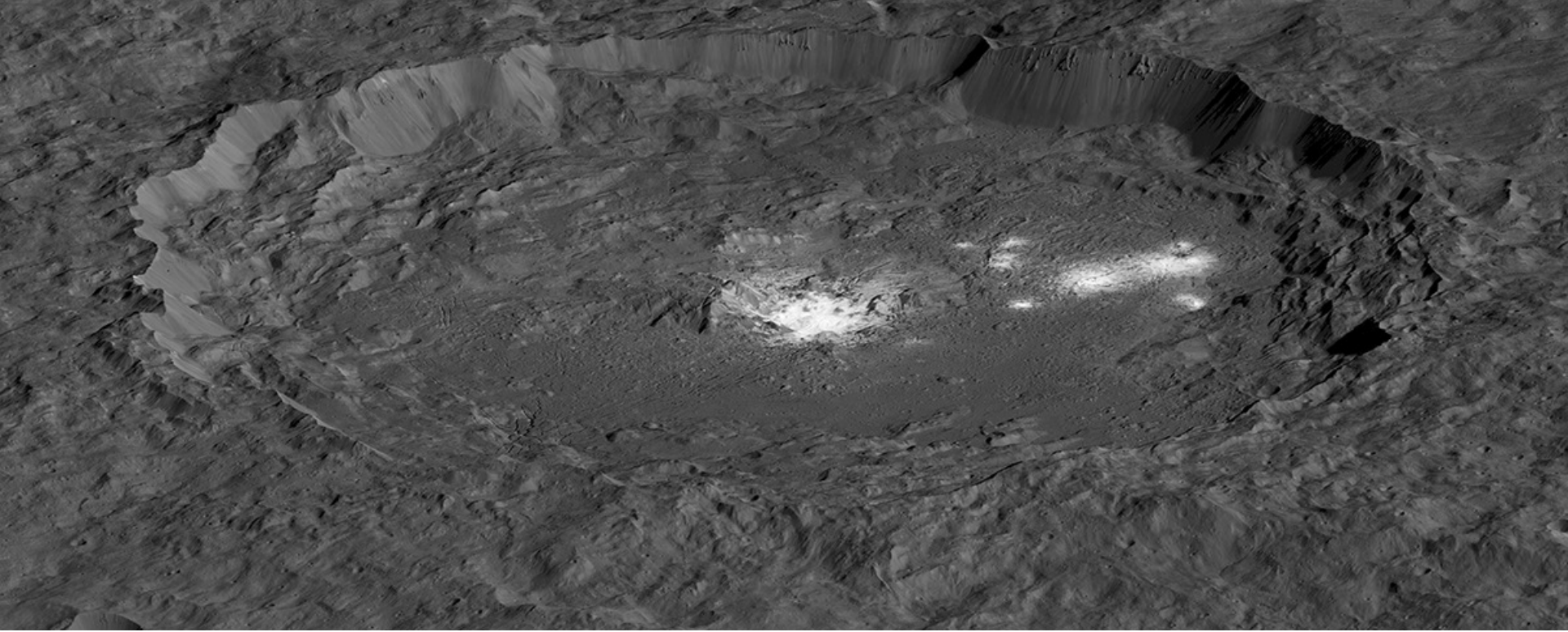


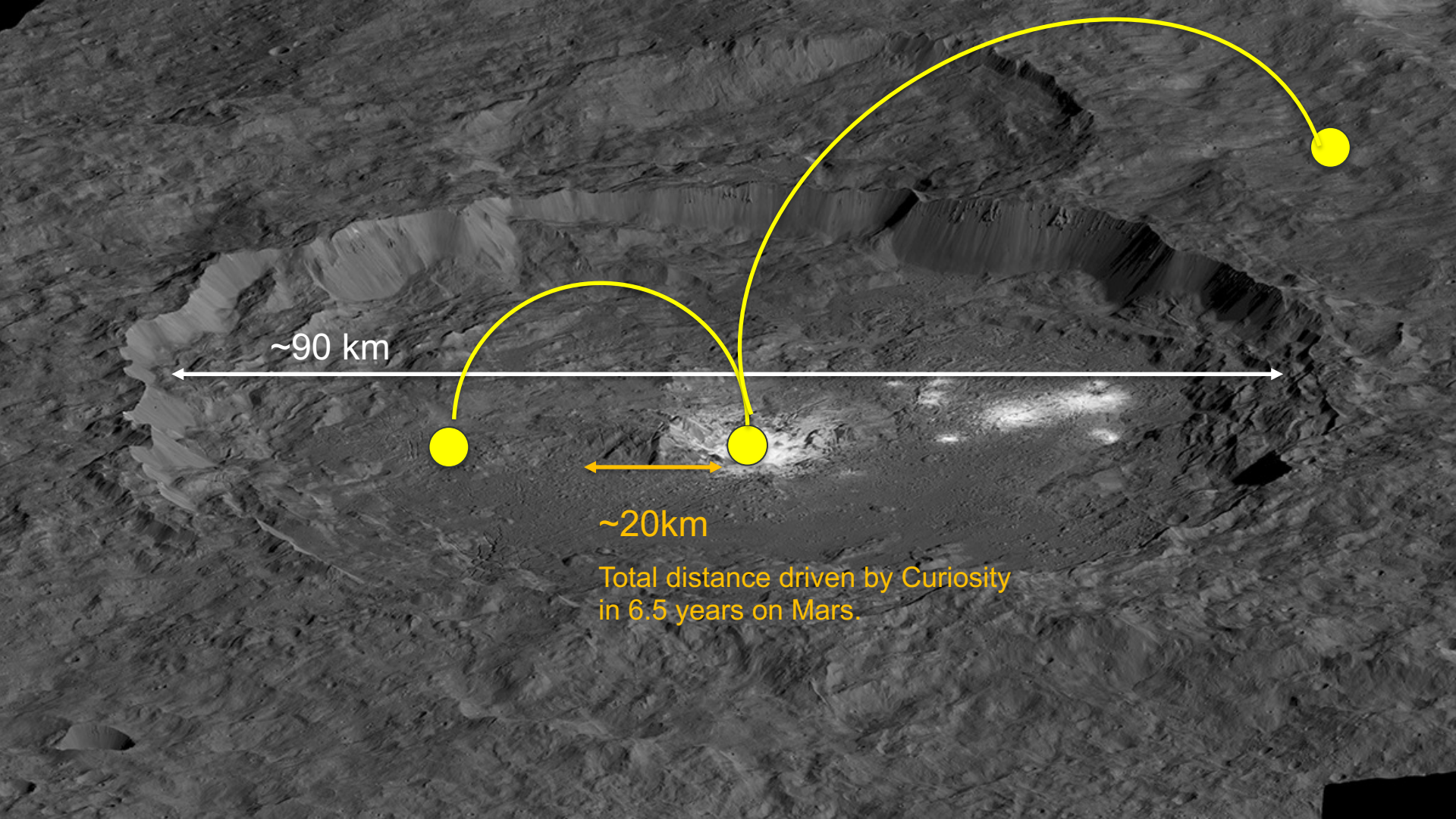
Lessons from Surveyor 6:

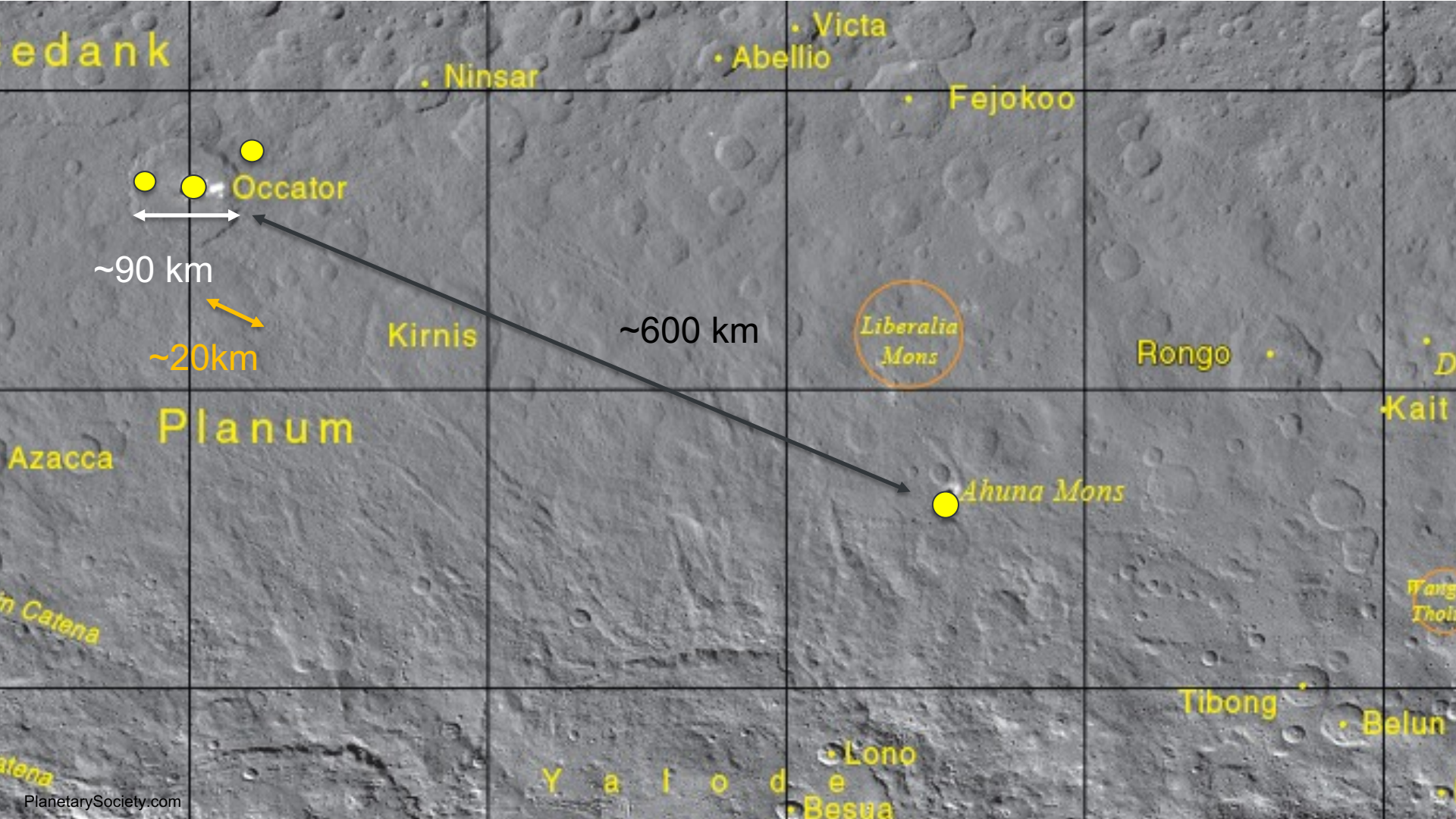
Hopping Spacecraft for Low-Cost Surface Mobility on Small Bodies

Niko Romer, Art Chmielewski, Nathan Barba, Nathan Fulmer.

March 5, 2019 IEEE 2019 Aerospace Conference

Jet Propulsion Laboratory
California Institute of Technology


~90 km
~20km
Total distance driven by Curiosity
in 6.5 years on Mars.

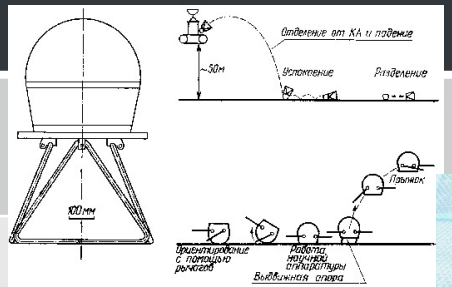

edank
Victa
Abellio
Ninsar
Fejokoo
Occator
~90 km
~20km
Kirnis
~600 km
Liberalia Mons
Rongo
Kait
Planum
Azacca
Ahuna Mons
Tibong
Belun
Lono
Yalode
Besua
PlanetarySociety.com

Why Hop?

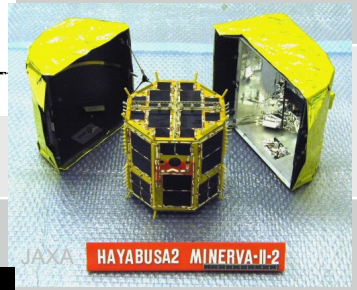
- Great scientific value in characterizing multiple regions.
- Travel farther, faster, and cheaper than rovers.
- Two types of hops can be considered:
  - Mechanical
  - Propulsive

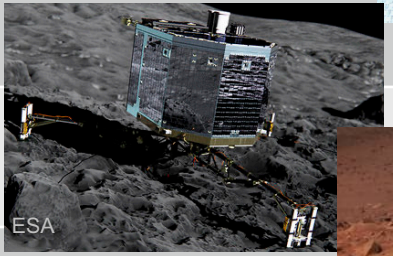
Hopping Categorized – Mechanical

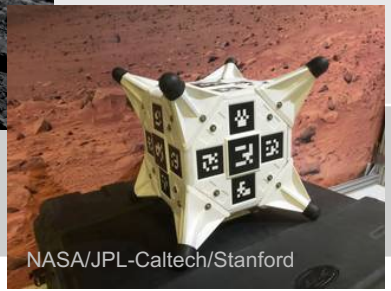
Agency	Mission	S/C	Year	Destination
USSR	Phobos 2	PROP-F	1988	Phobos
JAXA	Hayabusa	MINERVA	2005	Itokawa
JAXA/ DLR	Hayabusa 2	MINERVA-II/MASCOT	2018	Ryugu
DLR	Rosetta	Philae	2015	Comet 67P
NASA	N/A	Hedgehog	In dev.	Many possible



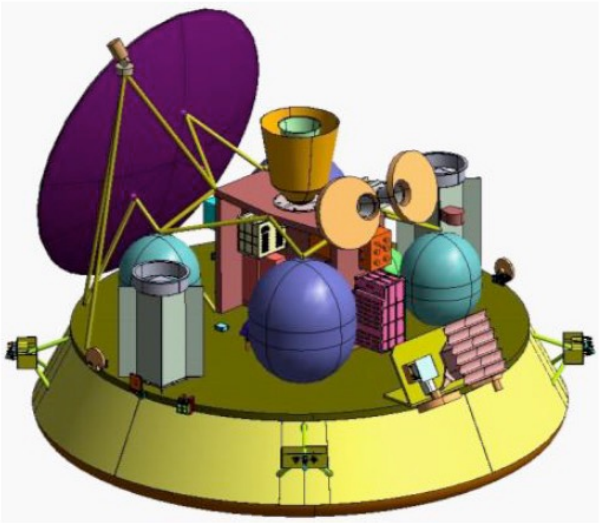
http://cyberneticzoo.com/walking-machines/1983-7-prop-fphobos-hopper-soviet/





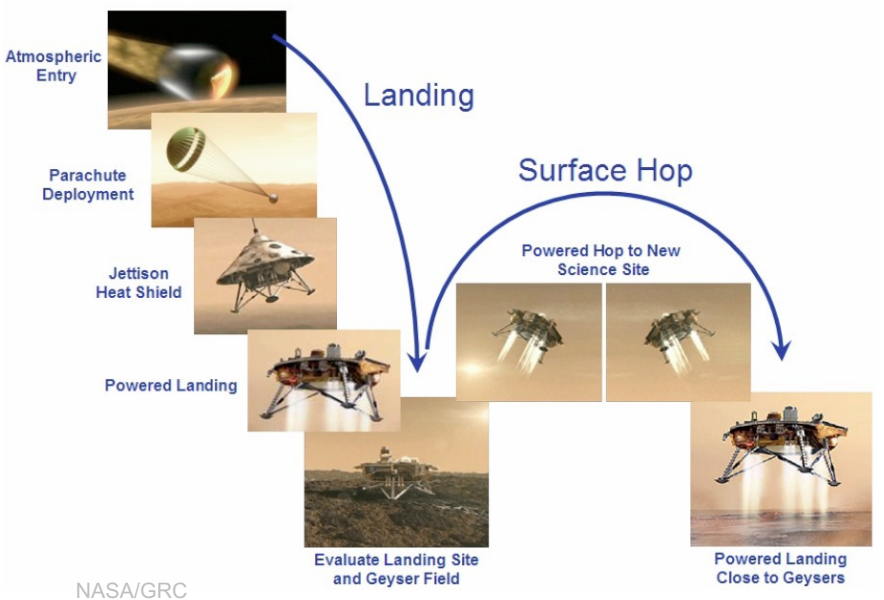


Hopping Categorized – Propulsive



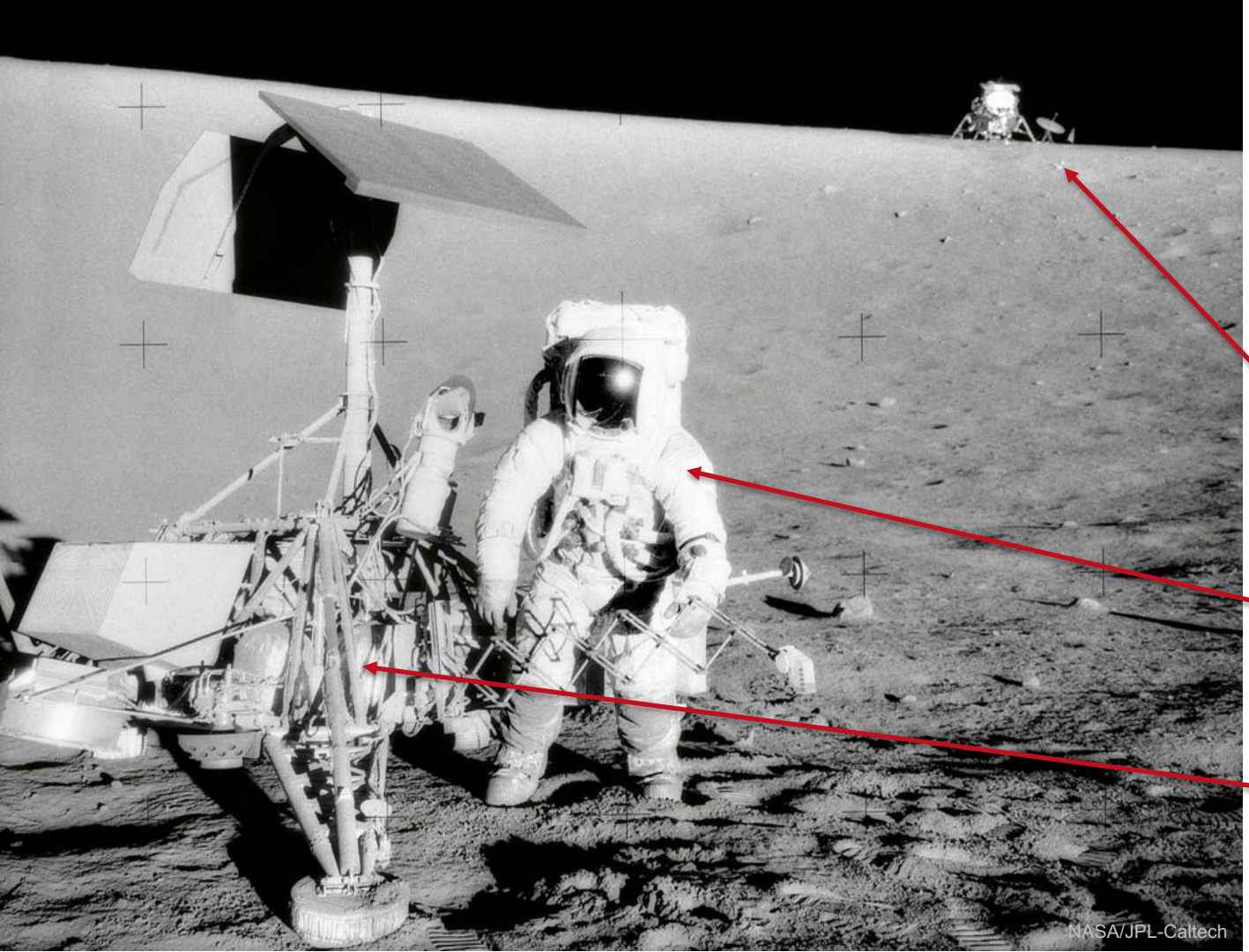
UMD/GSFC/NASA

- Chopper (Comet Hopper), NASA Goddard
  - Discovery Class Proposal for launch in 2016



NASA/GRC

- Mars Geyser Hopper, NASA Glenn
  - Discovery mission concept



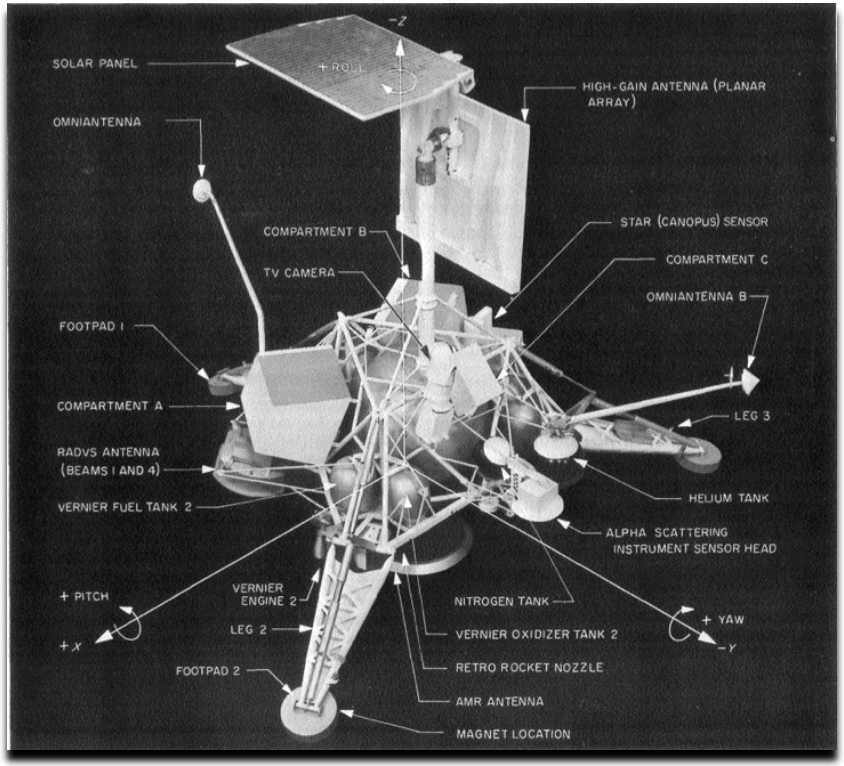
Surveyor Program:

- Seven Pre-Apollo robotic scouts.
- Program ran from 1966-1968.

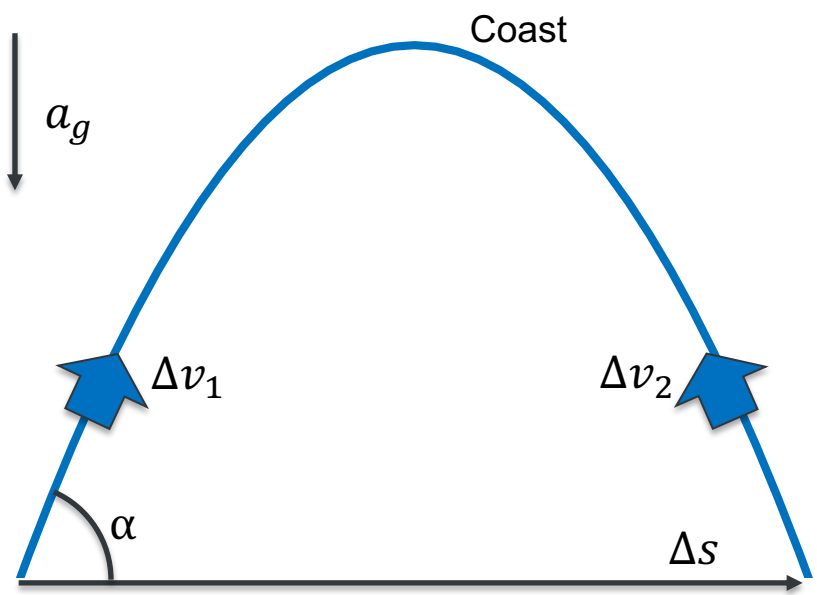
Surveyor 6 (1967)

First (and only until October 2018) successful hop on the surface of another body.

- Soft lander for Lunar Surface
- Dry Mass – 300 kg
- ~16kg of excess propellant not used during initial soft landing.
- Engineers performed a ”hop experiment.”
- 2.5 second fire of ACS thrusters.
- Average thrust 1390 N at +7° pitch.
- Rose 4 m vertically, and translated 2.5 m horizontally.



Surveyor Model

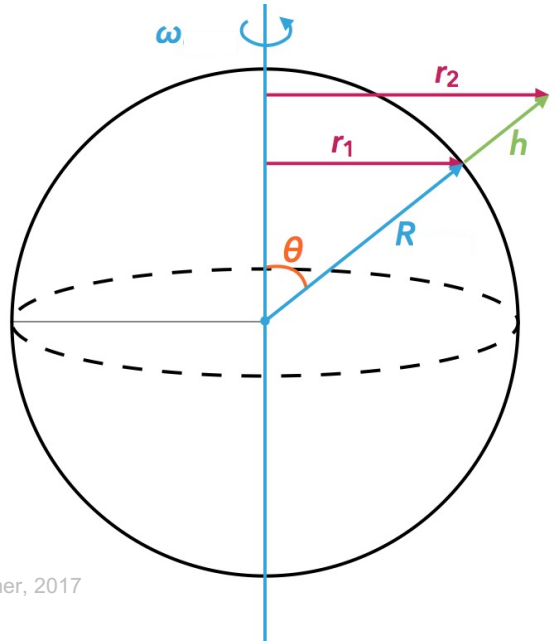


- We modeled a two-burn hop trajectory using a “Surveyor-like” 300 kg spacecraft.
- Surface curvature is ignored in this model.
- For both models in this study, Δv is the required initial velocity for a distance Δs.

$$\Delta v_{total} = \Delta v_1 + \Delta v_2 = 2\sqrt{\frac{a_g \Delta s}{sin2\alpha}}$$

a_g – gravity
Δs – distance of hop
α – launch angle
Δv_1 – initial burn
Δv_2 – Retrobraking burn

Jump and Wait – An alternative hopping method



Fulmer, 2017

- This method involves rising to an altitude *h* and waiting for the planet or body to rotate underneath the spacecraft.

- Jump and Wait can save some fuel on fast-rotating bodies with low gravity.

$$\Delta v_{total} = 2\sqrt[3]{\left(\frac{\Delta s a_g^2}{4\omega sin\theta}\right)}$$

a_g – gravity

θ – polar angle

Δs – distance of hop

ω – angular rate of rotation

R – mean radius of body

r_1, r_2 – moment arms from rotational axis

h – maximum altitude

Comparing Jump-and-wait with Hopping

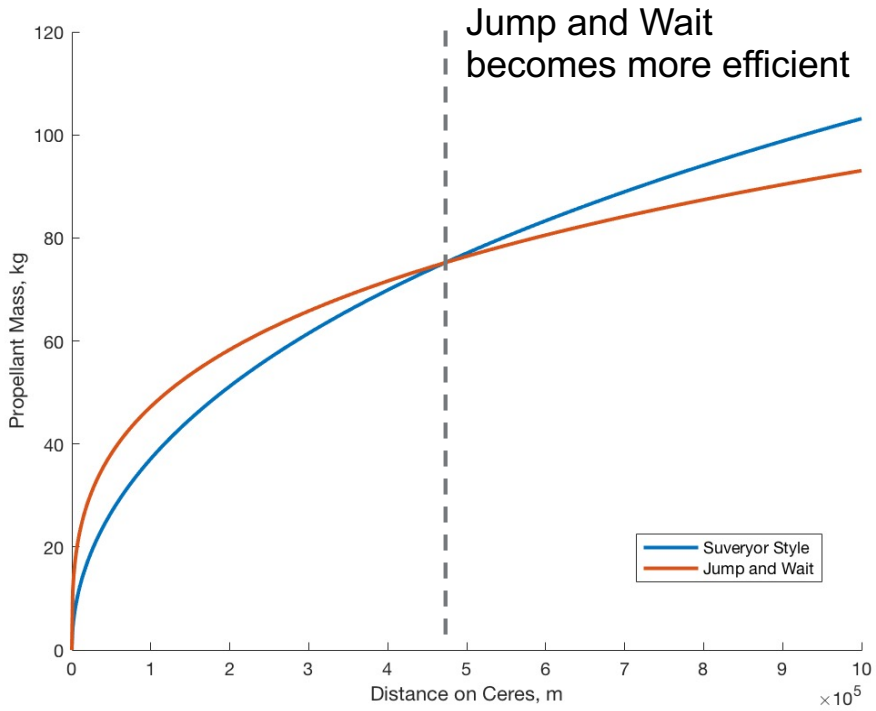
To determine when Jump and wait will save fuel on the equator:

$$\sqrt[3]{\frac{\Delta S a_g^2}{4\omega sin\theta}} < \sqrt{\frac{a_g \Delta s}{sin2\alpha}}$$

$$a_g < A\omega^2, \quad A = 2^4 \Delta s$$

Δs – distance of hop ω – Angular rate of rotation

Example: Hopping on Ceres



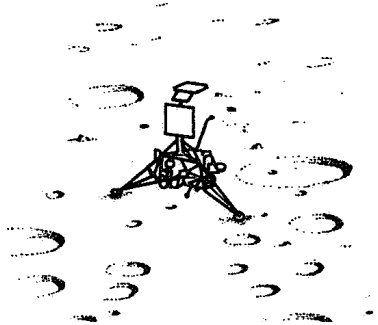
Comparison of Different Hops on Small Bodies

			Jump and Wait Surveyor		Hop requiring less ΔV			
Body	*GM (km^3/s^2)*	*Mean Radius (km)*	*Planet Gravity (m/s^2)*	*Period of Rotation (hours)*	*1 km*	*10 km*	*100 km*	*1000 km*
Ceres	*62.63*	*470*	*0.284*	*9.1*				
67P	*6.661E-07*	*2*	*1.67E-04*	*12.8*				
Moon	*4903*	*1738*	*1.624*	*655.7*				
Triton	*1428*	*1353*	*0.779*	*141.0*				
Phobos	*7.112E-04*	*11*	*0.006*	*7.7*				
Deimos	*9.850E-05*	*6*	*0.003*	*30.3*				
Europa	*3203*	*1561*	*1.315*	*85.2*				
Ganymede	*9888*	*2631*	*1.428*	*171.7*				
Io	*5960*	*1822*	*1.796*	*42.5*				
Callisto	*7179*	*2410*	*1.236*	*400.5*				
Enceladus	*7.203*	*252*	*0.113*	*32.9*				
Chiron	*2.669E-01*	*83*	*0.039*	*5.9*				
Okyrhoe	*2.722E-03*	*18*	*0.008*	*5.9*				

- Surveyor-like hops are usually more ΔV-efficient.
- Surveyor-like hops are better on Ceres until ~450km.
- Low-gravity gravity bodies with high rates of rotation like Phobos, Deimos, and Centaurs are good candidates for Jump and Wait.

Conclusions

- Hopping – both propulsive and mechanical– can increase the science return of landed missions.
- Hopping technique is dictated by the properties of the destination and the hop.
- Surveyor 6's experiment holds valuable lessons for propulsive hops.



NASA/JPL-Caltech

Thank you

Questions

Acknowledgment

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

This pioneering effort could also pave the way towards more sophisticated translations to be used on future spacecraft.

– Surveyor 6 mission report, 1968

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