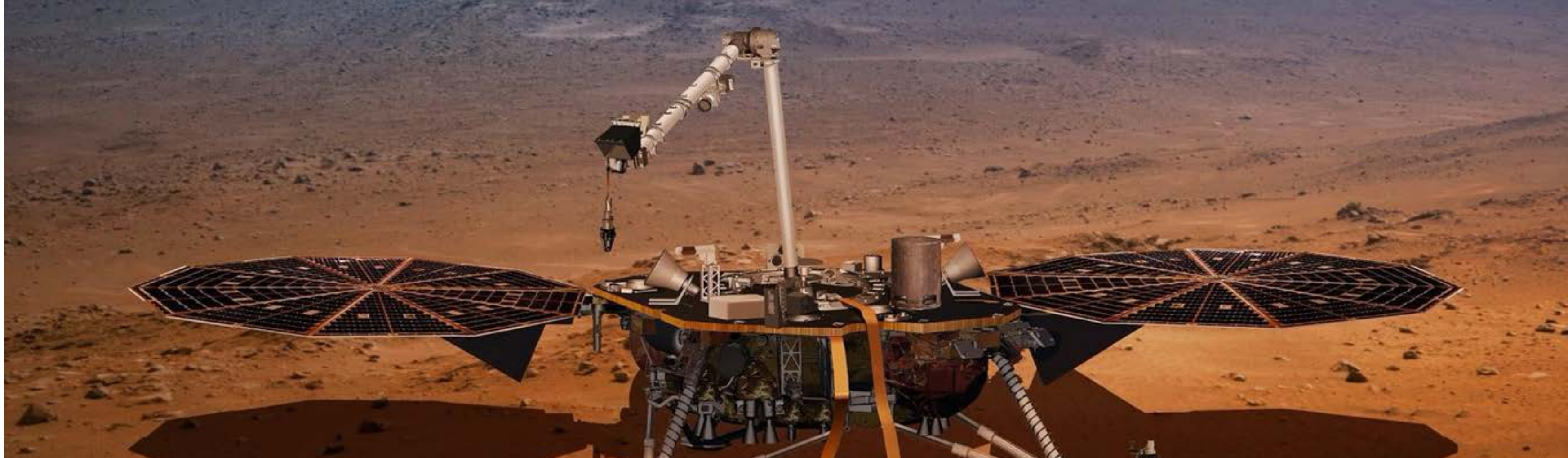


Planetary Seismology: Nearly 3 years on Mars, and a return to the Moon

Mars author list (Lunar list to follow later in the talk)

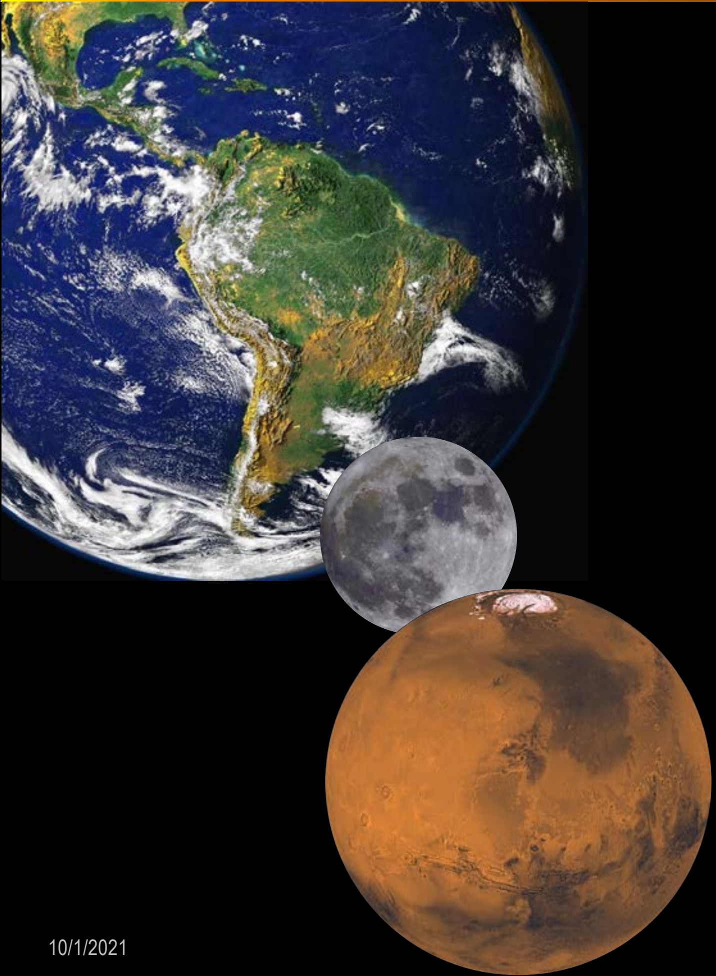
Mark Panning[1], W.B. Banerdt[1], P. Lognonné[2], W.T. Pike[3], D. Giardini[4], R. Lorenz[5], E. Bozdag[6], J. Clinton[4], R. Garcia[7], J. Irving[8], T. Kawamura[2], S. Kedar[1], B. Knapmeyer-Endrun[9], L. Margerin[10], D. Mimoun[7], N. Schmerr[11], N. Teanby[12], R. Weber[13], K. Hurst[1], M. Drilleau[2], M. Böse[4], S. Ceylan[4], C. Charalambous[3], M. van Driel[4], A. Horleston[12], A. Khan[4], M. Knapmeyer[14], G. Orhand-Mainsant[7], S. Stähler[4], A. E. Stott[3], A. Spiga[15], L. Fayon[2], B. Kenda[2], N. Brinkman[4], V. Lekic[11], N. Murdoch[7], C. Nunn[1], C. Schmelzbach[4], M. Schimmel[16], E. Stutzmann[2], B. Tauzin[17], S. Tharimena[18]

1. Jet Propulsion Laboratory, California Institute of Technology, 2. Institut de Physique du Globe de Paris, 3. Imperial College, London, 4. ETH Zürich, 5. Applied Physics Laboratory, Johns Hopkins University, 6. Colorado School of Mines, 7. Institut Supérieur de l'Aéronautique et de l'Espace (ISAE), 8. Princeton University, 9. University of Cologne, 10. Institut de Recherche en Astrophysique et Planétologie (IRAP), 11. University of Maryland, 12. University of Bristol, 13. NASA Marshall Space Flight Center, 14. DLR Berlin, 15. Laboratoire de Météorologie Dynamique, 16. Instituto de Ciencias de la Tierra Jaume Almera, 17. Australian National University 18. University of Vienna

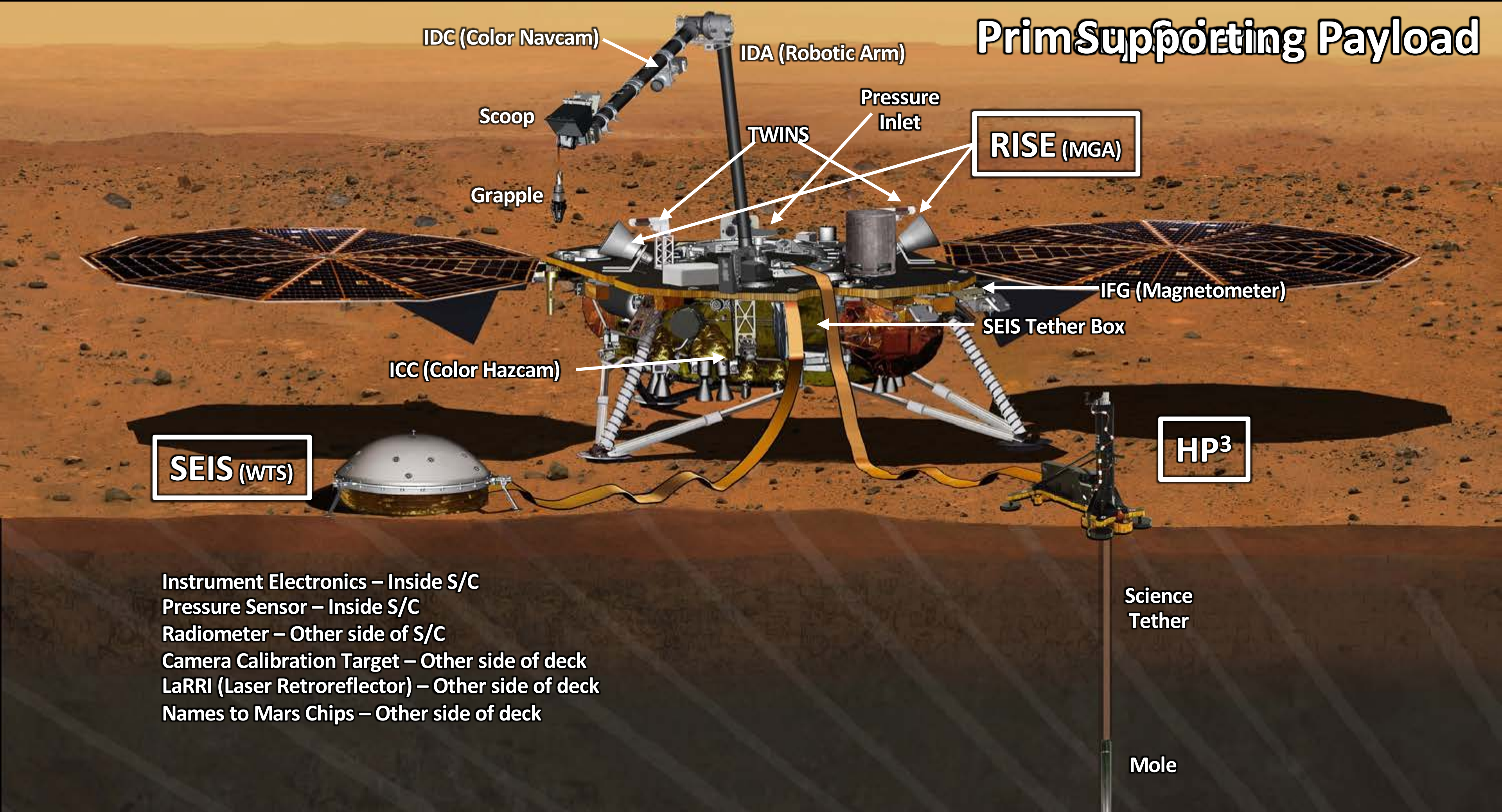
The InSight Science Team

Bruce Banerdt, Sue Smrekar, Daniele Antonangeli, ,Sami Asmar, Don Banfield, Caroline Beghein, Neil Bowles, Ebru Bozdag, Peter Chi, Ulrich Christensen, John Clinton, Gareth Collins, Ingrid Daubar, Véronique Dehant, Matthew Fillingim, Bill Folkner, Raphael Garcia, Jim Garvin, Domenico Giardini, Matt Golombek, John Grant, Matthias Grott, Jurek Grygorczuk, Troy Hudson, Jessica Irving, Catherine Johnson, Günter Kargl, Taichi Kawamura, Sharon Kedar, Scott King, Brigitte Knapmeyer-Endrun, Mark Lemmon, Philippe Lognonné, Ralph Lorenz, Justin Maki, Ludovic Margerin, Scott McLennan, Chloë Michaut, David Mimoun, Antoine Mocquet, Paul Morgan, Nils Mueller, Seiichi Nagihara, Claire Newman, Francis Nimmo, Mark Panning, Tom Pike, Ana-Catalina Plesa, Jose-Antonio Rodriguez-Manfredi, Chris Russell, Nick Schmerr, Matt Siegler, Aymeric Spiga, Tilman Spohn, Sabine Stanley, Nick Teanby, Jeroen Tromp, Nicholas Warner, Renee Weber, Mark Wieczorek, James Badro, Silvia Boccato, Pierre Delage, Guillaume Morard, Julien Siebert, Fang Xu, Elizabeth Barrett, Tammy Bravo, Paul Davis, Simone Dell'Agnello, Ken Hurst, Mike Malin, Liliya Posiolova, Haotian Xu, Peter Grindrod, Stephen Lewis, Manish Patel, Meng Jia, Paul Sava, Laurent Gizon, Walter Goetz, John-Robert Scholz, Rudolf Widmer-Schnidrig, Conny Hammer, Natalia Wojcicka, Eleanor Sansom, Ozgur Karatekin, Valery Lainey, Sébastien Le Maistre, Jean-Charles Marty, Marie-Julie Péters, Attilio Rivoldini, Tim Van Hoolst, Marie Yseboodt, Dustin Buccino, Danny Kahan, Ryan Park, Nicolas Compaire, Guénolé Mainsant, Léo Martire, Ryan Dotson, Fredrik Andersson , Amir Bagheri, Felix Bissig, Maren Böse, Nienke Brinkman, Savas Ceylan, Fabian Euchner, Johannes Kemper, Amir Khan, Johan Robertsson, Cedric Schmelzbach, Simon Stähler, David Sollberger, Martin Van Driel, Fred Calef, Eloise Marteau, Tim Parker, Sylvain Piqueux, Nathan Williams, Sharon Purdy, Cathy Weitz, Nicholas Attree, Doris Breuer, Christian Krause , Achim Morschhauser, Bartosz Kedziora, Ewelina Ryszawa , Lukasz Wisniewski , Anna Mittelholz, Lydia Philpott, Benoit Langlais, Norbert Kömle, Joshua Poganski, Keisuke Onodera, Victor Tsai, Josh Murphy, Alejandro Sebastian Carrasco Mo, Rakshit Joshi, Charissa Campbell, John Moores, Salma Barkaoui, Alexey Batov, Eric Clévédé, Françoise Courboulex, Melanie Drilleau, Nobuaki Fuji, Jeannine Gagnepain-Beyneix, Lucile Fayon, Marouchka Froment, Tamara Gudkova, Alice Jacob, Foivos Karakostas, Balthazar Kenda, Antoine Lucas, Milena Marjanovic, Sabrina Menina, Jean-Paul Montagner, Yasuhiro Nishikawa, Clement Perrin, Sébastien Rodriguez, Lucie Rolland, Maria Saade, Henri Samuel, Martin Schimmel, Eléonore Stutzmann, Martin Vallée, Frédéric Béjina, Micha Bystricky, Marie Calvet, Marc Monnereau, Denis Savoie, Lu Pan , Cathy Quantin-Nataf , Benoit Tauzin, Damian Walwer , Baptiste Pinot , Naomi Murdoch, Laurent Pou, Véronique Ansan-Mangold, Eric Beucler, Mickaël Bonnin, Yann Capdeville, Olivier Verhoeven, Mariah Baker, Kevin Lewis, Vedran Lekic, Ceri Nunn, Saikiran Tharimena, Simon Calcutt, Constantinos Charalambous, Jane Hurley, John McClean, Gerald Roberts, Zachary Slingsby-Smith, Alex Stott, Tris Warren, Sebastiano Padovan, Nicola Tosi, Antonio Molina Jurado, Jorge Pla-Garcia, Daniel Viúdez-Moreiras, Steve Joy, Yanan Yu, Quancheng Huang, Foivos Karakostas, Doyeon Kim, Ross Maguire, Angela Marusiak, Norbert Schorghofer, Mackenzie White, Jean-Pierre Williams, Jose Andrade, Daniel Nunes, Lujendra Ojha, Audran Borella, François Forget, Anni Määttänen , Ehouran Millour, François Ravetta, Axel Hagermann, Ernst Hauber, Ralf Jaumann, Jörg Knollenberg, Christos Vrettos, Benjamin Fernando, Anna Horleston, Kuangdai Leng, Bob Myhill, Tarje Nissen-Meyer, Jennifer Stevanović, James Wookey, Carène Larmat, Youyi Ruan, Maria Banks, Jesse Dimech, Heidi Haviland, Martin Knapmeyer, Brian Shiro, Adrien Broquet, Katarina Miljkovic, Tanja Neidhart, Andrea Rajsic, Mélanie Thiriet, Jeremie Vaubaillon,

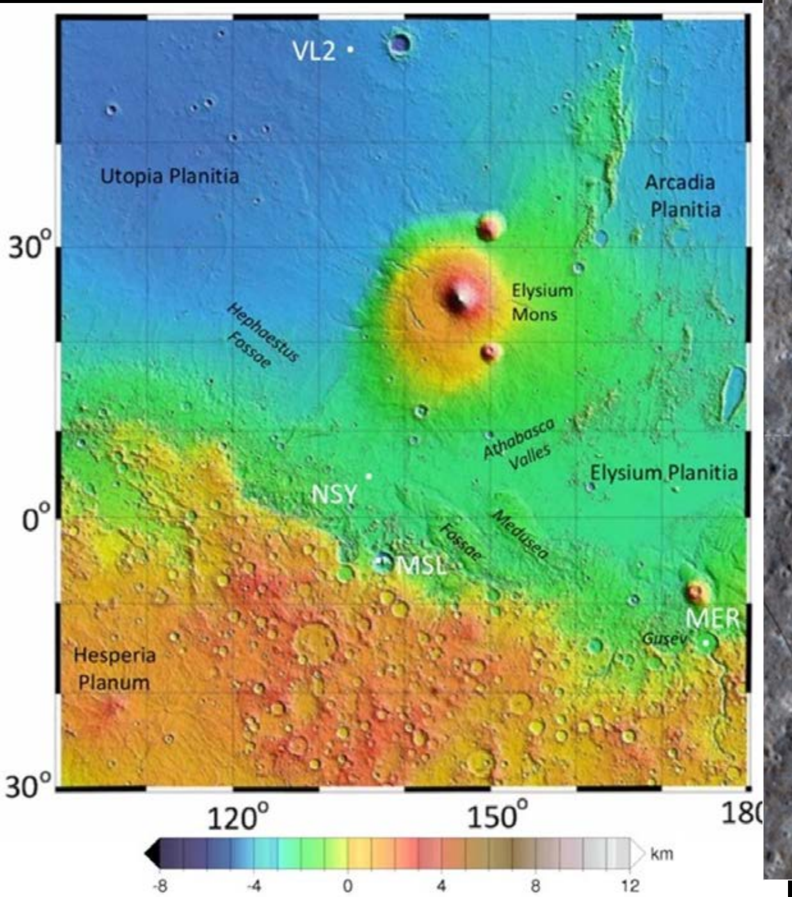
Mars is Only the Third Planetary Interior to be Investigated in Detail

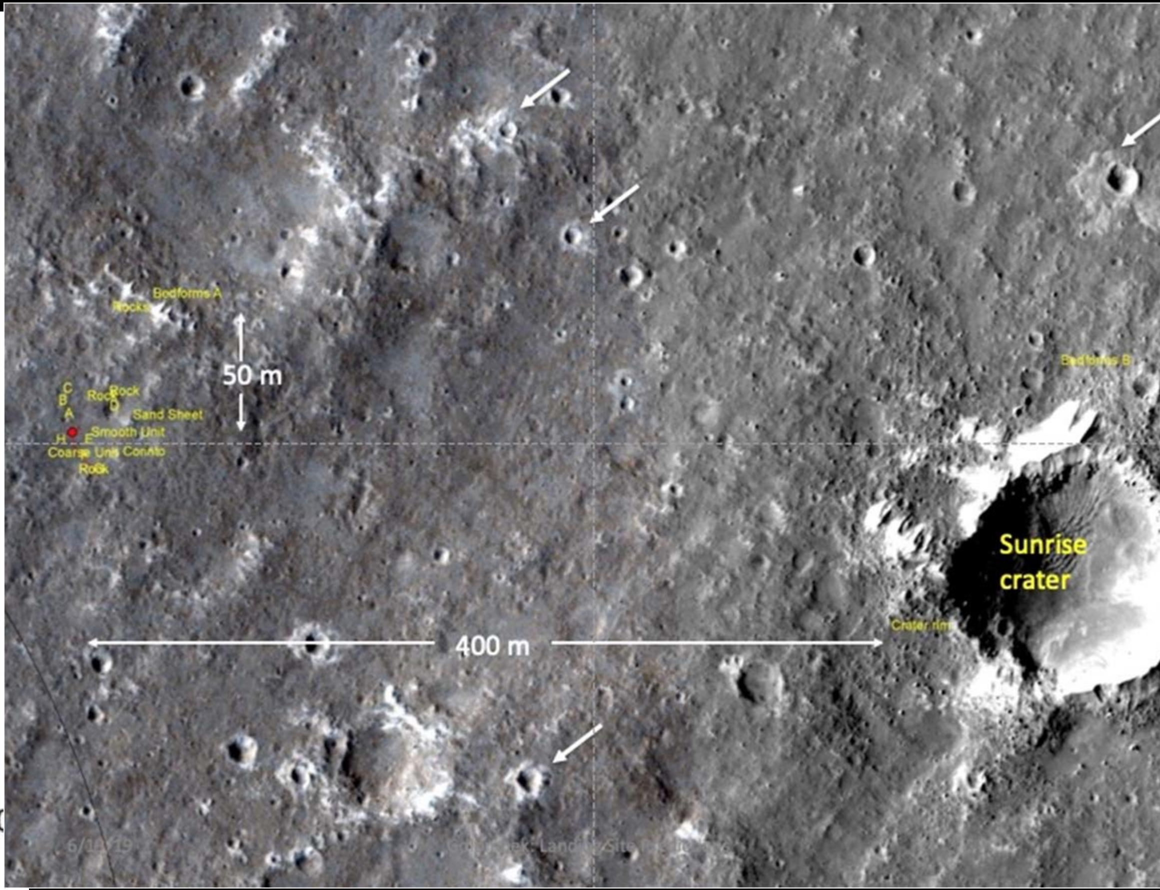


- InSight follows in the footsteps of terrestrial geophysics at the dawn of the 20th century, attempting to answer basic questions about the planet:
  - What is the thickness of the crust?
  - What is the structure of the mantle?
  - What is the size and density of the core?
  - What is the distribution of seismicity?
  - What is the planetary heat flow?
- It also follows a similar path taken a half-century ago on the Moon, when Apollo put in place a lunar seismic/heat flow/laser retroreflector network.
- The overarching goal motivating this mission is to better understand the processes of planetary differentiation that formed the terrestrial planets, and the global processes that subsequently modify them.


PrimSupporting Payload
IDC (Color Navcam)
IDA (Robotic Arm)
Scoop
Grapple
TWINS
Pressure Inlet
RISE (MGA)
IFG (Magnetometer)
SEIS Tether Box
ICC (Color Hazcam)
SEIS (WTS)
HP³
Instrument Electronics – Inside S/C
Pressure Sensor – Inside S/C
Radiometer – Other side of S/C
Camera Calibration Target – Other side of deck
LaRRI (Laser Retroreflector) – Other side of deck
Names to Mars Chips – Other side of deck
Science Tether
Mole

Landing Site: Elysium Planitia



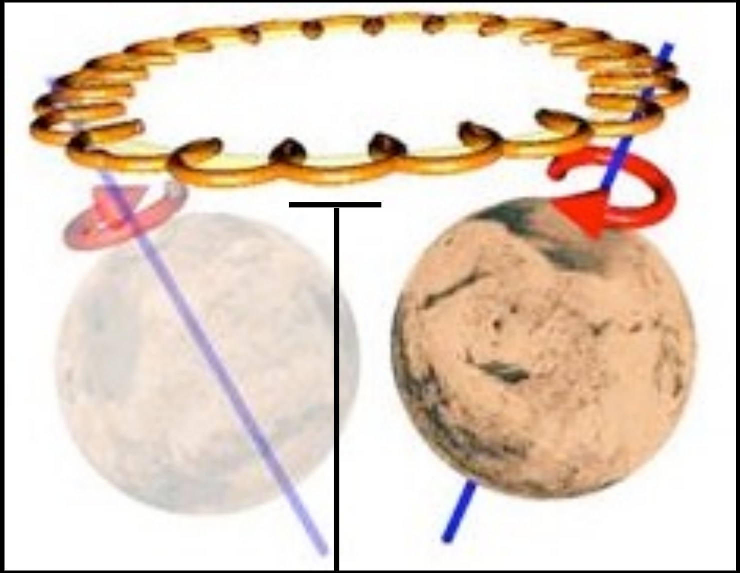


Landing Site: Elysium Planitia

Precise Radio Tracking from RISE

- Determines spin axis direction in 20 years intervals (Viking-Mars Pathfinder-InSight)
- 2 years of data needed for:
  - core radius & density
  - Free core nutation constrains CMB density jump

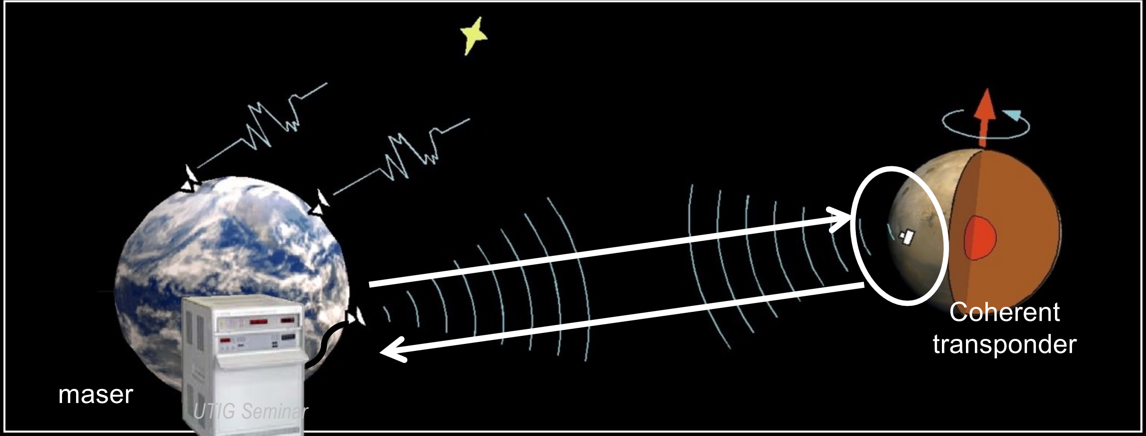
Precession (165,000 yr)



Nutation (≤1 Mars yr)

RISE Status

- X-band tracking determines lander location <10 cm in inertial space.
- Several 1-hr long measurements/week (reduced to 30 minutes in extended mission)
- Improved precession estimate verifies moment of inertia and liquid (outer) core
- The prograde semi-annual and retrograde ter-annual nutations require a core radius between 1780 and 2080 km, towards the upper end of pre-mission expectations

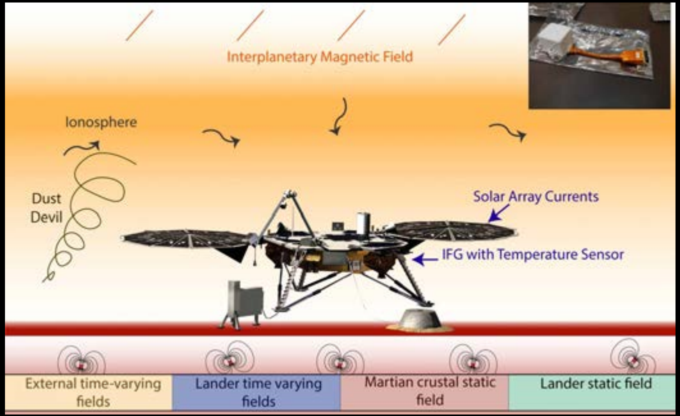


Magnetic Field Results (IFG – InSight Fluxgate Magnetometer)

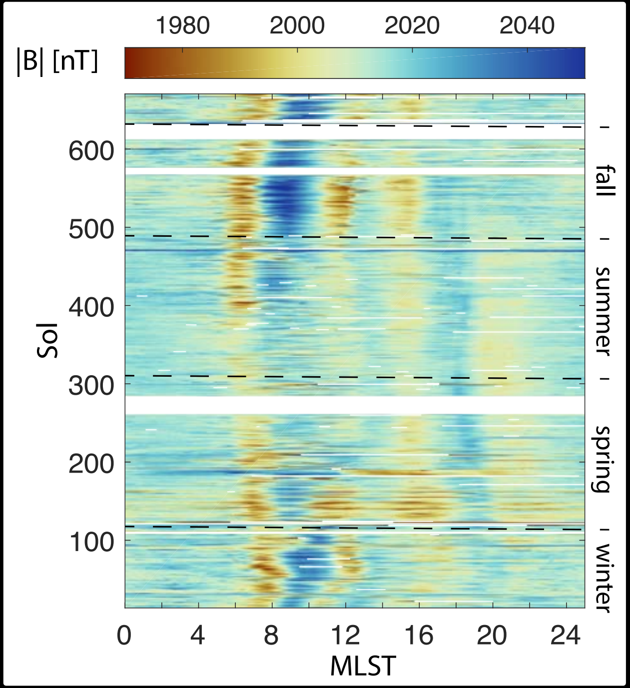
First magnetic measurements from the surface of Mars.

- **Crustal Field:** The DC field at the landing site ~2000 nT (10x larger than orbital predictions) → significant crustal field variations at spatial scales <~150 km.

- **Time Varying Fields:** Different periodicities, e.g.
  Pulsations (T~ 10-100s)
  Ionospheric wind-driven fields (diurnal/annual)

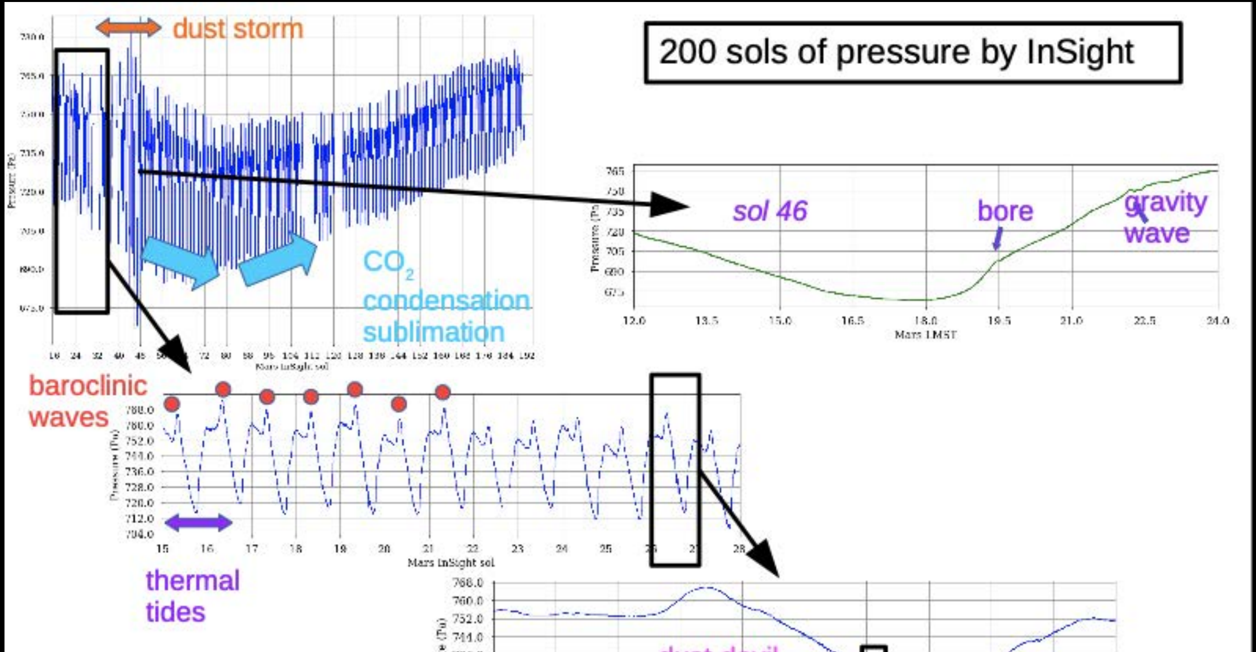


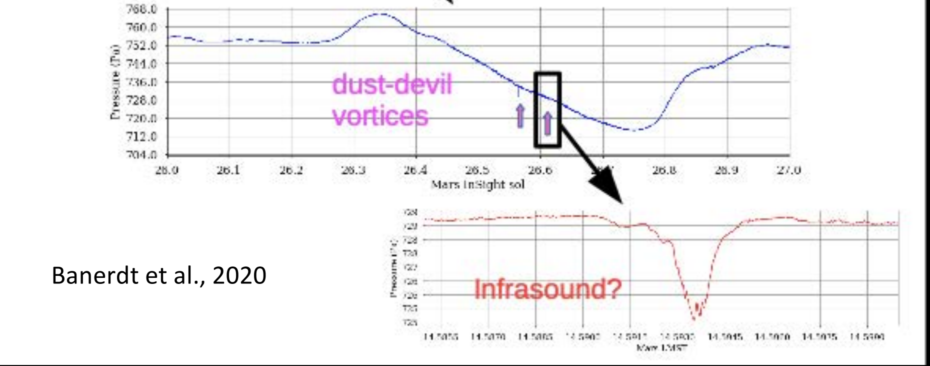
Johnson et al., *Nat. Geo.*, 2020; Mittelholz et al., *JGR*, 2020



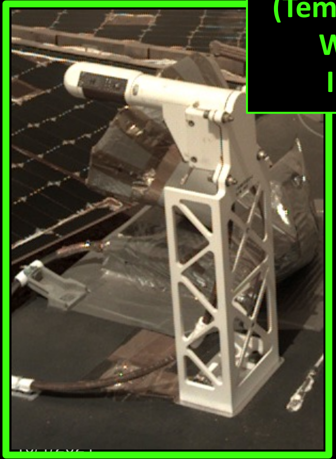
InSight Meteorology

InSight is returning continuous high-rate pressure, temperature, and wind measurements, providing an unprecedented view of atmospheric behavior at time scales from less than a second to months and seasons.





TWINS (Temperature & Wind for InSight)



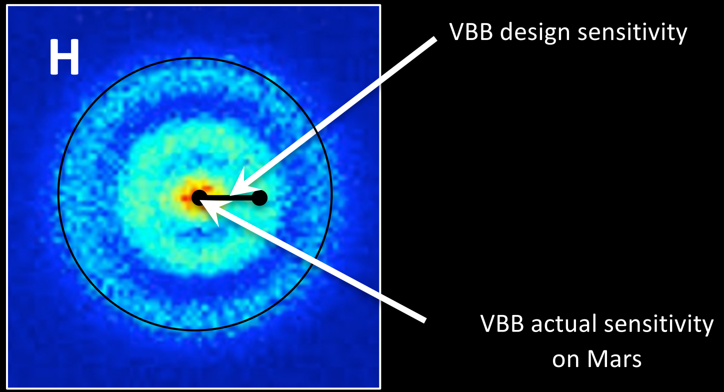
Pressure Sensor

The Challenge of Operating a Seismometer on Mars

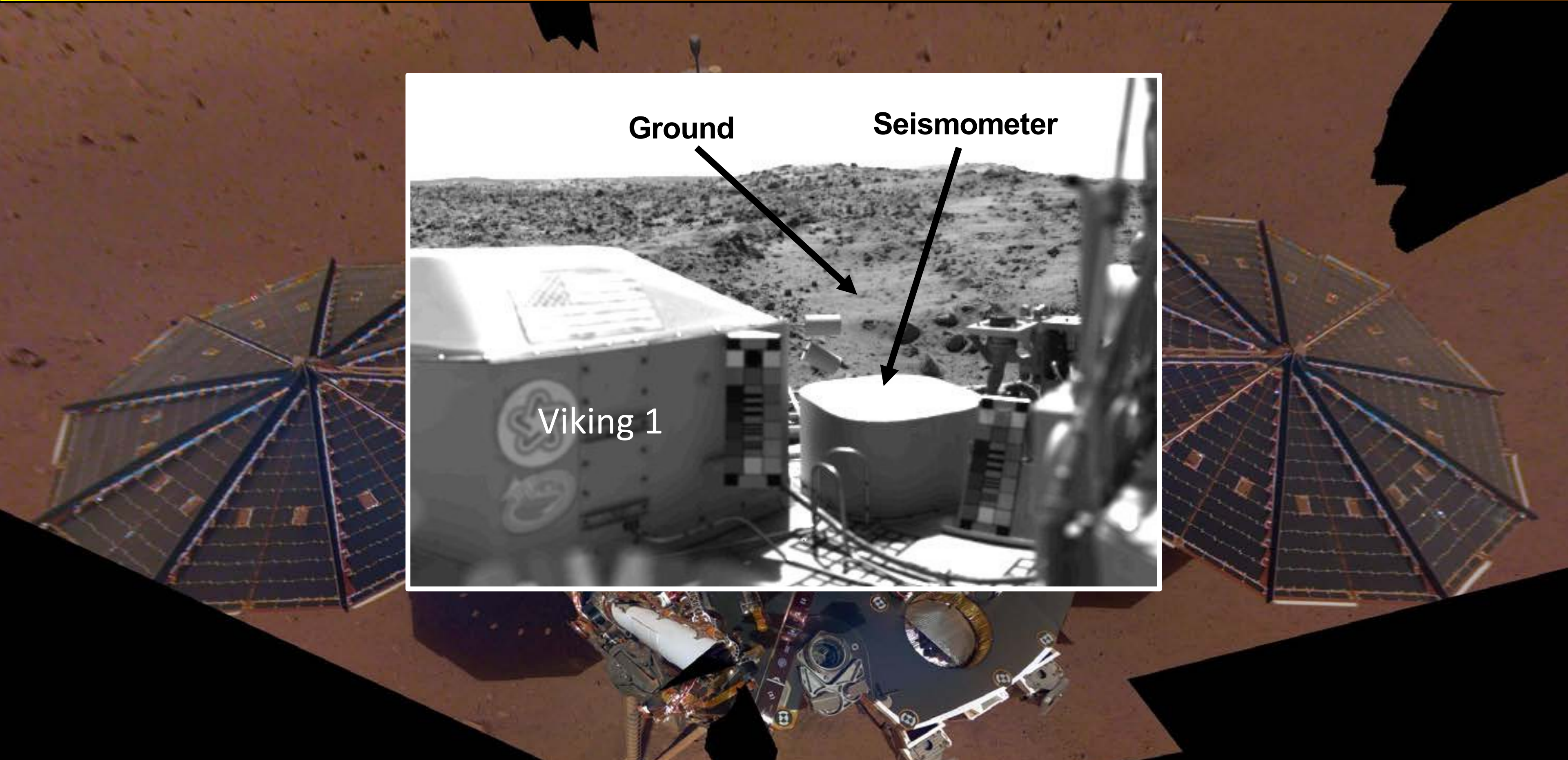
It's All About the Noise!

- Need extremely high sensitivity – expect fewer and smaller quakes than on the Earth
  - Sensitivity target: $2.5\times10^{-9}\,\mathrm{m/sec^2/Hz^{1/2}}$
  - This is equivalent to displacement amplitudes smaller than a hydrogen atom

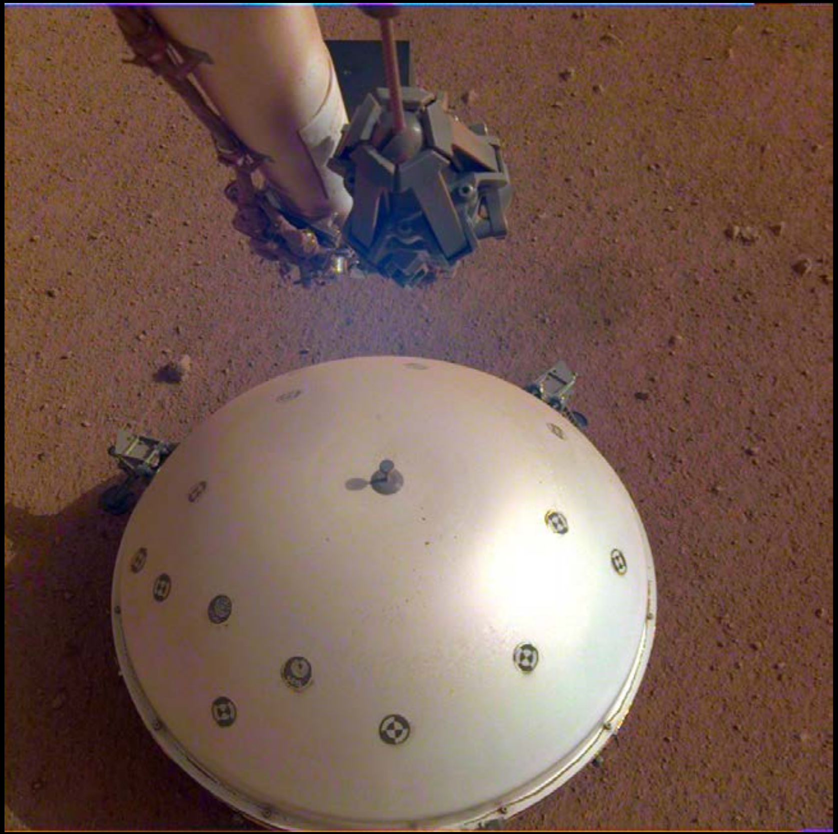
- Therefore one must minimize/compensate for all noise sources:
  - Instrument intrinsic noise
  - Temperature variations
  - Wind
  - Atmospheric pressure variations
  - Magnetic field variations
  - Lander vibrations



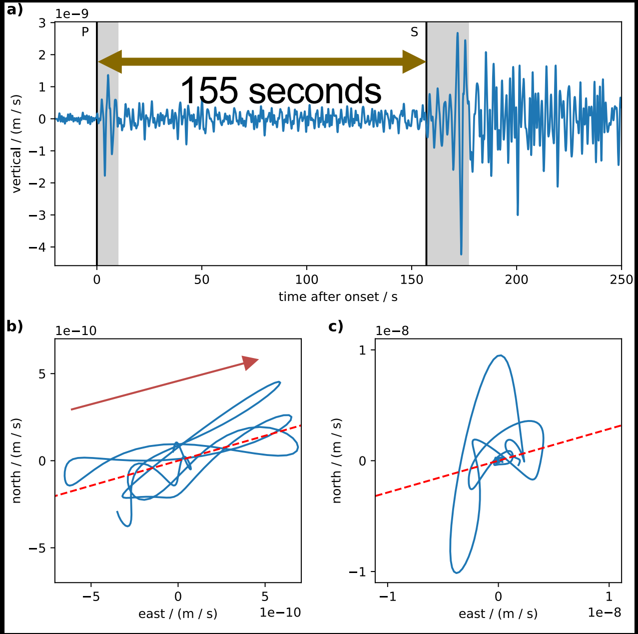
SEIS on Mars – Almost



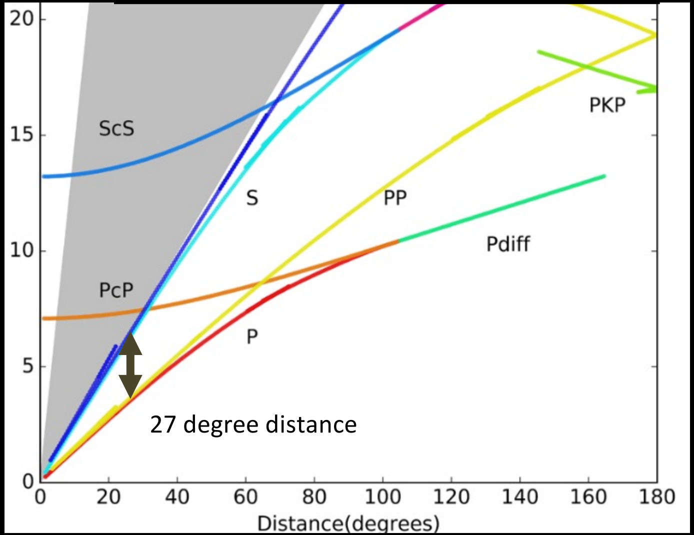
SEIS Deployment



Locating marsquakes with a single station



M. van Driel

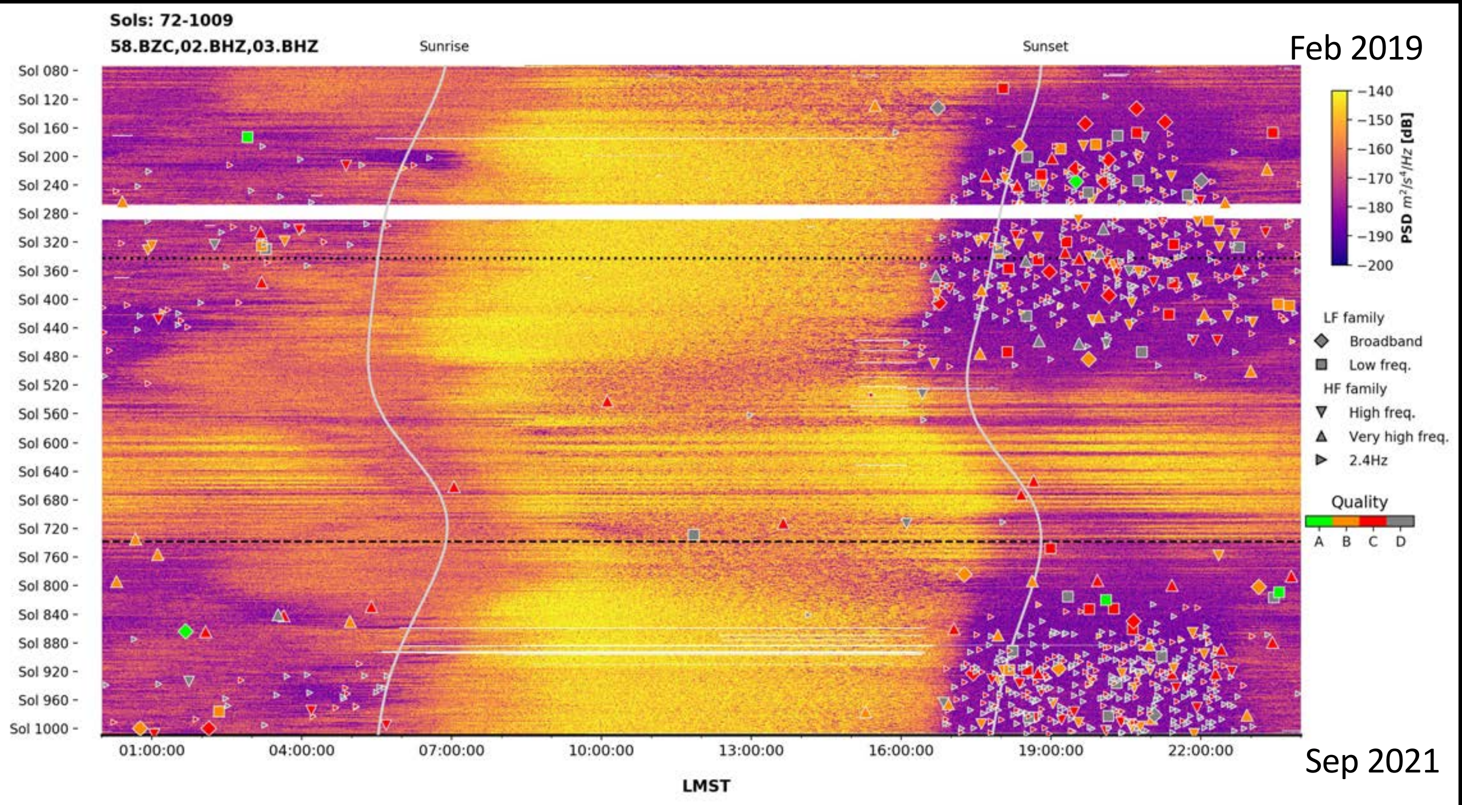


Ceylan et al. (2017)

Direction

Distance

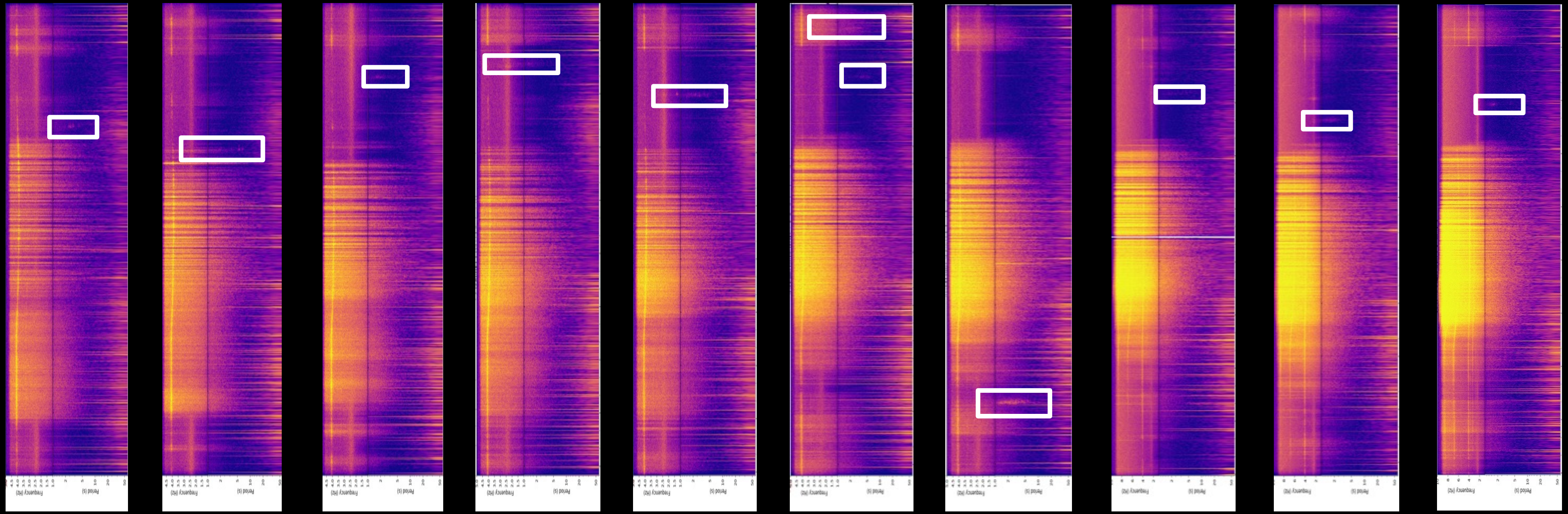
All Seismic Data Through Sol 1008 (Monday)



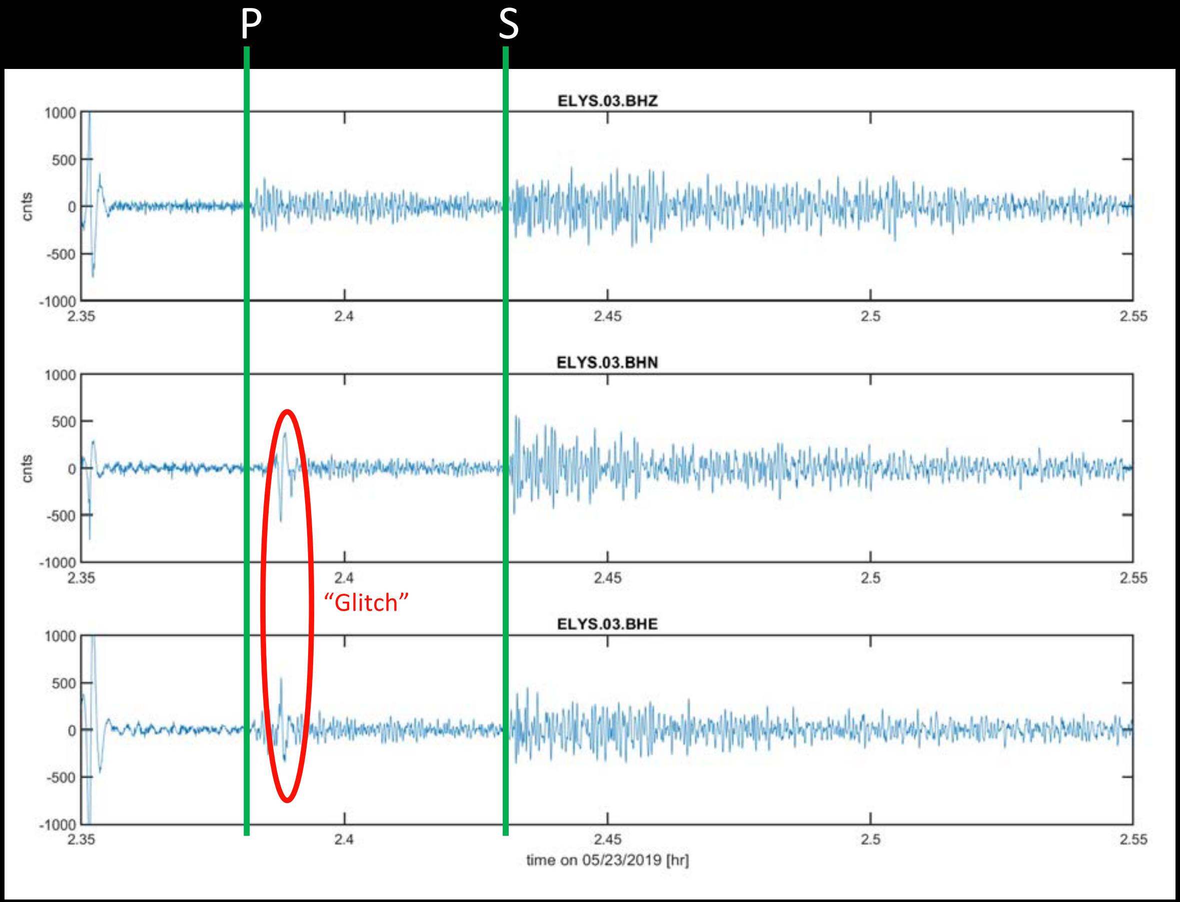
- 938 events total
- Most are high frequency events.
- Quiet evening period disappeared due to seasonal effects, but returned when we wrapped around to the time of year of full deployment

Some example SEIS event detections

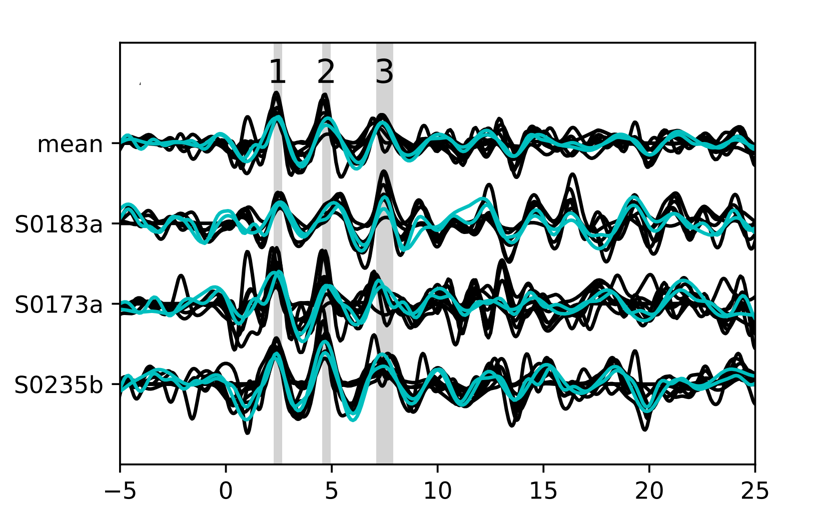
Sol-Long Images – Some early Low Frequency and Broad Band Events through sol 200



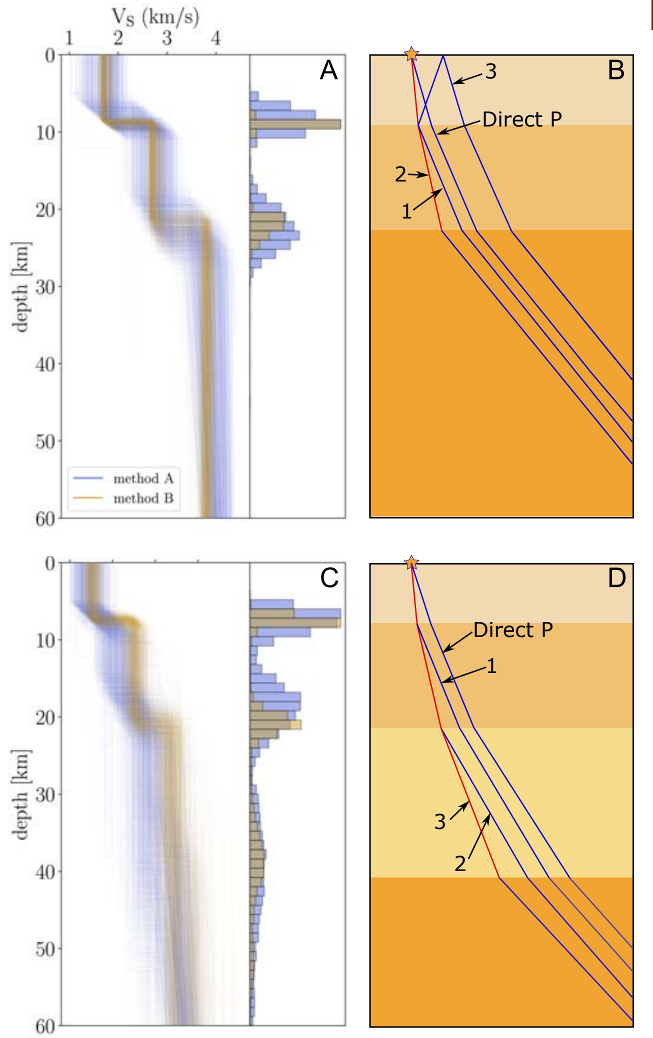
First “large” event: S0173a (BA), Magnitude 3.7



SEIS constraining the crust

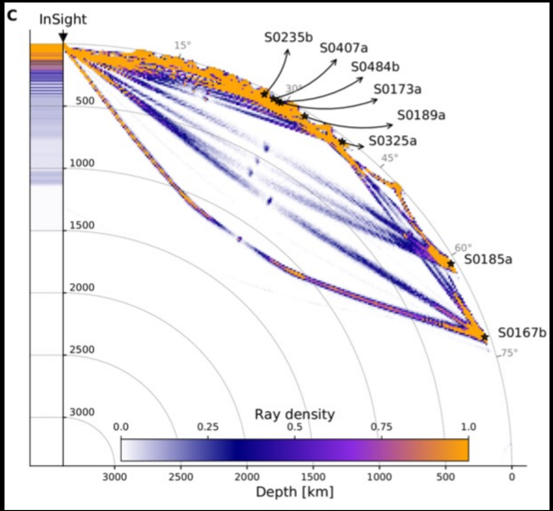


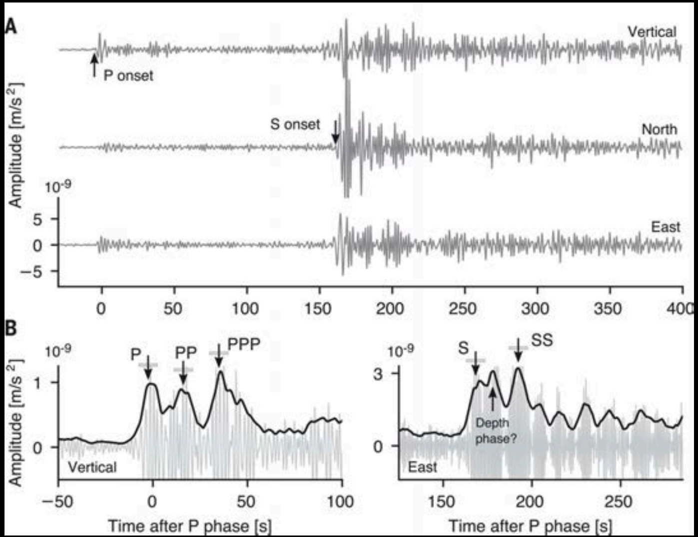
Figures from Knapmeyer-Endrun et al. (Science, 2021)

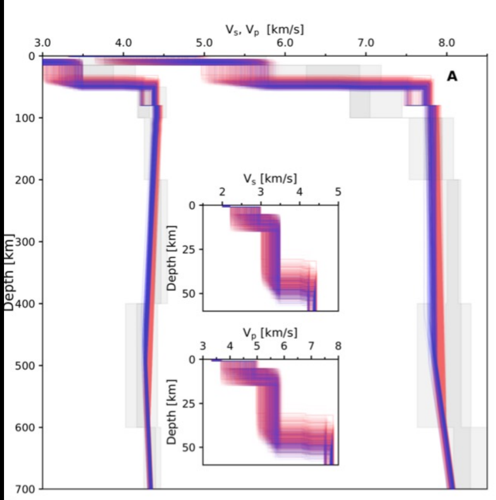


- We can look for arrivals buried after the P-wave that represent conversions to S waves below the lander
- 3 events had clean enough polarized records to try this on (more recent ones appear to be consistent as well)
- 3 arrivals could be from 2 or 3 layer model – 2 possible crustal thicknesses

SEIS constraining the mantle







From Khan et al. (Science, 2021)

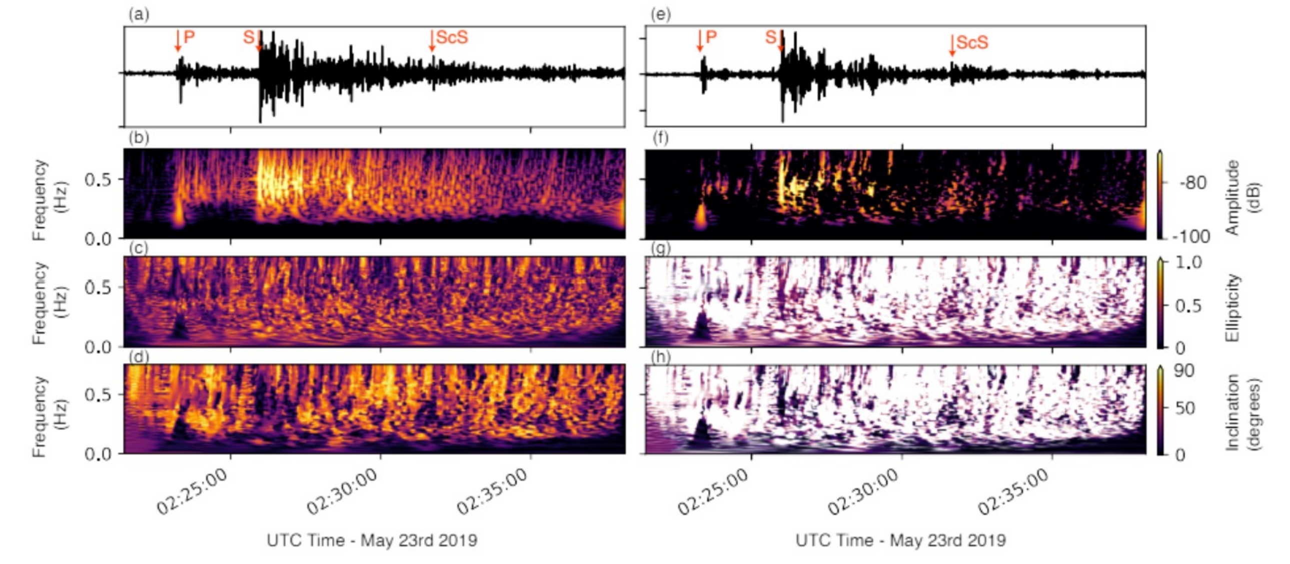
First results for mantle seismic velocities

- Relies on picks of seismic phases which bounce off the surface (PP, PPP, SS, SSS)
- S-wave Low Velocity Zone in upper mantle.
- Thermal gradients 1.6–2.5 K/km.
- Thermal lithospheric thickness 400 – 600 km.
- Mantle potential temperature 1600-1700K.

→ Thermal structure more compatible with ‘cool’ mantle models

→ Puzzle cf crustal results. May point to 3D structure.

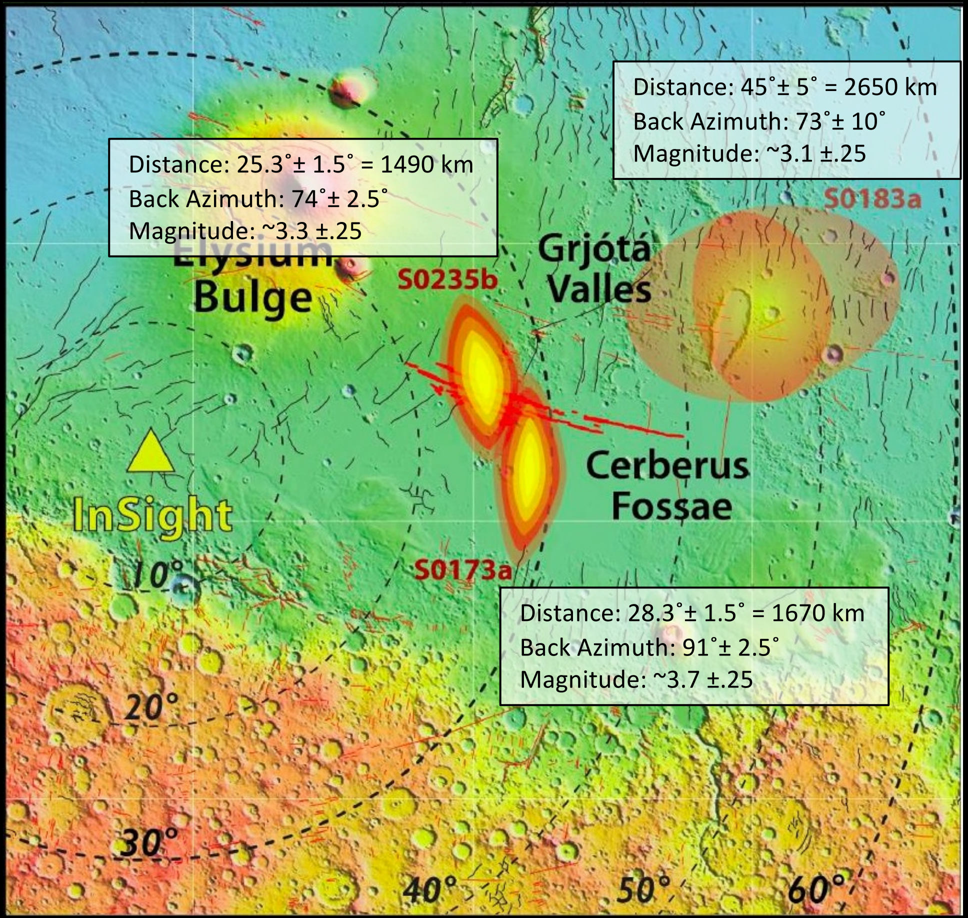
SEIS constraining the core



- With careful polarization filtering, a phase consistent with ScS (which bounces off the core), can be spotted in 6 events just above the noise, including the clearest one in S0173a (left)
- All show arrivals consistent with a core radius of ~1830 +/- 40 km, in general agreement with the RISE results

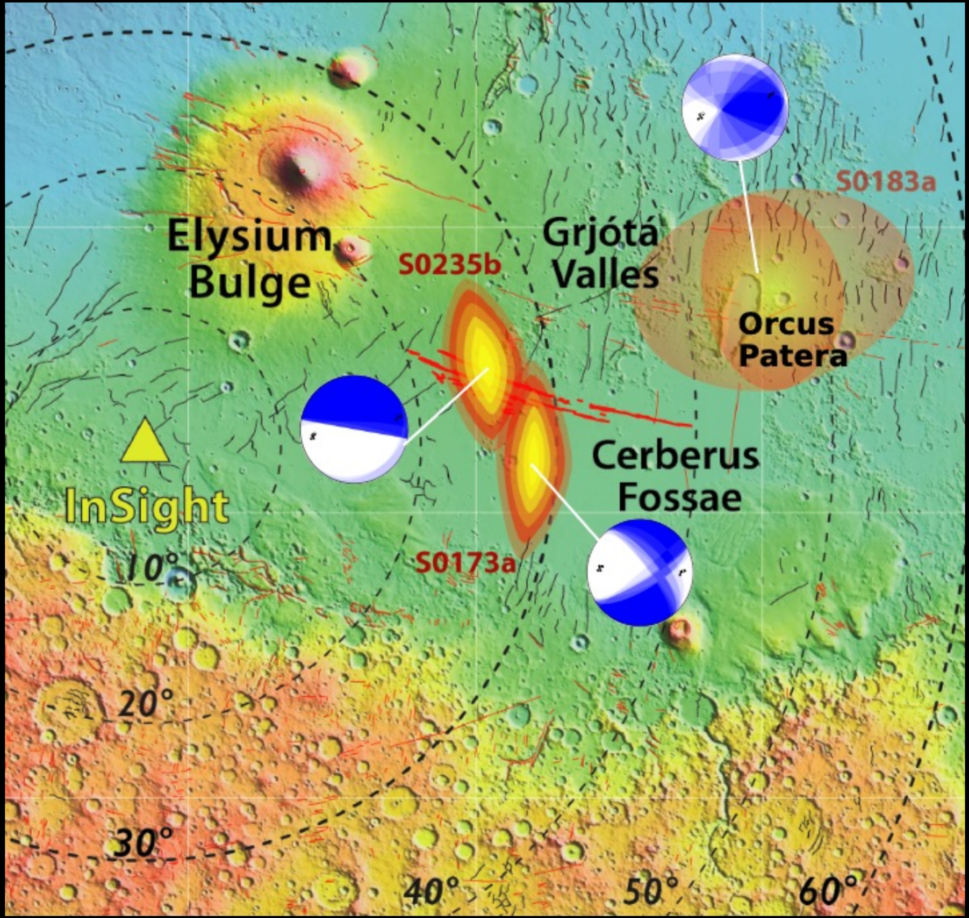
From Stähler et al. (Science, 2021)

Source Locations for Three Events



From Giardini et al., 2020

Source Mechanisms for Three Events

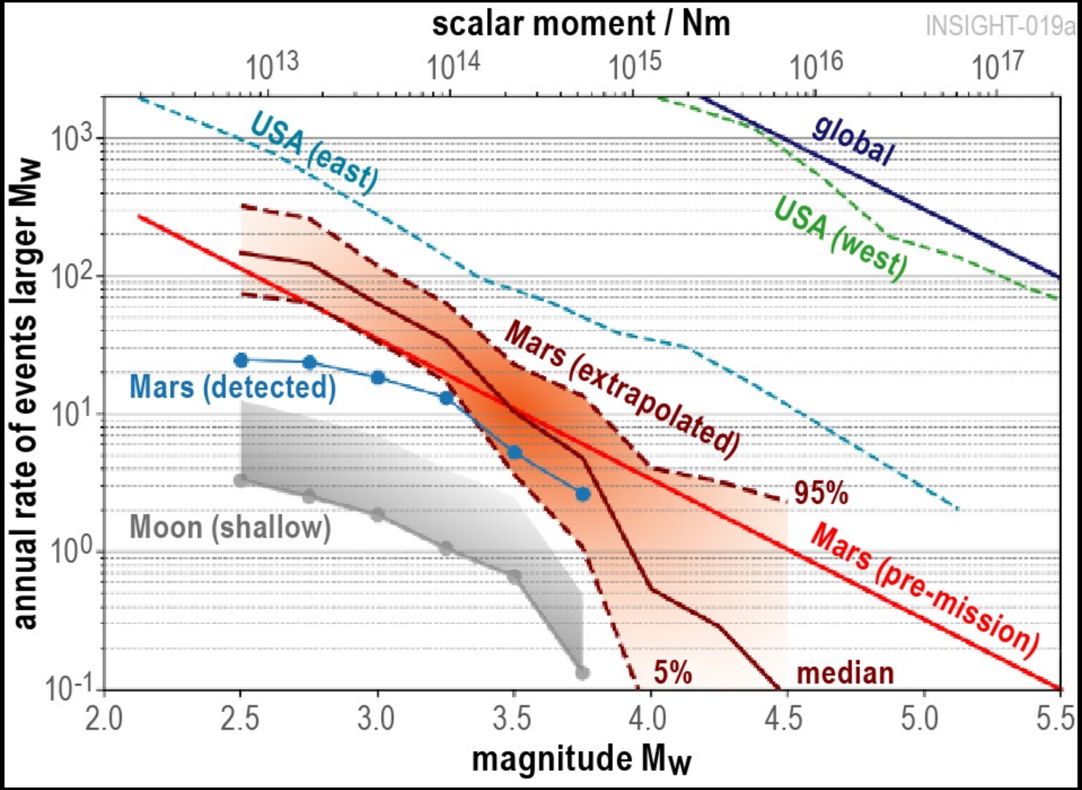


- Based on waveform inversions for the three events
- S0235b gives the cleanest results consistent with near-vertical normal faulting aligned with Cerberus Fossae fractures
- S0173a is less well-resolved and more oblique
- S0183a is relatively poorly resolved

From Brinkman et al., 2021

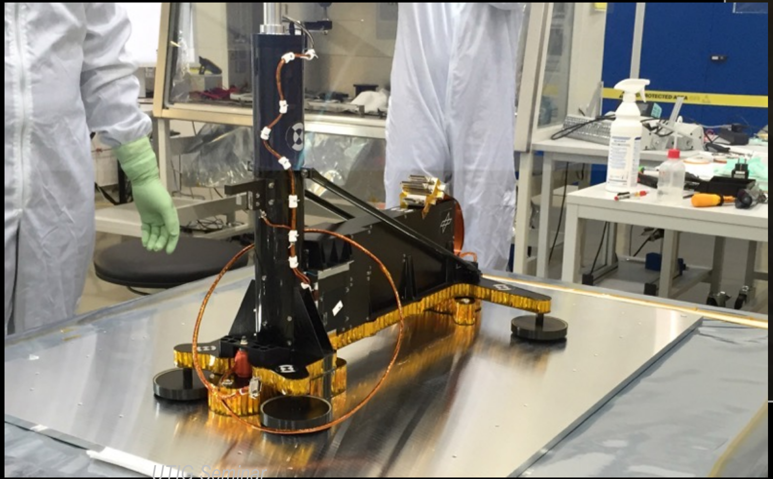
Estimating Seismic Activity Rate

- Mars' activity appears to be close to pre-InSight predictions, perhaps somewhat higher
- However, there is an apparent deficit of larger marsquakes, which may be bad luck.
- Hopefully, we'll be more lucky in the upcoming extended mission… or we'll find out Mars acts different than the Earth!



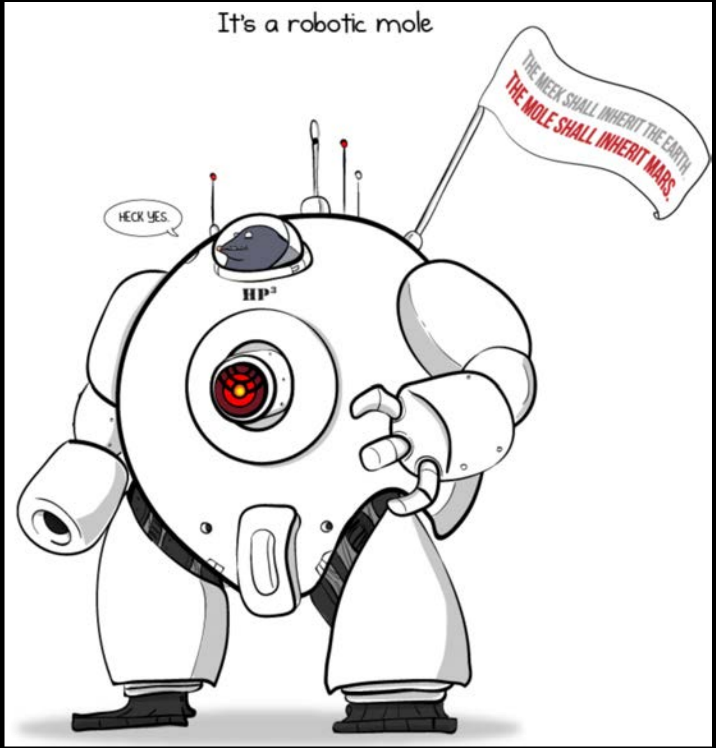
Heat Flow and Physical Properties Measurement – HP^3

- HP^3 includes a penetrator (the “mole”) that was designed to burrow up to 5 meters below the surface.
- Cable and mole contain precise temperature sensors to measure the temperature changes with depth and the thermal conductivity in order to measure heat flow
- A radiometer to measure the surface radiation temperature to constrain boundary condition and near-surface properties completes the package



What about the Mole?

- The Heat flow and Physical Properties Package (HP3) was designed with a “mole” which was supposed to hammer itself down to a depth of 3-5 meters and measure heat flow.
- After release, it hammered very quickly down to about 35 cm, and then stopped



Slightly fictional visualization of the Mole by The Oatmeal (© 2018 Matthew Inman https://theoatmeal.com/comics/insight)

To make matters worse, after our first round of trying to help it down, the darn thing backed itself out.

Space is hard!

The end of the line

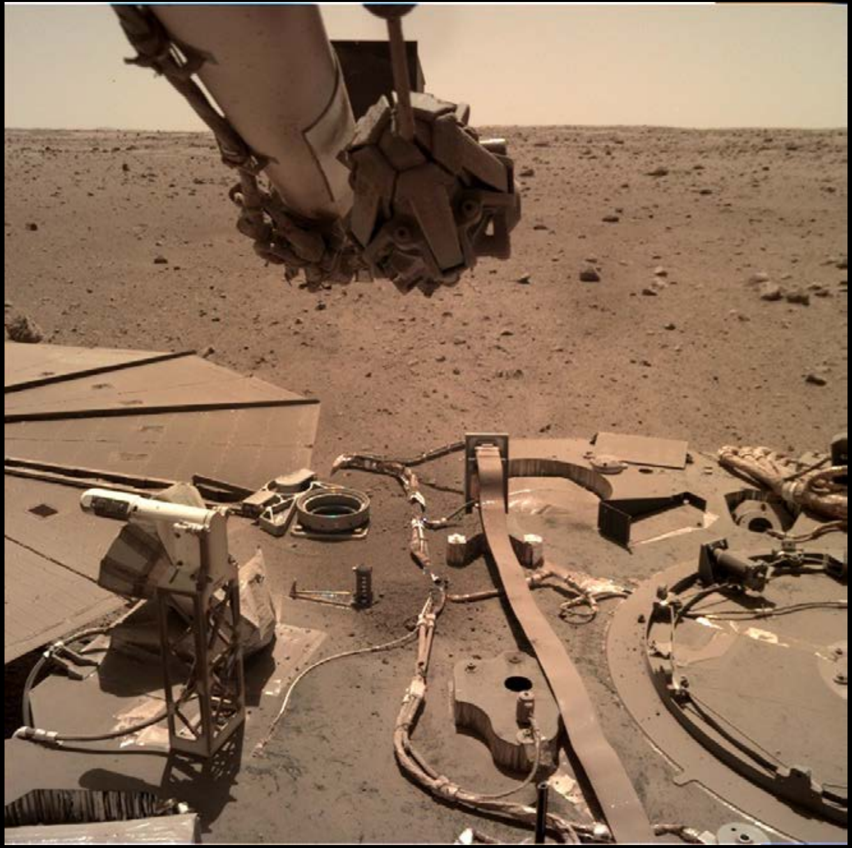
Our engineering team did heroic work to get the mole buried, but in January, we officially ceased efforts to get the mole to depth. It is still a buried thermal properties sensor, and the radiometer continues observation providing constraints on near-surface thermal properties and surface-atmosphere heat exchange.

Energy concerns…

Mars is a dusty place, and the solar panels are currently generating much less energy than at the beginning of the mission

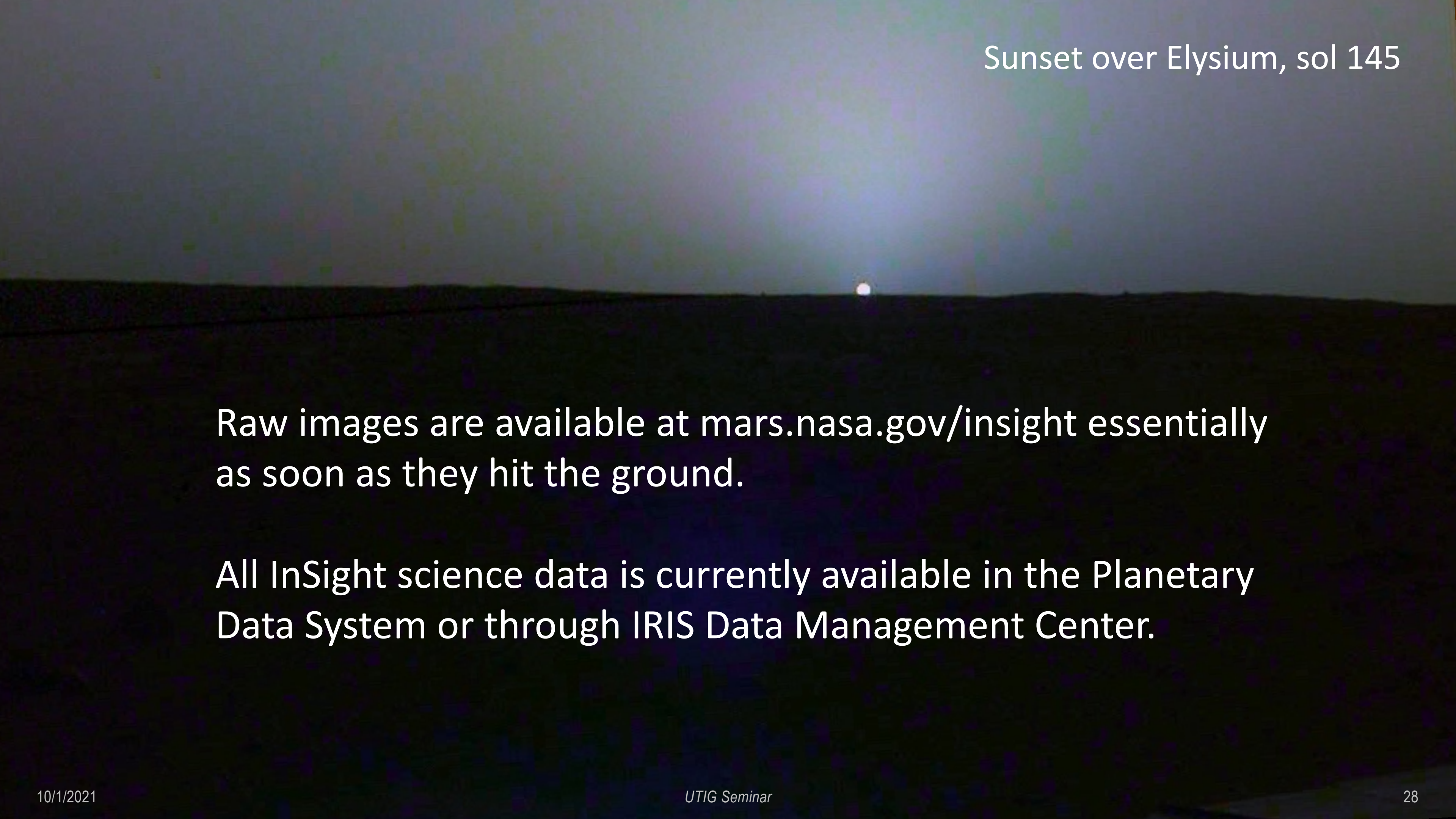
We've just passed through aphelion, when our energy production is at its lowest, and our heating needs are at their greatest

We've continued operating with two main approaches to extending operations



Summary for InSight discussion

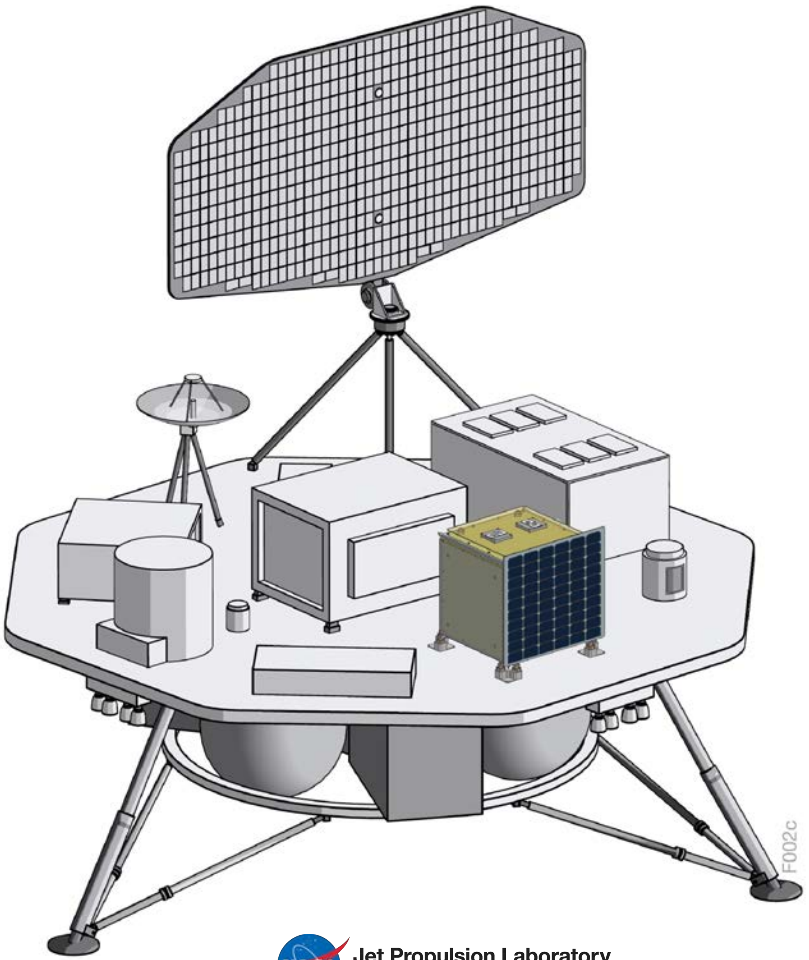
- Deploying a seismometer on Mars is a long, slow process.
- The data, though, is quieter than anywhere on Earth in some frequency bands
- We have detected many events and located several of them
- Working on Mars with a robot you can only command every few days or once a week is hard



Sunset over Elysium, sol 145

Raw images are available at mars.nasa.gov/insight essentially as soon as they hit the ground.

All InSight science data is currently available in the Planetary Data System or through IRIS Data Management Center.

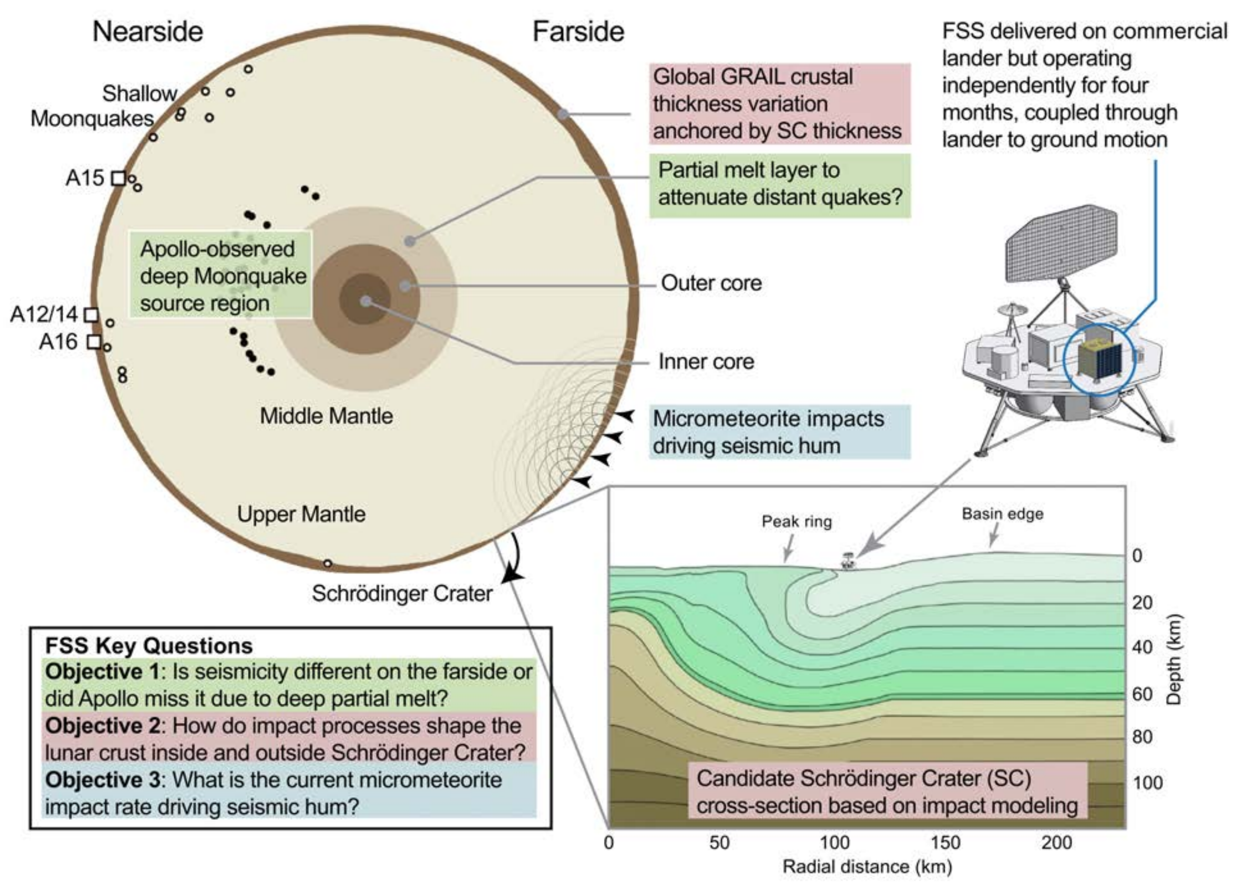


Part 2: Farside Seismic Suite

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], Philippe Lognonné[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 Laboratory, 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

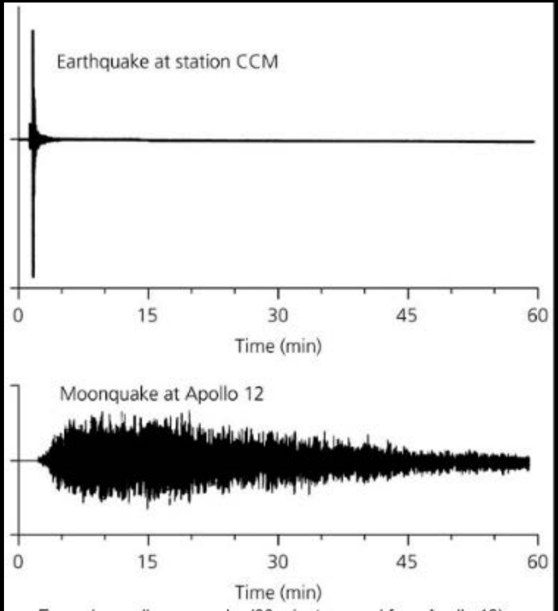
The Concept

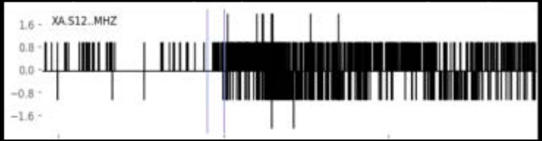


Global cross-section adapted from Wieczorek et al. (2009) and Schrödinger cross-section from Kring et al. (2016)

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

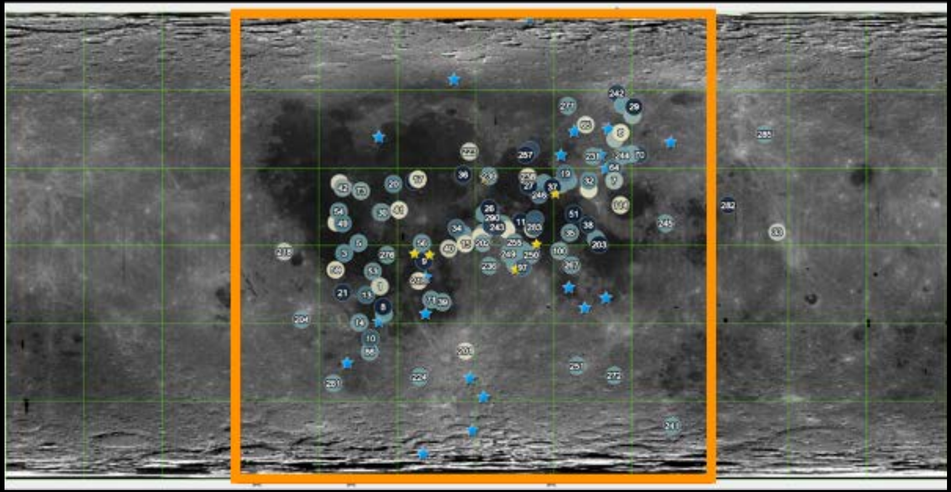


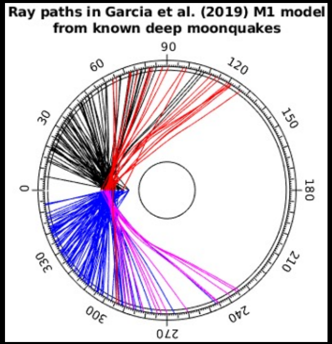


- Lunar seismology is very different than Earth seismology with unique challenges
- The Apollo instruments were extremely sensitive instruments, but were limited by very coarse digitization
- Apollo measurements were only made at the nearside landing locations
- Landing modern, sensitive instruments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

Farside Seismicity

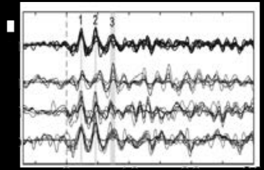
- Nearly all located deep moonquake clusters and shallow moonquake locations are on the nearside of the Moon
- How much of this is due to attenuation in the deep lunar mantle and how much is due to fundamental differences in seismicity?
- Paths from known repeating deep moonquake locations to Schrödinger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

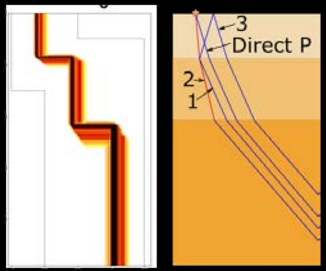




Local structure at Schrödinger

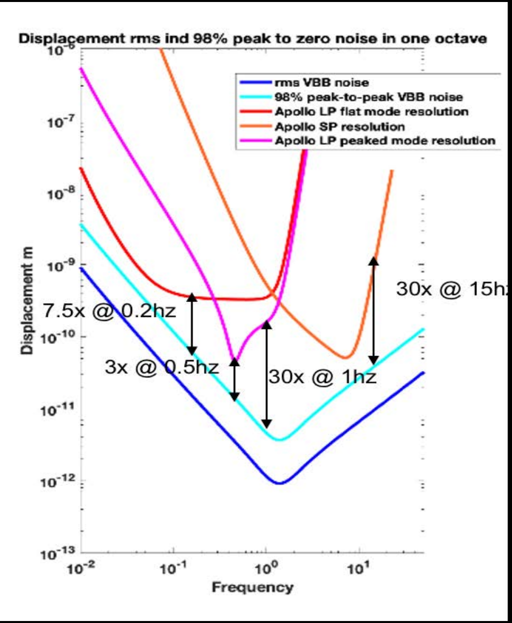
- Schrödinger Crater is well-preserved impact crater with a peak ring and smooth floors interpreted as impact melts
- 3-component seismic records present the potential for resolving crustal thickness and layering through a receiver function approach
- Continuous noise records can be autocorrelated to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



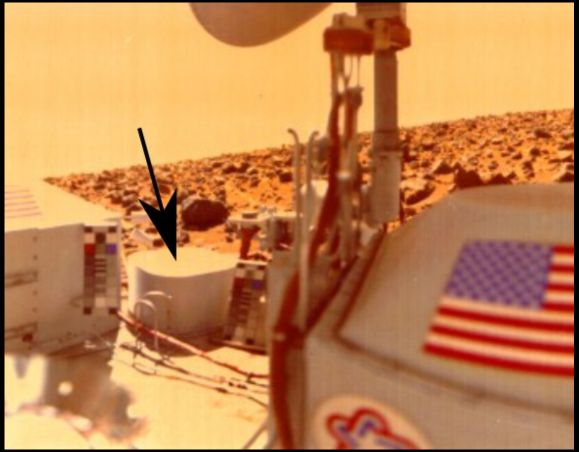


The lunar background hum

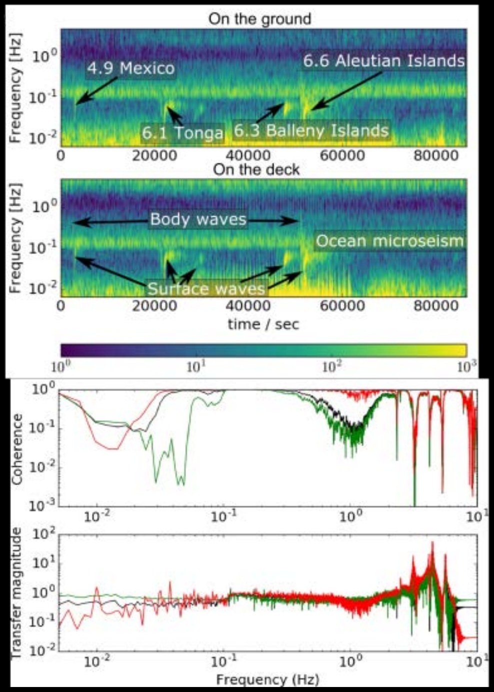
- The background seismic noise on the Moon is expected to be driven by the regular impacts of micrometeorites (Lognonné et al. 2009)
- Apollo seismometers were not able to record the level of this background noise due to the sensitivity of the instruments and the digitization noise
- VBBZ will record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



Can we record without deploying to the surface?

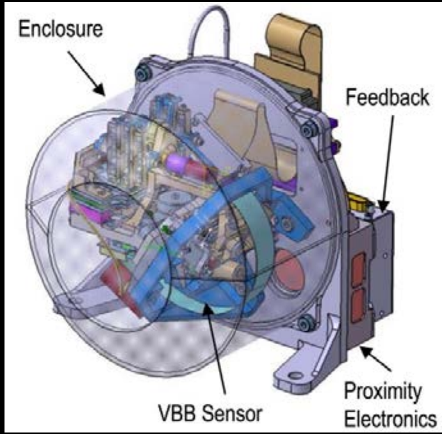


- The Viking mission (and InSight before deployment) taught us that a deck-mounted seismometer faces difficulties
- But experiments on the engineering model of the MSL Curiosity rover show ground motion can be well-coupled through the structure of a spacecraft below the resonant frequency
- On the Moon, 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)

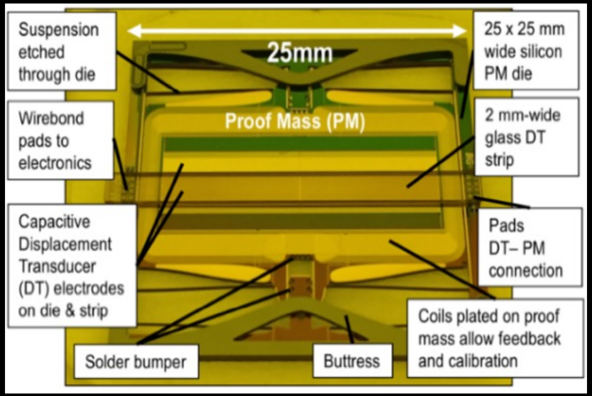
The VBBZ seismometer

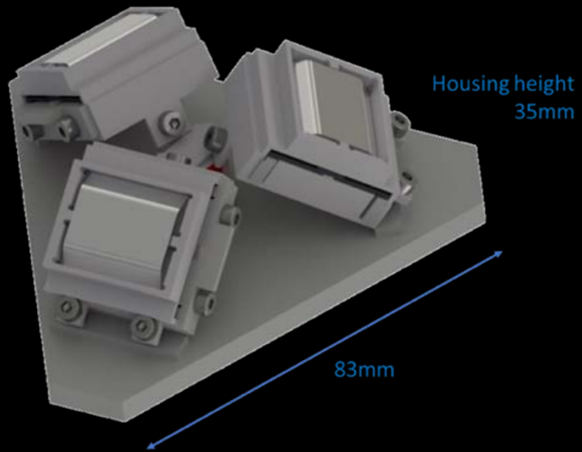


- Uses a flight spare VBB seismometer from the InSight mission
- Spring needs to be replaced to account for lunar gravity and rotated to sense vertical motions (rather than 3 tilted components as in InSight)
- Packaged in enclosure which allows venting to attain vacuum on the Moon
- Contributed by CNES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

The SP seismometer

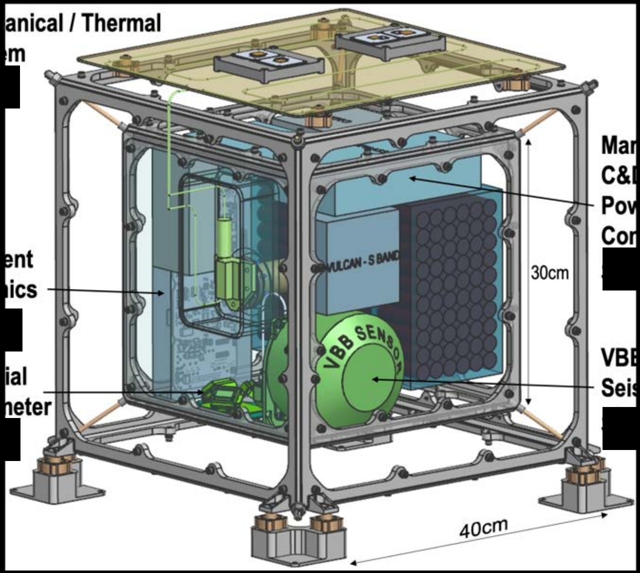
- Micromachined silicon system
- New build based on InSight heritage
- Spring adjusted for lunar gravity and changed to Galperin configuration (3 tilted components) rather than 1 vertical and 2 horizontal sensors as on InSight
- Delivered by Kinemetrics, Inc. in collaboration with Oxford University and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



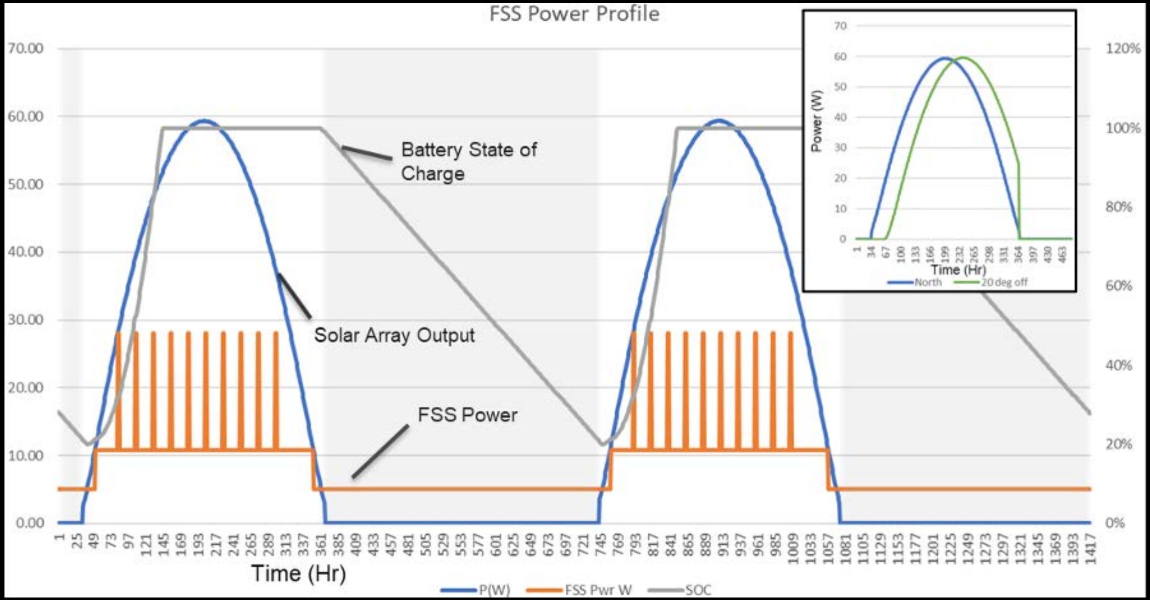


The package design

- 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



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

Prospects for a Lunar Geophysical Network (LGN)?

- With FSS, LITMS, and LuSEE, PRISM 1b includes most of the primary instrumentation proposed for LGN (Neal et al., 2020)
- While FSS has defined science goals reachable for a single station, a long-lived network opens many more possibilities for seismology
  - Networked locations open up many more events for detailed study
  - Expanding the broadband instrument to 3 components possibly deployed on the surface (expanding the number of events accessible to detailed analysis)
  - Long-lived networked data sampling the whole Moon
- FSS can serve as a key pathfinder for LGN
  - Quantifying tradeoffs of an undeployed seismic package
  - Demonstration of candidate instrumentation
  - Demonstration of compact night-surviving package which could be adapted for a complete geophysical instrument suite in the context of possible LGN mission design

Summary

- FSS outlives its commercial lander delivery to deliver key lunar science from the farside of the Moon
- Addresses key questions about farside seismicity rate, deep lunar structure, local structure at Schrödinger Crater, and micrometeorite impact rate
- Innovative thermal design allows continuous operation through the lunar night
- PRISM 1b can serve as a model for potential future LGN nodes