Searching for Liquid Water in the Martian Deep with TH_2OR

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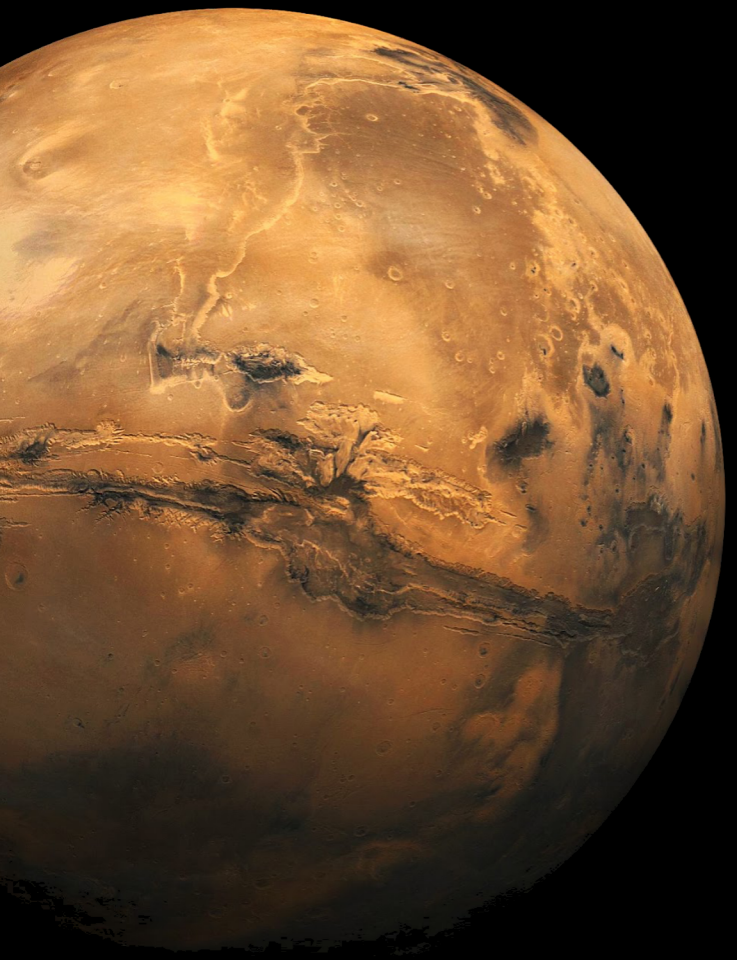
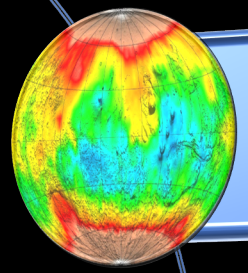
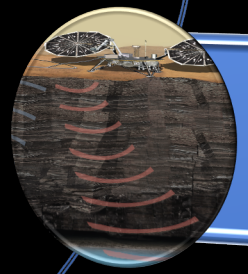


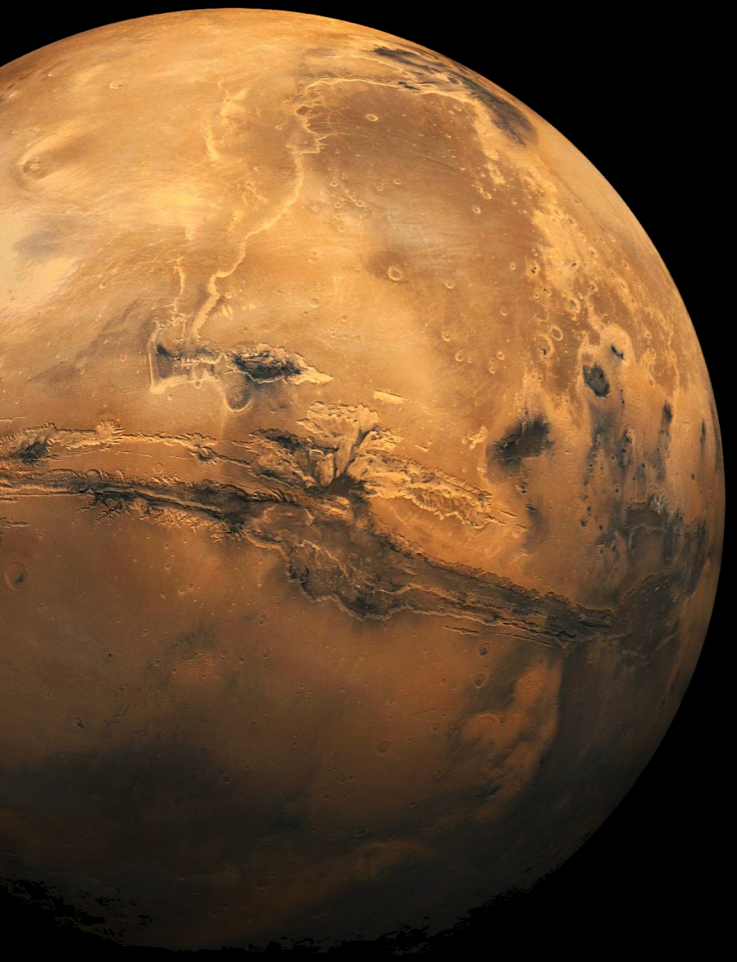


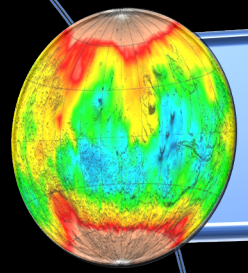
Intro

TEM



Mission Implementation





Intro

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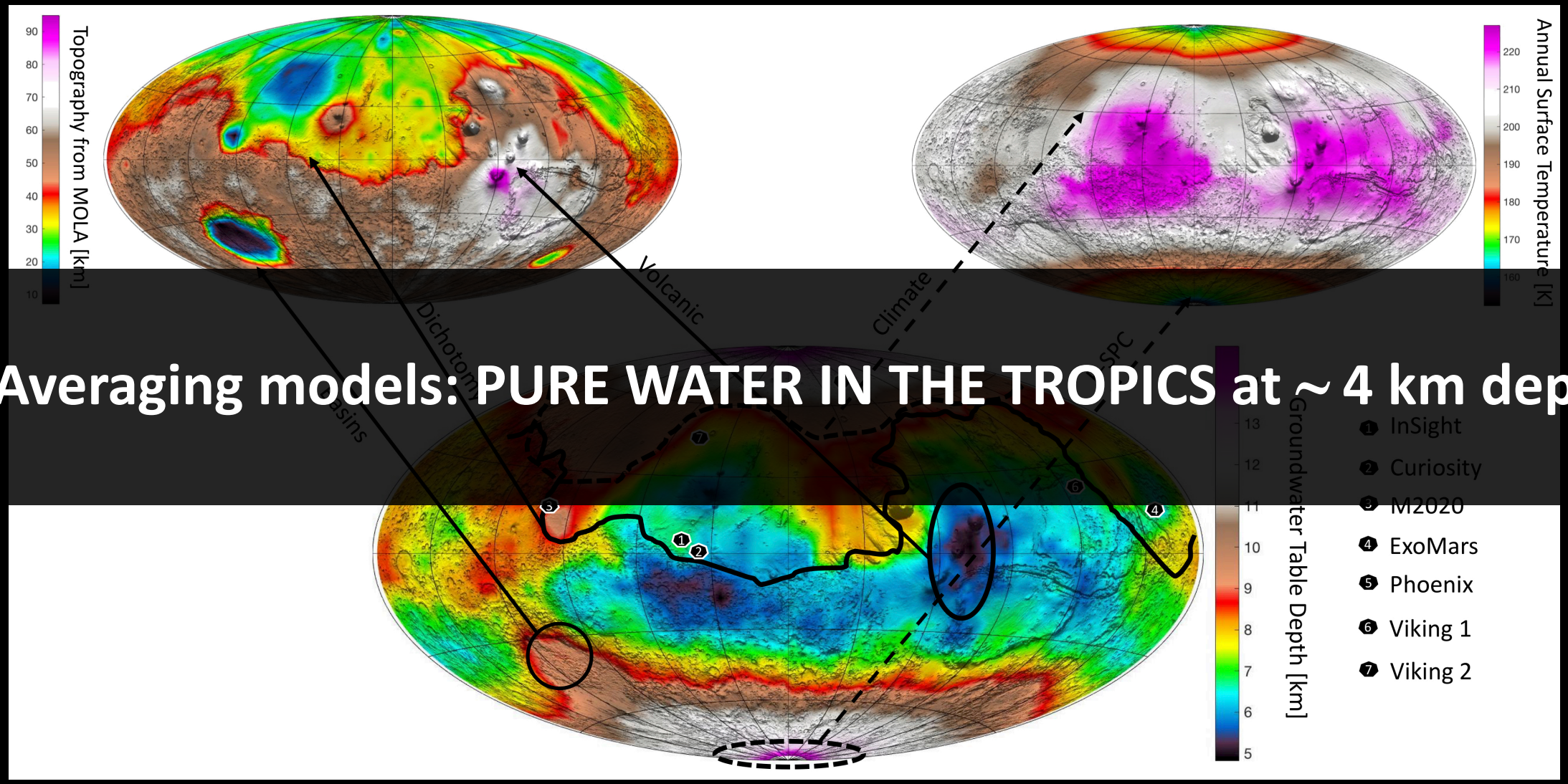
Mission Implementation

Liquid water is deep



Averaging models: PURE WATER IN THE TROPICS at ~ 4 km depth

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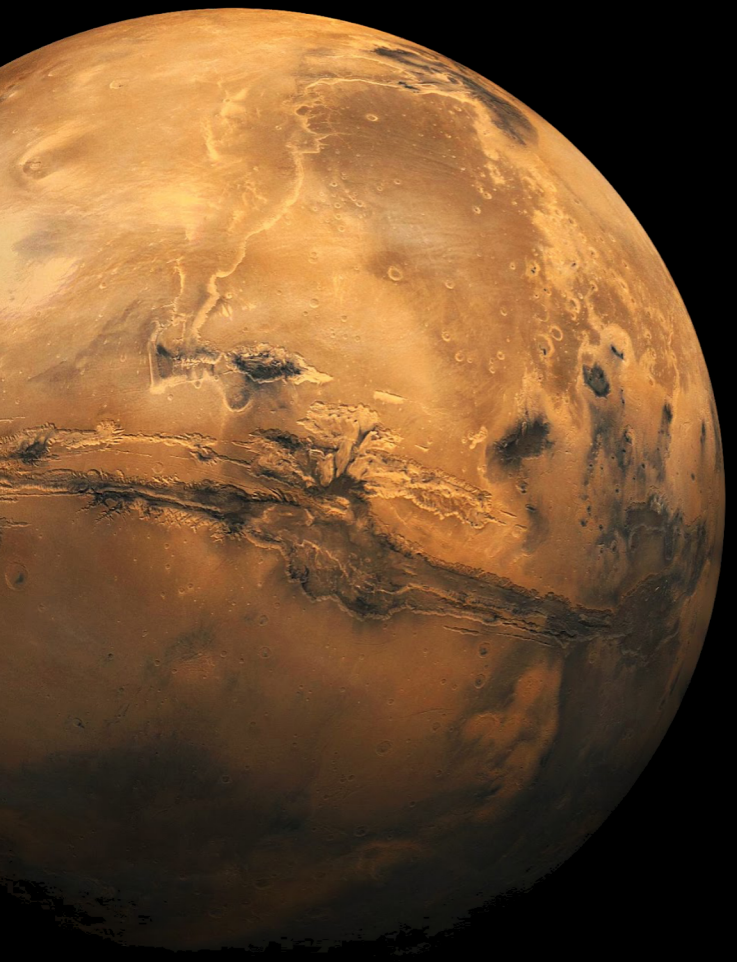

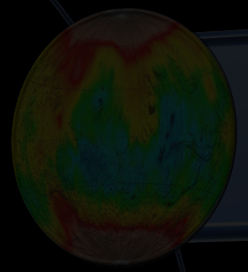

Intro

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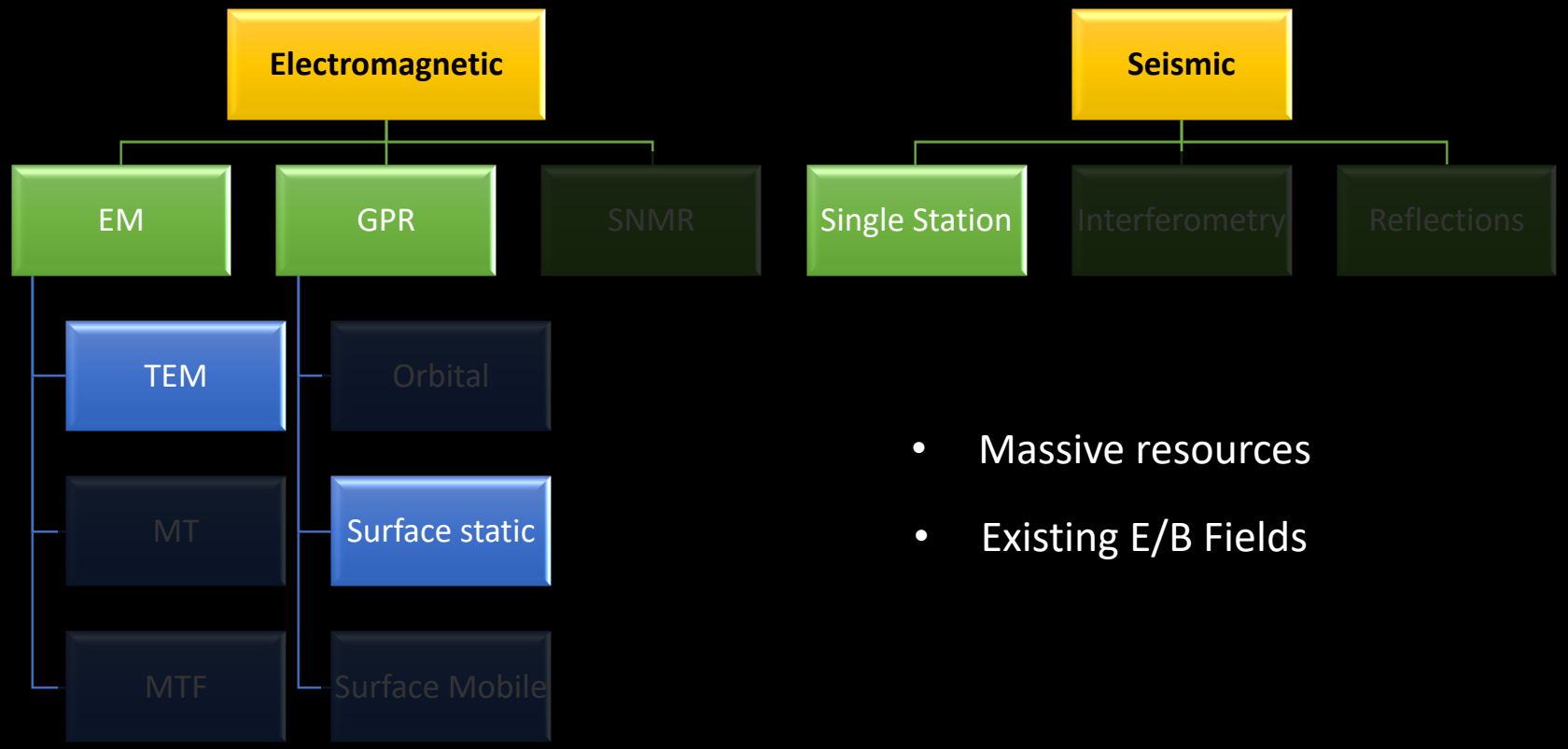
Limited possibilities to detect liquid water



- Massive resources
- Existing E/B Fields

EM: Electromagnetics
GPR: Ground Penetrating Radar
SNMR: Surface Nuclear Magnetic Resonance
TEM: Transient EM
MT: Magnetotellurics
MTF: Magnetic Transfer Function

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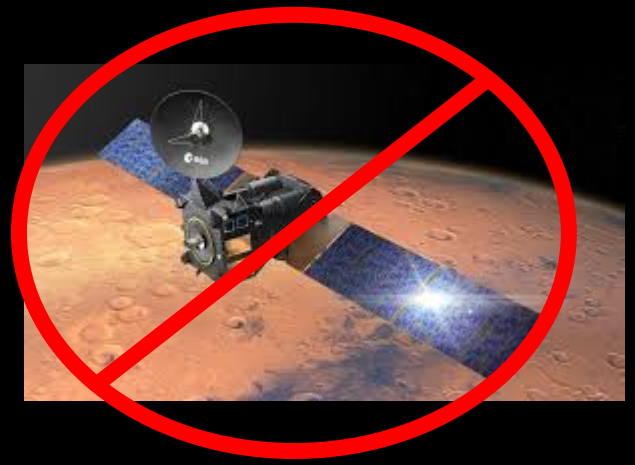
We need to go to the surface…

Power requirement is too high!

- Loss tangent for induction >> 1 by definition
- Induction has much higher power dissipation and spreading proportional to $1/R^4$ instead of $1/R^2$ for radar looking at a planar interface
- Space-based transducers (loops) are impractical to get shut off. Steady current necessary to generate eddy currents in subsurface



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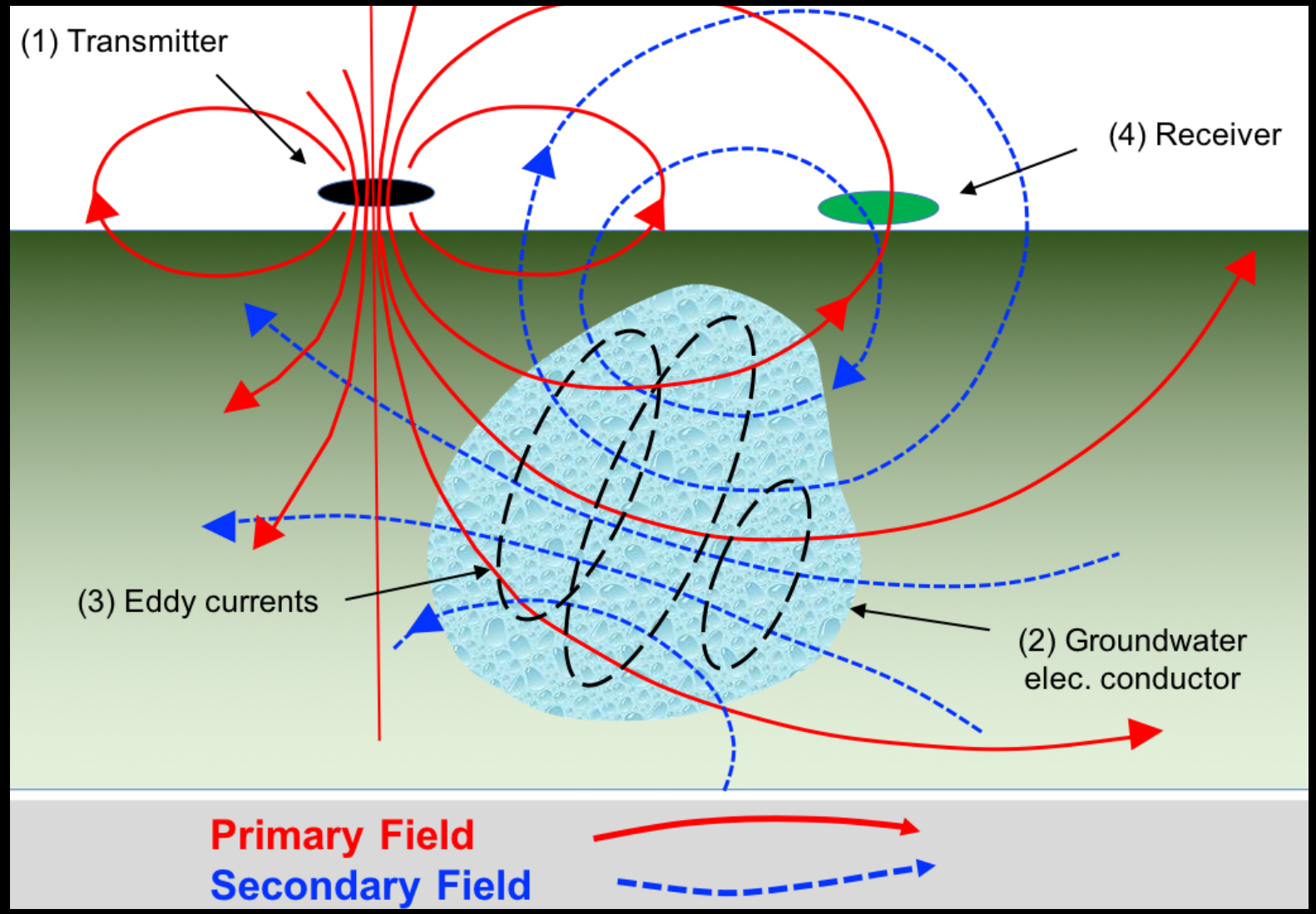
TH$_2$OR (Transmissive H$_2$O Reconnaissance)



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Mars is better suited for TEM than the Earth

Earth

Typical Earth crust: 10^{-2} S/m

Ocean water: 1 S/m

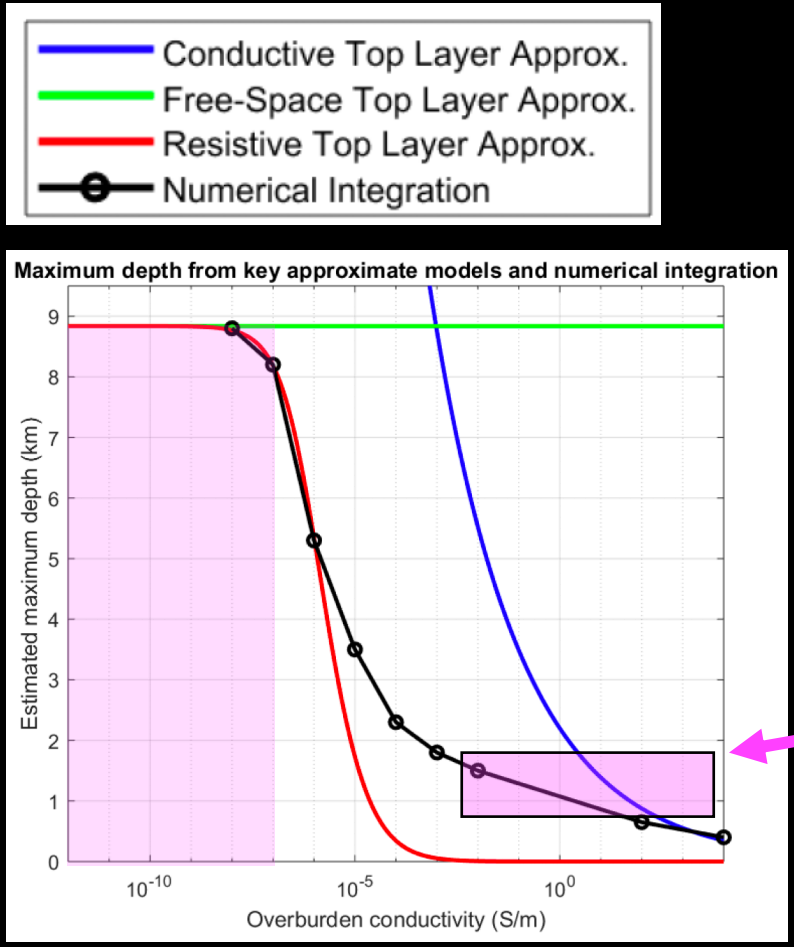
Contrast ratio: ~10^{2}

Mars

Dry Mars crust: ~10^{-7} S/m

Ocean water: 1 S/m

Contrast ratio: ~10^{7}



Earth TEM rule of thumb

$l \sim d$

Mars increase by x 10

Description	Value
TEM bandwidth	20 kHz
Transmitter power	10 W
Receiver's noise figure	10 dB
External noise temperature	450 Kelvin
Surface temperature	-55 C

Description	Value
Wire Gauge	32 AWG
TX/RX diameter	1000m
# of turns	1
Groundwater conductivity (σ_2)	0.1 S/m
Groundwater body thickness	100 m
Integration time	1 hour
Step Repetition Frequency	1 Hz

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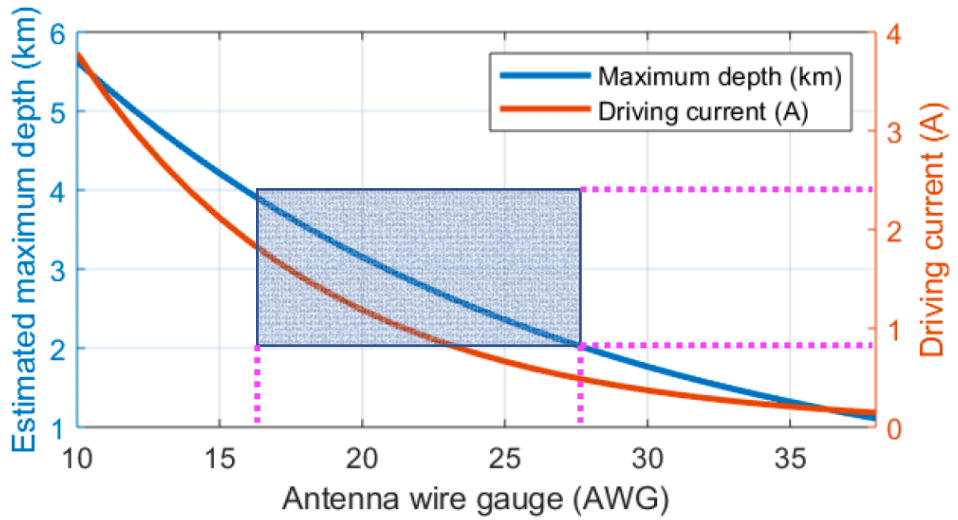
Small mass, significant implementation flexibility

If we want to go → 10 km

- ~100 m diameter loop, low transmit power (<10 W), low weight (1-7 kg) and small integration time (~1 h).
- Smaller (~10 m diameter) system at a higher transmit power (~100 W), more turns (~10), and larger integration time (~sols).



Dependence on power and AWG (100 m)

Description	Value
TEM bandwidth	20 kHz
Transmitter power	Variable
Receiver's noise figure	10 dB
External noise temperature	450 Kelvin
Surface temperature	-55 C
Overburden conductivity (σ_1)	1e-12 S/m

Description	Value
Wire Gauge	Variable
TX/RX diameter	100m
# of turns	1
Groundwater conductivity (σ_2)	0.1 S/m
Groundwater body thickness	100 m
Integration time	1 hour
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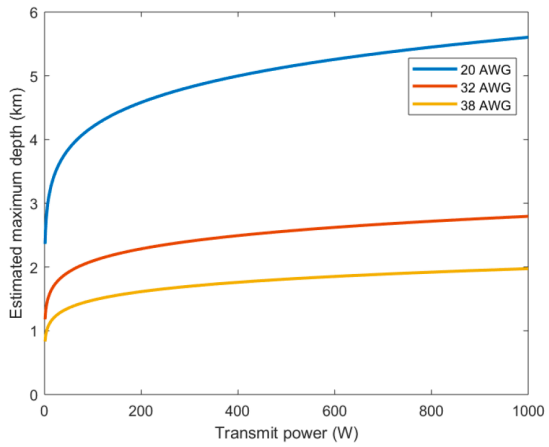

Description	Value
TEM bandwidth	20 kHz
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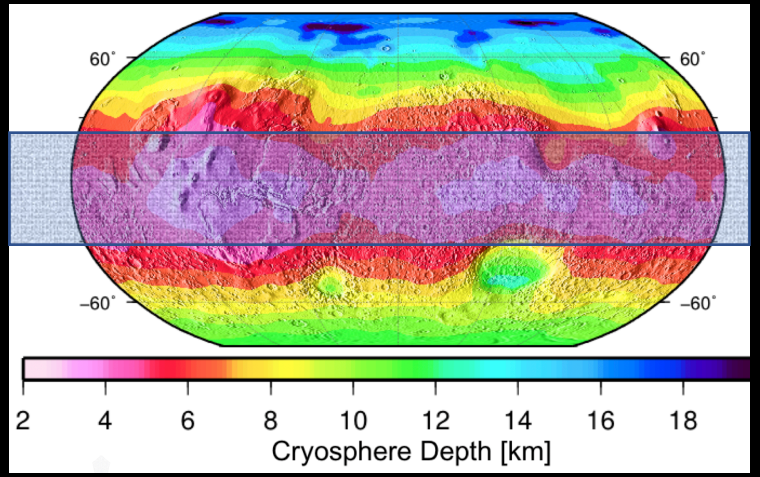

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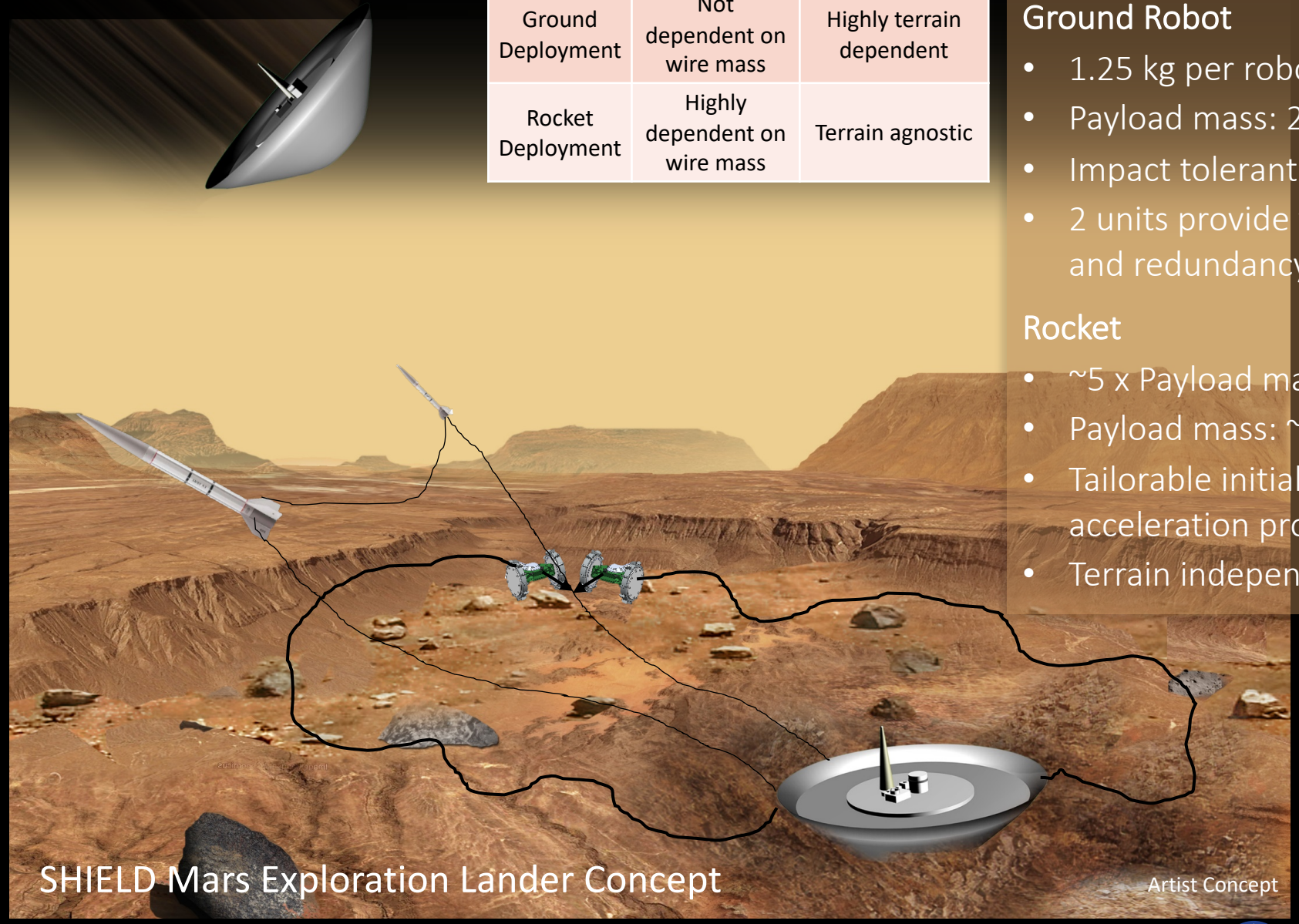
Loop deployment is simple & light

Method	Mass Consideration	Terrain Consideration
Ground Deployment	Not dependent on wire mass	Highly terrain dependent
Rocket Deployment	Highly dependent on wire mass	Terrain agnostic



The 2 leading methods of deployment

Ground Robot

- 1.25 kg per robot
- Payload mass: 2 kg per robot
- Impact tolerant design
- 2 units provide faster deployment and redundancy

Rocket

- ~5 x Payload mass
- Payload mass: ~ 20% of total mass
- Tailorable initial impulse and acceleration profile
- Terrain independent

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Getting to the solution

General

Dry crust (ice is similar)

- ~ 10^{-7} S/m

Aquifer depending on age

- ~ 0.01-1 S/m (Myr → Gyr)

Potential Issues?

- Mars vs Earth: Fe/Mg is larger (0.1 → 0.3). Ores? Fe-rich rocks?
- More sulfur-rich volcanic material (sulfides?).
- Many clay provinces are mapped.

Solutions

- So far, no indications for concerns.
- However, local geology must be mapped and will help us interpret data.

oxidized state.

- Sulfides (<< 1% of crust), no large ore bodies observed so far.
- Even if such bodies remain undetected in the surface, they are often irregularly shaped and could be characterized from multicomponent sounding.

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Hardware & prototypes

- Terrestrial prototype in 2020
- Mars prototype in 2021

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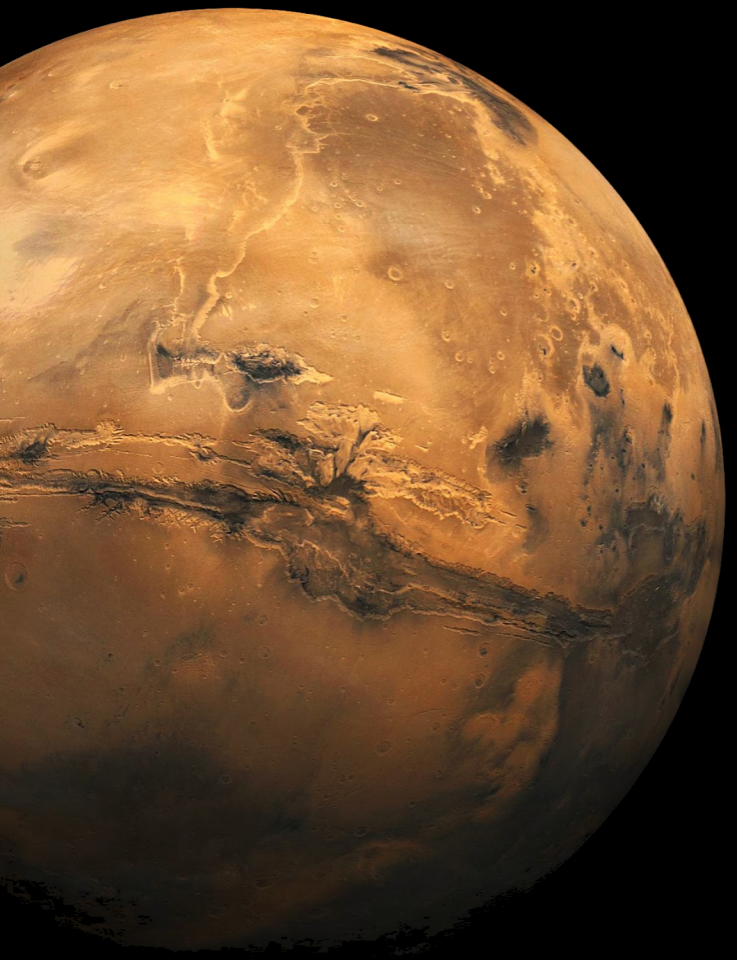

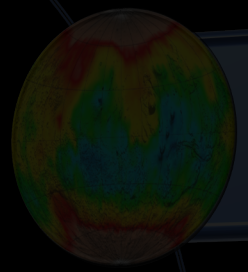

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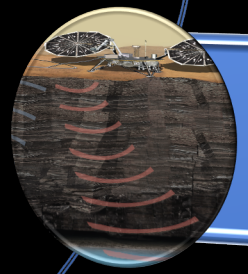
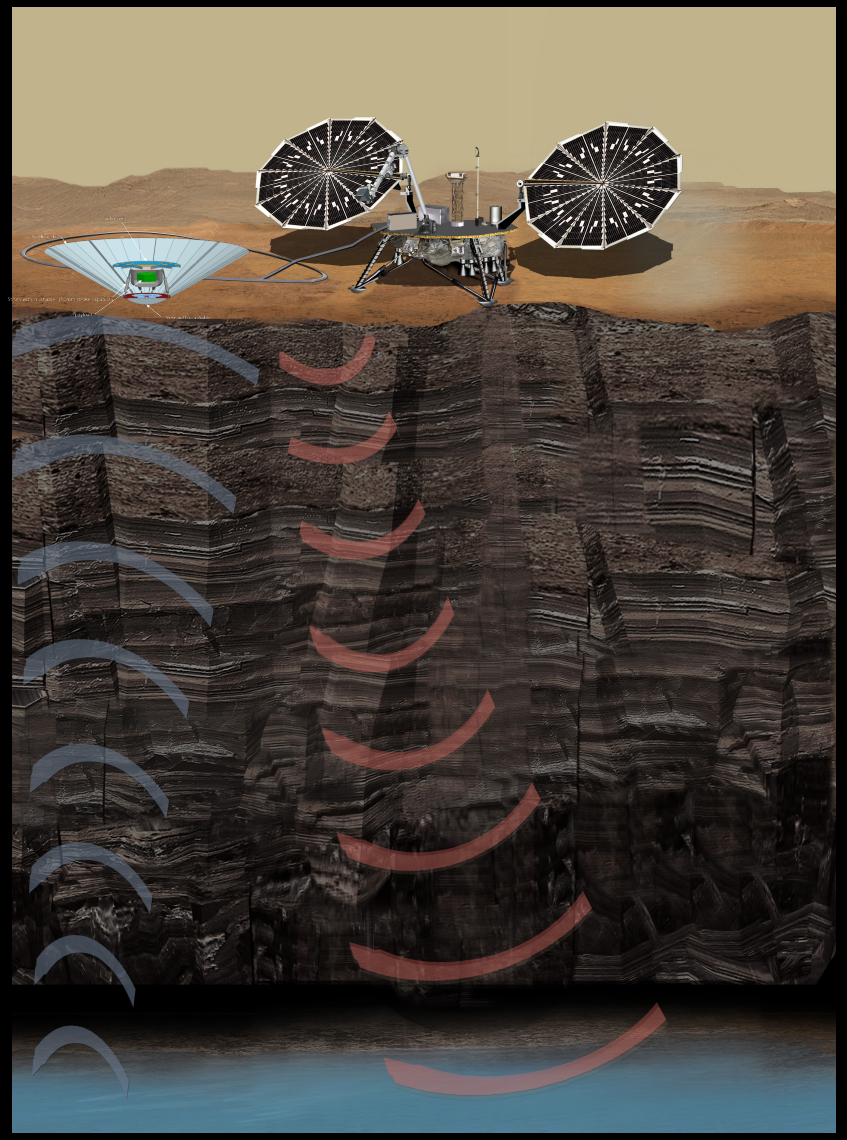


Mission Implementation

Mission Concept – Discovery to New Frontiers-type

Objectives

- If heritage-based system: Phoenix-type lander.
- Small-spacecraft compatible (<10 kg): SHIELD



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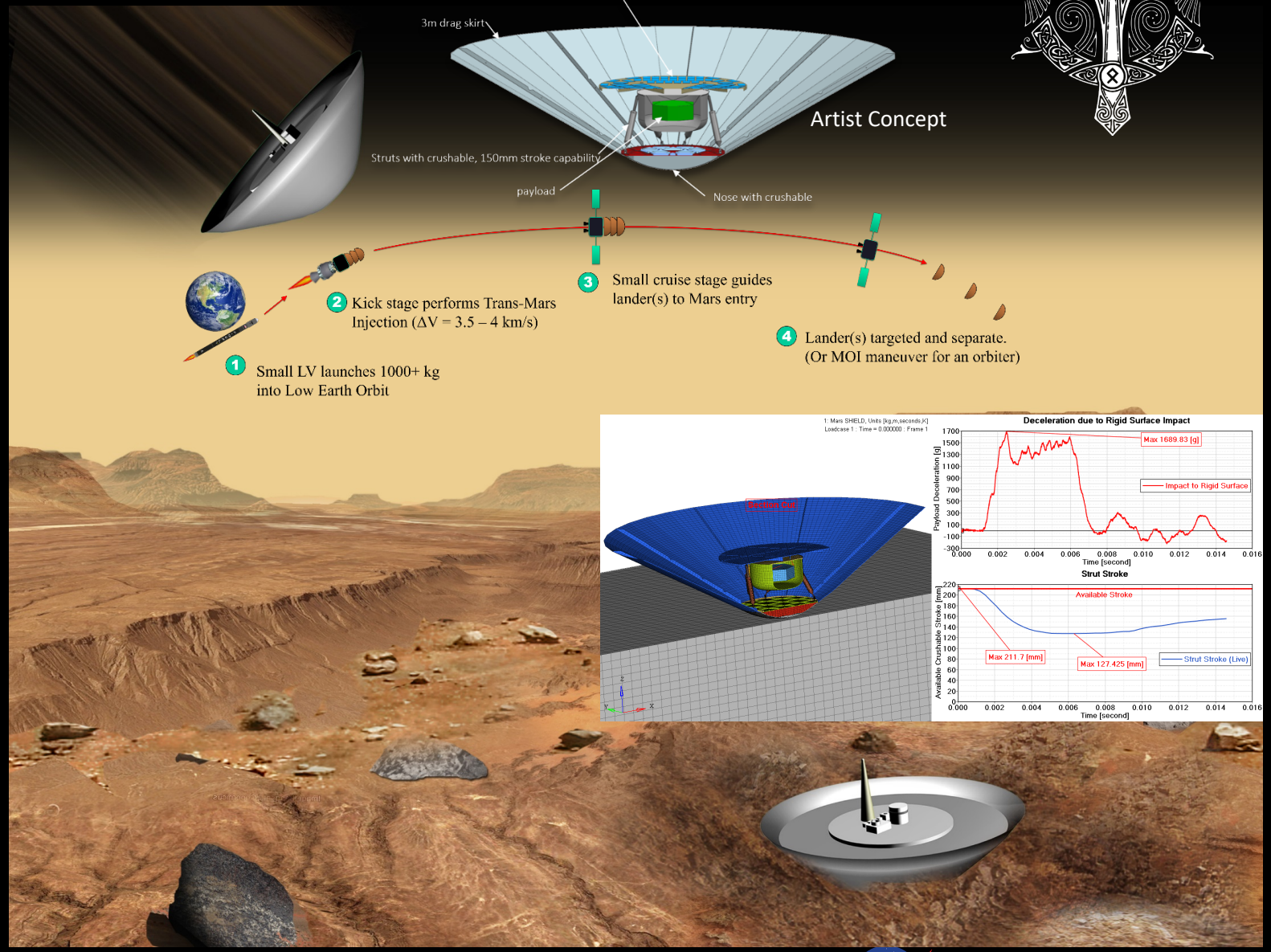
Mission Concept – Smallsat-type

<u>Small High Impact Energy Landing Device</u>

SHIELD enables the transportation of small scientific payloads affordably to the surface, such as TH_2OR

- Landed Mass: 50 kg
- Entry speed: 60 m/s
- Impact load range 1000 g – 2000 g
- Total science payload up to 6 kg
- Hosted, secondary, or dedicated P/L configurations
- Investigating options for mobility
- Expected Mission Duration range from 90 sols to 1 Martian year (latitude dependent)



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Where do we land?

We could land where:

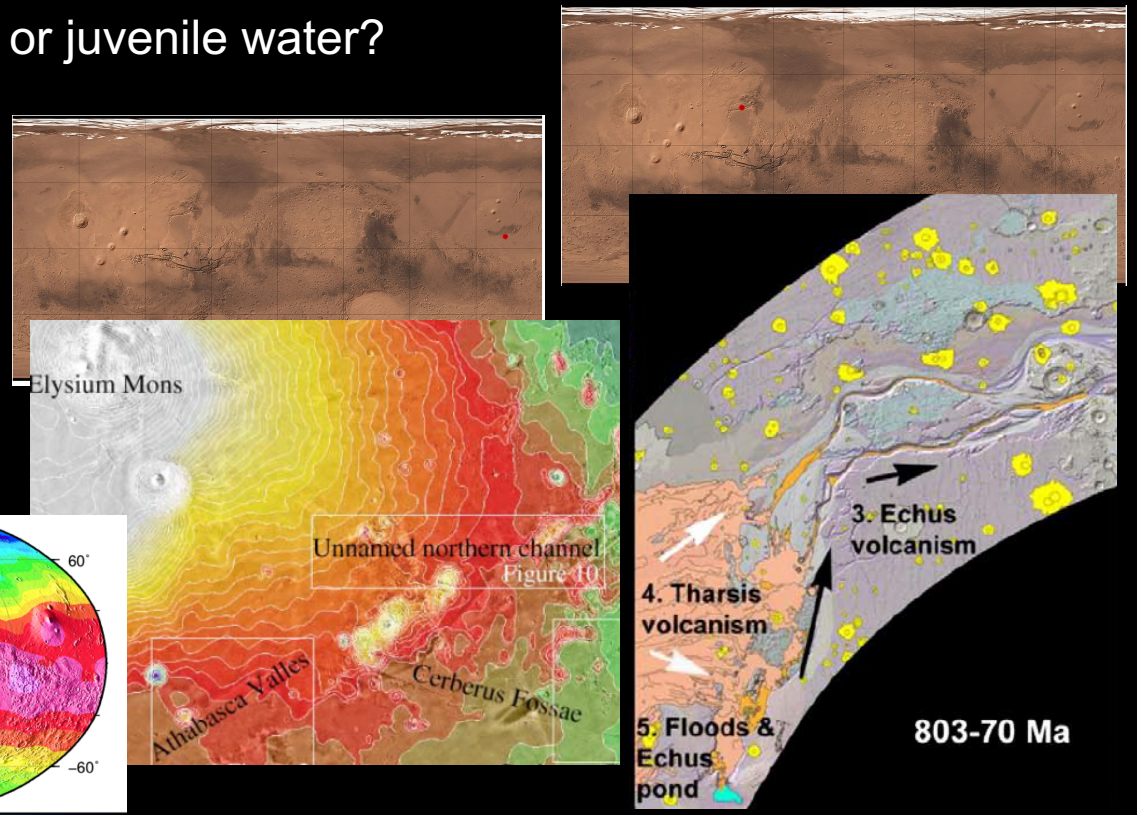
- Available data suggest
  - Recent water outflows
  - Trace gas outgassing (East of Gale crater)?
- Models predict:
  - Shallow liquid water accumulation

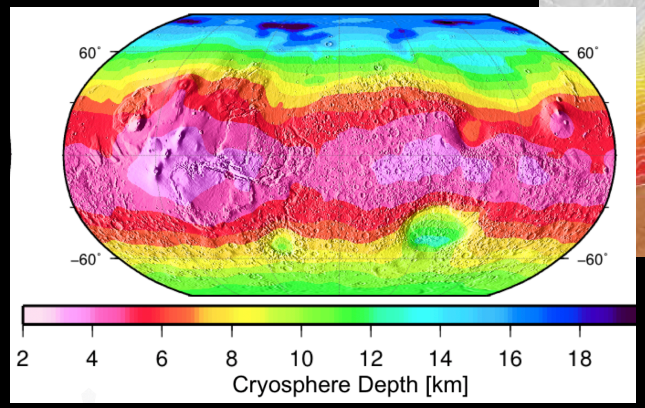
➢ Any place will help us estimate global water inventories (especially if we land on low altitude or more than one device).

Young Outflow Channels in Athabasca and Kasei

[Burr et al., 2002; Chapman et al., 2010]

- Aquifer or juvenile water?





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Summary

THANK YOU!

- Liquid water can exist at ~ kms depth and is the best location for habitable zones on contemporary Mars
- Transient Electromagnetic Sounding is best suited to detect & characterize liquid groundwater on Mars with small mass & costs
  - Penetration depths of many kms
  - Does not depend on ambient sources
  - Modest resource requirements
  - ➢ TH_2OR can detect liquid groundwater with a payload mass < 10 kg
- Small high-g landers (SHIELD) and Phoenix-type architectures can be tractable up to Discovery class. Active mobility would likely bring it into a New Frontiers class.
- We can finally answer the question: Is there liquid water on Mars?

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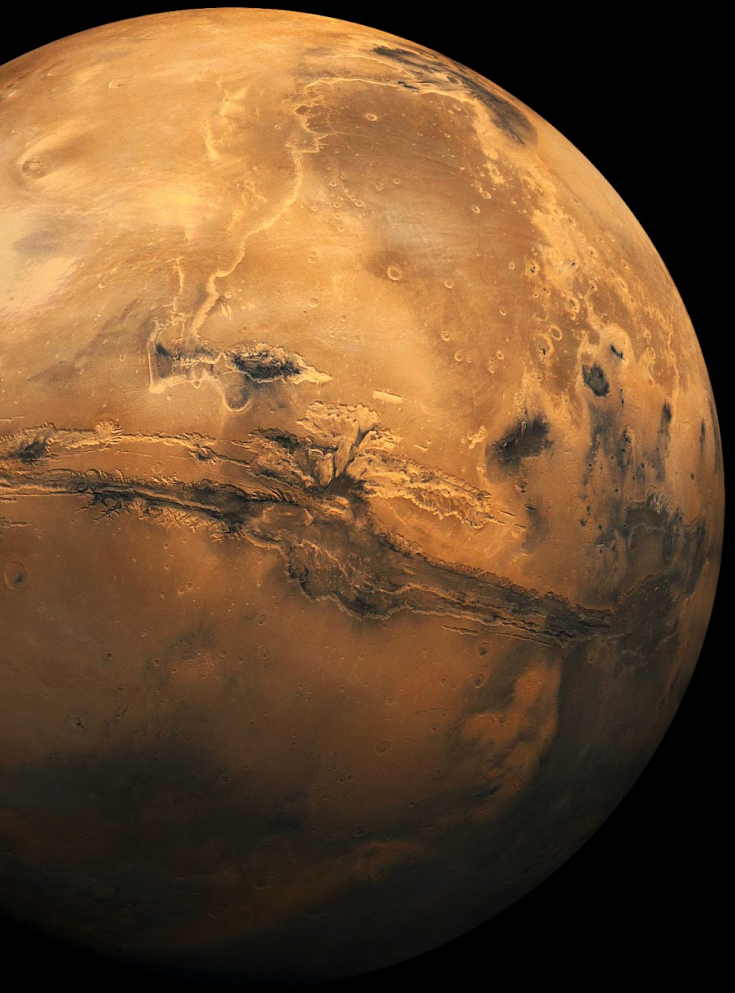

EXTRAS

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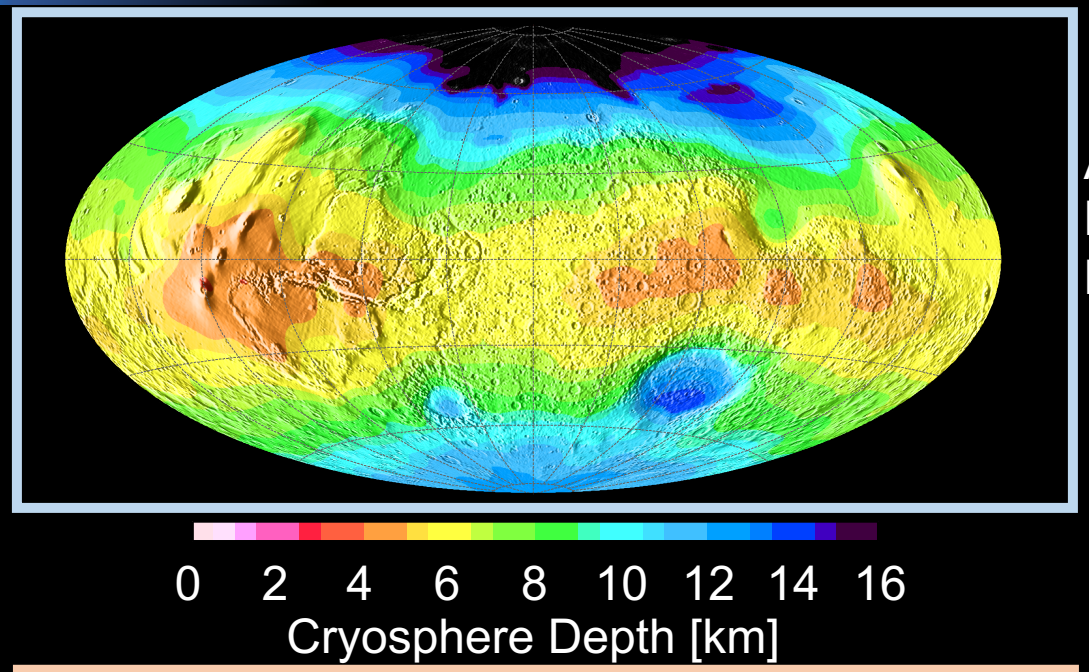
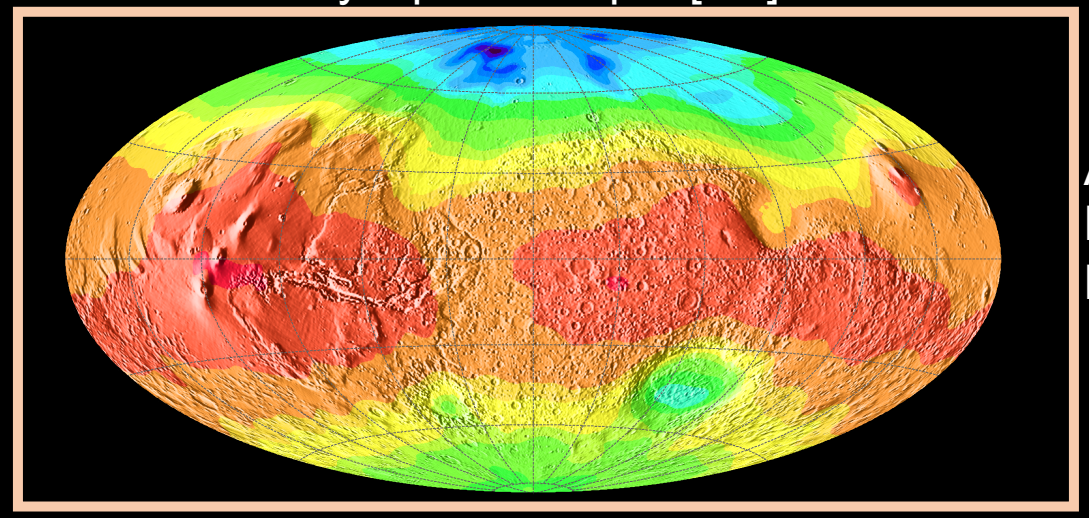
Where is the water: thermal conductivity variability

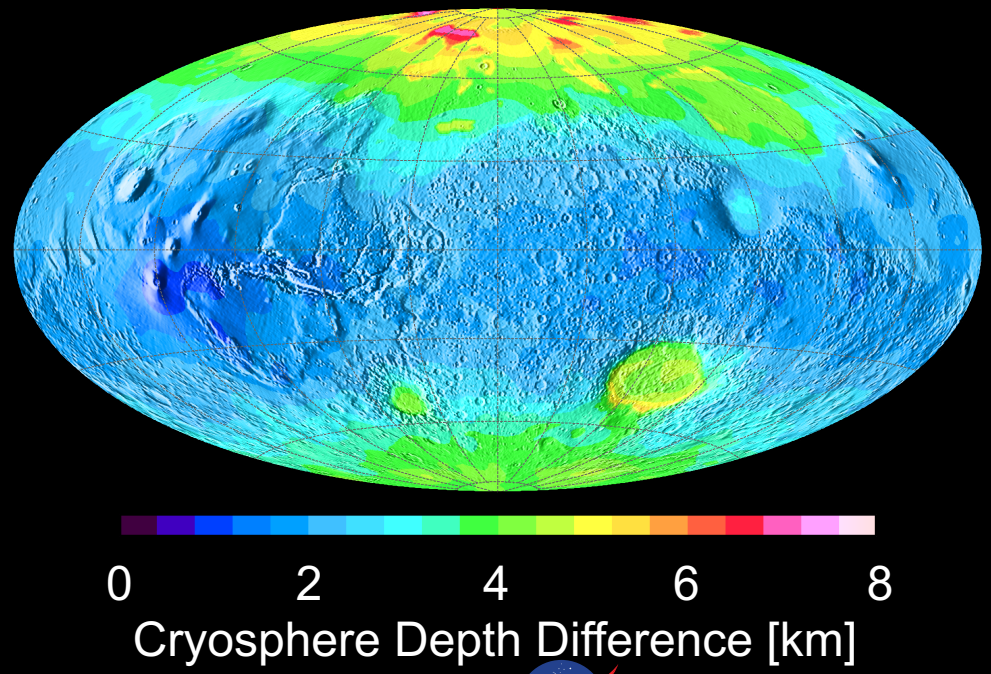


Avg: 8.07 km
Min: 3.97 km
Max: 21.97 km

k = 3 W / m K	k = 2 W / m K
k = 4 W / m K	k = 4 W / m K



Avg: 5.44 km
Min: 2.91 km
Max: 15.12 km



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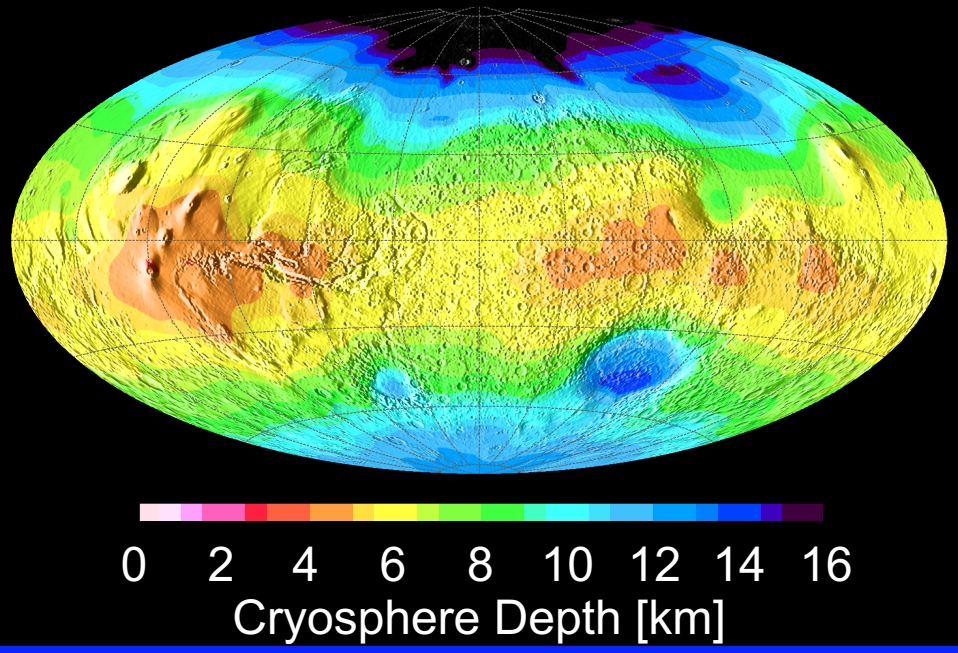
Where is the water: $Ca(ClO_4)_2$



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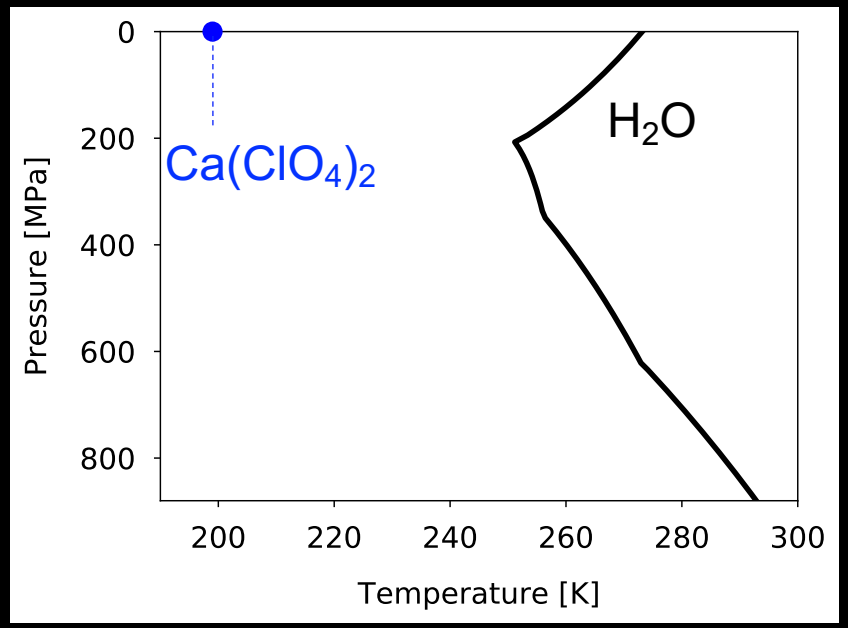
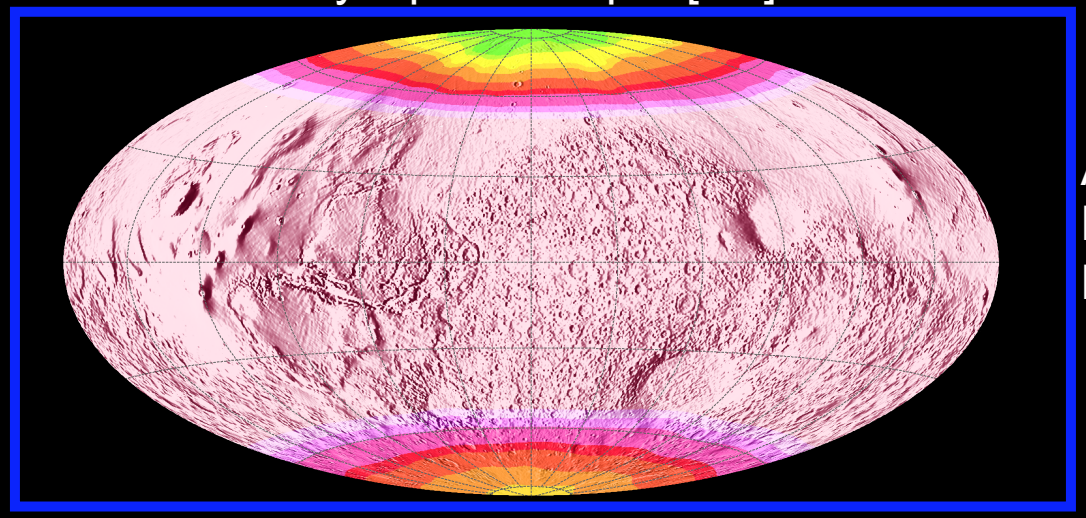
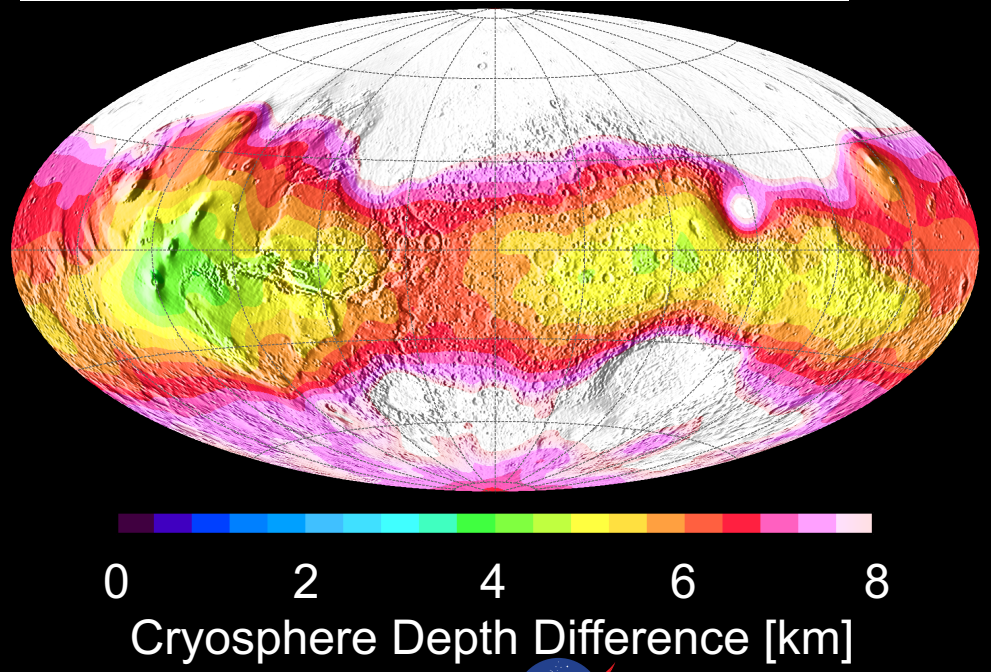




Avg: 0.63 km
Min: 0 km
Max: 8.24 km



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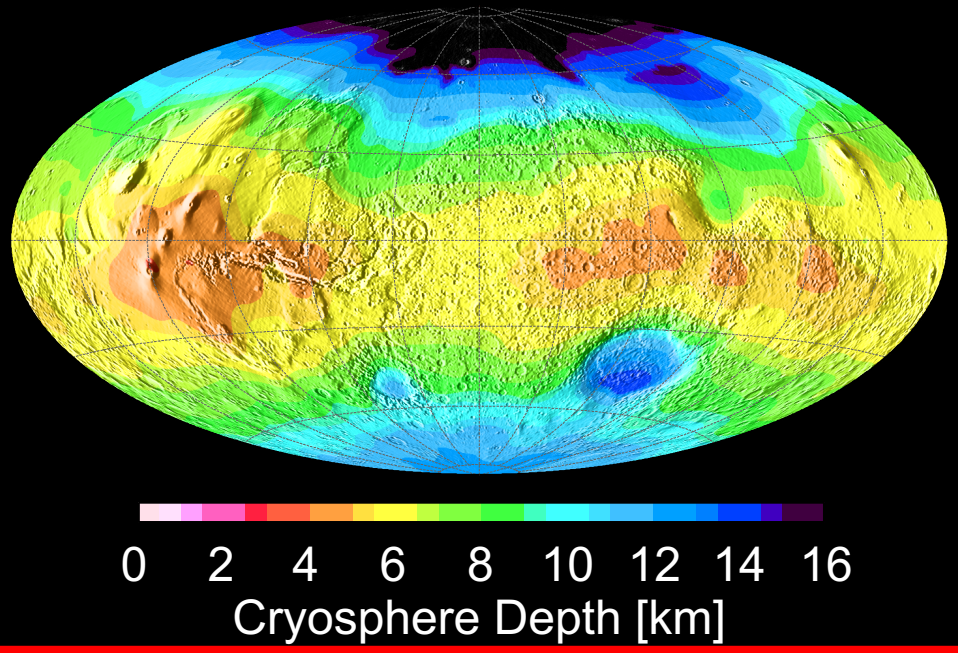
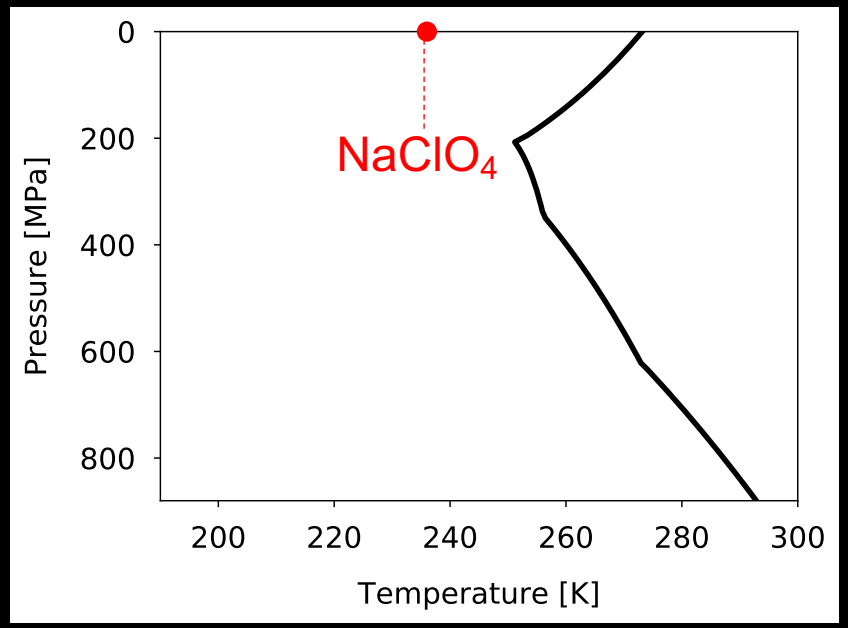
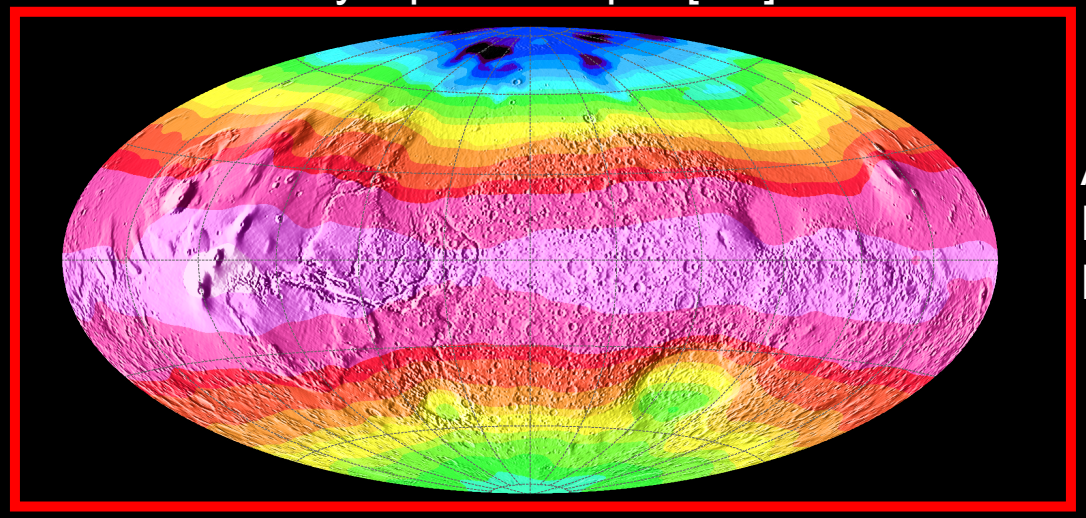
Where is the water: $NaClO_4$

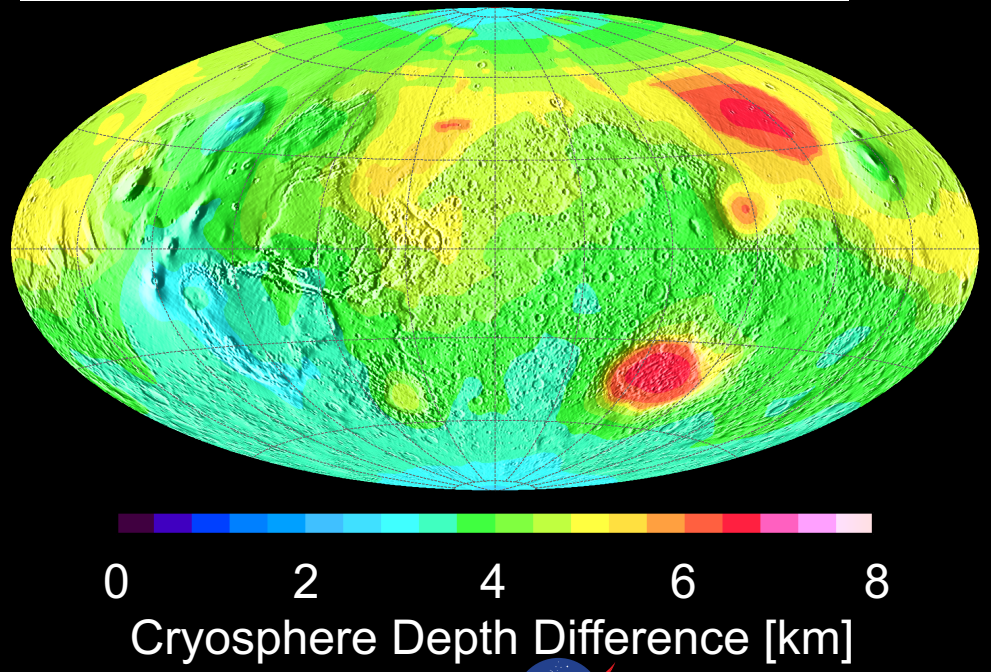


Avg: 8.07 km
Min: 3.97 km
Max: 21.97 km





Avg: 3.92 km
Min: 0.90 km
Max: 17.22 km



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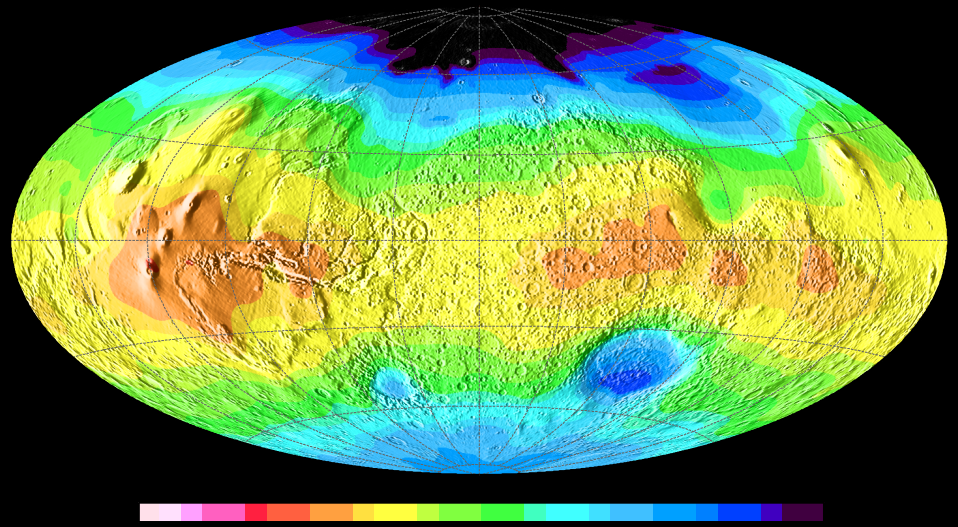
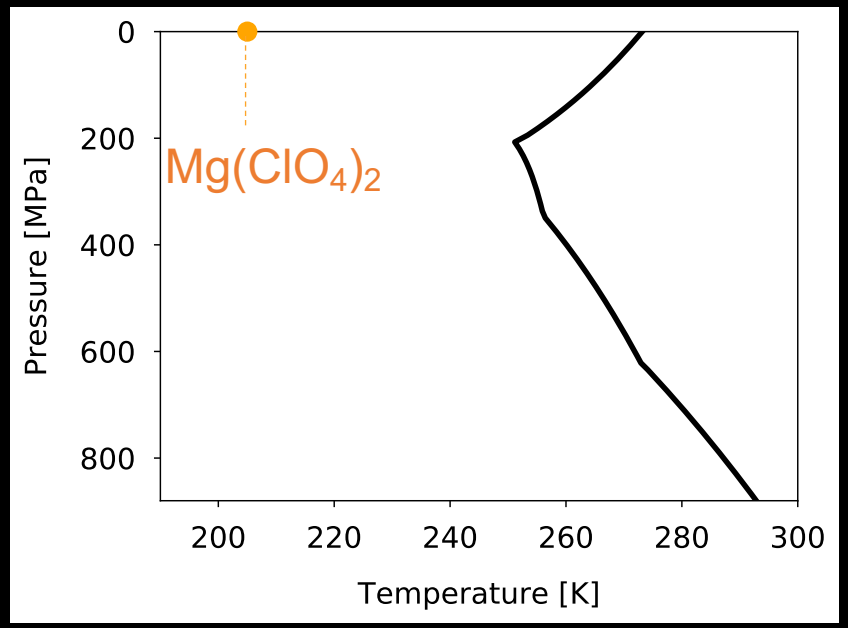
Where is the water: $Mg(ClO_4)_2$

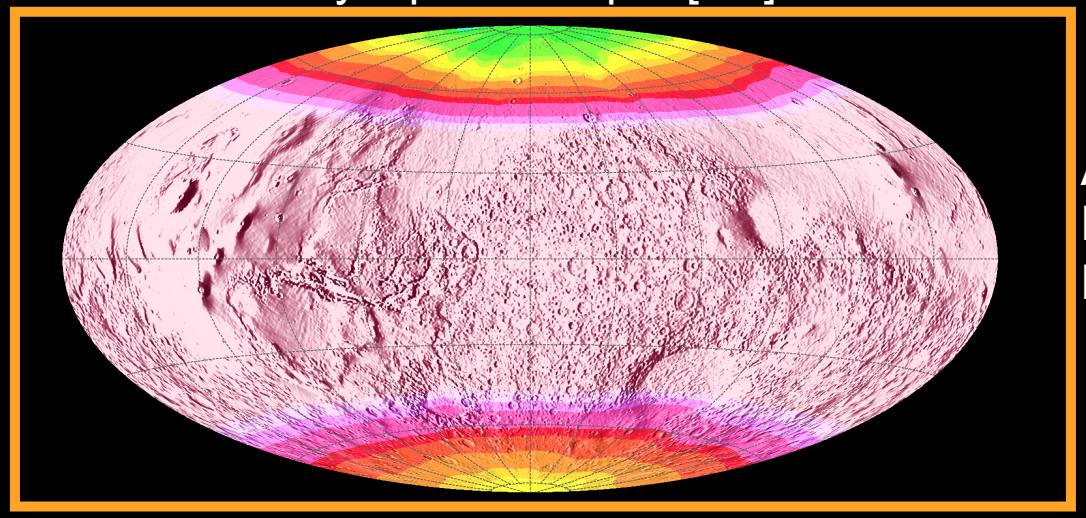


0 2 4 6 8 10 12 14 16

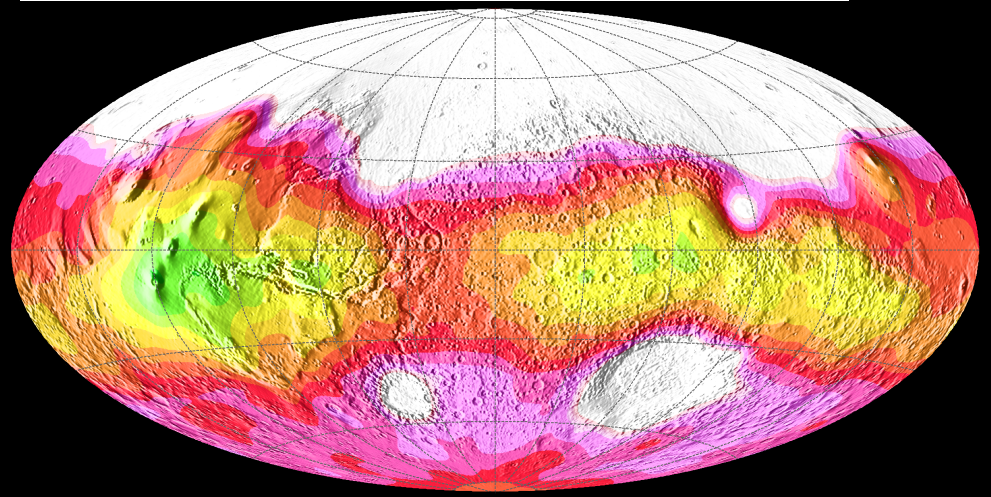
Cryosphere Depth [km]

Avg: 8.07 km
Min: 3.97 km
Max: 21.97 km





Avg: 0.88 km
Min: 0 km
Max: 9.32 km



0 2 4 6 8

Cryosphere Depth Difference [km]

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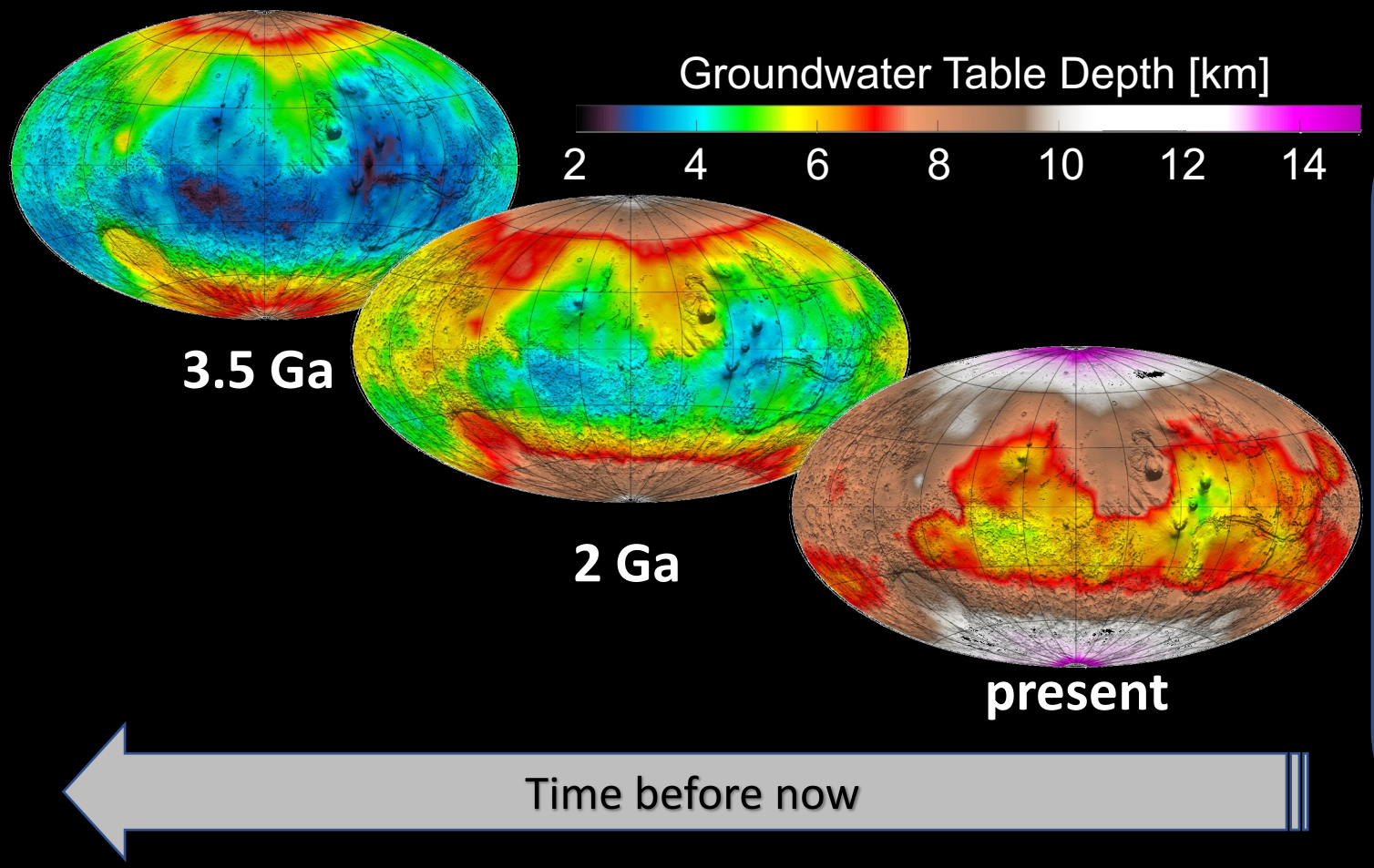
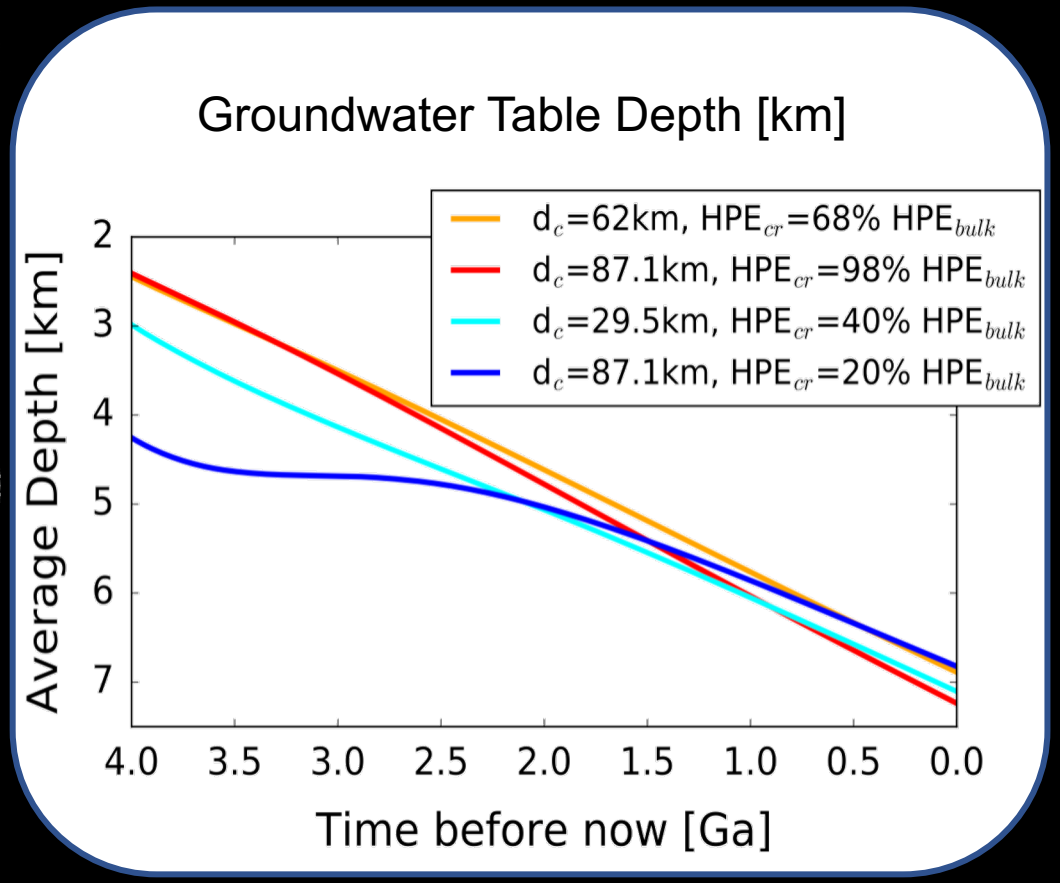
Where is the water: liquid water was possibly always deep





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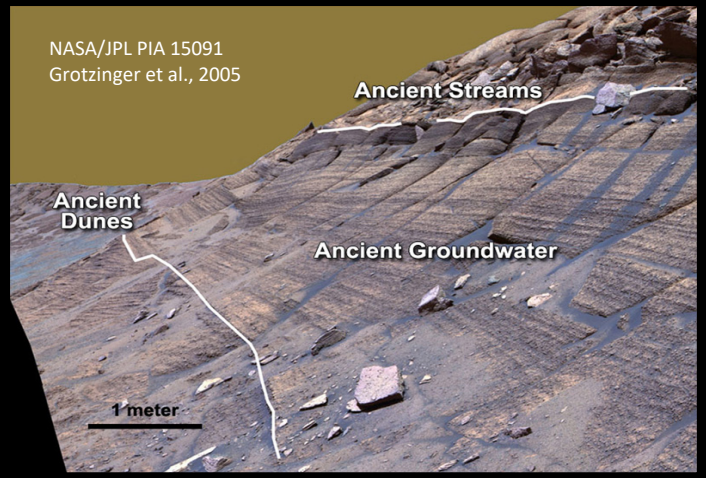
A refresher: old water… groundwater dominated?

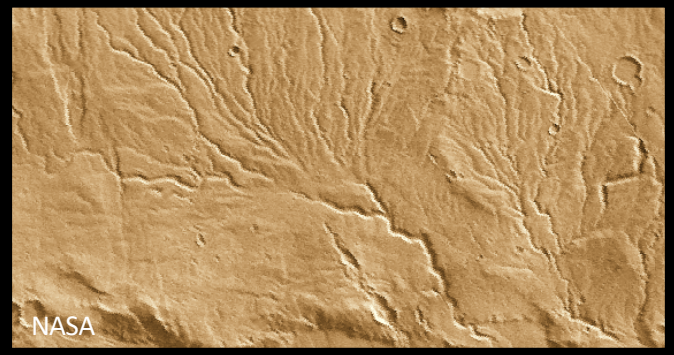
Cementation/Alteration of Sedimentary Deposits (Noachian)



MnO_2 veins (MSL, Gale Crater)

Chaos & Outflow Channels (Hesperian-Amazonian, e.g. Kasei Valles)

Valley Networks? (Noachian-Hesperian)



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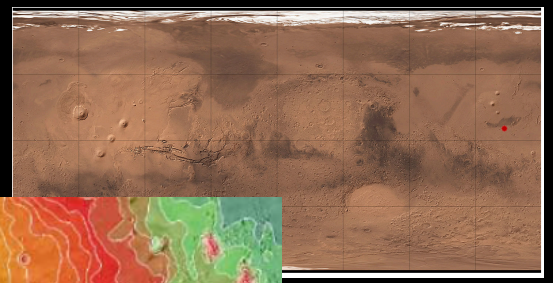
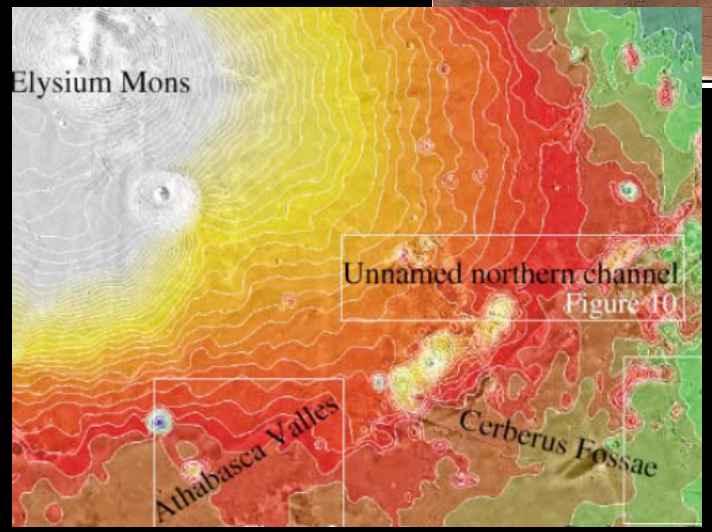
A refresher: young groundwater?

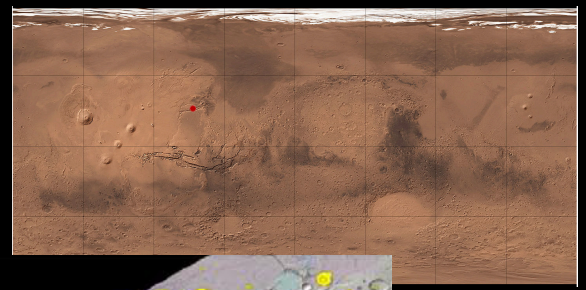
Young Outflow Channels in Athabasca and Kasei

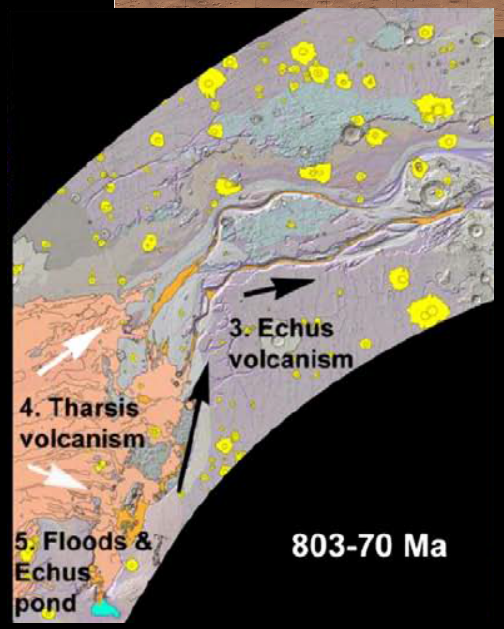
[Burr et al., 2002; Chapman et al., 2010]

- Aquifer or juvenile water?









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Limited possibilities

Expanding current state of the art

Method	SNMR Surface Nuclear Magnetic Resonance	TEM Transient Electromagnetics	MT Magnetotellurics	MTF Magnetic Transfer Function	Orbital GPR Ground-Penetrating Radar	Static GPR	Mobile GPR	Seismic Single Station	Seismic Interferometry	Seismic Reflection
Family		Low Frequency Electromagnetic			High Frequency Electromagnetic			Seismic		
Source	Active + Crustal Field	Active	Passive	Passive	Active	Active	Active	Passive	Passive	Active
Water Discrimination	**Excellent** (Nearly Unique)		**Very Good** Reflectivity 20-85%		**Good** No aquifer penetration. Reflectivity ~20%			**Fair** Reflectively ~3%, mode conversions ~0.3%		
Aperture	100 m	100 m	10 m	n/a, but requires orbital reference	<10 m	10 m	<1 m	n/a	kms	kms
Investigation Depth	100s m	kms	>10s km	10s km	100 m	km	10s m	>10s km	kms	kms
Coverage	Static, 1D	Static, 1D	Static, 1D anisotropic	Local (on rover)	Global 2D or 3D	Static, 1D anisotropic	Local (on rover)	Static, 1D	Local	Local
Resources	N/A (>100 kg)	Medium (10 kg, 30 W)	Low-Medium (3 kg, 7 W)	Low (for ground asset)	Low	Low-Medium	Low (<10 kg, 15 W)	Low-Medium SP only vs LP+SP	High to N/A	N/A

Resource assessment relative to a single Discovery to NF-class mission (orbiter, Phoenix/InSight class lander, or MER-class rover) dedicated to groundwater detection. N/A = cannot accommodate, HIGH = takes significant portion of mission, MEDIUM = nominal part of multinstrument payload but with a nonstandard deployment, LOW = nominal part of multinstrument payload,

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Why not orbits

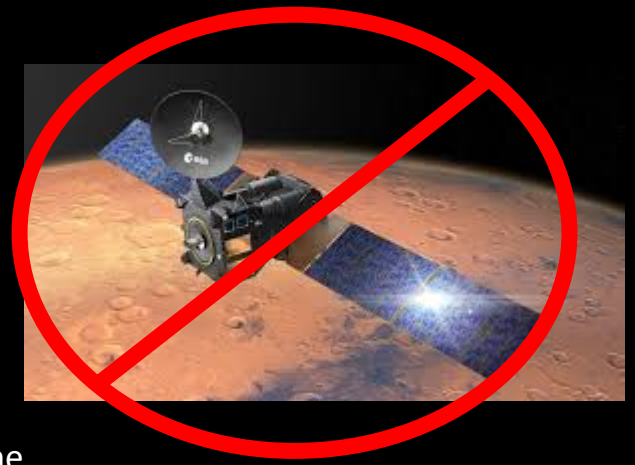
Orbiter will be around at least a few hundred kilometers high and any loop deployed in space whose side length ranges in the size of kms, will be dominated by radio wave propagation as opposed to Induction at the target distance

Loss tangent factor required for the target is much greater than 1 for induction regime operation, whereas for radar propagation such factors will require loss tangents to be much less than 1 for propagation. In this way the depth of the water layer can not be ascertained

$$\sigma >> \sqrt{\frac{2\epsilon 0}{\mu 0 d^2}}$$

If we were to use induction modelling from space (with free space over burden) the voltage received in time is proportional to:

$$Vz = M_{RX}\partial b_z \partial t = \frac{3\mu MRXMTXb}{2\pi(bt+2d)^4}$$ (Here b is the $\frac{2}{\mu\,\sigma h}$,



h: thickness of the target,
σ: conductivity of the target
d: depth of target
M_{TX},M_{RX} : Magnetic dipole moments of Tx and Rx loop respectively

As shown, the dissipation loss is proportional to (d^4)
(more loss than radar with (d^2)- which is why an orbiter will suffer heavy losses if needed to work in induction regime

Deployment of a large loop in orbit is impractical, due to such high dissipation loss in induction regime the power required for any practical TEM is orders of magnitude higher when compared to a loop on the surface

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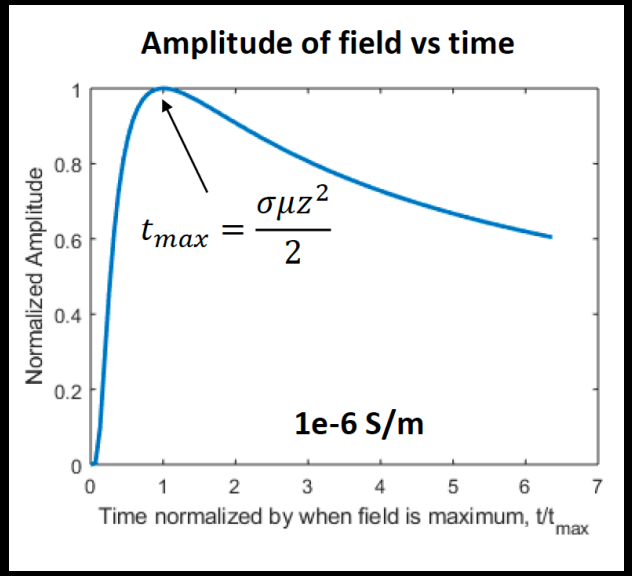
TEM Case Study

$$\frac{\partial^2}{\partial z^2}\begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{Bmatrix} - \sigma\mu\frac{\partial}{\partial t}\begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{H}\end{Bmatrix} = \mathbf{0}$$

$$e_x(z,t) = \frac{2H_0}{\sigma}\frac{1}{\sqrt{2\pi}}\sqrt{\frac{\sigma\mu}{2t}}\,e^{-\left(\frac{\sigma\mu}{2t}\cdot\frac{z^2}{2}\right)}$$



Maximum Voltage

$$t_{max} = \frac{\sigma\mu z^2}{2}$$

For: $\mu \sim \mu_0$, $z \sim 2\text{-}4\text{km}$, $\sigma \sim 10^{-7}\text{-}10^{-4}\text{S/m}$

We get t_{max}~0.1µs-ms

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TEM Case Study

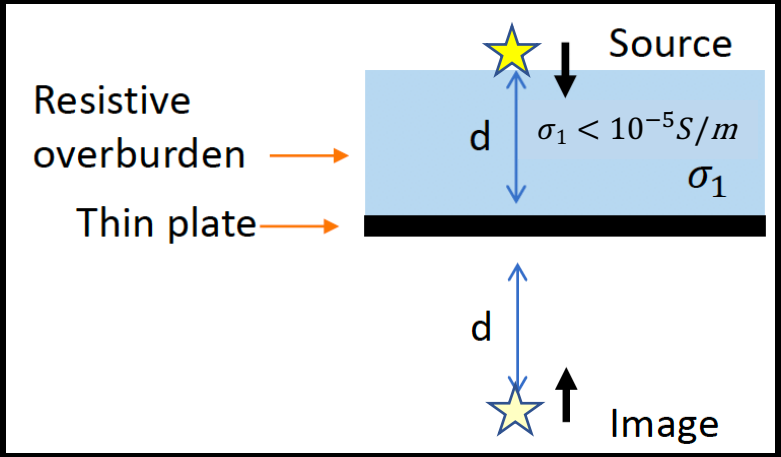

Image Theory

$$B_z \sim -\frac{\mu M_{TX}}{2\pi(v_0 t + 2d)^3} e^{-2\alpha d}$$

Faraday's law of induction

$$V_z = M_{RX} \frac{\partial B_z}{\partial t}$$

$$n_v = V_z \sim M_{RX} \frac{\partial B_z}{\partial t} = \frac{3\mu M_{RX} M_{TX} b}{2\pi(bt + 2d)^4} e^{-2\alpha d}$$

At early times, $bt \ll 2d$, and:

1. Voltage is directly related to layer depth
2. Response voltage (and SNR) is the greatest

So we can use this as a best case analysis

Maximum Voltage

$$v_0 = \frac{h}{t} = \frac{h}{\frac{\sigma\mu h^2}{2}} = \frac{2}{\mu\sigma h}$$

$$t_{max} = \frac{\sigma\mu z^2}{2}$$

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TEM Case Study

Excluding resistance effects

$\boldsymbol{d \sim A^{1/2} \sim l}$ (with resistivity effects ~$l^{3/4}$)!

$\boldsymbol{d \sim \#^{1/2}}$

$d \sim P_t^{1/8} \overset{P_t = VI = RI^2}{\approx} I^{1/4}$

$d \sim N_{avg}^{1/8}$ → **+250%** (10 min→10 d)

$d \sim [1 + \alpha(Ts - 293K)]^{-1/4}$ → **+7%** from Earth to Mars (20°C→-50°C)

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TEM Case Study

- On Earth: TEM goes one order of magnitude deeper.
- Much bigger contrast for water in conductivity than permittivity.
- Skin depth as a guideline $\sim \delta \sim \sqrt{\frac{2}{\mu\omega\sigma}}$
- Cannot well penetrate aquifer (hence no thickness or salinity info).

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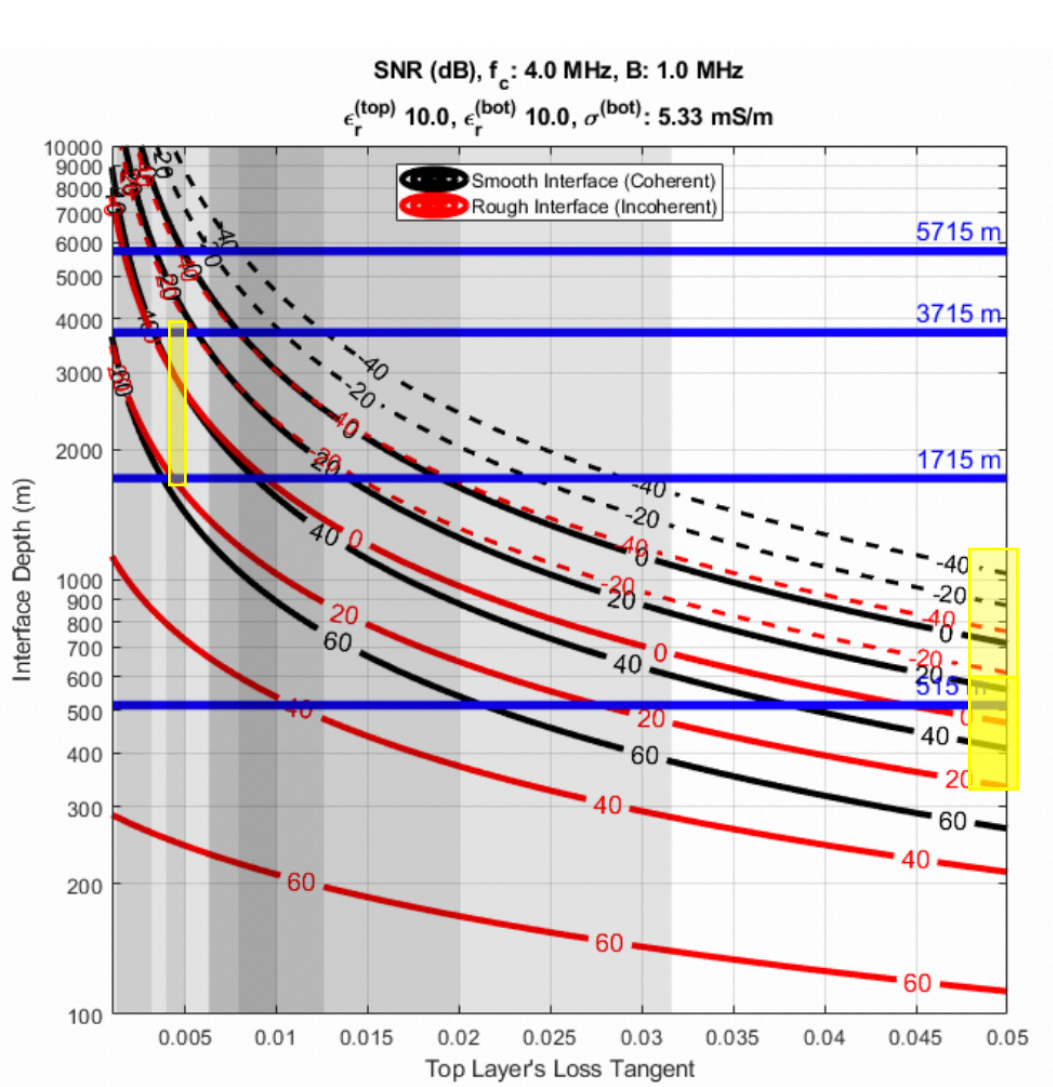
TEM Case Study

- Low loss tangent only acceptable in limited regions (ice, low-density volcanic ash)
- Volume scatter and clutter are ignored.
- Mobility is generally needed.
- We look at rather optimistically scenarios with SNR_0=147 dB (tens of dB larger than common systems).
- Scattering: Effective conductivity derived from MARSIS/SHARAD is either due to a greater electric conductivity from adsorbed water or geometric scattering. TEM would clarify that.
- **Staying in ~ 1 km regime.**



Peak TX Power	10 W
Antenna Length	37 – 90 m
Electronics Mass	6 kg
Antenna + Deployment Structure Mass	<5 kg
Electronics Power	15 W

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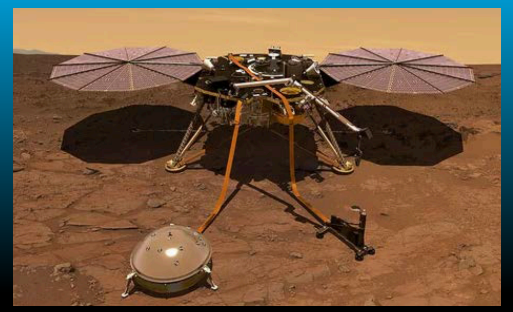
TEM Case Study

- Large-scale reflection or interferometry measurements at the surface of Mars could identify aquifers.
- But both require long lines (conservatively, many kms) composed of 100 or more receivers or a buried DAS line.
- Surface-wave dispersion needs multiple stations or very well-located events, which could require a long passive deployment to achieve desired accuracy.
- **The receiver-function method can operate from a single station and will be tested by InSight. Single-station seismology could operate as a complementary method to primary TEM sounding for groundwater on Mars to obtain larger-scale bulk water properties of the crust.**



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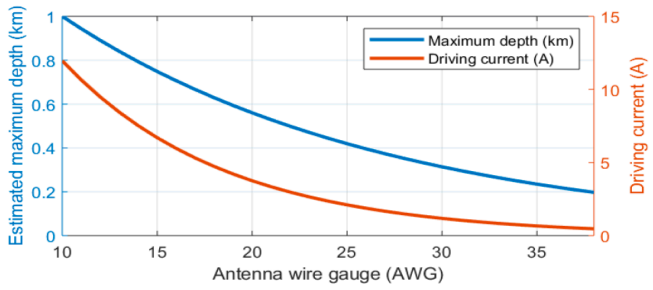
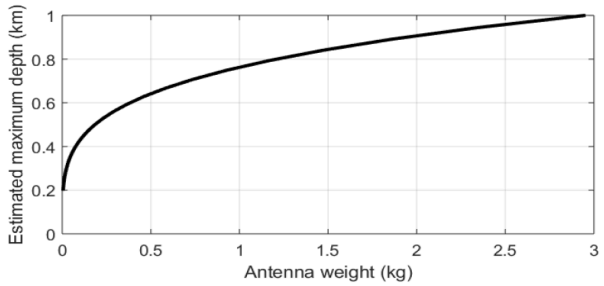
Smaller loop

Description	Value
TEM bandwidth	20 kHz
Transmitter power	10 W
Receiver's noise figure	10 dB
External noise temperature	450 Kelvin
Surface temperature	-55 C
Overburden conductivity (σ_1)	1e-12 S/m

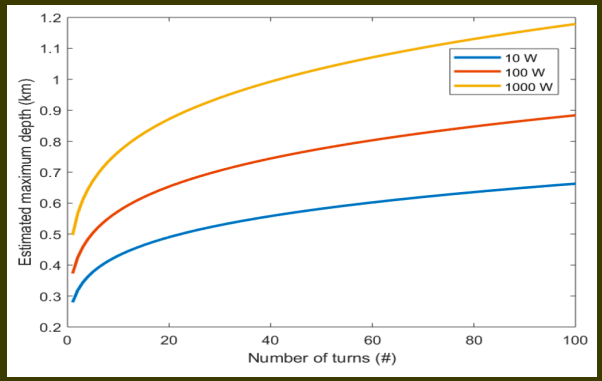
Description	Value
Wire Gauge	Variable
TX/RX diameter	10m
# of turns	1
Groundwater conductivity (σ_2)	0.1 S/m
Groundwater body thickness	100 m
Integration time	1 hour
Step Repetition Frequency	1 Hz

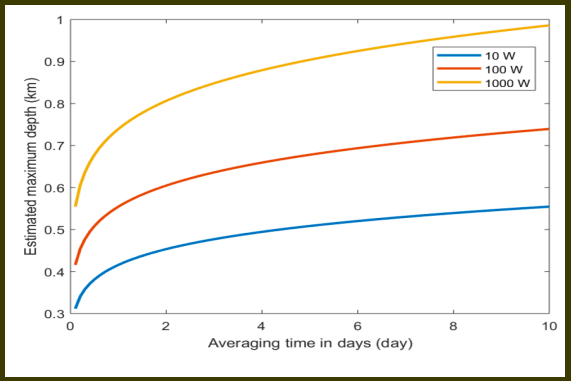


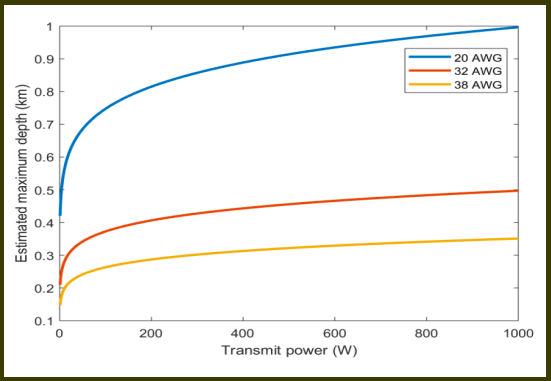


Examples @ 2.9 kg.

- 10 m, 10 turns, 200 W @ 50% duty cycle, AWG=20, 10 days → **2.5 km**.
- 2 m, 50 turns, 200 W @ 50% duty cycle, AWG=20, 10 days →**1.0 km**.
- **There are enough knobs to play with to get deep!**







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SPLD case

- Without judgement whether the SPLD MARSIS 1.5 km aquifer results are correct, we will test the hypothesis with a system consisting of about a 100m loop capable of 10W of power (Tx and Rx) using the Free-Space Top layer approach

- The figure to the right shows the extent of depth capable of scanning with different loop sizes and layer models. The highlighted green color represents which model is most suited to use based on conductivity

Results for single/multi-turn systems

Diameter (TX & RX)	Number of Turns	Antenna Weight	Overburden conductivity (σ_1 S/m)	Depth (1 hour integration @ 1Hz SRF		
				Conductive Top Layer	Free-Space Top Layer	Resistive Top Layer
1000m	1	1.8kg	1e-6	>10km	8.8km	5.3km
100m		0.18kg		8.7km	1.6km	1.4km
10m		18g		2.1km	280m	272m
1m		2g		550m	50m	49m
1m	100	0.18kg	1e-4	430m	118m	64m
			1e-8	2.7km	118m	118m
			1e-12	>10km	118m	118m
10m	10	0.18kg	1e-4	1.2km	430m	128m
			1e-8	7.8km	430m	430m
			1e-12	>10km	430m	430m
1000m	1	1.8kg	1e-4	>10km	8.8km	344m
			1e-8	>10km	8.8km	8.7km
			1e-12	>10km	8.8km	8.8km

Description	Value
TEM bandwidth	20 kHz
Transmitter power	10 W
Receiver's noise figure	10 dB
External noise temperature	450 Kelvin
Surface temperature	-55 C
Wire Gauge	32 AWG
Groundwater conductivity (σ_2)	0.1 S/m
Groundwater body thickness	100 m
Integration time	1 hour
Step Repetition Frequency	1 Hz

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