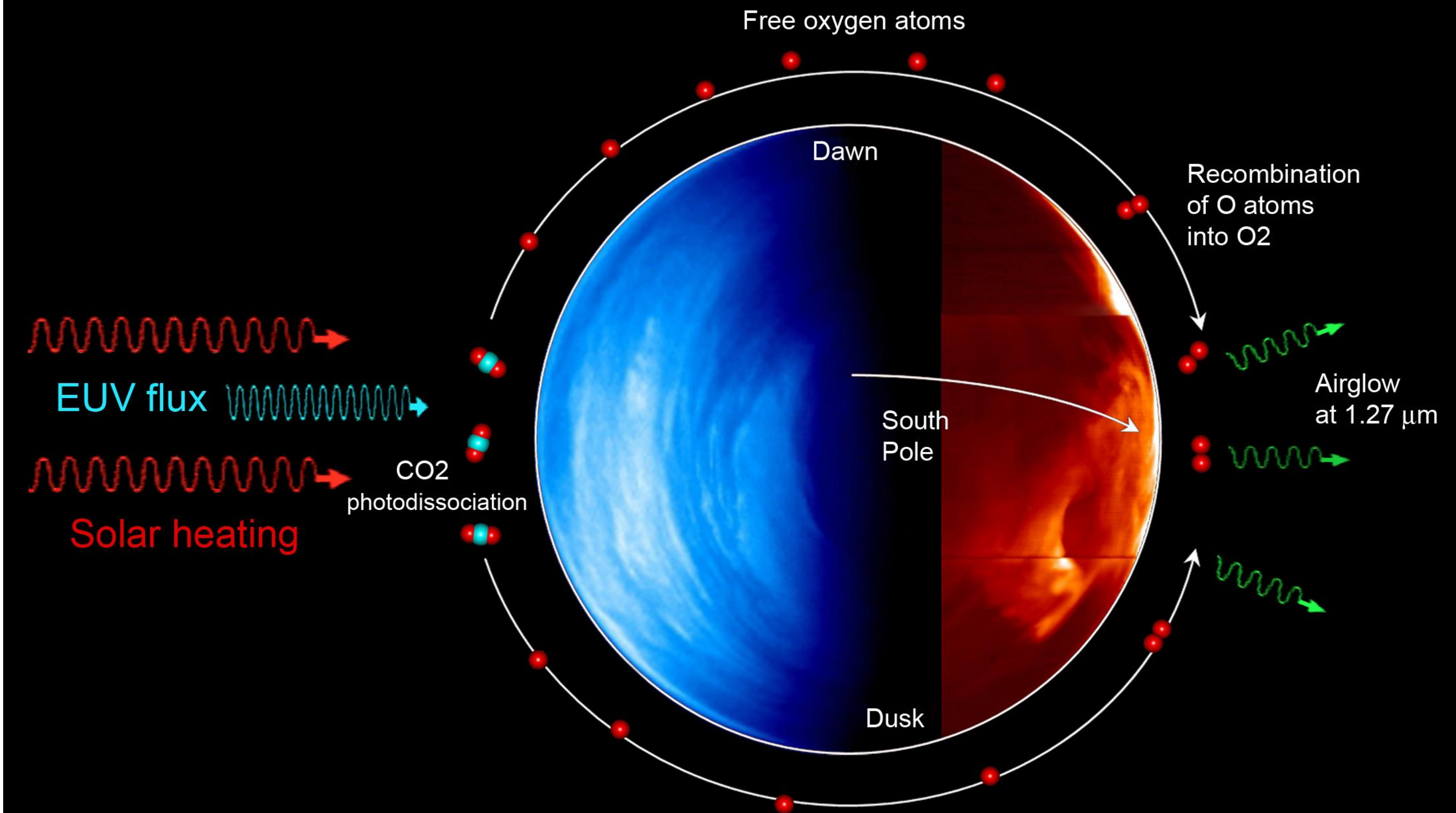
Chili, September, 20125 over Hawaii

Proprietary Data: J.Makela, Univ. Illinos.
Makela et al., 2011

Venus

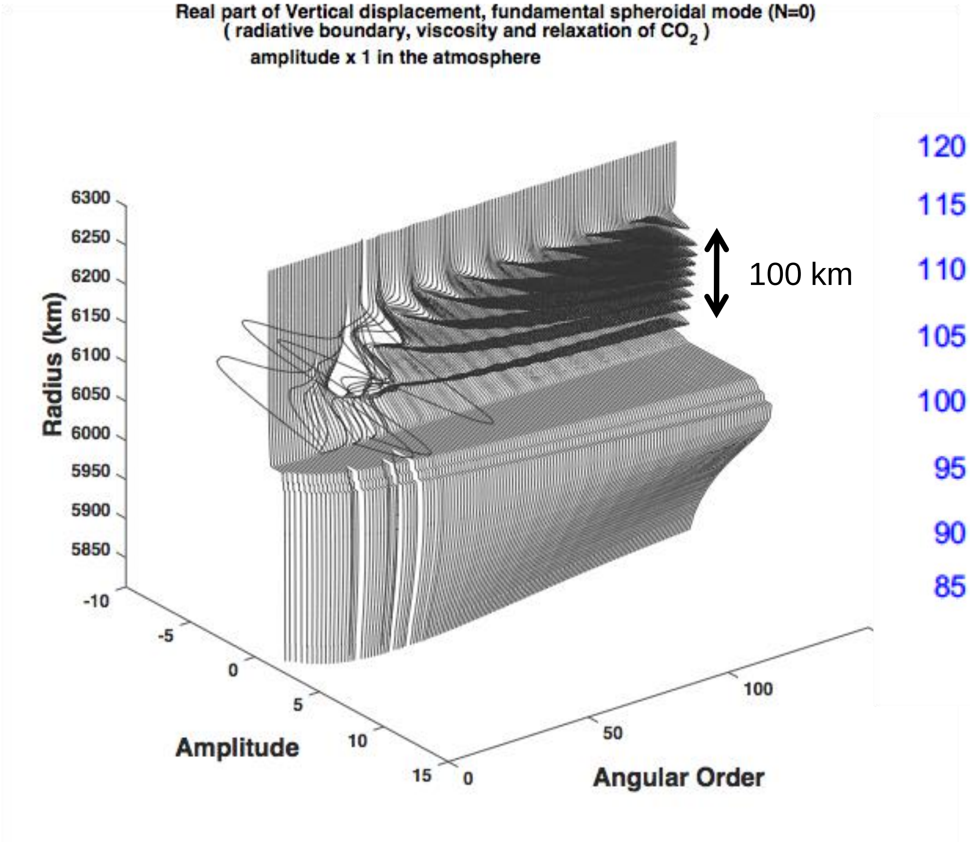
Can we detect there quakes though airglow ?

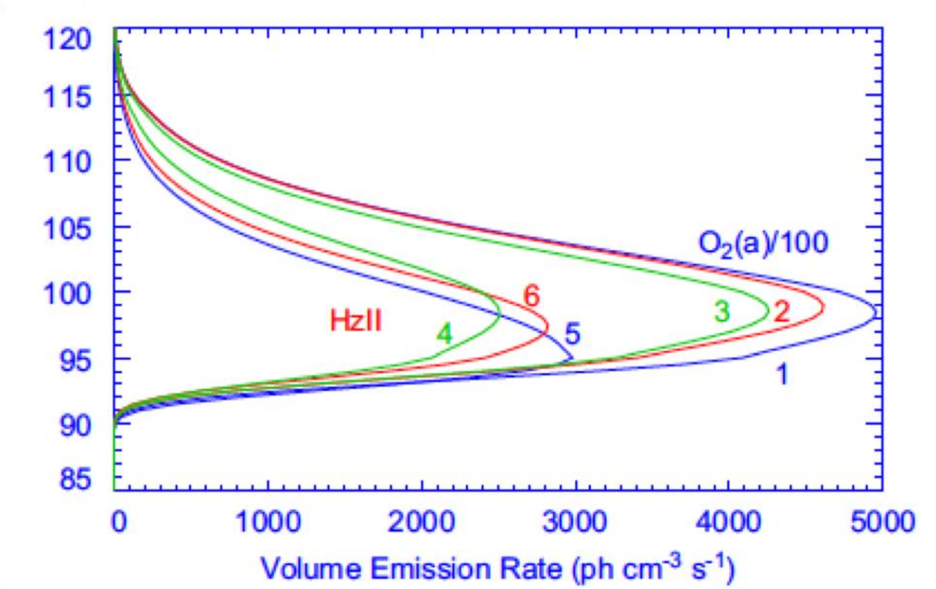
airglow?



Venus airglow Rayleigh waves forcing (2/2)

- sound speed at 100 km is about 200 m/s
- 100 sec waves have a 20 km wavelength, comparable to the thickness of the emitting layer
- The emission of the layer is easily modulated through density modulation (i.e. light bulbes density)





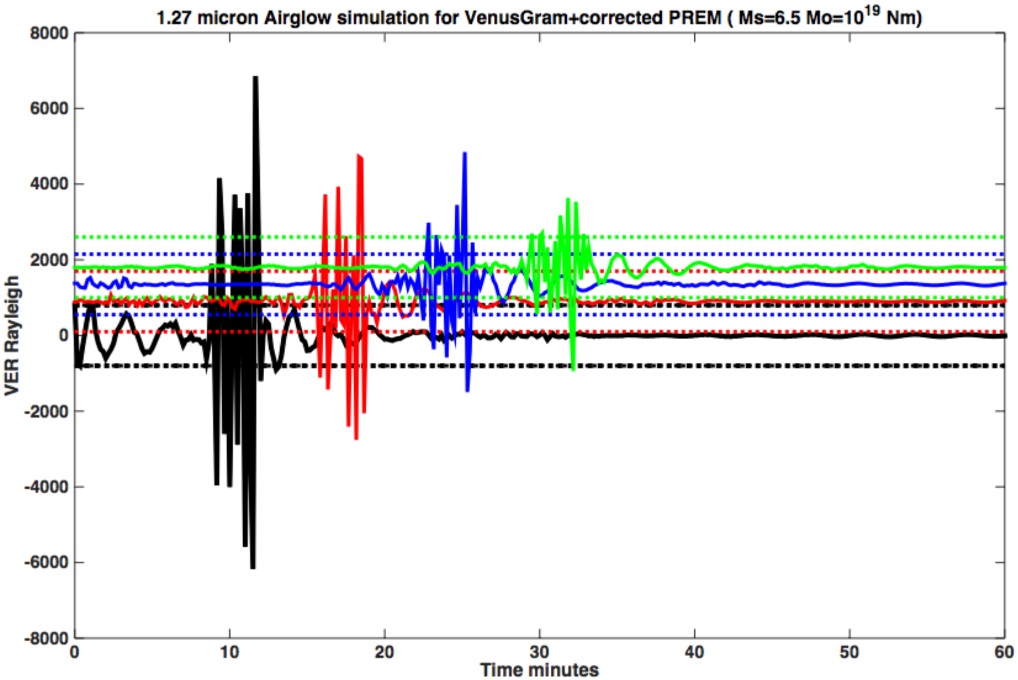
Venus airglow Rayleigh waves forcing (1/2)

- Modelling for 1.27 mm airglow

$$\delta VER = \Lambda_i[\delta O_2^i] = -\frac{\tau_i}{1+i\omega\tau_i} div\left(\Lambda_i[O_2^i]\vec{v}\right) = -\frac{\tau_i}{1+i\omega\tau_i} div(VER \times \vec{v})$$

- Signal is the flux of the Volumetric Emission Rate generated by waves, low passed by the radiative lifetime

This suggests detection feasibility with existing imaging systems for M~6 up to 60° of epicentral distance
(and less with new systems)



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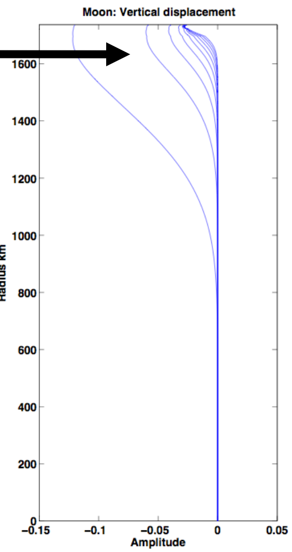
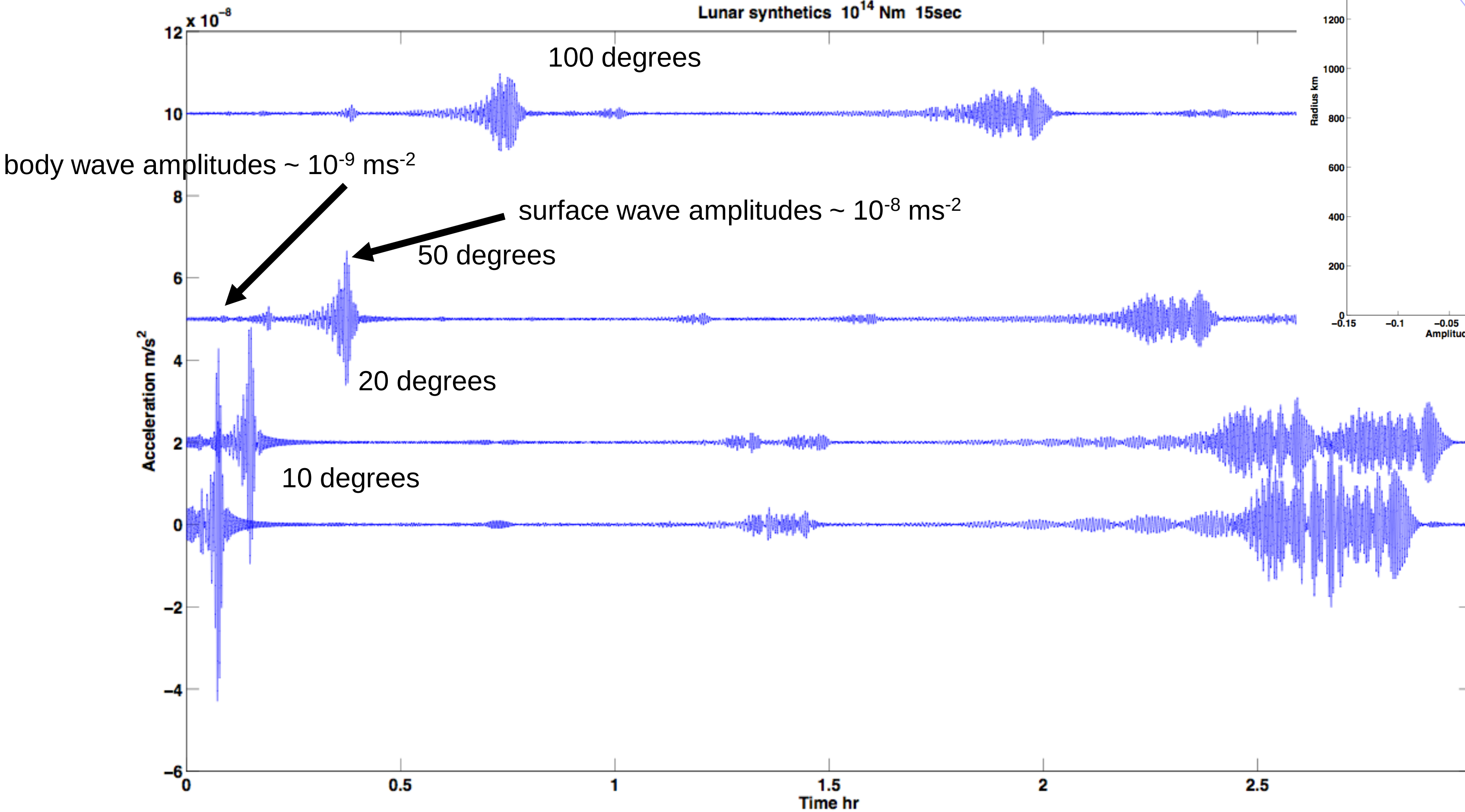
Network on the Moon…. Seismometer view

- 10 km depth quake comparable with the Lunar typical Shallow Moonquakes

Surface waves ARE concentrated at the surface





Network on the Moon…. Displacement view

- 10 km depth quake comparable with the Lunar typical Shallow Moonquakes
  - red(just Rayleigh waves), blue (all waves)