Mars Lift and Tramway

Components of Omaha Trail, a system for high-efficiency transport between Earth and Mars

Lake Matthew Team + ISEC

constructed with independently valuable components

Lake Matthew Team / Celestia

Omaha Trail, Components

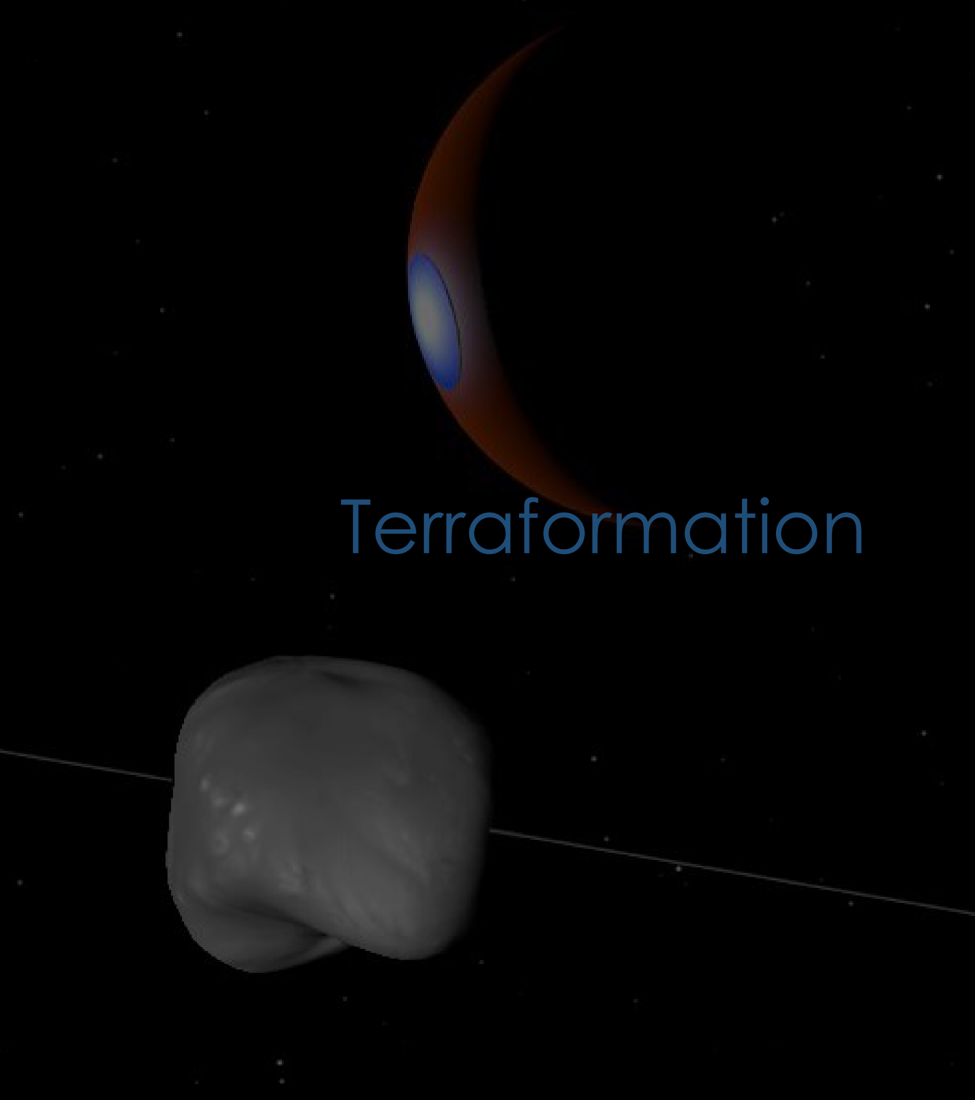
1. **Local Enhanced Terraforming:**
   - MATT: The Mars Terraformer Transfer
   - Omaha Crater: Cargo & Propellant

   => More at lakematthew.com!
2. **Deimos Infrastructure:**
   - Deimos Dock
   - Deimos Rail Launcher (DRL)

   => More in our SEC 2017 presentation at lakematthew.com
3. **Elevator-type Components:**
   - Mars Lift
   - Tramway

Overarching Goals:

Reduction of Earth Launches -> Lower Transport Costs
Faster Transit Times -> Less Radiation Exposure
Reduction of Resource Use on Mars
Mid-Term Mars Settlement



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Omaha Trail, Terraforming

Omaha Trail, Components

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   - Tramway

- **Self-Sufficiency:**
  - **Breathing and propellant gases, treated water and brine, hydroponics and food, most construction materials**
  - **in situ resource utilization (ISRU) => ~90% cut in cargo**

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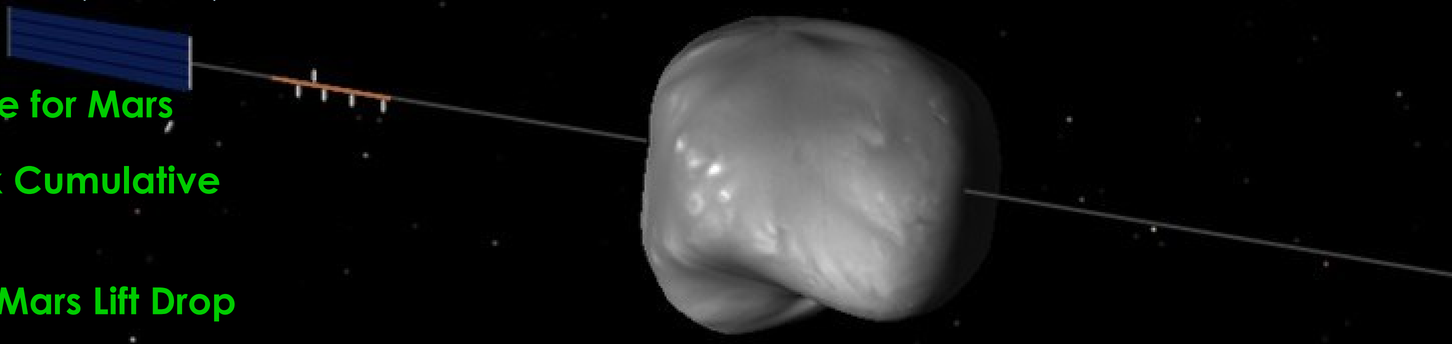
Omaha Trail, Deimos Infrastructure

1. Local Enhanced Terraforming:
   - MATT: The Mars Terraformer Transfer
   - Omaha Crater: Cargo & Propellant
2. **Deimos Infrastructure:**
   - Deimos Dock
   - Deimos Rail Launcher (DRL)
3. Elevator-type Components:
   - Mars Lift

- **Deimos Dock:**
  - **Power (PV)**
  - **Volatiles** (Deimos density 1.5 g/cm^3, Murchie et al. 2013, South Pole Mining, 50%wt volat., Fanale and Salvail 1990, CAVoR, Nichols 1993)
  - **Construction Materials for Deimos Infrastructure, Tether, and Counterweight of Mars Lift**
  - **Outside (most) of the Mars Gravity Well**
  - **Propellant Replenishing off the Mars Surface for Mars Round-Trip**
  - **4x PV compared to Mars Surface due to 4x Cumulative Solar**
  - **Proving Ground for Technology**
  - **Support for Construction and Operation of Mars Lift Drop Line**

- **Deimos Rail Launcher:**
  - **Boost without Propellant to Mars/Earth/Top of Elevator** (1km/s Δv)
  - **Speed-up and Propellant-Savings, e.g., for Mars-Earth Transfer**
  - **Most efficient conversion of PV power to Δv**
  - **Combined option for Mars EDL and Earth return with decision point at Mars periapsis.**
  - **Helical-coil EM launcher concept.**
  - **Potential for acceleration and deceleration**
  - **Potential for lightweight tether frame structure.**
  - **300 MW HVDC ~600 GJ during launch, superconducting magnetic energy storage (SMES) for extra 2.8 TJ.**
  - **Gentle acceleration, e.g., 0.5 m/s2 over 1000km rollout.**

Terraformation



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3. Elevator-type Components:
Mars Lift
Tramway

- **Value:**
  - **Space Elevators and Tramways follow the Railway Paradigm:**
    - Invest in infrastructure, reap benefits from it.
  - **Case for a Mars Space Elevator**
    - Drastically cut propellant requirements compared to landing rockets on the planet and taking off again for faster buildup of Mars infrastructure.
    - Lighter demands than Earth due to the Mars-Moons System promising a lighter feasibility condition.
  - **Mars Lift**
    - Reduced requirements for an architecture as close as possible to implementation.
    - One way going down to start, effective drop-line compared to propulsive landing.
  - **Tramway**
    - Railway equivalent with low requirements: low number of pylons and high tension elevator cable.

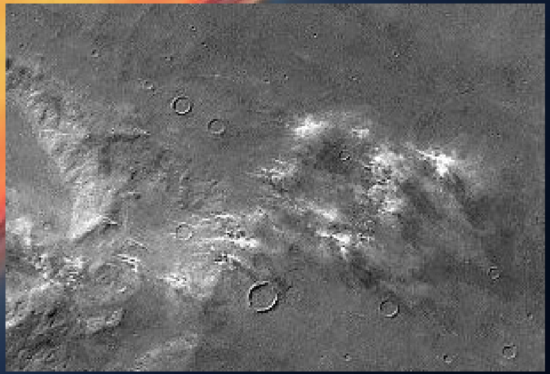
Boundary Conditions for Mars Lift

Plus

1. Lower gravity of Mars (~ 1/3 Earth) and similar rotation speed (ω) => **better for elevators than Earth**
2. Moons, with elevators

Minus

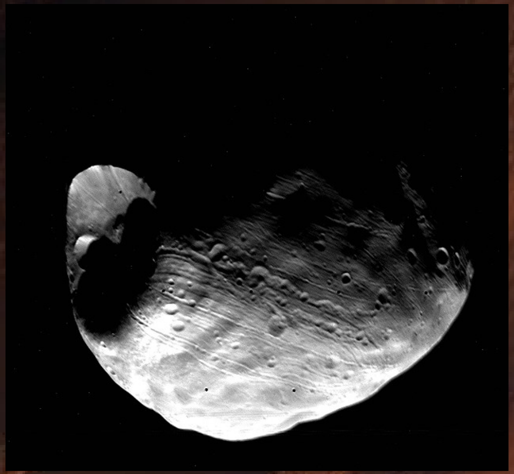
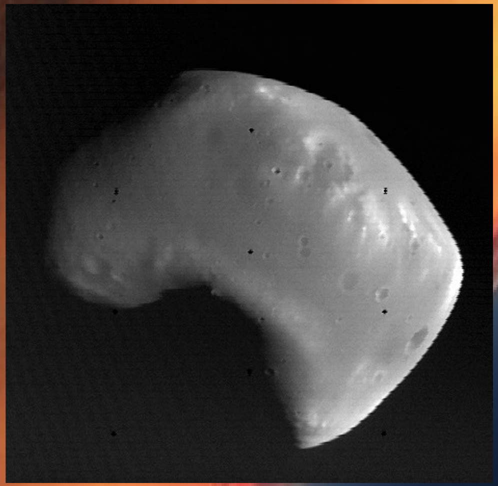
1. Moons, to avoid
2. Dust storms up to 80 km altitude ⬄ Not even the highest peaks avoid them (Clancy, 2008)
3. Static electricity in the Martian atmosphere ⬄ ~2 orders of magnitude higher conductivity than Earth. Frequent discharges (dry lightning, dust devils, electrostatic dust). (Simoes et al. 2008; Aplin, et al. 2011)
4. Remote environment ⬄ Everything has to be brought in at first. In situ resource utilization (ISRU) is imperative for the whole Mars Lift concept.



Dust Devils with Glowing Tops, Mars Global Surveyor/Malin Space Science Systems, 2010

and the Elevator Feasibility Condition

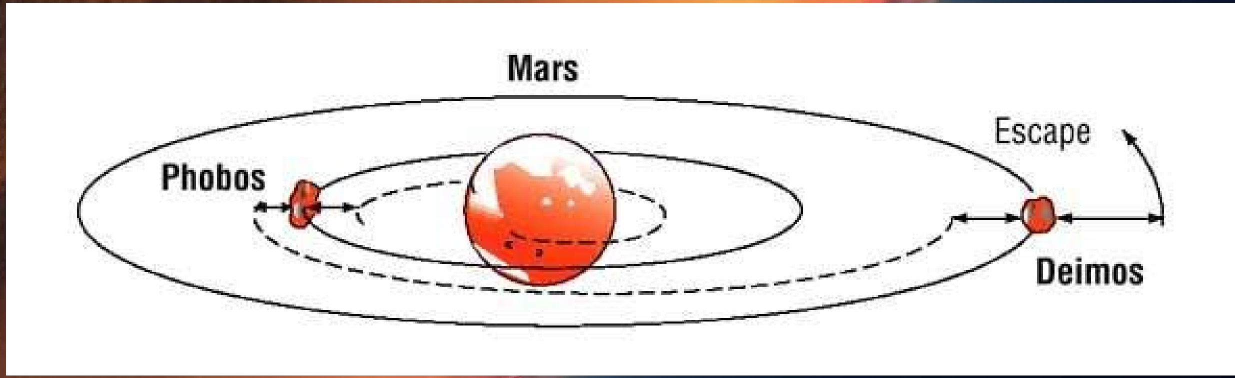
Mars and Moons

	Phobos	Deimos
		
• km from Mars center (above surface)	9380 (5840)	23436 (~20100)
• Orbit period:	27600 s	109000 s
(Mars days)	0.319	1.262
• Projected speed over ground:	1920 km/h	162 km/h (retrograde)
• Mass:	1.072 10^{16} kg	1.5 10^{15} kg
• Radius:	11.1 km	6.2 km

- Mars radius: 3396 km
- Areostationary Orbit, km from Mars center (above surface): 20427 (17031)

Options for Mars Lift

1. **Use the Moons**
   - Phobos Tethers
     - Drop Tether of ~5740 km to avoid Mars atmosphere
     - Phobos Elevators L1, L2
   - Deimos Tethers
     - Deimos Elevators, L1, L2



(Penzo, P. , July 1984)

2. **Avoid the Moons**
   - Oscillations (Fountains of Paradise, 25. Orbital Roulette, Clarke)
     - Continual energy input required
     - Another degree of freedom that can be used as necessary
   - Off-Equator Mars Lift to avoid the moons
     (compare Earth/general framework, Gassend 2004; Levin/Pearson 2005)
     - "Elevated ground state"

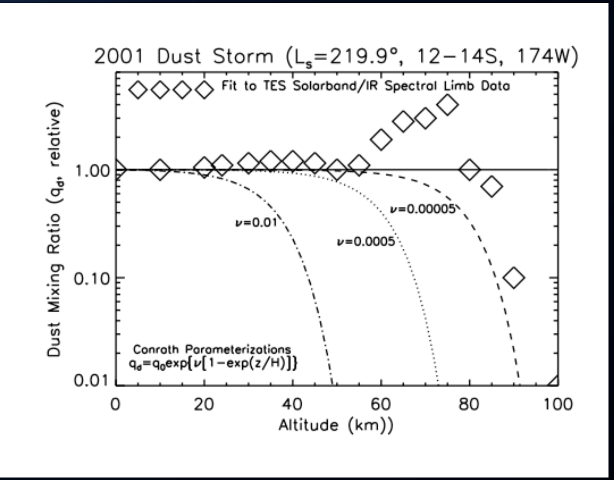
1. Use mountains (Olympus Mons, etc.) to avoid dust
2. Do not use mountains

Conclusions: Elevators for Mars Lift

- **Phobos Drop Tether**
  - + Avoids dust storms and electrostatic charge of the Mars atmosphere
  - + Is the shortest possible tether of only ~6000 km
  - 100 km vertical remain to be bridged
  - Terminal velocity in Mars atmosphere is ~1000 km/h
  - Even taking the lateral 1920 km/h of Phobos out with some other constructs, the vertical fall is hard to brake
  - Braking a 100 km fall
    - Mars atmosphere: ~600 Pa, 0.6% of Earth. There will be no hypersonic aerodynamic Mars cargo planes!
    - Adding a parachute for 10 mt to every container or similar seems impractical (20m diameter supersonic parachute for 1 mt load for curiosity rover!)
    - Rockets burn propellant, which we are trying to avoid. ~3 mt per 10 mt cargo container, prohibitive
    - Infrastructure to brake the containers from the ground would be huge and therefore appears also prohibitive

  ⇒ **Mars atmosphere is just dense enough to be annoying but not useful**

  ⇒ **Drop tether economics appears undesirable**



- **Ground Tether**, **has to be**
  - robust against dust or requires a cleaning mechanism
  - protected against electric discharge
  - clear of the moons, therefore needs to be deployed off the equator
  - almost ~20000 km long (or longer, clearing Deimos)

⇒ **Conclusion: Ground Tether further Investigated**

(Scenarios different than NIAC phase II study, p45, Edwards)


Ludovic
Celle

Mars Lift, Feasibility Condition

New Version/Mars of the feasibility condition (work in progress):

1. The usual “leaky integrator” equation for the constructed/decaying tether that needs to be regularly serviced to remain in operation.
2. Moves from sums to factors where possible, stronger optimization criterion.
3. Includes a Geometry Condition: Irrespective of tether strength, a minimal tether size/surface area needs to be provided for climbers/rappellers to operate.
4. No Capstaning (wrapping around the wheels) for vehicles on Space Elevators
5. For Mars Lift, the direction is down and no climber motors or (almost no) power sources are necessary. Service/material comes from Deimos.

Candidate Anchor Site 1, Elevator Peak

- Elevator Peak
  - ~ 6200 m Elevation
  - 18 S, 59.5 W

Candidate Anchor Site 2, Pinnacle Station

- Morava Valles
  - ~ -2000 m
  - 12.65 S, 23.6 W

Mars Lift, Tether Strength and Taper

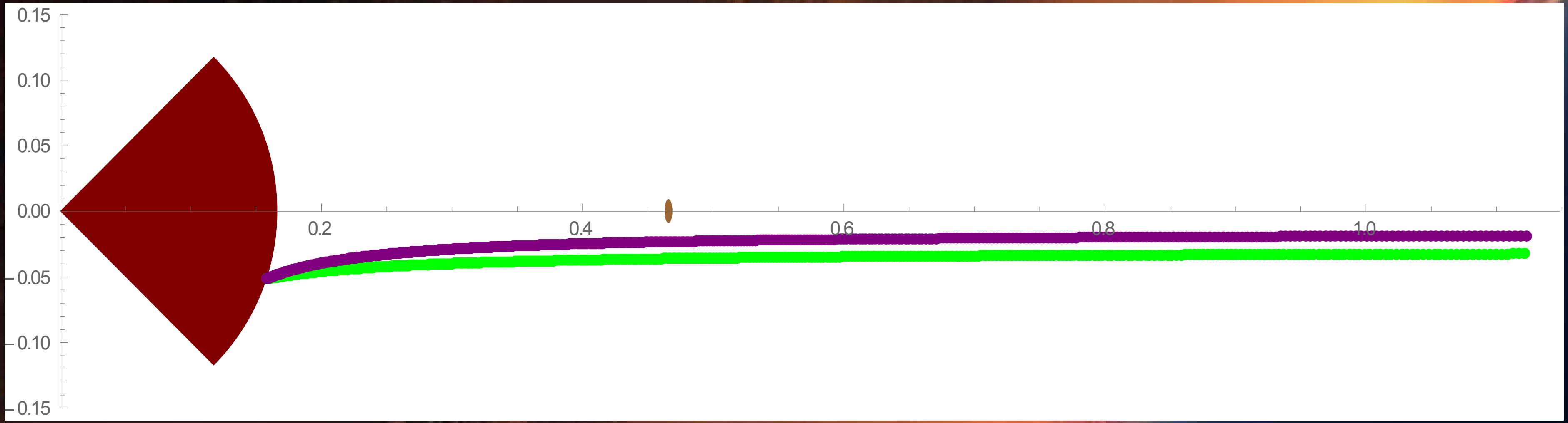
- Specific Strength in MYuri is the relevant variable for Space Elevators
  - MYuri is a derived unit equal to N/tex (with tex = g/km) and GPa/(g/cm^3) or 10^6 Nm/kg = 10^6 m^2/s^2
  - We assume a specific mass of CNTs of ρ=1.5 g/cm^3 (values 1.3 – 2 are common)
  - Investigated are typically two tether strengths σ0 of:
    - 10 GPa => 6.6 MYuri
    - 20 GPa => 13.3 MYuri
  - Potential composed of gravitational pull, dependent on the distance from the center of gravity, and centrifugal force, dependent on distance from the rotation axis $$V = -V0\left(\frac{r_s}{r} + \frac{1}{2}\frac{{r^2}_\perp}{{r_s}^2}\right)$$ with $V0_{Mars} \approx 2.097$ km^2/s^2
  - and the relationship between tether cross section on the ground and the maximum at the aerostatic orbit is: $$\frac{T}{T0} = \frac{A}{A0} = e^{\frac{\rho}{\sigma 0}\Delta V}$$
- Taper factors
  - 10 GPa tether: 4.15 (just tether, no loads)
  - 20 GPa tether: 2.03 (just tether, no loads)

with A0 = 50 mm^2 (10x safety factor for 20 GPa) => bracket for Tether Mass: ~1700 mt

Mars Lift, Curvature, Elevator Peak

$$\frac{d^2\tilde{\vec{r}}}{d\tilde{s}^2} = -\alpha\left(\vec{g}\left(\vec{r}\right)\right)_\perp$$

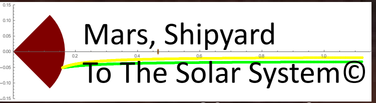
- The curvature follows the tether shape equation
- Curvatures for 10 GPa and 20 GPa tethers anchored at18° latitude for Elevator Peak:



- Clearance of moving Phobos orbit requires at least 185 km from the equator at Phobos orbit (brown ellipse) (1.12° latitude, Jacobson/Lainey, 2014)
- Presented are first approximative results. Shape will slighly change. Units of plot are in fraction of areosynchronous Orbit Radius (compare Gassend, 2004)
- Tether angles off the vertical ~28° (20 GPa) and ~40.7° (10 GPa)
- Payload goes with the Cos of tether angle!

Mars Lift, Curvature, Pinnacle Station

- Lower latitude of 12.65° vs. 18° => less curvature of the elevator => tether angles: ~20° (20 GP) and ~28.5° (10 Gpa)
- Still clears Phobos orbit comfortably by a factor of ~1.8 of the orbit change in this first calculation.
- If dust is tolerable, the lower latitude site offers integration advantages for the Omaha Trail.



Mars Lift, Counterweight

- The safest option appears to terminate Mars Lift inside the Deimos orbit, e.g., at ~23000 km radius, put the top Ares station at ~400-500 km inside Deimos orbit.
- Bracketing the counterweight mass preliminarily for this situation:
  - The gradient of the combined potential of gravity and centrifugal force leads to

$$\vec{V}\ \mathrm{V}\,(60000\ \mathrm{mt}, 23000\ \mathrm{km}) \approx 2\cdot 10^{6}\ \mathrm{N}$$

  - A 20 GPa tether has at areostationary Orbit approximately that strength and that counterweight condition should not be exceeded.
- The Geometry Condition leads to a relatively strong elevator, variations of the counterweight mass scenario are still investigated.
- Putting the counterweight mass further out, e.g., past Deimos, will help to reduce the counterweight mass if necessary.
- Keep Ares Station close to Deimos for efficient transfers.

Mars Lift, Deployment and Anchor Forces

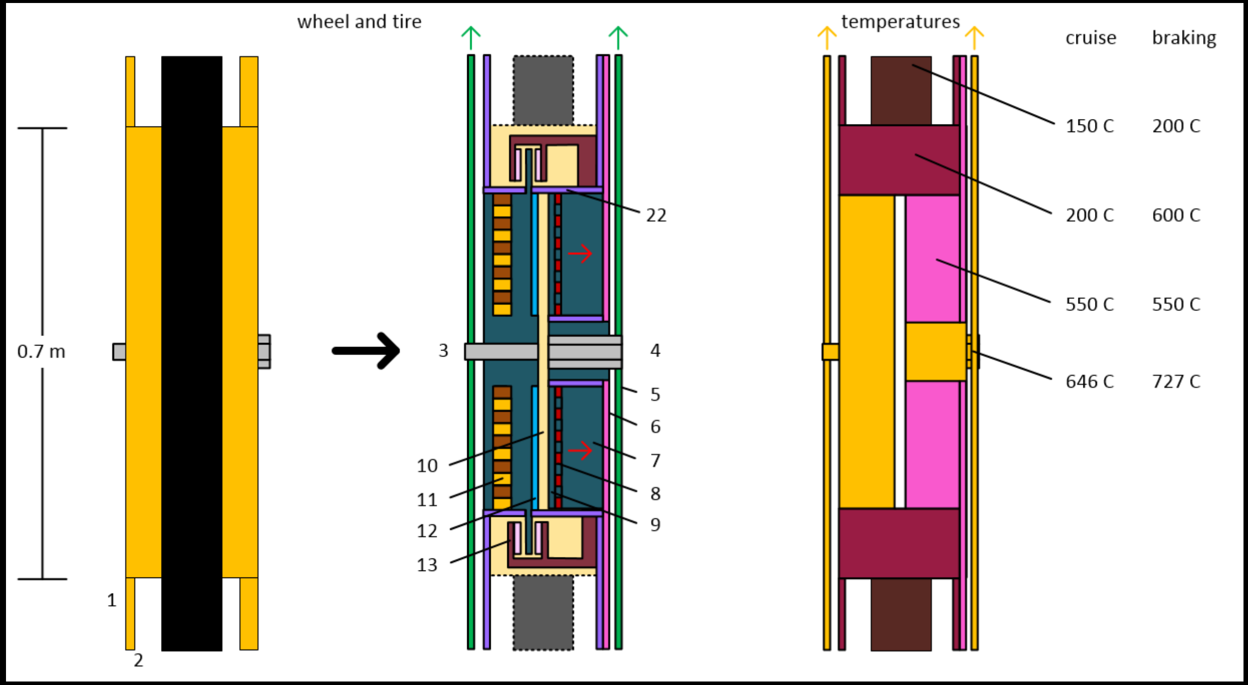
- Expected is a ground force of up to10^6 N for a functional elevator and to pull it into place for deployment.
- A large tractor (e.g., group of tanks) will have to pull the elevator to position or it will have to be deployed in its lightest form (TBD) and to be built up.
- How can an off equator configuration be kept stable while the elevator is built up, including building the counterweight?
- It is an advantage that the counterweight mass can be iteratively increased by transporting material from Deimos.

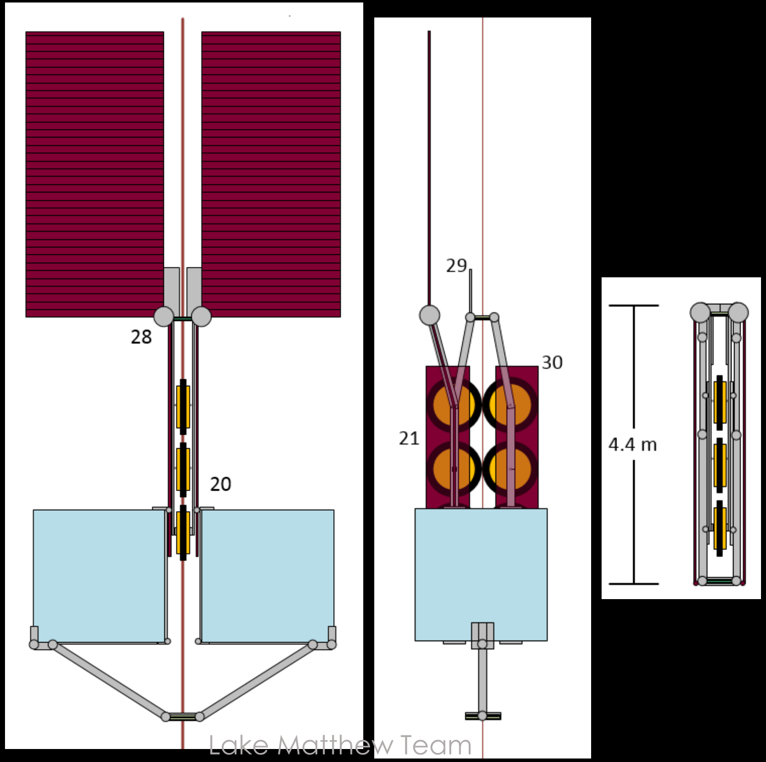
- **It is easier to build from above.**

Mars, Shipyard
To The Solar System©

Mars Lift Rappeller

- Rappeller heat management:
  - Brakes must counter gravitational acceleration
  - Friction brakes would quickly overheat
  - Eddy current brakes can work, but radiators are required





- Rappeller design considerations:
  - Unpowered descent for cargo delivery
  - Should be a mass-produced vehicle, easily repaired at Omaha Crater
  - Lightweight, with compact storage
  - Notional 10-ton payload (5 tons x 2)

Lake Matthew Team

Tramway

- Conceptual design in the spirit of lunar tramway (Pearson et al. 2005)

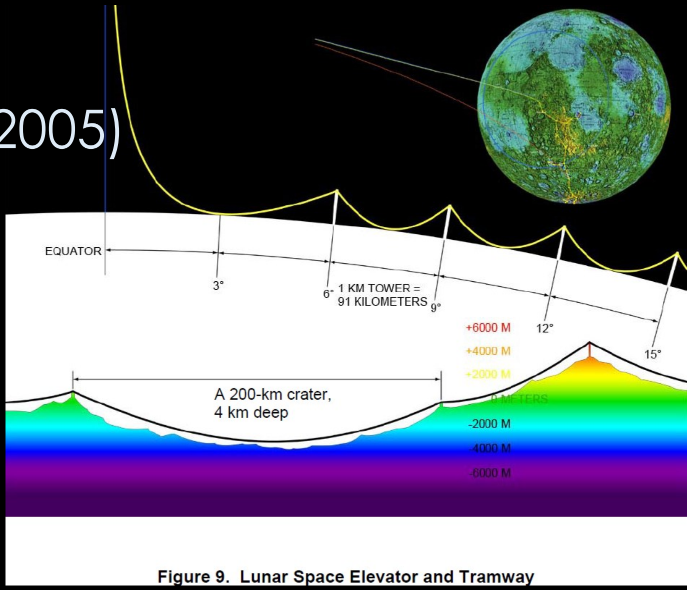
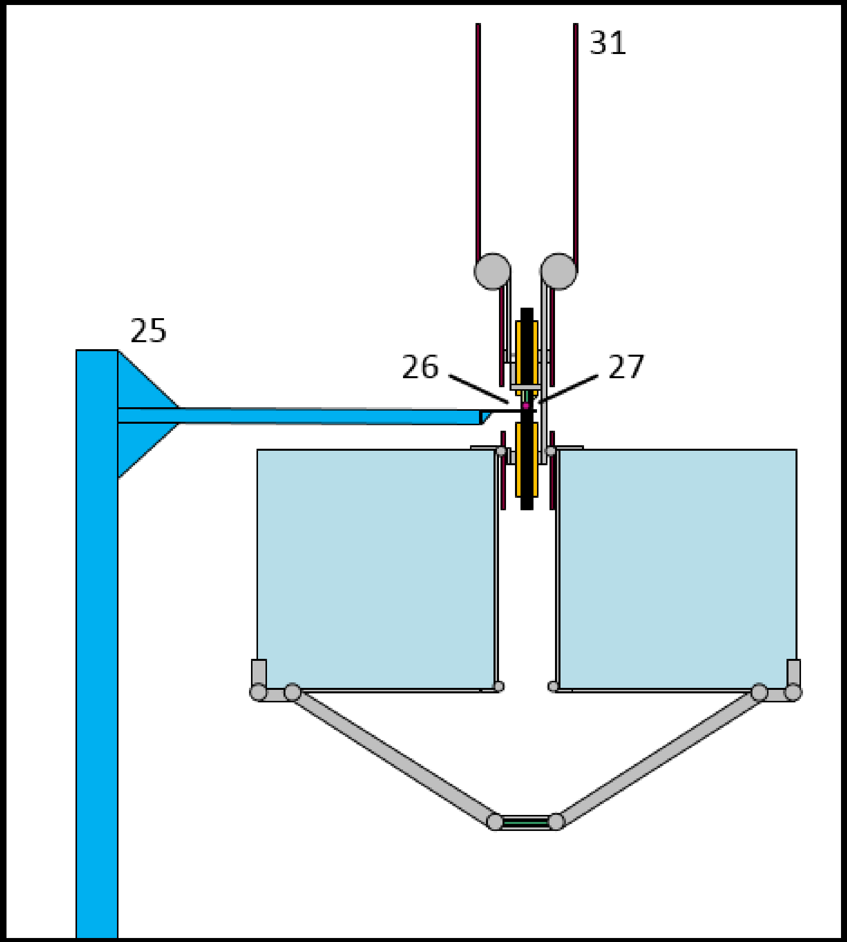


Figure 9. Lunar Space Elevator and Tramway

- The rappeller designed to convert into HVDC "trammer"
- ISRU alloy pylons
- 30+ km pylon separation, peak-spanning, 400+ m pylon height
- CNT cables with Omaha Crater HVDC power
- Notionally 10x60 mm^2 cable cross-section with 70 kN tensioning



Pearson et al. 2005

Mars Lift and Tramway, Summary

- A simplified feasibility condition using rappellers and only going down, no large power source required.
- Empty trammers are folded up and recycled to Deimos/Mars Lift Top via rocket.
- The energy gained going down could possibly be used to build up (e.g., fuse new material to) or protect (e.g., clean/sweep) the Mars Lift elevator.
- To Do:
  - Look for further minimization of Elevator requirements
  - Investigate ideas for elevator protection and growth
  - Investigate deployment scenarios

Thank you!

Lake Matthew Team / Celestia

References I

Disclaimer: All presented Omaha Trail results are first approximations and may undergo corrections without notice.

- LakeMatthew.com
- Most astrodynamics data via Wolfram system (Mathematica, etc.)
- nasa.gov
- Background artwork: Kees Veenenbos, www.space4case.com and data: MOLA Science Team (NASA)
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Image Credits

Blair, Jonathan S. / National Geographic / Getty Images: Eden Project greenhouse, Cornwall, England

Celestia Software: Simulated imagery of Mars system

Celle, Ludovic: Mars illustration

Clark, Chuck: natural boundary mapping of Deimos

HiRISE / MRO / LPL (U. Arizona) / NASA: Deimos imagery

NASA / JPL-Caltech / Malin Space Science Systems: Mars imagery

Öner, Tayfun / USGS / Thomas, Peter: Deimos mappings and orthographic renderings

Pearson et al. 2005: Lunar Space Elevator and Tramway

Pioneer Astronautics: CAVoR visualization

SpaceX: ITS visualizations

SSL / ASU /P. Rubin / NASA / JPL-Caltech: 16 Psyche artist's concept

Toshiba / Chubu Electric: SMES unit

U.S. Navy: F-14 on catapult

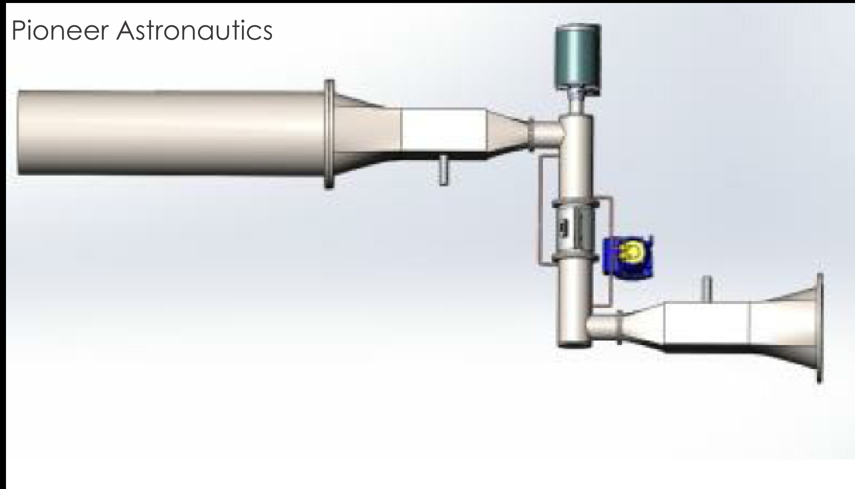
Wood, Roy: Surprise Lake inside Aniakchak Caldera

Veenenbos, Kees: Olympos Mons rendering: www.space4case.com, and Data: MOLA Science Team (NASA)

Backup Slides

Deimos ISRU

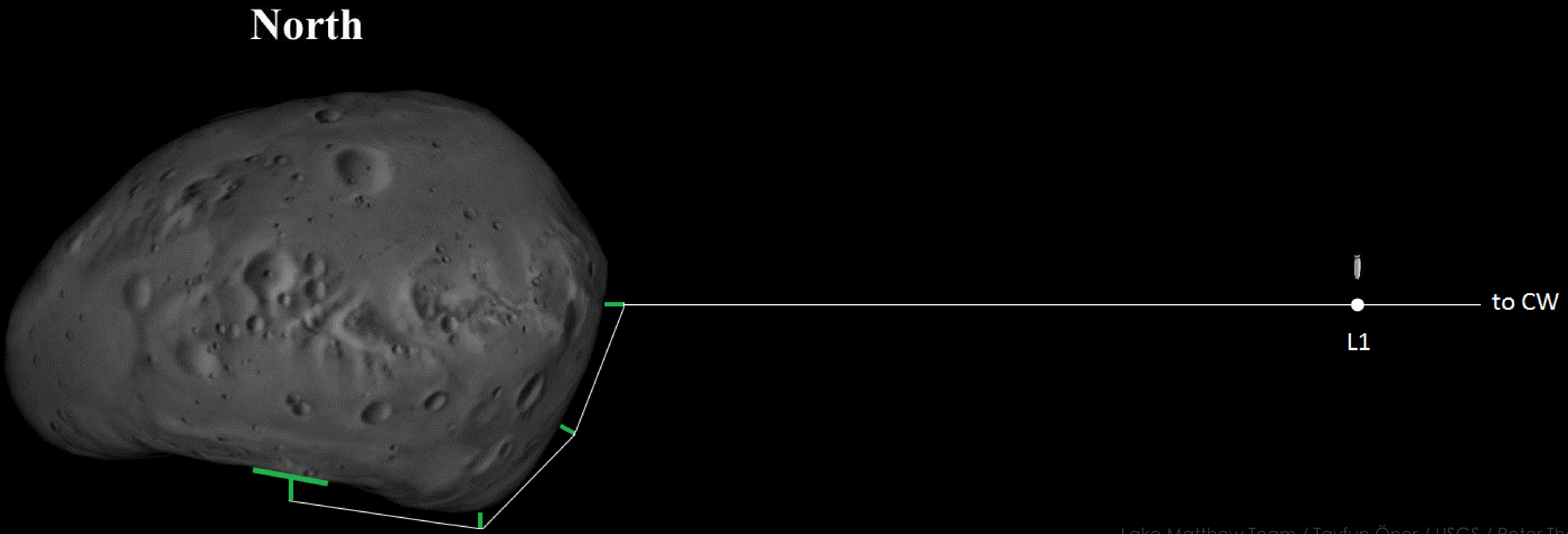
- Deimos density: 1.5 g/cm^3 (Murchie et al. 2013)
- ~50 wt% volatiles, within 20-60 m of polar surface (Fanale and Salvail 1990)
- Products: oxygen, methane, treated water
- Methods: CAVoR, alternate coal gasification reactions (Nichols 1993)



Carbonaceous Asteroid Volatile Recovery (CAVoR) system, Phase I

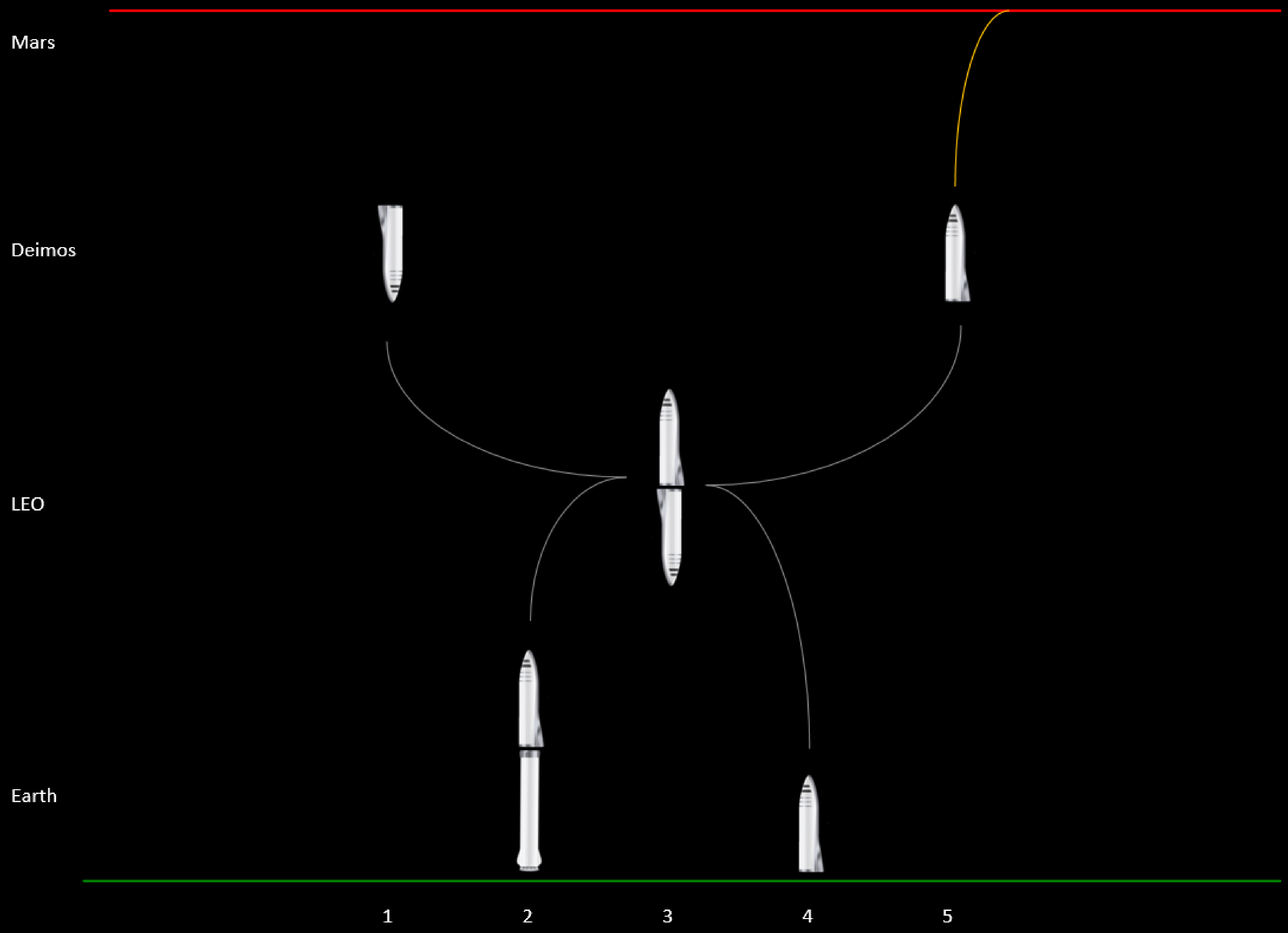
HiRISE / MRO / LPL (U. Arizona) / NASA

Deimos Dock



Lake Matthew Team / Tayfun Öner / USGS / Peter Thomas

Cargo



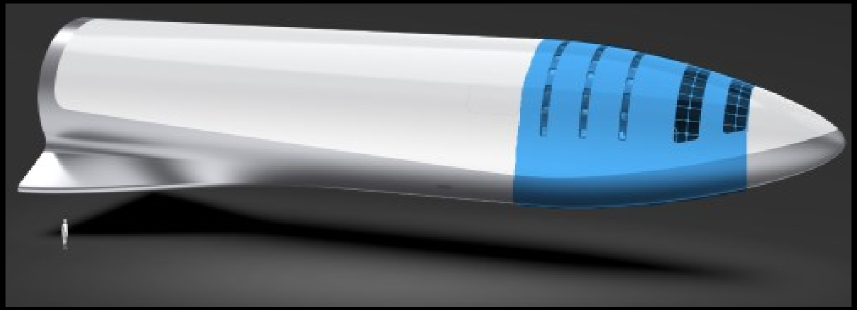
2017-11-07

Cargo

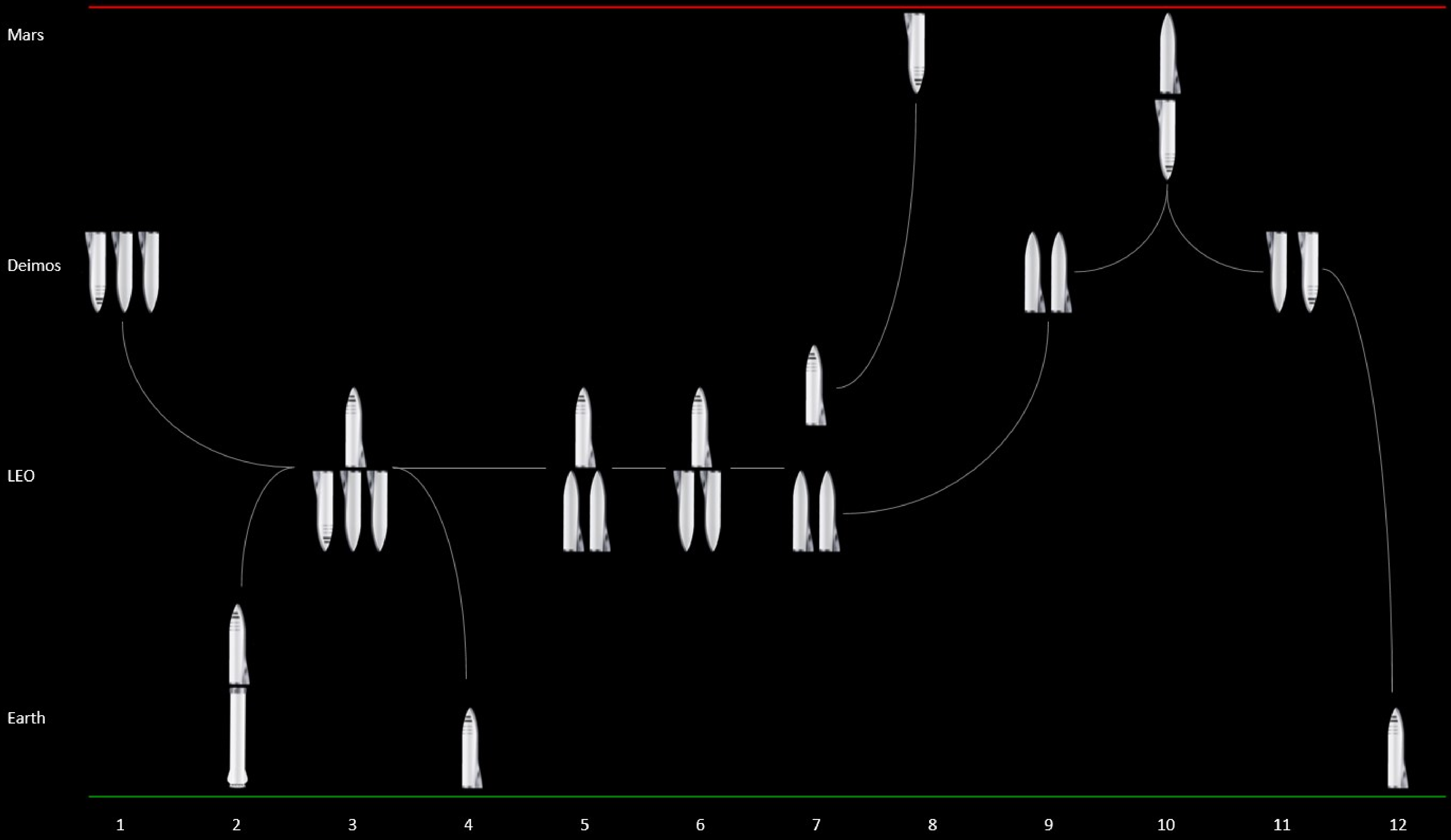
- Comparing with SpaceX 2017 baseline:
  - Propellant per ton of cargo delivered: cut **68%**
  - Number of Earth launches per mission: cut **71%**

Crew

- Water shielding: a Deimos ISRU product



Crew



2017-11-07

Crew

- Comparing with SpaceX 2017 baseline:
  - Propellant per ton of crew & cargo delivered: cut **65%**
  - Number of Earth launches per mission: cut **83%**

Crew

- Comparing with SpaceX 2017 baseline:
  - Extra shielding against solar flare protons in transit:
    - Water blocks extra **90%** en route to Mars
    - Water blocks extra **95%+** en route to Earth
- Solar flares no longer require transit storm shelter
- Add subaqueous habs and magnetostatic ground-surface shielding, for end-to-end protection. Prospect: an unlimited Mars career, with no career-limiting radiation dose, over decades of Mars work.