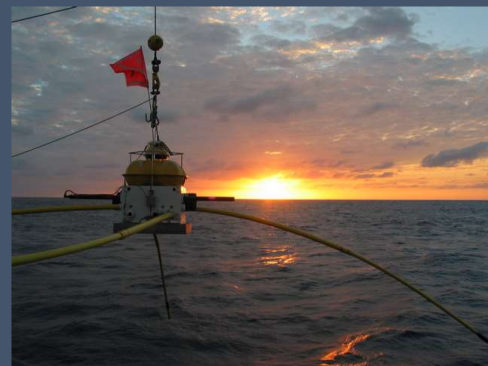
geopartner.pl

Constable et al., 1998



Firefly Aerospace

Magnetotellurics on the Moon and Other Worlds

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MTNet EMinar

April 12, 2023

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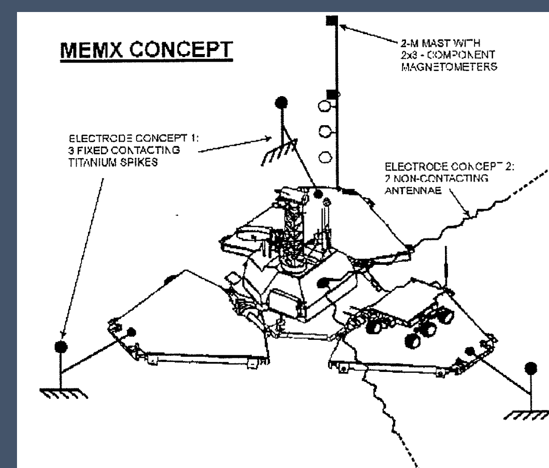
Overview

- Planetary EM Sounding
  - Targets
  - Methods
- Moon
- Europa
- Ceres
- Mars
- Conclusion

Mercury, Venus, Uranus interesting but neglected here!

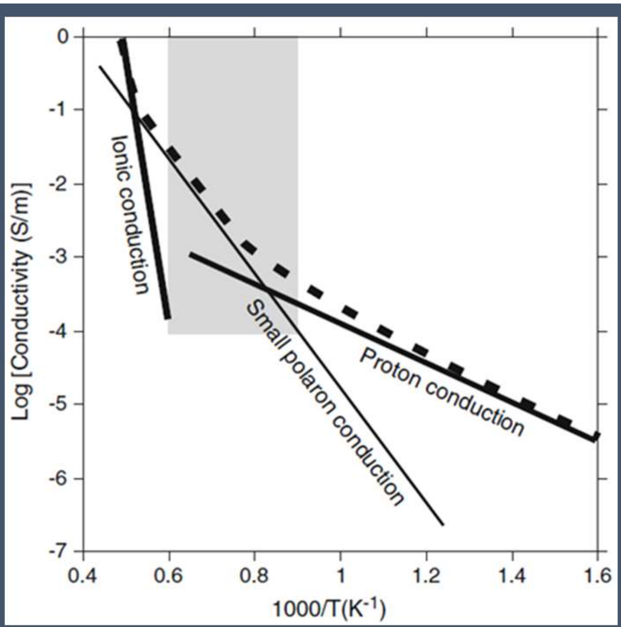
Apollo 12 Lunar Surface Magnetometer, 1969

MT Concept for Mars, 1997

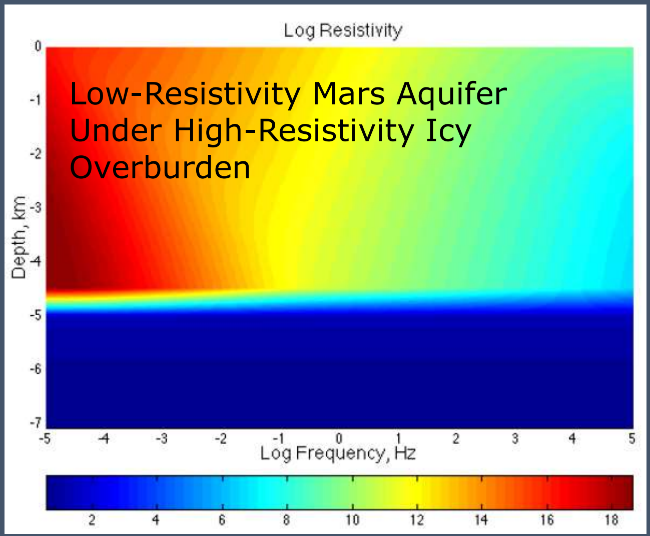


What Does EM Sounding Reveal?

- Temperature Structure
  - Arrhenius relationships are dominant $\sigma = \sigma_0 \exp(-T_0/T)$
- Rock Composition
  - Electrically conductive point defects in mineral structure
  - Fe^{3+} substitution for Mg^{2+} ("small polaron")
  - Proton hopping ($H_2O \leftrightarrow H^+ + OH^-$)
- Water/Brines
  - Electrolytic conduction.
  - Orders of magnitude more conductive than rock with even small quantity of dissolved solids.
  - Near-ideal EM target compared to resistive overburden.



Yoshino, 2010



Grimm, 2002

Electrical Conductivity of the Earth vs Other Worlds

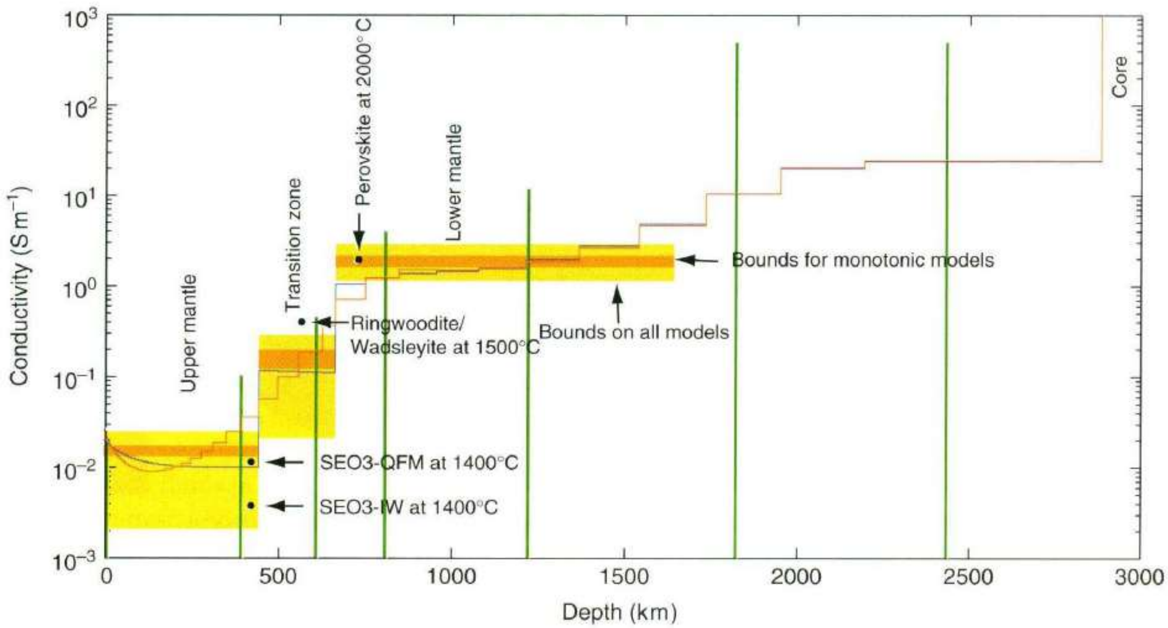
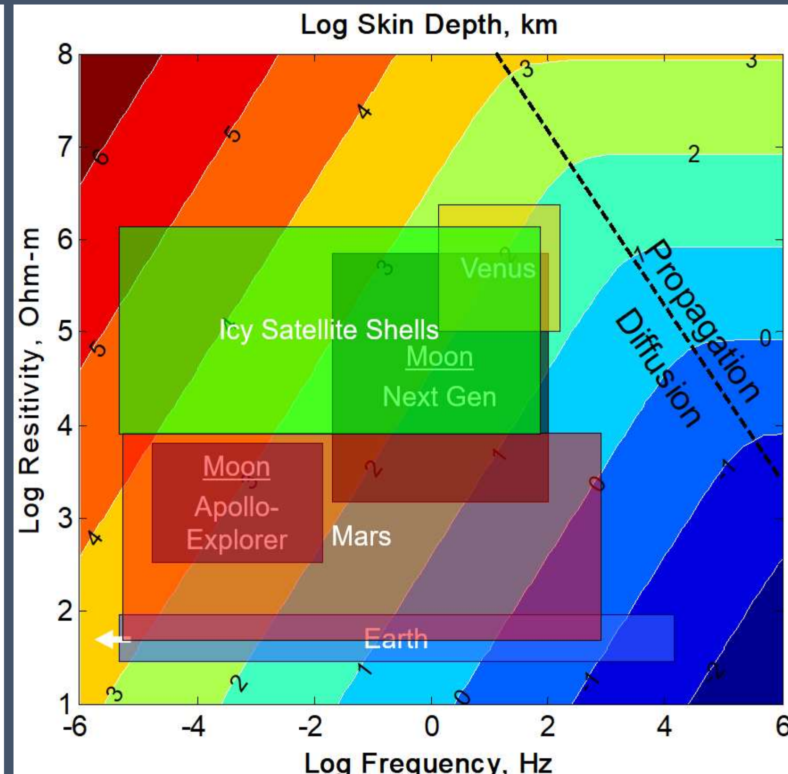


Figure 34 Models fitting the data set shown in **Figure 33**. Green lines are the D$^+$ model divided by 10^5, red line is a first-derivative maximally smooth model, and the blue line is a smooth model that is allowed to jump at 440 and 670 km. The yellow boxes represent bounds on average conductivity from Medin *et al.* (2006). Values of selected mineral conductivities from **Figure 26** are also shown.

Constable, 2007

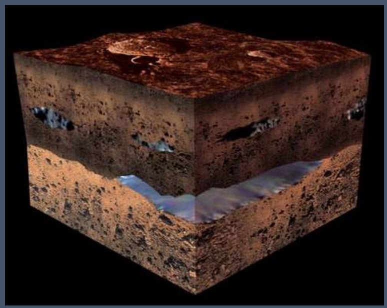


- Typically high resistivity / low conductivity compared to Earth.
  - Interior temperatures are lower.
  - Free water is rare.

Some Planetary Science Questions for Electromagnetic Geophysics

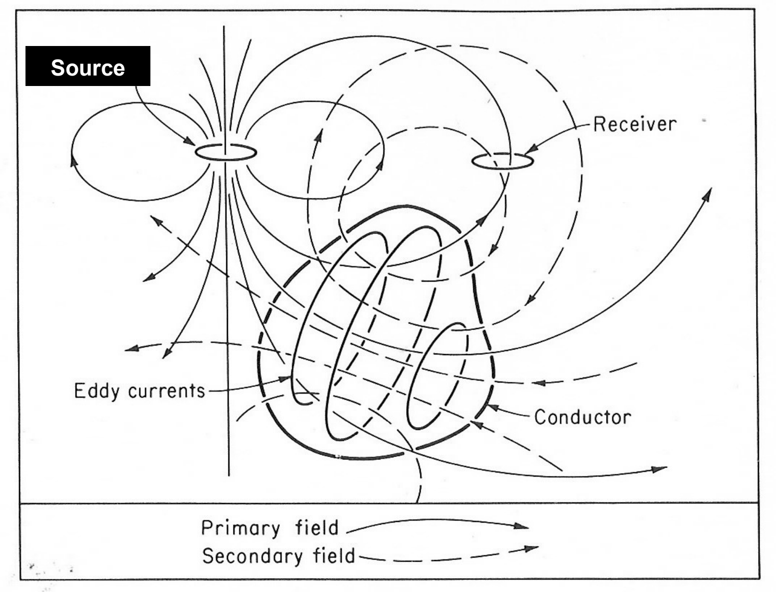
- Moon
  - Does the lunar interior preserve any compositional layering from crystallization of the global magma ocean?
  - Does the asymmetric surface composition of the Moon reflect deep-seated lateral heterogeneity?
  - What is the current temperature structure of the lunar interior and what are its implications for global thermal evolution?

- Ceres
  - Is Ceres truly an "ocean world," with a global internal water or mud layer?
  - Do "magma" (water) bodies presently exist within the icy crust?
- Mars
  - Does Mars have groundwater today?

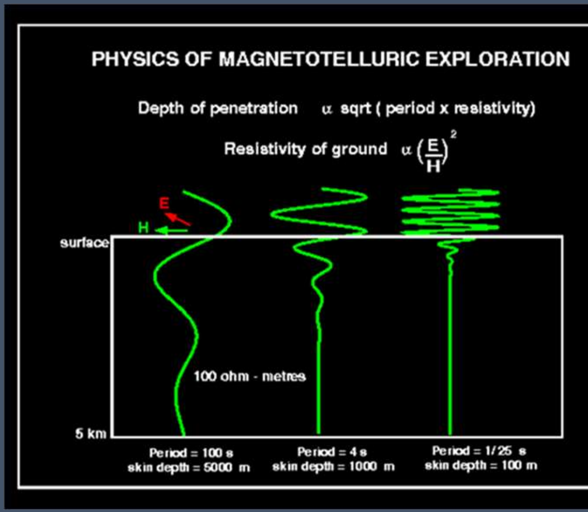


Electromagnetic Induction

- Application of Faraday's Law
  - Time-varying primary magnetic field induces eddy currents in target.
    - Natural or artificial sources.
  - Secondary fields detected at receiver.
    - Challenge is primary-secondary separation.
- Determine electrical structure
  - Skin depth (km) = 0.5 $\sqrt{\rho/f}$ = 0.5 $\sqrt{T/\sigma}$.
  - f = Frequency, Hz, T = Period, s; ρ = resistivity, Ω-m, σ = conductivity, S/m.
- Diffusion, not wave propagation.



Grant & West, 1965



earthweb.ess.washington.edu

Approaches to EM Sounding

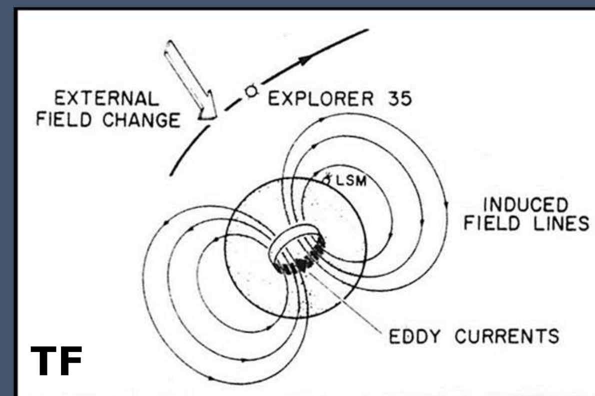
- Golden Rule: Always need 2 independent quantities to determine impedance (e.g., Ohm's Law Z = V/I).
    - One quantity is almost always magnetic field near target.
- Geomagnetic Depth Sounding (GDS, aka Z/H): Mag fields only, known geometry (usu. n=1).
- Magnetic Transfer Function (TF): Mag fields only, measure source field simultaneously.
- Magnetotellurics (MT): Mag + Electric fields, no source info needed.
- Active methods: generally Mag only, source is specified.

GDS

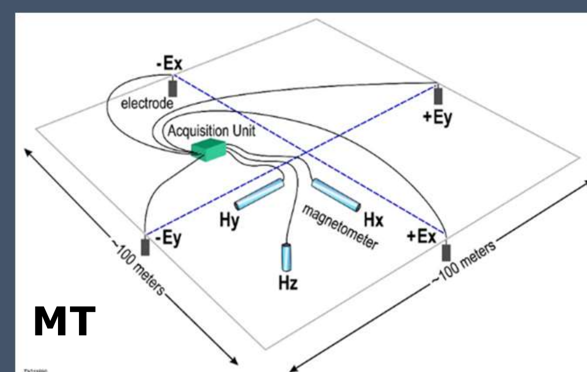
$$B_r = \left[-e_1^0 + 2 i_1^0 \left(\frac{a}{r} \right)^3 \right] \cos(\theta)$$

$$B_\theta = \left[e_1^0 + i_1^0 \left(\frac{a}{r} \right)^3 \right] \sin(\theta)$$

Constable, 2007



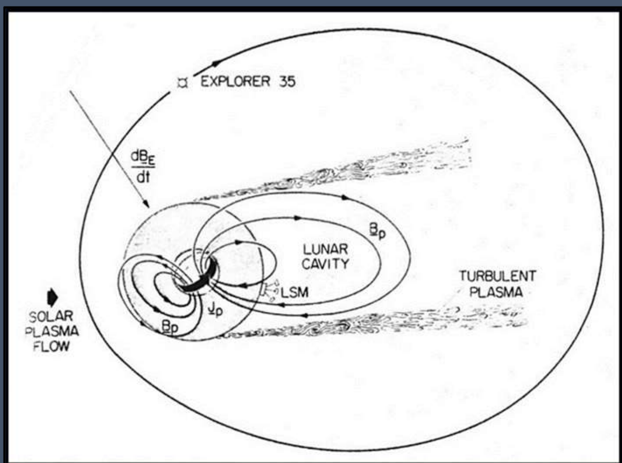
Dyal et al., 1974

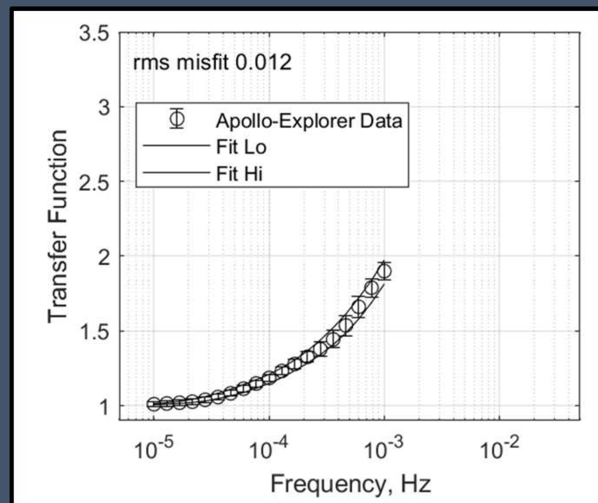


after Moombarriga Geosciences

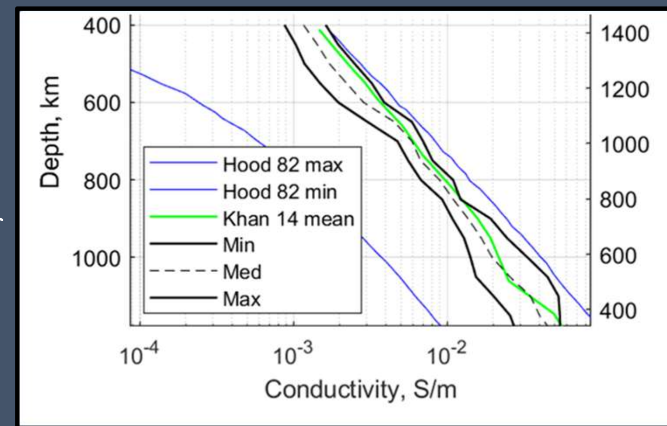
Moon: Magnetic Transfer Function

Dyal et al., 1974





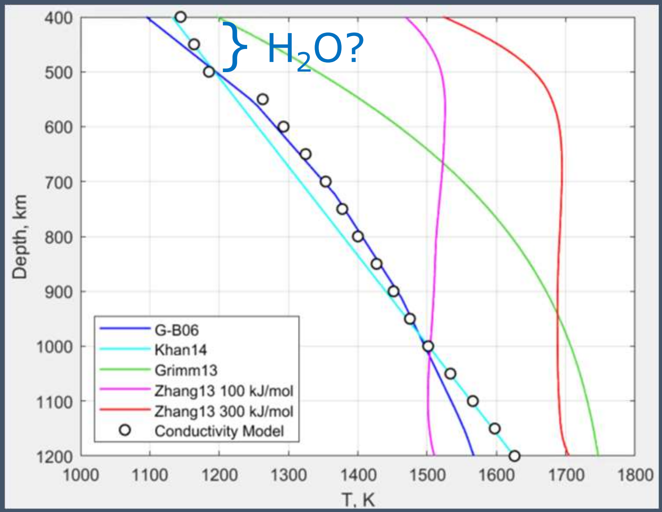
Grimm,2023



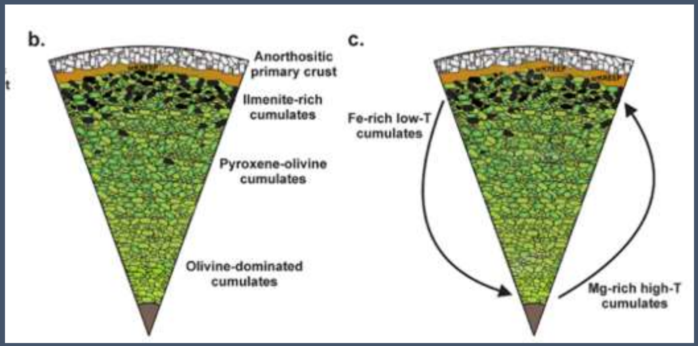
- Explorer 35 – Apollo 12, 1969-70.
  - $A_{R,T} = (B^E_{R,T} + B^I_{R,T})/B^E_{R,T}$ $C = (a/2)(A_R/A_T)$ $\rho_a = \omega\mu C^2$
    - R,T = Radial, Tangential components, respectively. A_R = 1 in solar wind. See Sonett, 1982, for review..
- Increases with freq. due to increased screening by eddy currents and solar-wind confinement.
- Dipole response limited by finite wavelengths in plasma to <1-10 mHz.
  - Most analyses <1 mHz, min depth >400 km.
- Regularized inversion for $\sigma(r)$ in spherical geometry.
- Reproducible deep conductivity profile. σ [S/m] = $1.76\times10^{-4}\exp(z[\mathrm{km}]/210)$ ($r^2 = 0.994$).

Moon: Interpretation

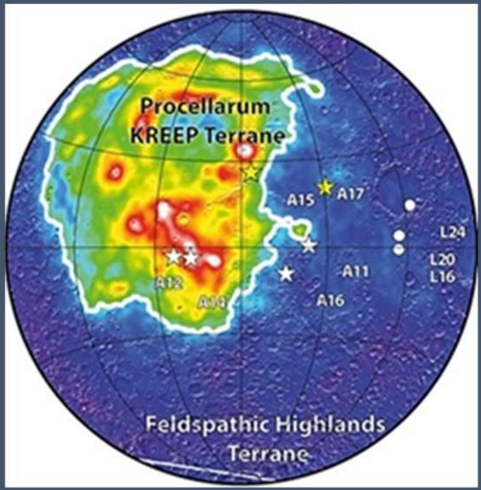
- Deep temperature profile consistent with thermal conduction and near-uniform composition (Hood et al. 1982; Khan et al, 2014; Grimm, 2023).
  - My analysis: Mg# 80-85 (olivine), possible 100s ppm upper-mantle H_2O.
  - Interior has been well-mixed following solidification and turnover of magma-ocean stratigraphy.
- Apollo 12 in anomalous Procellarum KREEP Terrane (PKT).
  - "Dregs" of magma ocean.
  - Is mantle anomalously hot here?
- Want higher frequencies (shallower imaging) and global coverage!



Grimm,2023

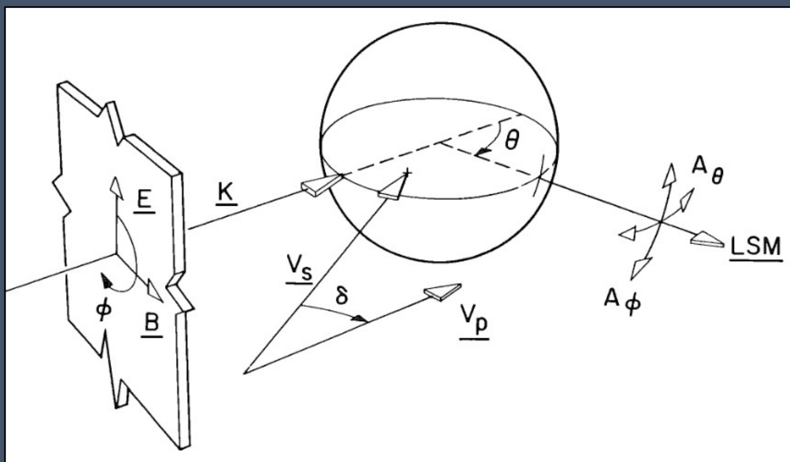


McCubbin et al., 2015

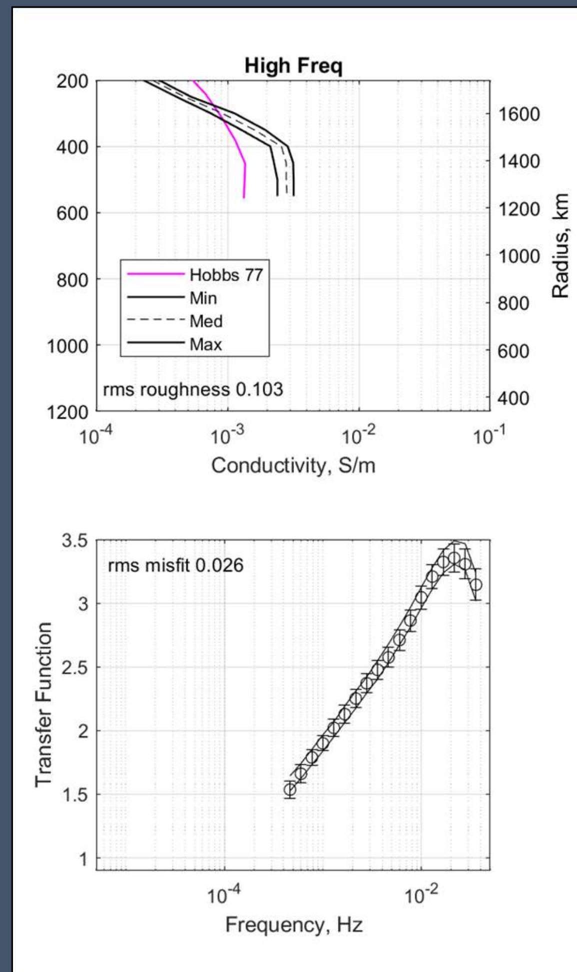


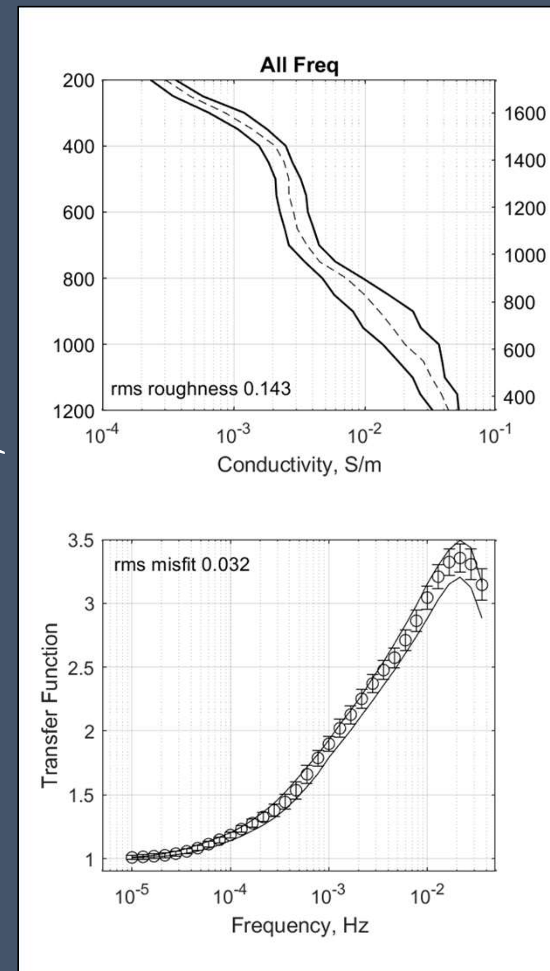
Laneuville et al., 2013

Moon: “High” Frequency Magnetic Transfer Function



Sonett et al., 1972



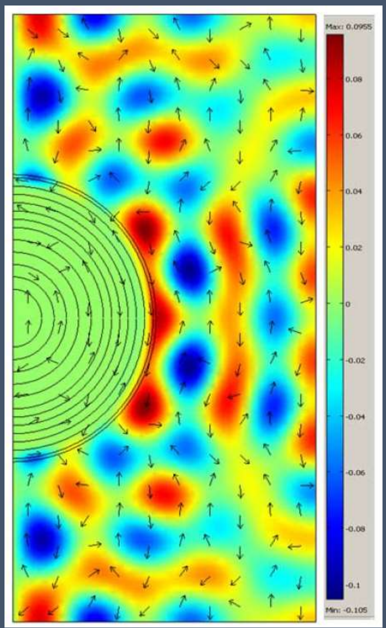


Grimm, 2023

- Multipoles appear when source wavelength (plasma) approaches lunar circumference.
- Introduces dependence on source-coordinate colatitude θ and solar-wind velocity v_p.
- Merged LF & HF data: Conductivity profile now near-constant 400-750 km.
- Does not fit any plausible temperature or composition configuration.

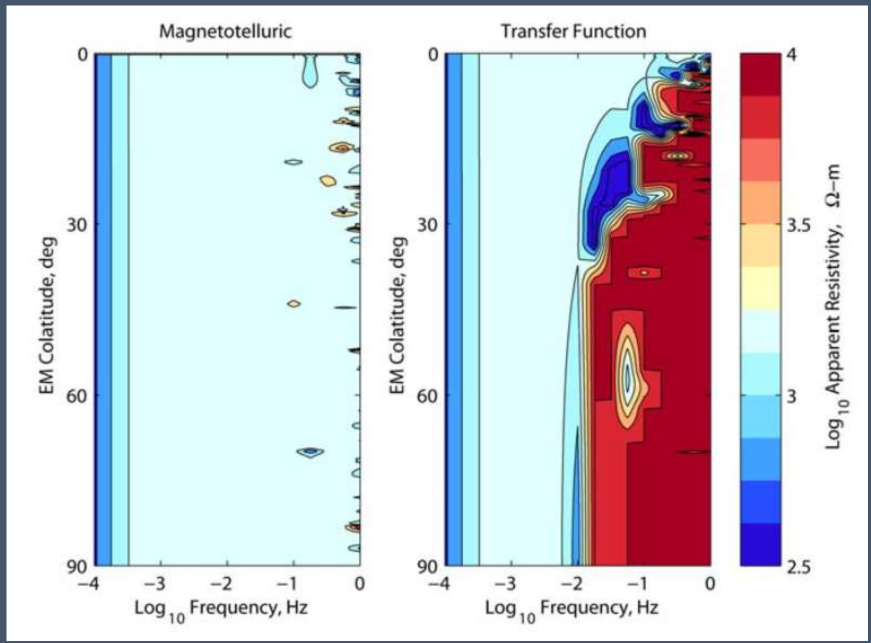
Moon: Magnetotellurics

- Single station: no orbiter needed.
- Largely insensitive to multipoles (finite wavelengths in plasma).
    - Expands bandwidth over full diffusion regime (>100 Hz, min. z = 50-100 km).
    - Must still remove noninductive plasma signals.

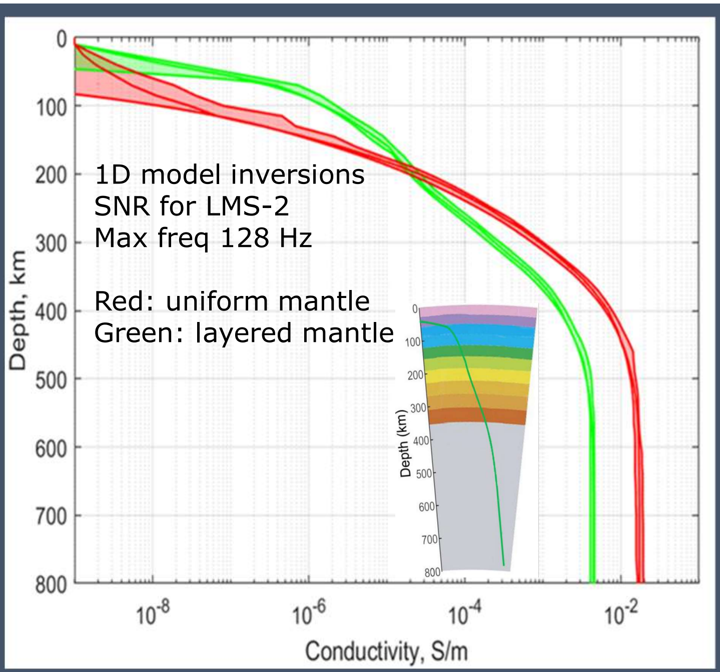


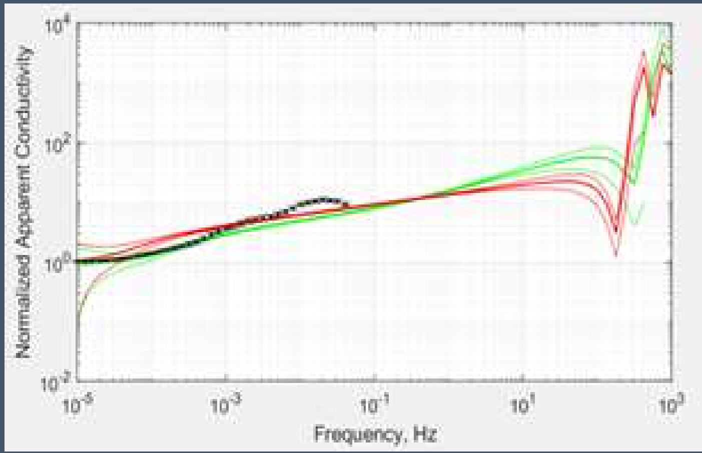
Model turbulence in 400 km/s solar wind

Grimm & Delory, 2012



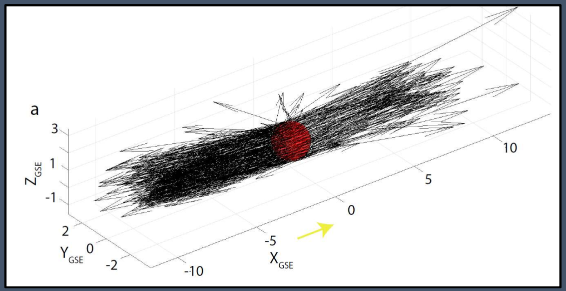
Numerical model of response of uniform 1000 Ω-m Moon



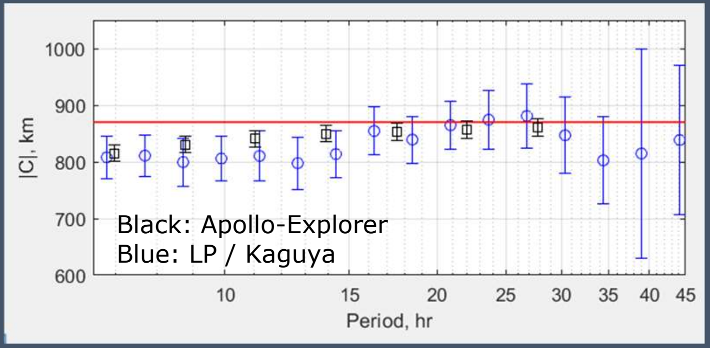


Moon: Geomagnetic Depth Sounding

- GDS w/ Lunar Prospector & Kaguya low-orbit measurements (Mittelholz et al., 2021).
- Analogous to satellite induction of the Earth (e.g., Olsen, 1999) except source is the magnetotail instead of ring current (n=1).

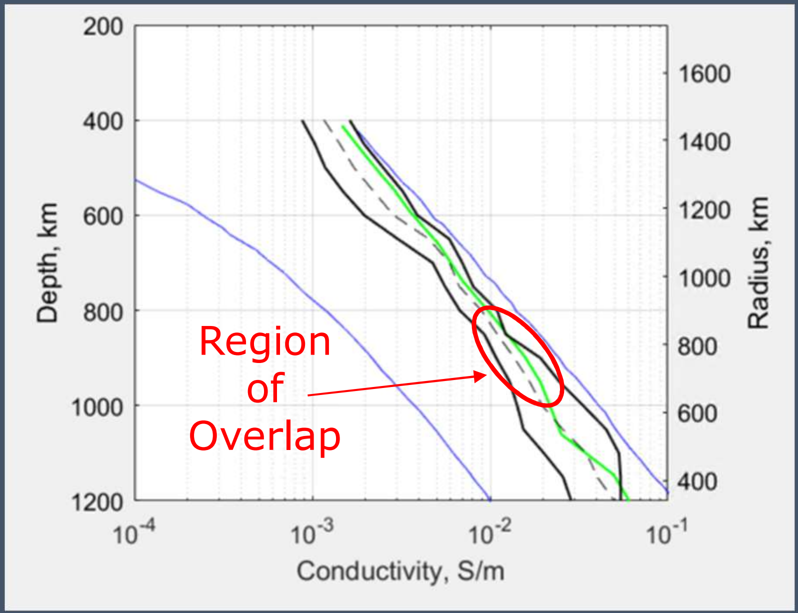


Mittelholz et al., 2021



- *Offers possibility of global average cf. point measurement*.
- Results comparable to Apollo at 7-14 hrs = 800-1000 km depth.
  - Long-period error bounds exceed physical limits.
  - Global average of ~8% of lunar volume *is* consistent with Apolo 12 site.

→Important proof-of-concept for future missions: single orbiter only, possibility for core detection at long period.

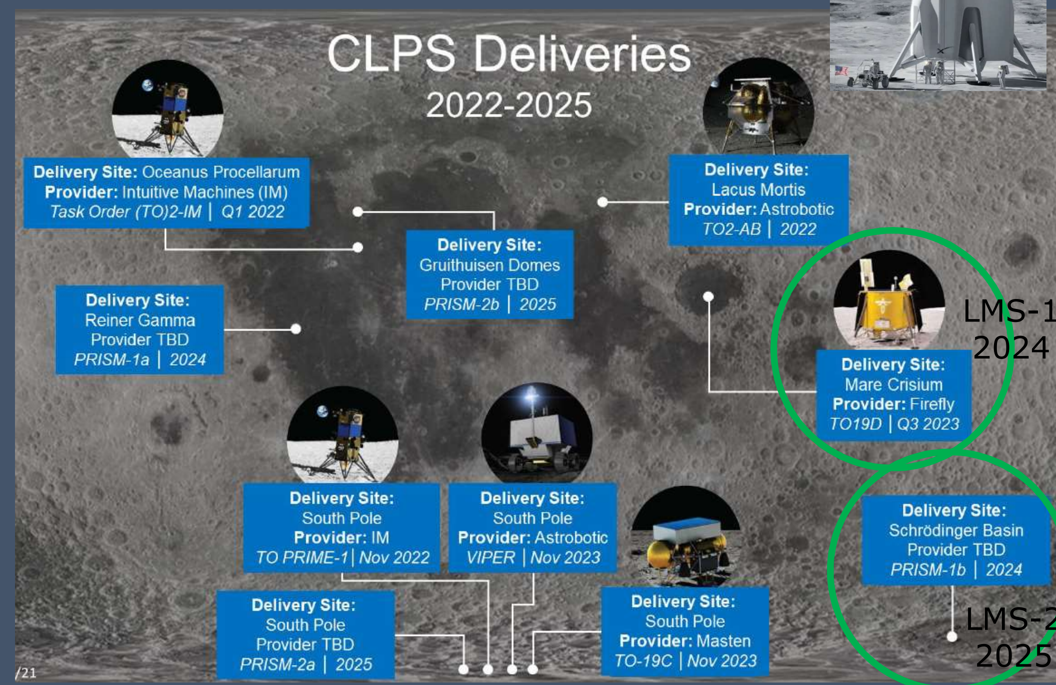


Artemis: Return to the Moon

- 2017: Presidential Space Policy Directive 1 emphasizes return to the Moon in public-private partnership.
  - 2020: Int'l Artemis accords signed.
- 2018: NASA announces Commercial Lunar Payload Services (CLPS) program
  - Desire 2 robotic missions per year.
  - "Fedex to the Moon"
  - "More Shots on Goal"
- July 2019: Lunar Magnetotelluric Sounder (LMS-1) selected.
  - Heat-flow probe (LISTER-1: TTU/HBR) and retroreflector separately selected.
- July 2021: Lunar Interior Temperature and Materials Suite (LITMS) selected.

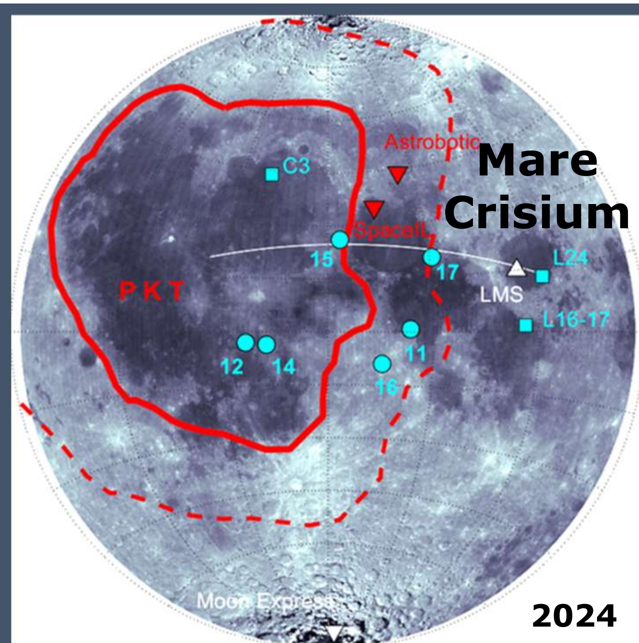
  = LMS-2 + LISTER-2

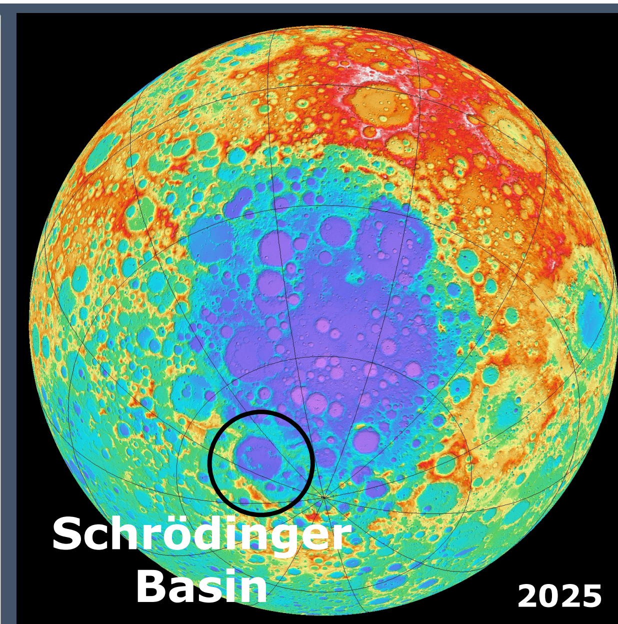
- Ongoing CLPS opportunities.
- Artemis III landing 2026?
  - Propose geophysical station.

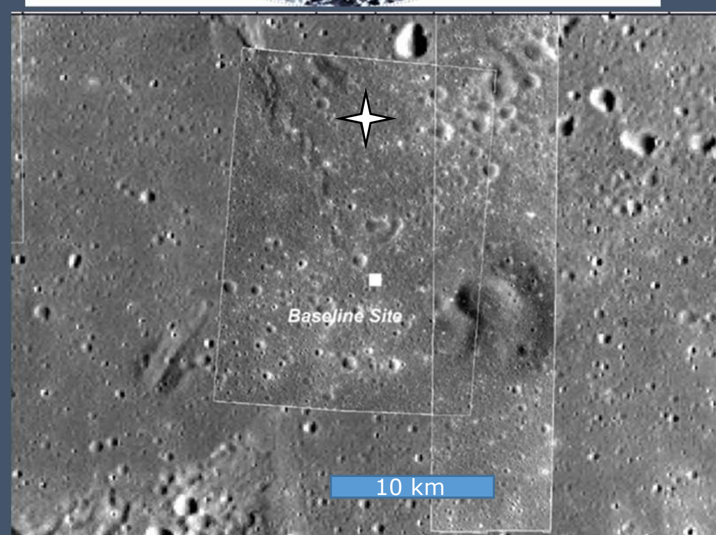


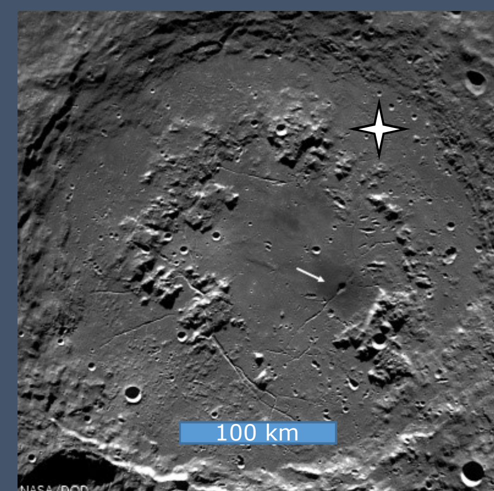
Lunar Destinations and Payloads

- Mare Crisium desired by LMS + LISTER because it is outside PKT
  - Get "background" electrical conductivity and heat flow.
  - Other payloads agnostic.
  - NASA approved!
- Schrödinger specified by NASA for competed instrument suites.
  - Farside Seismic Suite (JPL).
  - LITMS = LMS + LISTER.
  - Lunar Surface Electromagnetic Experiment (LuSEE): magnetometers.
  - First "complete" post-Apollo geophysical station!

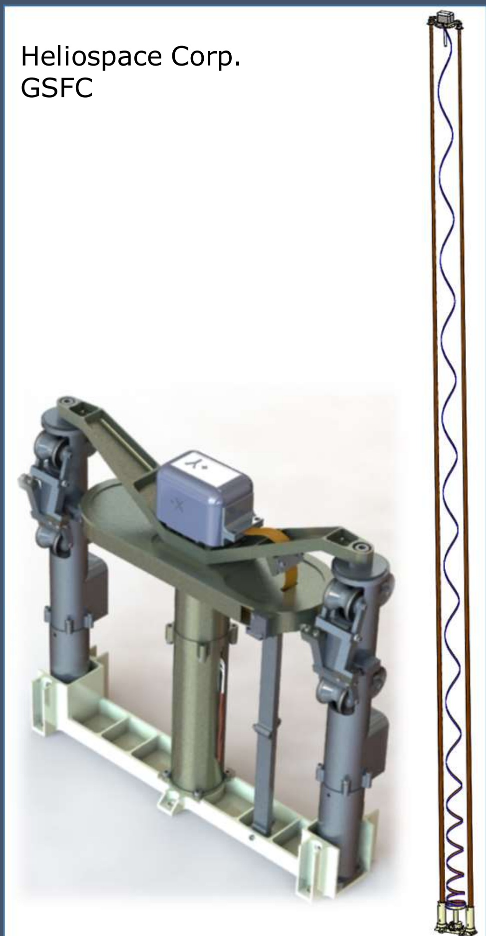




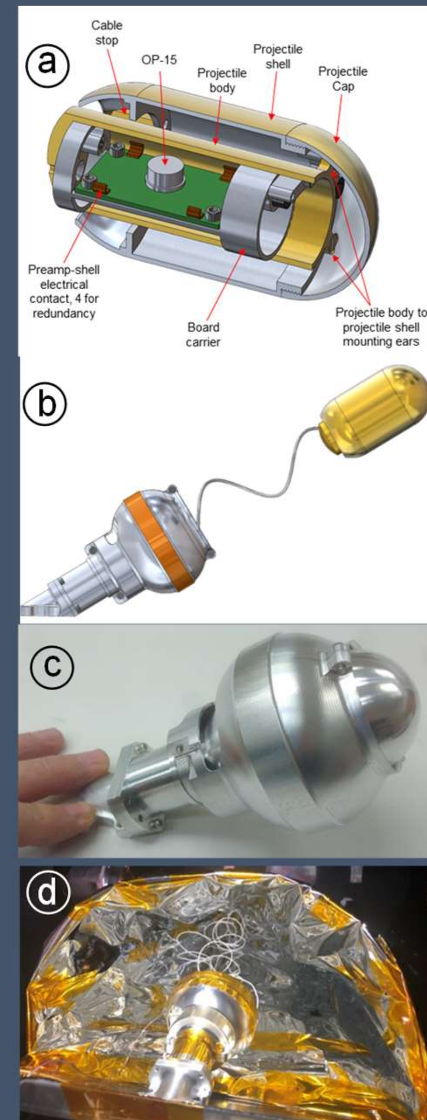




Lunar Magnetotelluric Sounder



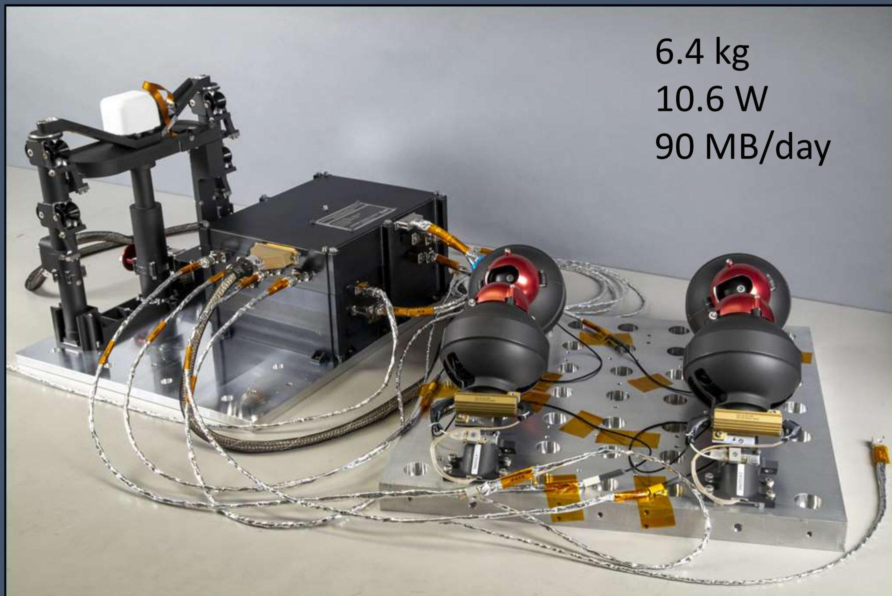
- Good SNR due to stronger fields in solar wind & magnetosphere, ample integration time, and high resistivity of the Moon .
- Compact fluxgate magnetometer (NASA Goddard), deploys to 2.5 m height on dual-stacer mast.
  - Max. freq ~10 Hz.
- 4 electrodes (Heliospace Corp.) spring-launched to 20-m distance (>40-m baseline).
  - High-impedance preamp, actively driven to eliminate capacitive pickup of wire.
  - Bias voltages to match plasma potential.
  - Essentially a space-physics experiment operated on the ground. Also some analogy to marine MT.
- Central electronics box (SwRI).



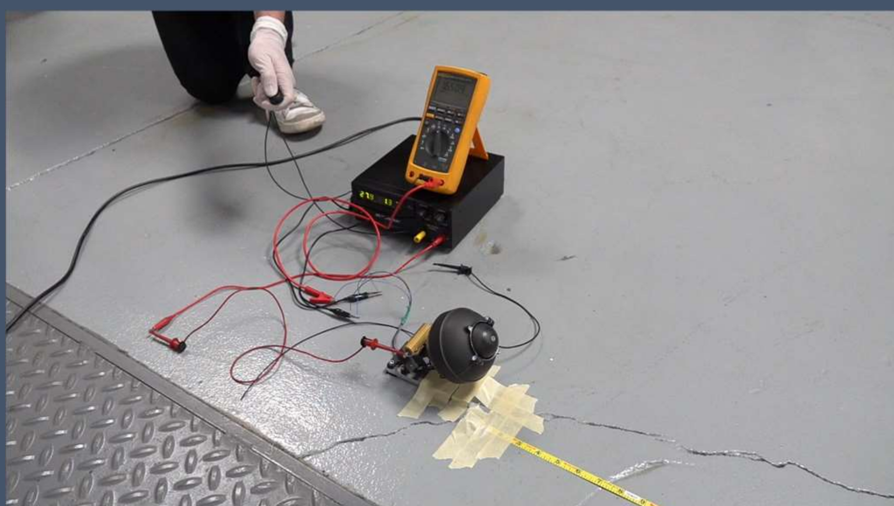
Heliospace Corp.

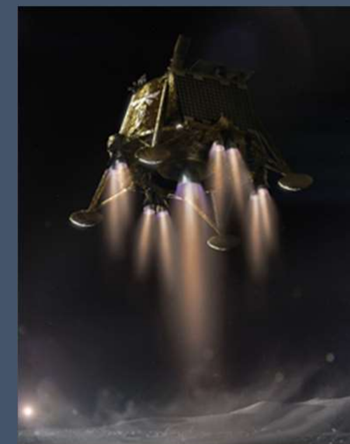
Lunar Magnetotelluric Sounder

SwRI/Heliospace/GSFC



Heliospace

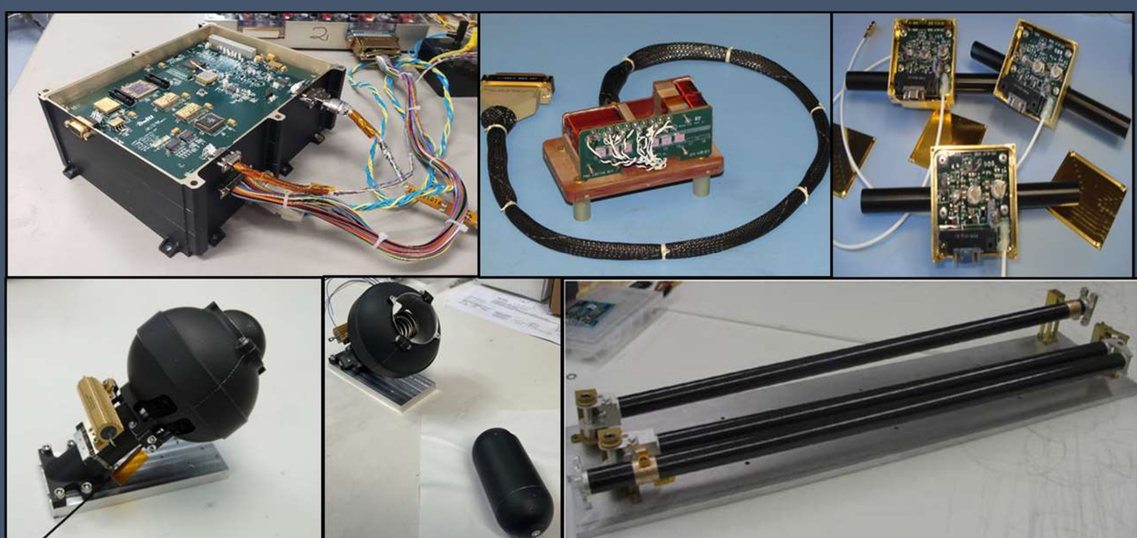


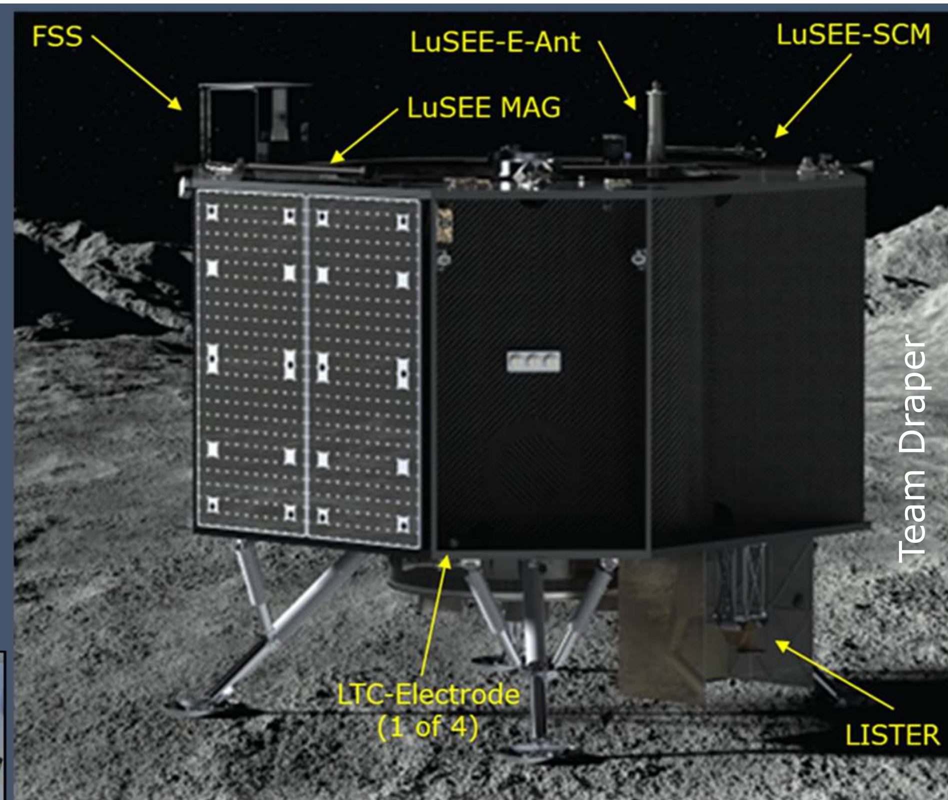


Firefly Aerospace

Lunar Magnetotelluric Sounder 2+

- E-field electrodes & electronics.
- Use B-field data from LuSEE.
  - Includes searchcoil mag to 100s Hz.
- Future experiments (LGN, Artemis): incorporate searchcoil + fluxgate back into LMS.



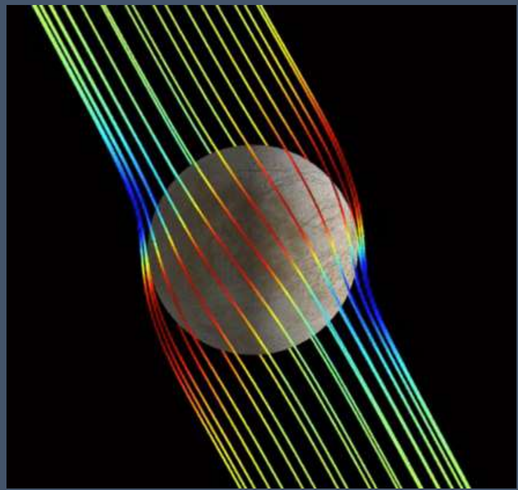


NASA

Europa

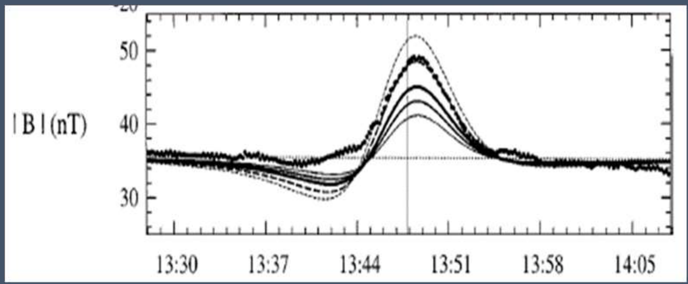
- Galileo spacecraft detected subsurface oceans on icy satellites using special case of GDS (e.g., Khurana et al., 1998).
  - Known static field of Jupiter rotates past moons = induction (11-hr period).
- Europa Clipper will pass closer, possibly exploit multipoles.
  - Better constraints on ocean.
- Europa Lander (cancelled) seeks any water within ice shell: too shallow, too high freq. for GDS.
  - Measure response to magnetospheric waves using MT.

Hand et al., 2016



NASA / Europa Clipper

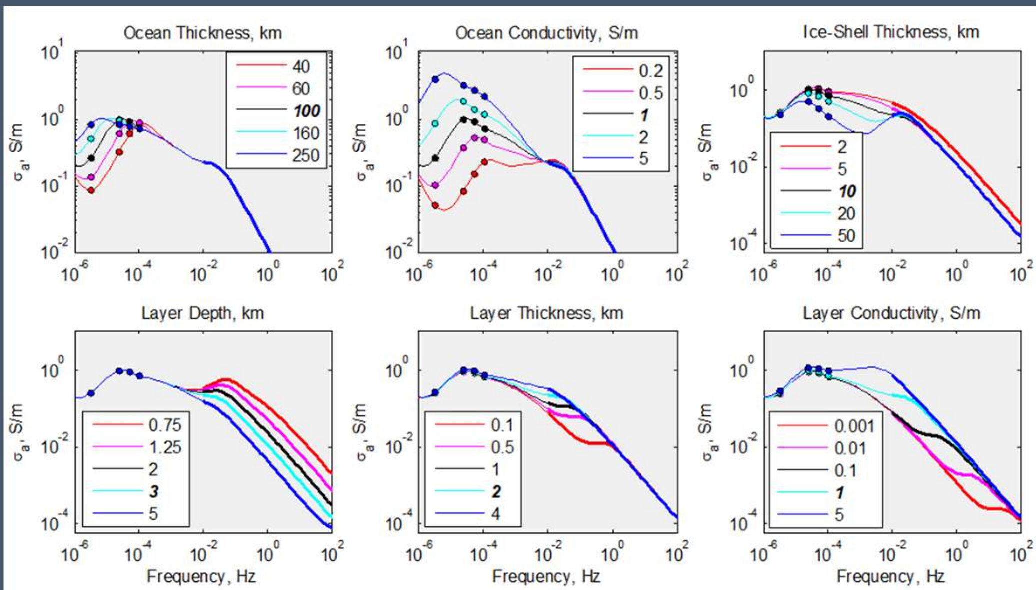
Dipole induction signature of interior conductor (ocean)



Khurana et al., 1998

Europa

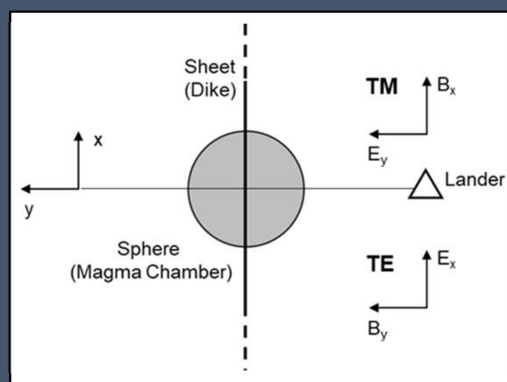
Grimm et al., 2021

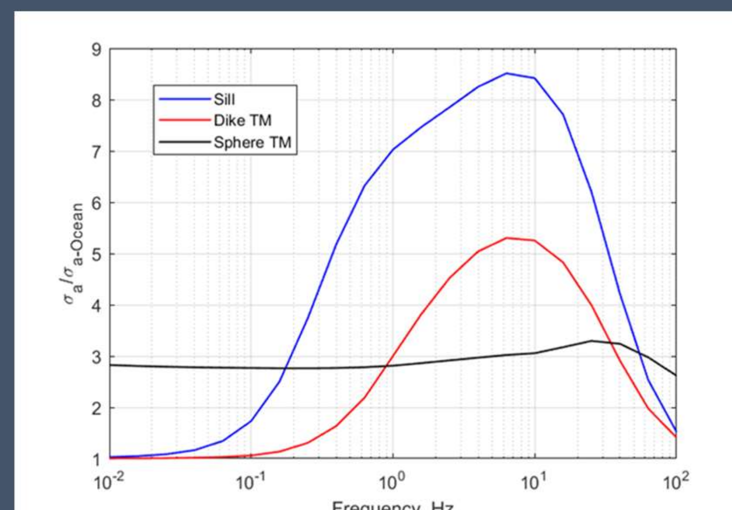


← Discrete frequencies from magnetospheric rotation determine ocean depth and conductivity-thickness.

← Magnetospheric continuum determines intrusive layer depth and conductivity-thickness.

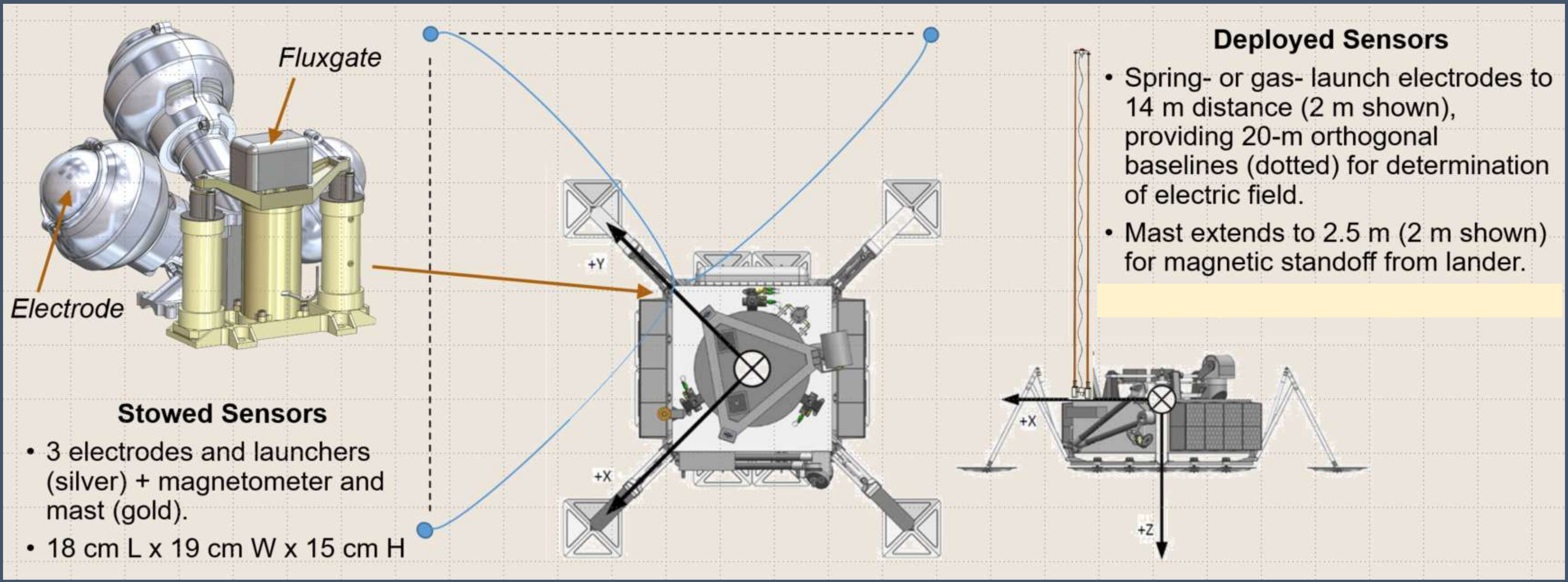
Anisotropy may allow discrimination of different water-intrusion shapes.





Grimm et al., 2021

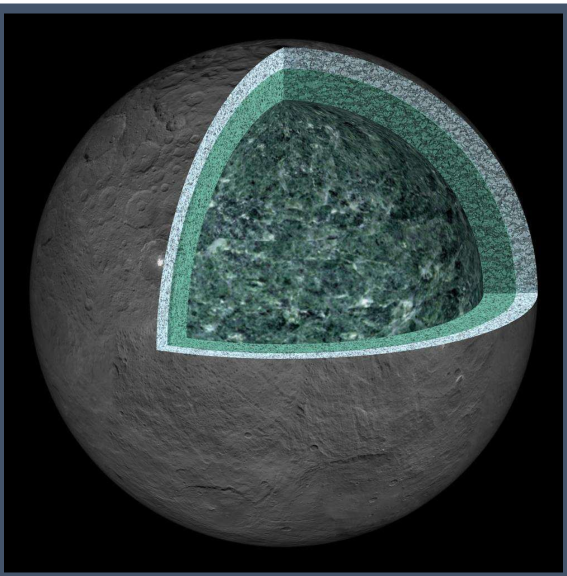
Europa Magnetotelluric Sounder



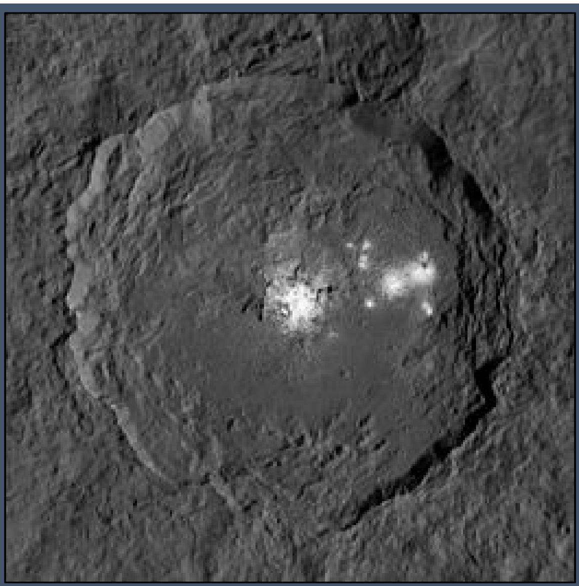
See also Grimm et al., ASR, 2021

Ceres

- Dwarf planet 940 km dia.
- From Dawn orbital mission, infer ice-rock crust (40? km), brine/mud (60? km thick), hydrated silicate core.
- Occator crater has salt deposits, likely recent communication to subsurface brines.
- New lander mission study (Castillo-Rogez & Brody, 2020) includes MT to search for subsurface liquid.

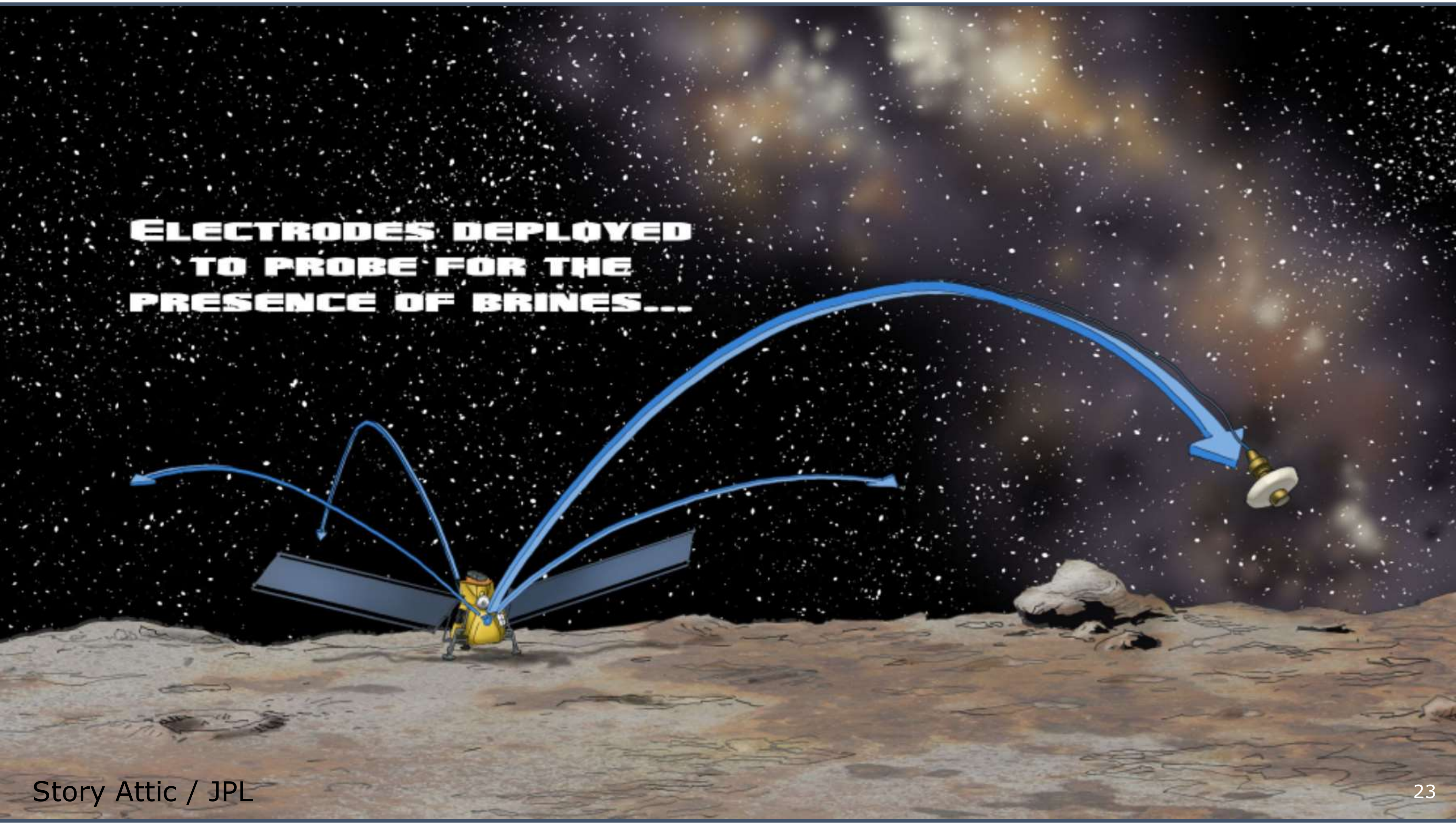


NASA



- Adjoint MT study (Grimm et al., Icarus, 2021)
  - Assumed LMS with increased electrode launch distance (50 m).
  - Demonstrated that solar-wind turbulence sufficient for EM sounding.
  - Detect both deep brine layer and intracrustal water intrusions with MT (direct analogy to Europa).

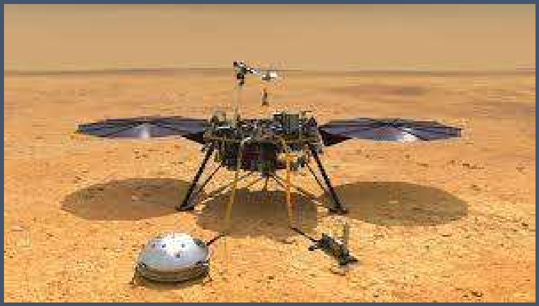

Story Attic / JPL

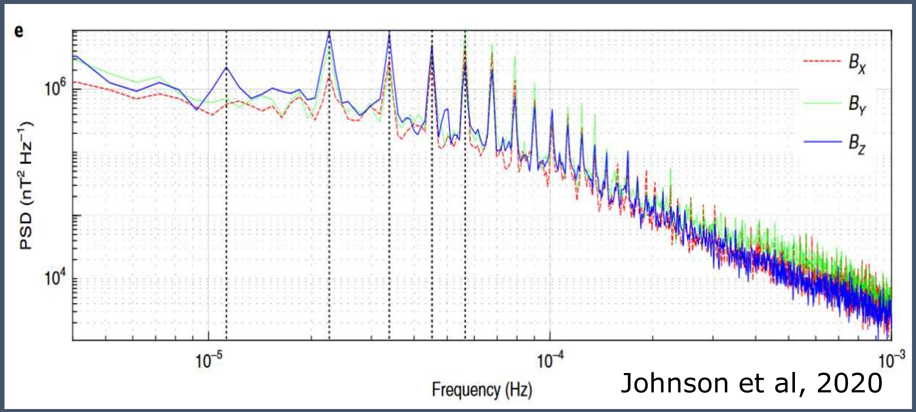


Story Attic / JPL


...USING ELECTROMAGNETIC SOUNDING.
5 1
Story Attic / JPL

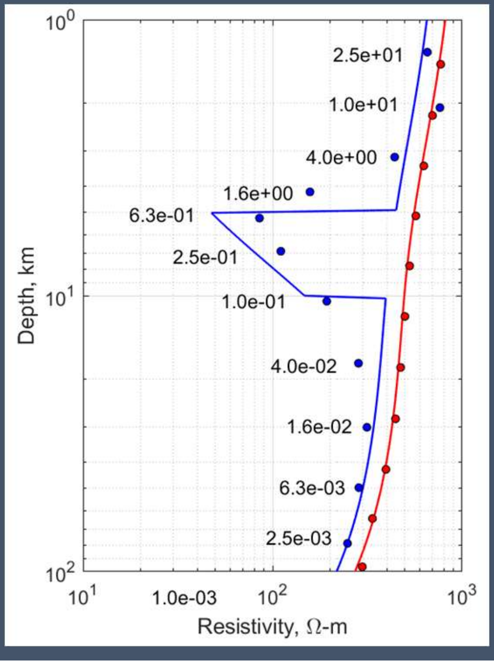
Mars: Natural Sources

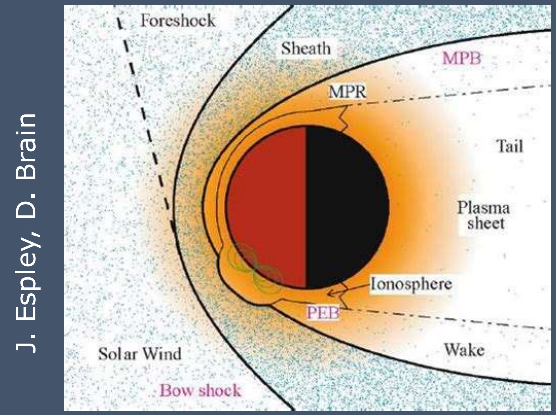




Fluxgate magnetometer on InSight lander.

- Body-mounted: significant interference.
- Abundant low-frequency (<1 mHz) energy as harmonics of 1 sol.
    - GDS (Z/H) unsuccessful due to inability to infer geometry of ionospheric signals.

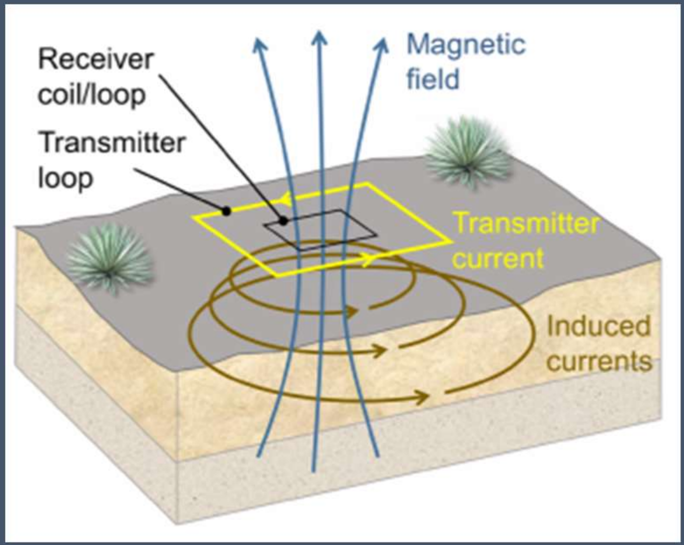




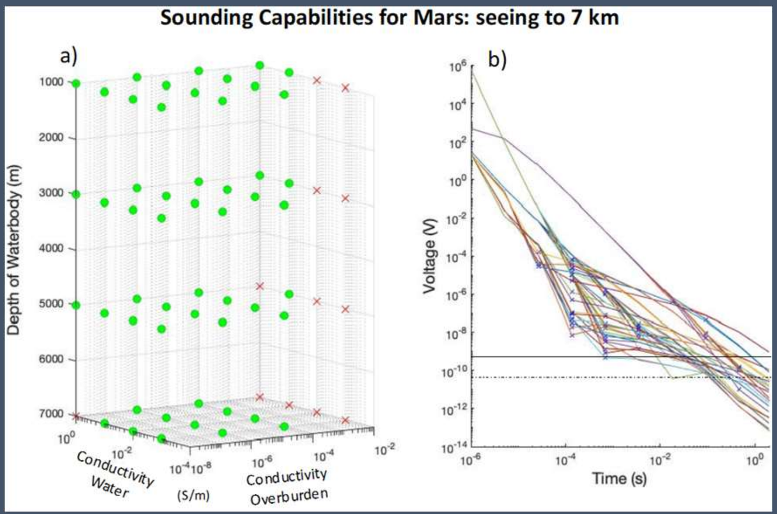
- Proper MT experiment *could* detect deep groundwater
    - High-frequency energy (lightning?) unknown.

Mars: Artificial Source

- Transient Electromagnetic (TEM)
  - Higher mass & cost than MT, but no uncertainty about source strength.
  - 100-m scale transmitter loop, stack for days, target depth 5-10 km.



Bücker *et al.* (2017)



S. Krieger / JPL

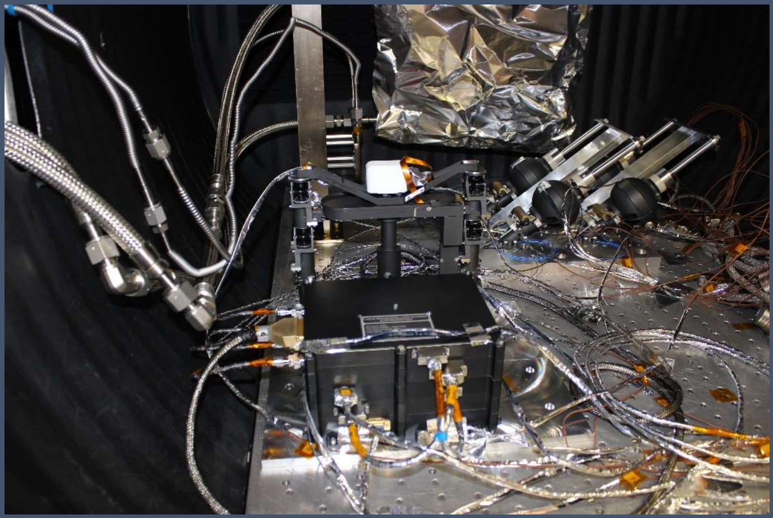
Grimm et al. (2009)

McGarey et al., 2022

Conclusion

- Electromagnetic sounding can provide key information on interior temperature and composition of many rocky & icy worlds in the Solar System.
- Can be as simple as a single magnetometer if additional knowledge of source field exists.
- Magnetotelluric method has distinct advantages:
  - Single station, don't need source info.
  - Relatively low mass & power.
  - Insensitive to plasma wavelengths.
- Lunar MT experiments in 2024, 2025!
- Mercury, Jovian-satellite orbiters 2025-2030.
- Ceres, Mars 2030s TBD.

LMS in thermal-vacuum testing, Jan 20203



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