Developing an Aerial Transport Infrastructure for Lunar Exploration

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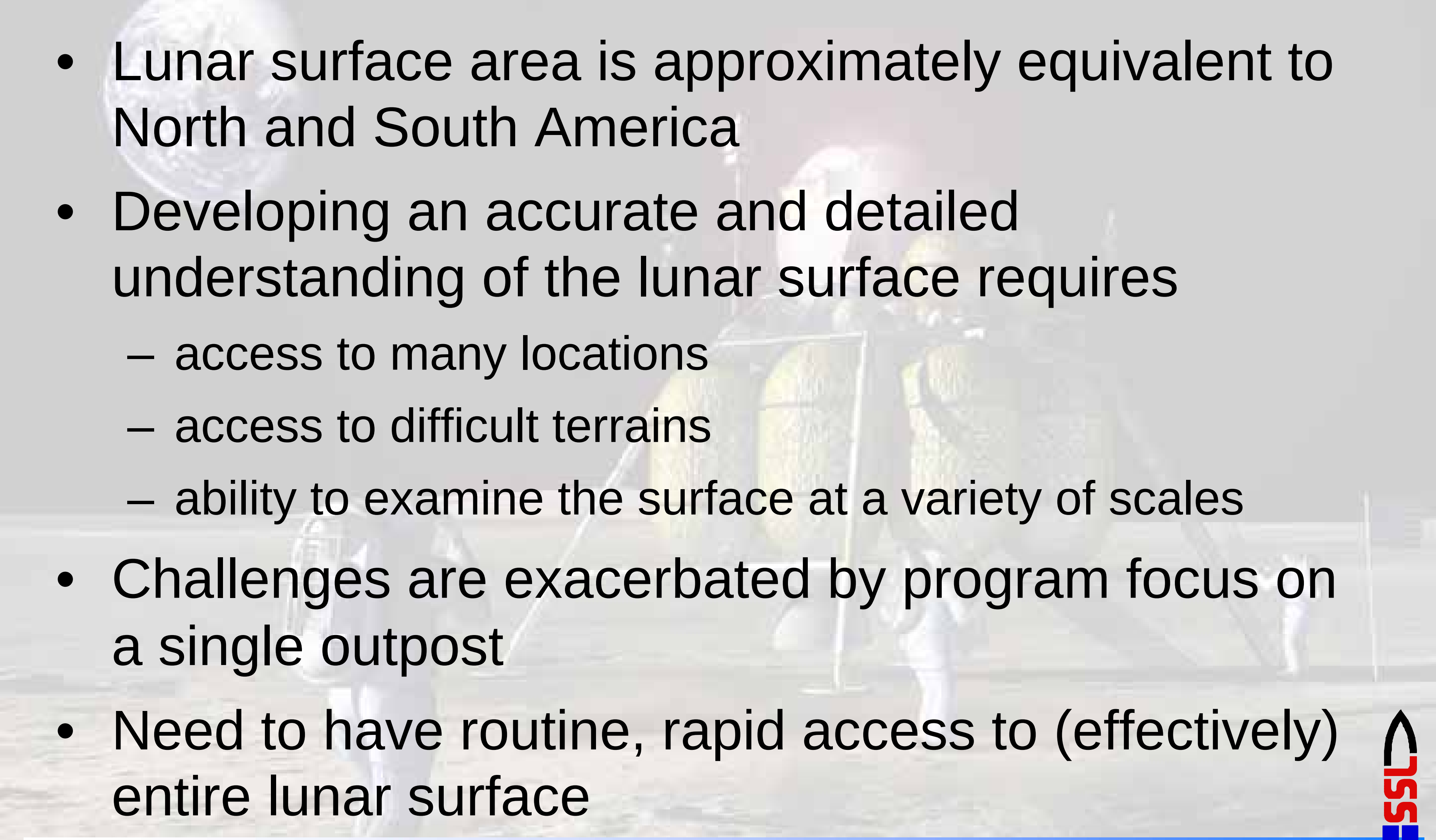
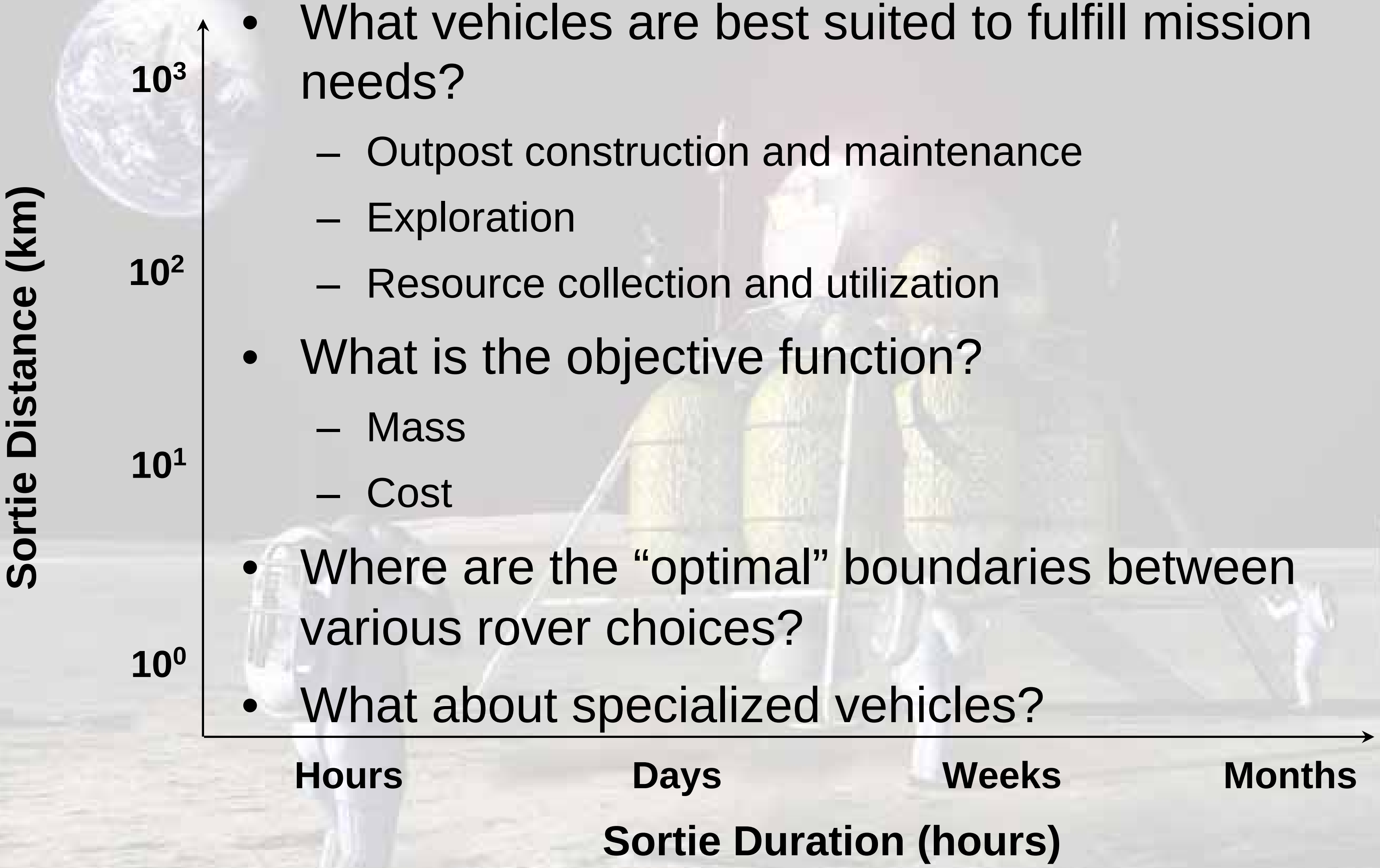
Problem Statement



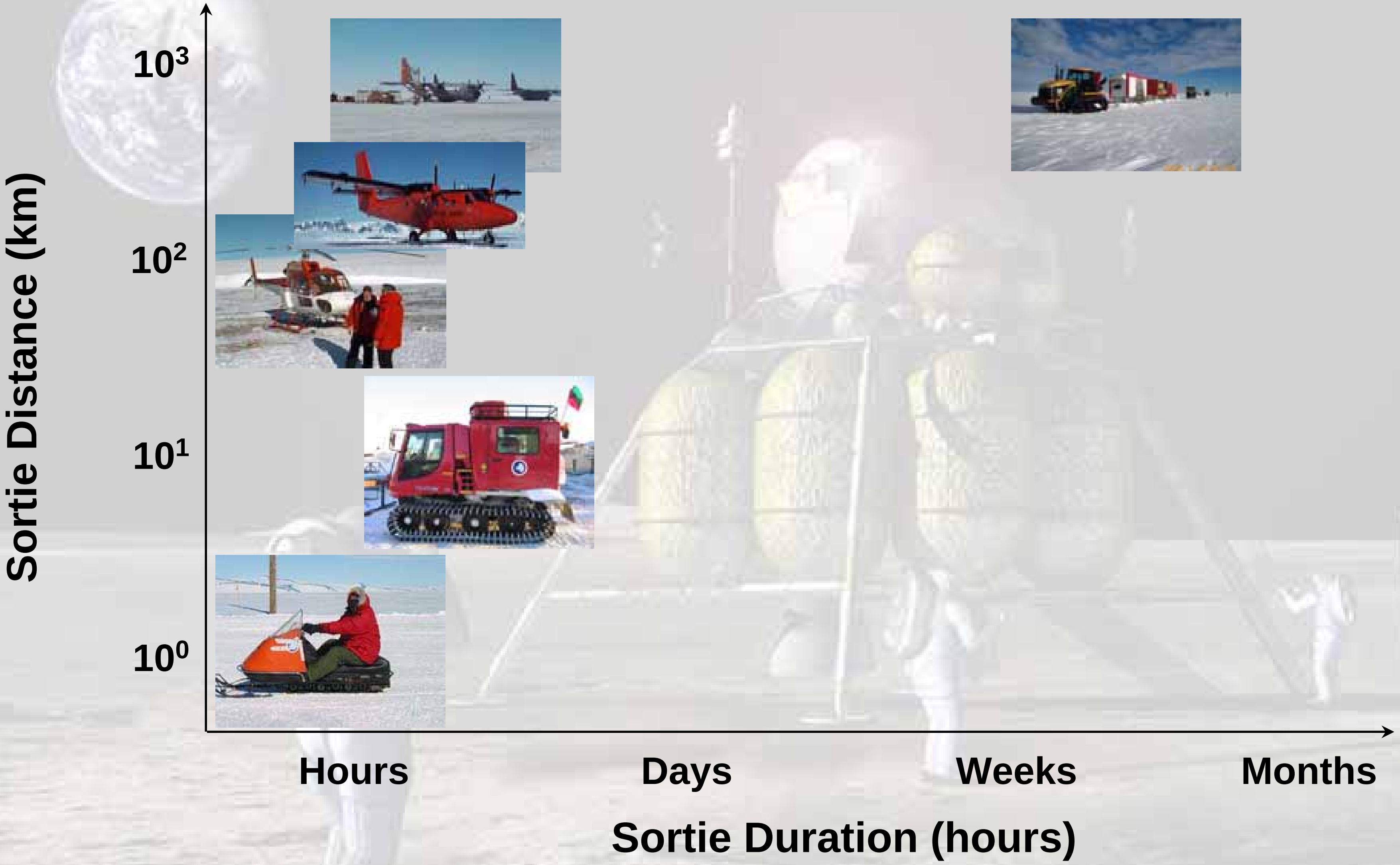
- Lunar surface area is approximately equivalent to North and South America
- Developing an accurate and detailed understanding of the lunar surface requires
  - access to many locations
  - access to difficult terrains
  - ability to examine the surface at a variety of scales
- Challenges are exacerbated by program focus on a single outpost
- Need to have routine, rapid access to (effectively) entire lunar surface

Notional Mapping of Rover Performance

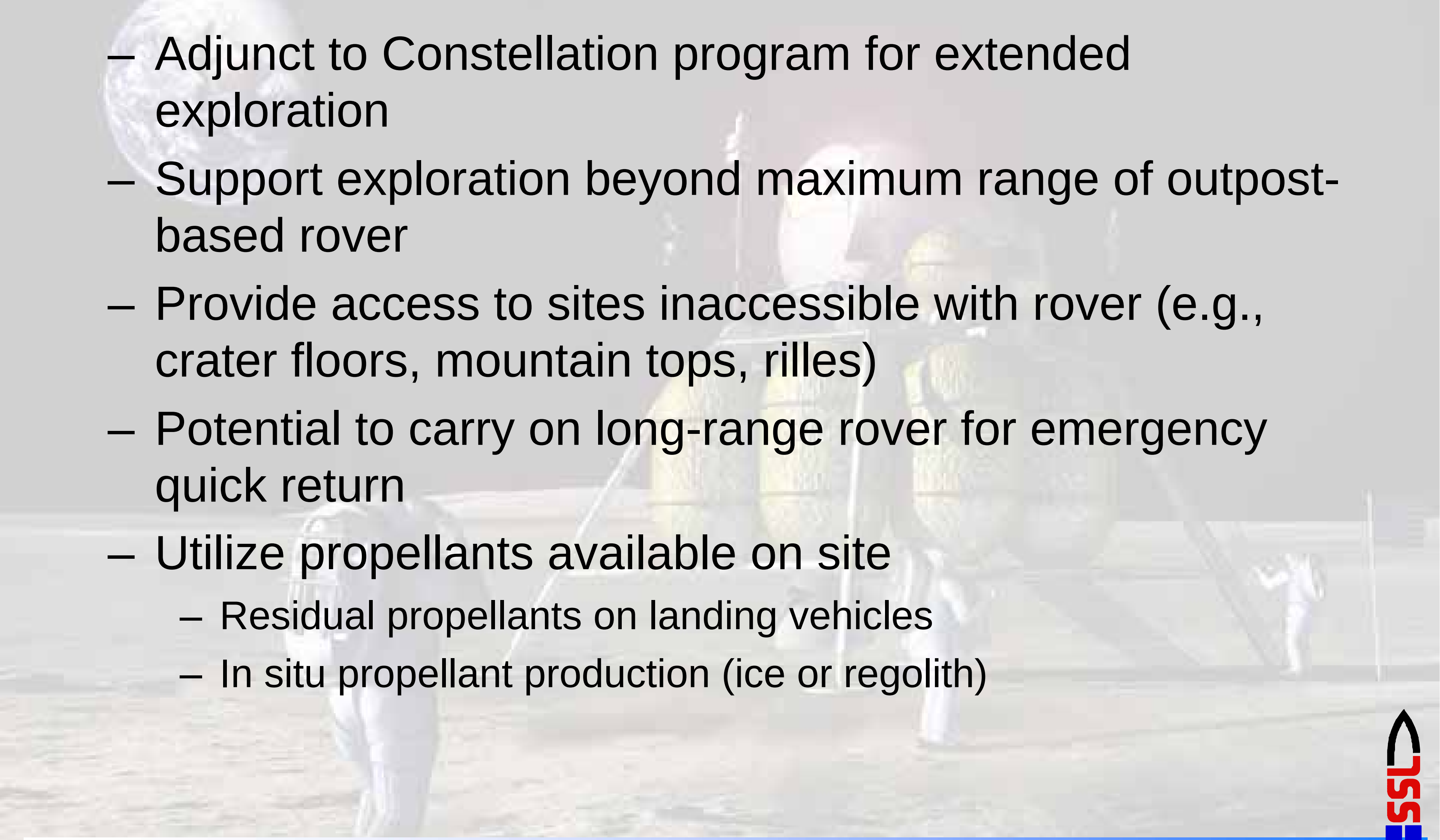
- What vehicles are best suited to fulfill mission needs?
  - Outpost construction and maintenance
  - Exploration
  - Resource collection and utilization
- What is the objective function?
  - Mass
  - Cost
- Where are the “optimal” boundaries between various rover choices?
- What about specialized vehicles?



Antarctica as Analogue

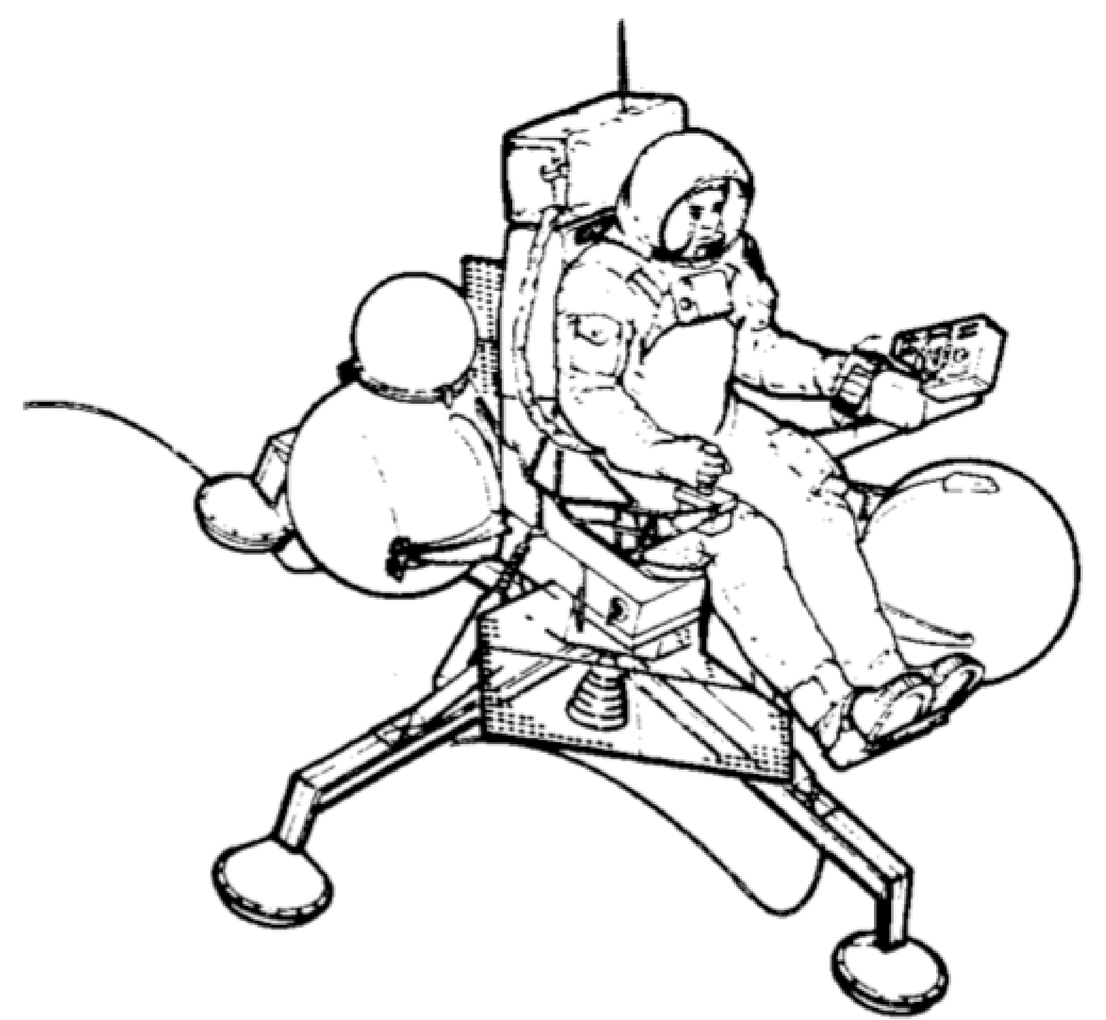


Lunar Flying Vehicle



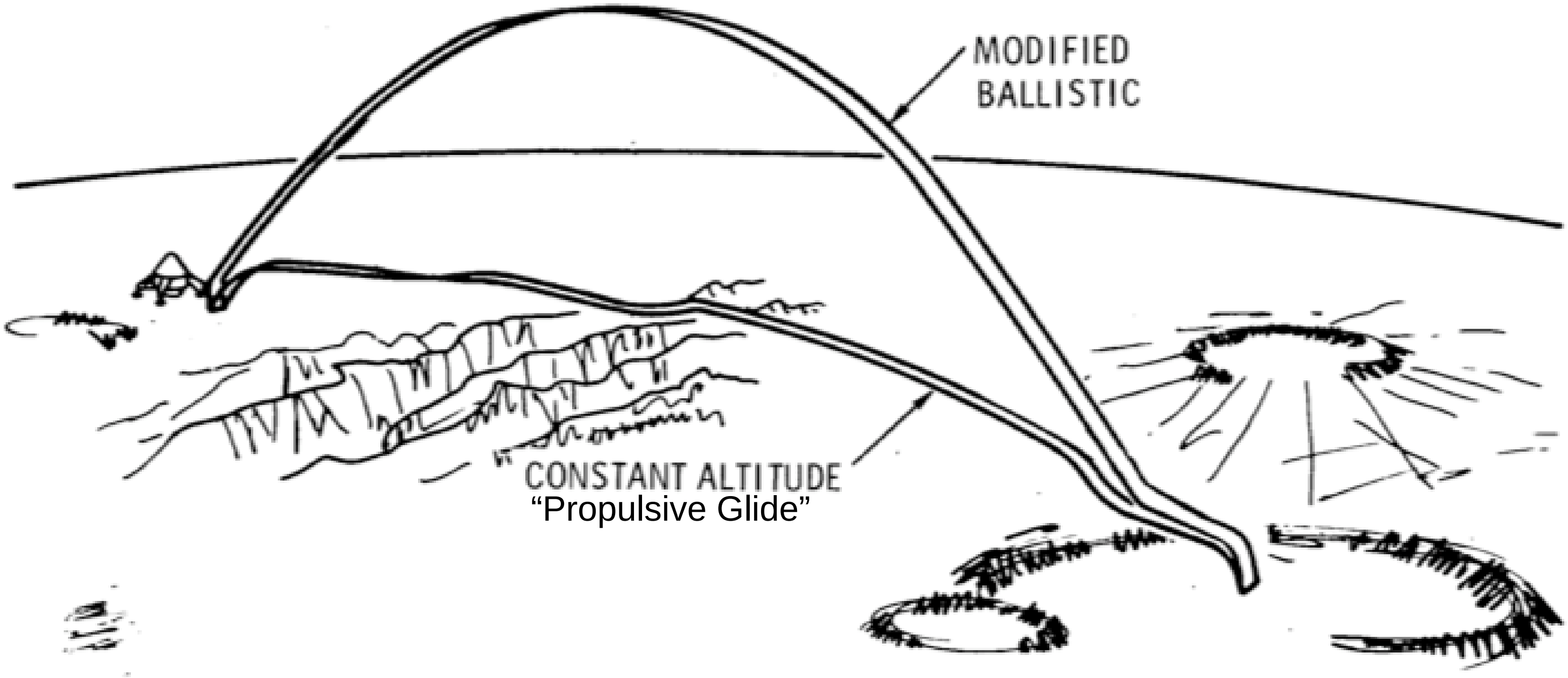
- Adjunct to Constellation program for extended exploration
- Support exploration beyond maximum range of outpost-based rover
- Provide access to sites inaccessible with rover (e.g., crater floors, mountain tops, rilles)
- Potential to carry on long-range rover for emergency quick return
- Utilize propellants available on site
  - Residual propellants on landing vehicles
  - In situ propellant production (ice or regolith)

Apollo Lunar Flying Vehicle Concept



from “Study of One-Man Lunar Flying Vehicle - Final Report Volume 1: Summary” North American Rockwell, NASA CR-101922, August 1969

Notional Concept of LRV Sortie



"Propulsive Glide"

SELECTION CRITERIA

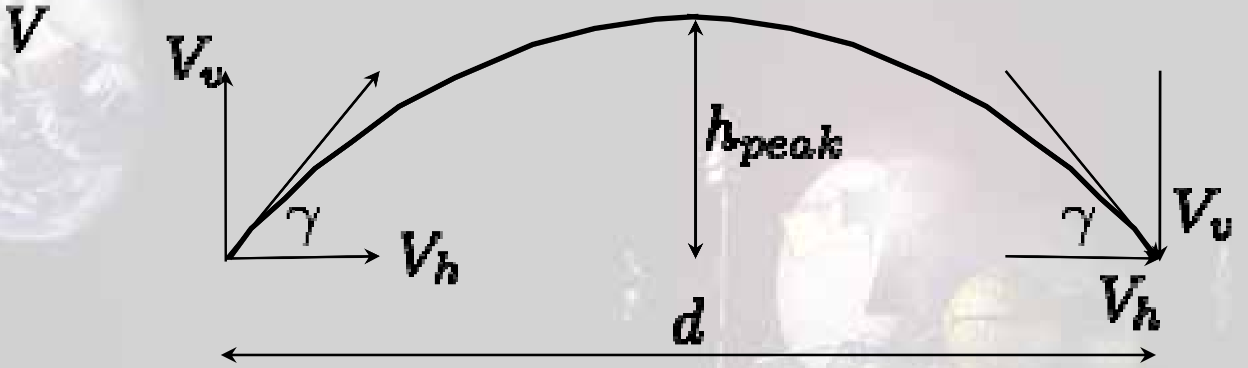
PROPELLANT REQUIRED

PILOT DEMANDS

TARGET VISIBILITY

from "Study of One-Man Lunar Flying Vehicle - Final Report Volume 2: Mission Analysis"
North American Rockwell, NASA CR-101922, August 1969

Ballistic Hop (Airless Flat Planet)



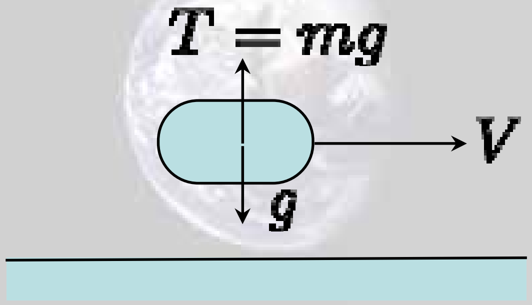
After some analysis, can show that optimum $\Delta V = 2\sqrt{dg}$

$$h_{peak} = \frac{d}{4}$$

$$g = \frac{\mu}{r^2} \Rightarrow \Delta V = 2\frac{\sqrt{\mu d}}{r} = 2\sqrt{\frac{\mu}{r}}\sqrt{\frac{d}{r}} = 2V_c\sqrt{\frac{d}{r}}$$

$$\Delta\chi \equiv \frac{V}{V_c} = 2\sqrt{\frac{d}{r}}$$

Propulsive Glide (Airless Flat Planet)



Assume horizontal velocity is V

$$\Delta V_h = 2V$$

(includes acceleration and deceleration)

$$t_{flt} = d/V \qquad \Delta V_v = g t_{flt} = \frac{gd}{V}$$

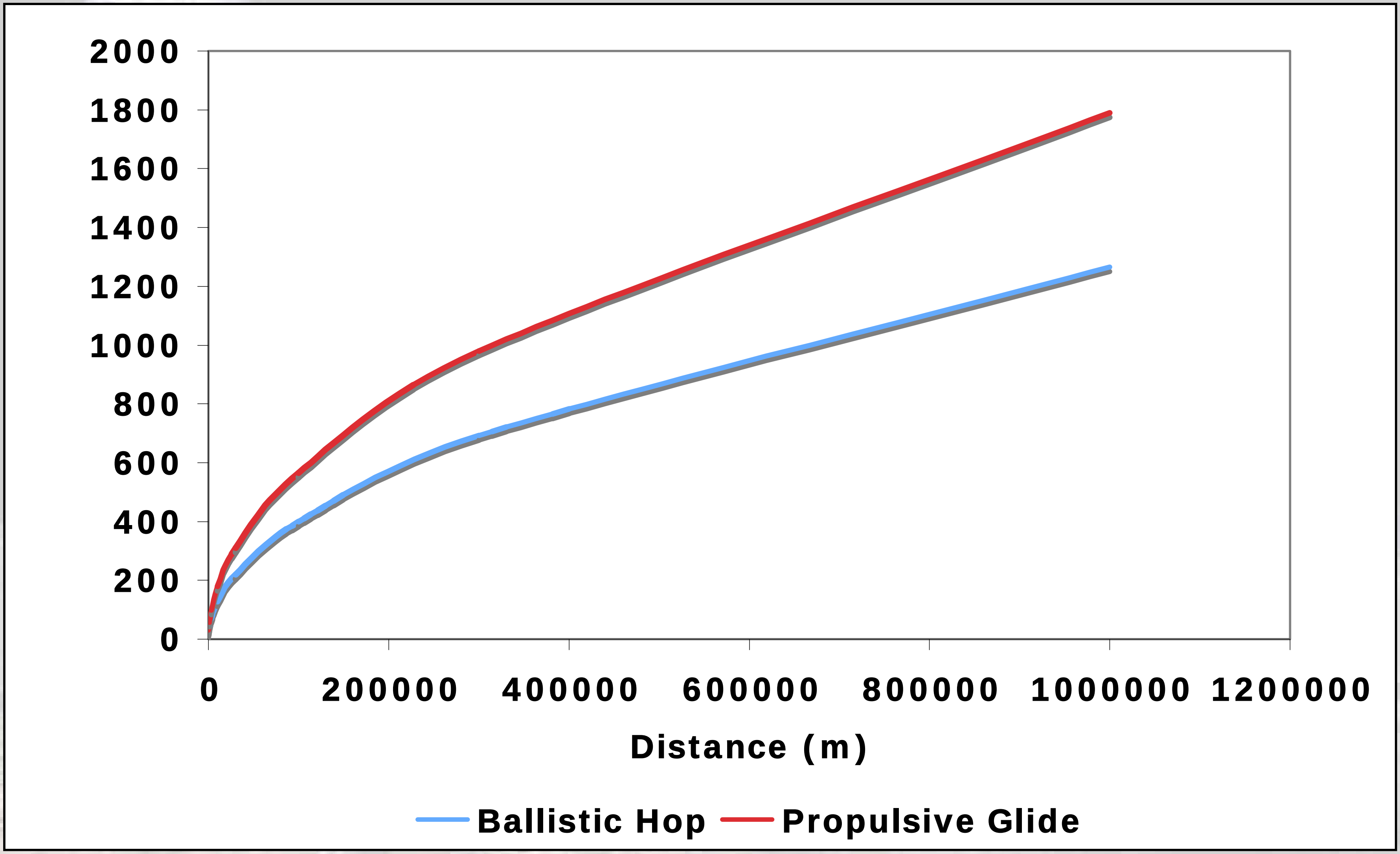
Total ΔV becomes

$$\Delta V_{total} = \Delta V_v + \Delta V_h = 2V + \frac{gd}{V}$$

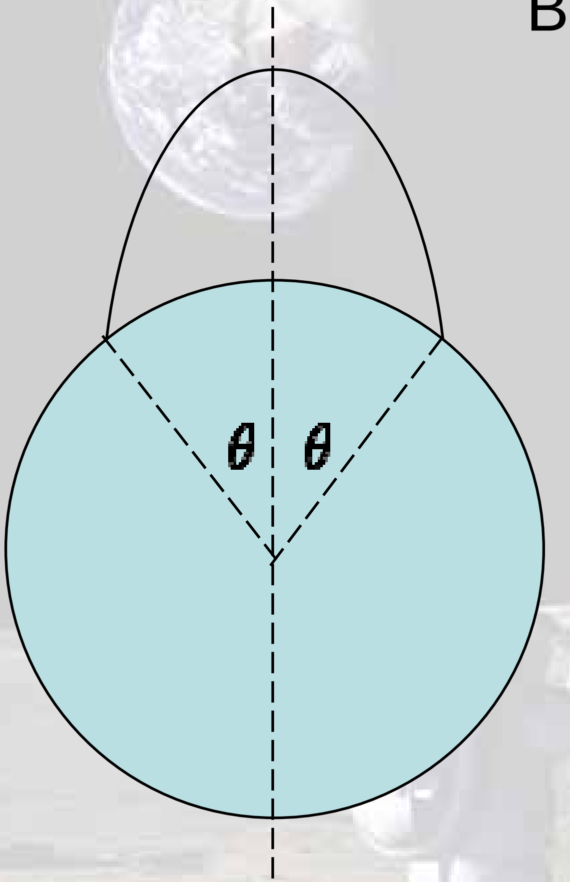
which with some algebra turns out to be

$$\Delta V_{total} = 2\sqrt{2}\sqrt{gd}$$

Delta-V for Hopping and Gliding



Ballistic Hop (Spherical Planet)



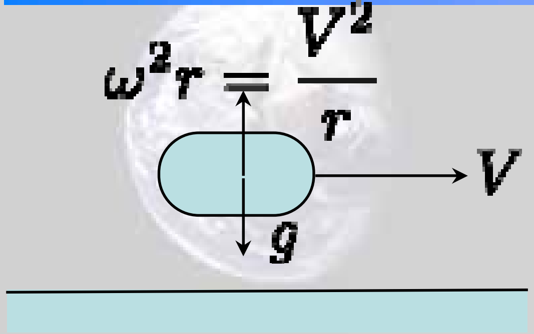
Basic orbital mechanics produces

$$e_{opt} = \frac{1 - \sin\theta}{\cos\theta}$$

$$a_{opt} = r\left(\frac{\sin\theta}{1 - e_{opt}^2}\right)$$

$$\Delta V = 2\sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}$$

Propulsive Glide (Airless Round Planet)



Assume horizontal velocity is V

$$\Delta V_h = 2V$$

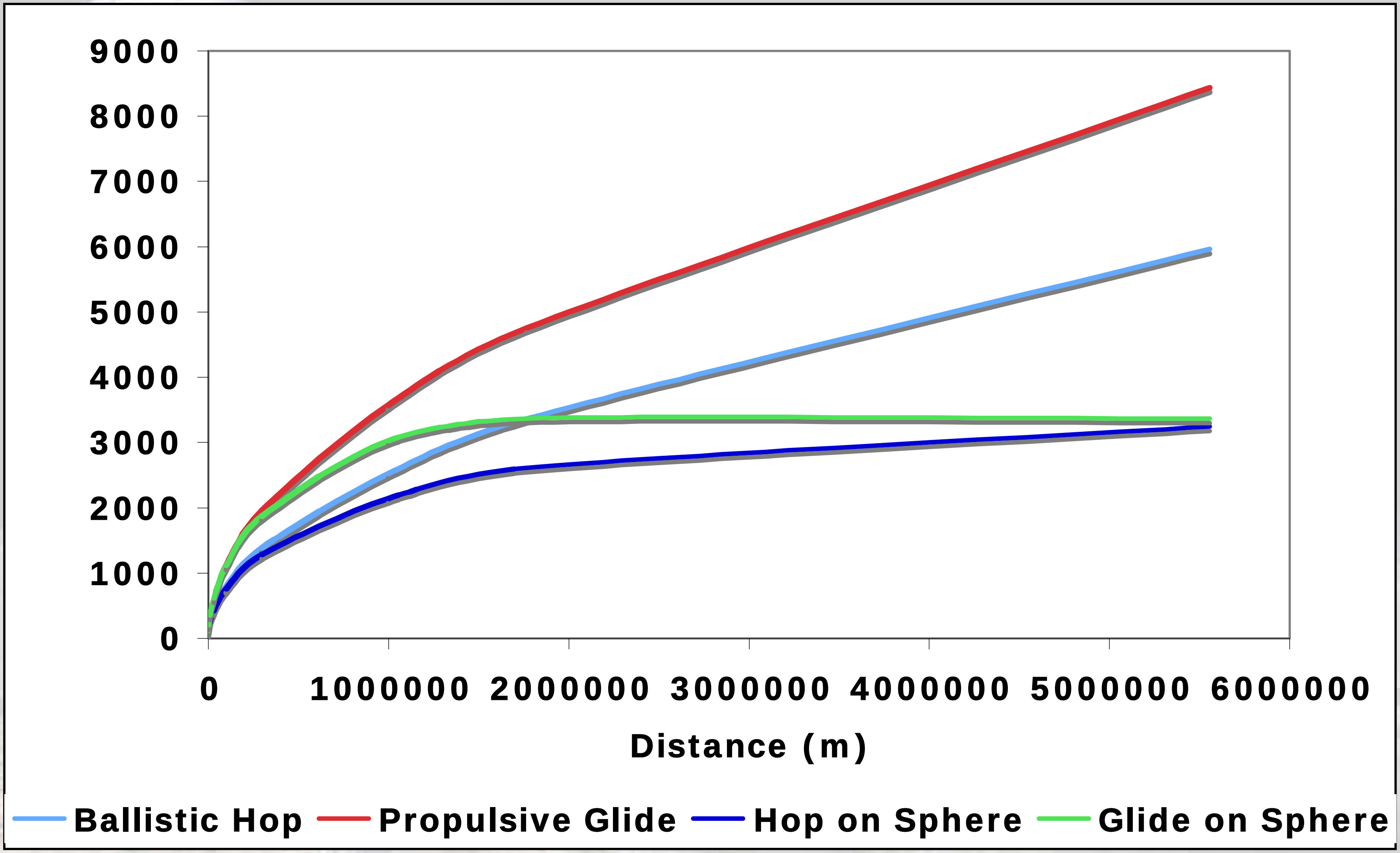
(includes acceleration and deceleration)

$$t_{flt} = d/V \qquad \Delta V_v = \left(g - \frac{V^2}{r}\right) t_{flt} = \frac{gd}{V} - \frac{dV}{r}$$

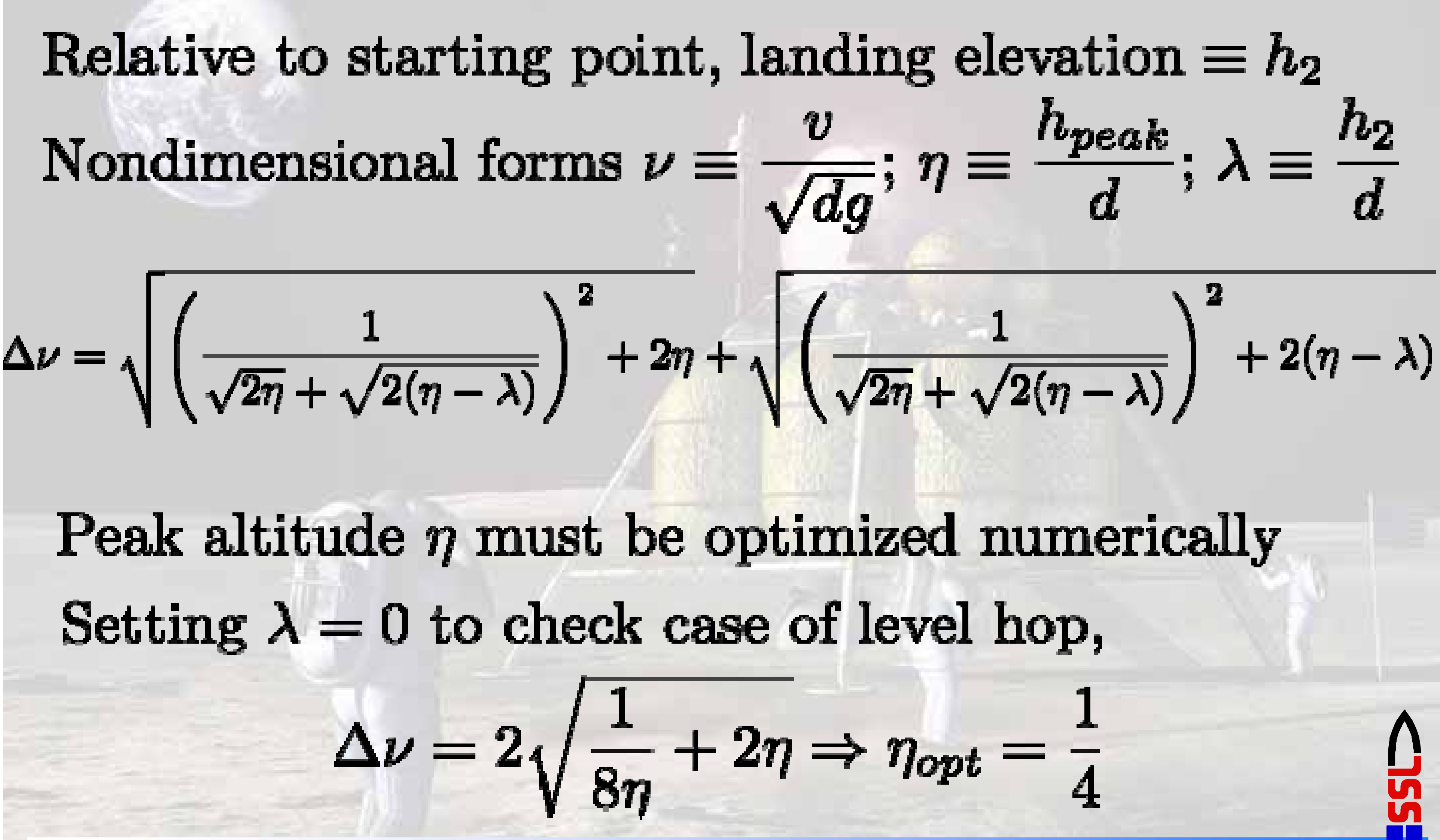
Total ΔV becomes

$$\Delta V_{total} = 2\sqrt{2 - \frac{d}{r}}\sqrt{gd}$$

Hopping on Flat and Round Bodies



Hopping Between Different Altitudes



Relative to starting point, landing elevation $\equiv h_2$

Nondimensional forms $\nu \equiv \dfrac{v}{\sqrt{dg}};\ \eta \equiv \dfrac{h_{peak}}{d};\ \lambda \equiv \dfrac{h_2}{d}$

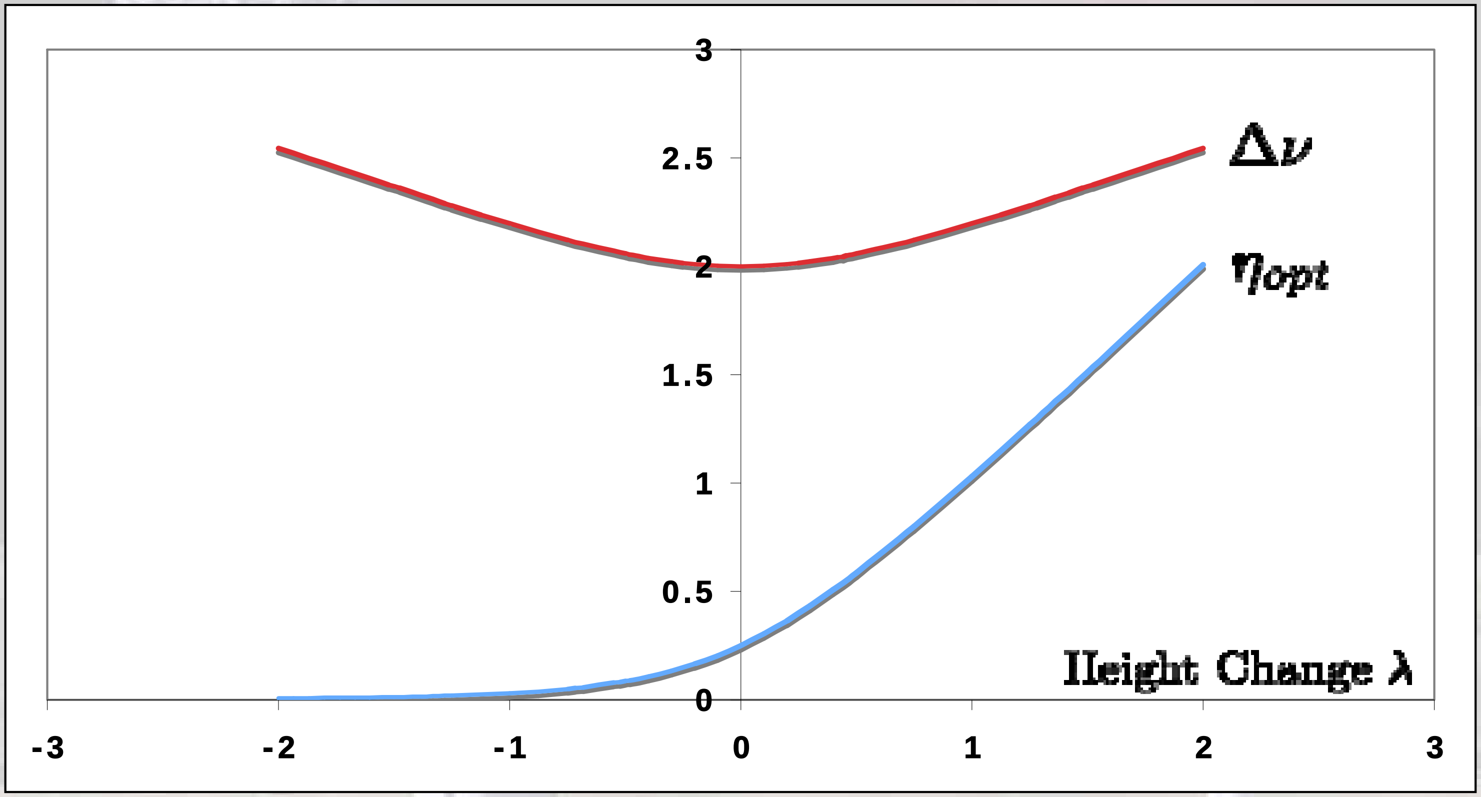
$$\Delta\nu = \sqrt{\left(\frac{1}{\sqrt{2\eta}+\sqrt{2(\eta-\lambda)}}\right)^2 + 2\eta} + \sqrt{\left(\frac{1}{\sqrt{2\eta}+\sqrt{2(\eta-\lambda)}}\right)^2 + 2(\eta-\lambda)}$$

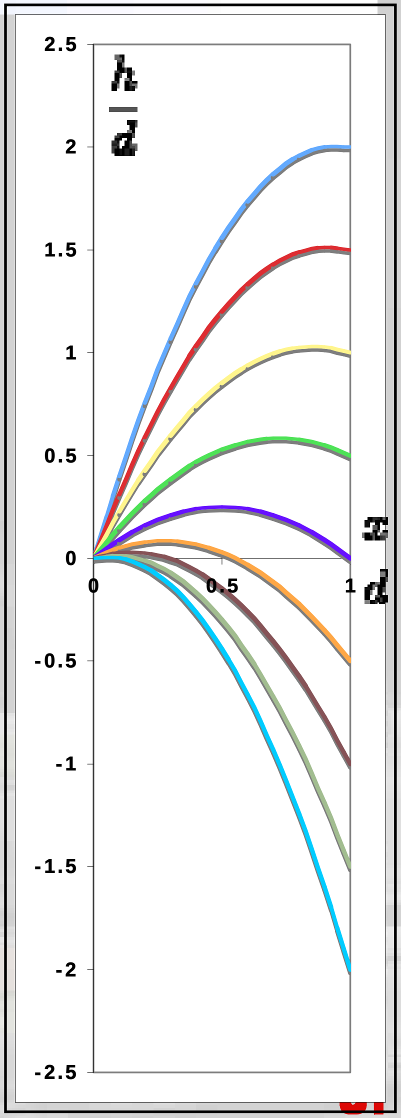
Peak altitude η must be optimized numerically

Setting $\lambda = 0$ to check case of level hop,

$$\Delta\nu = 2\sqrt{\frac{1}{8\eta} + 2\eta} \Rightarrow \eta_{opt} = \frac{1}{4}$$

Trajectory Design for Altitude Change

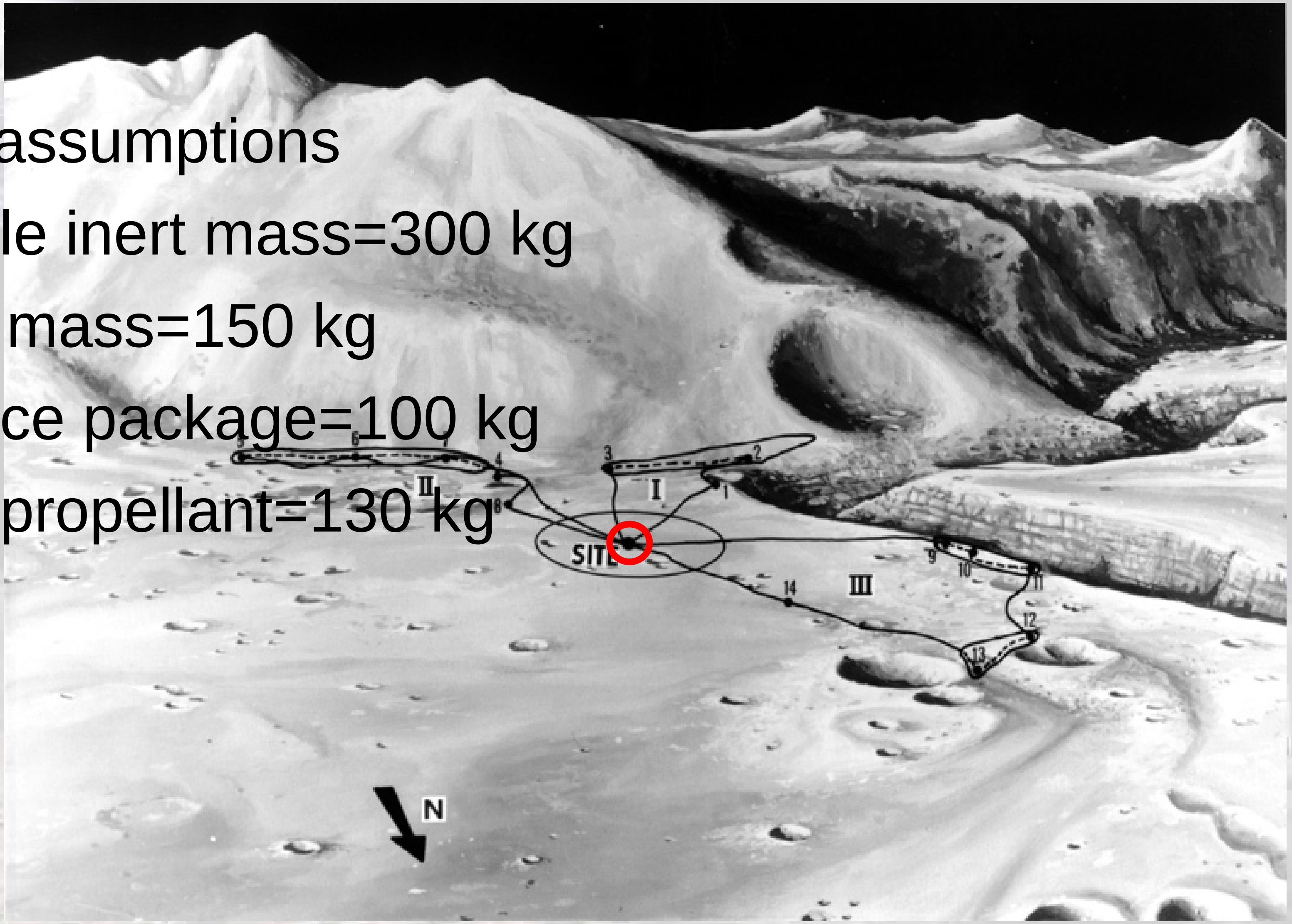




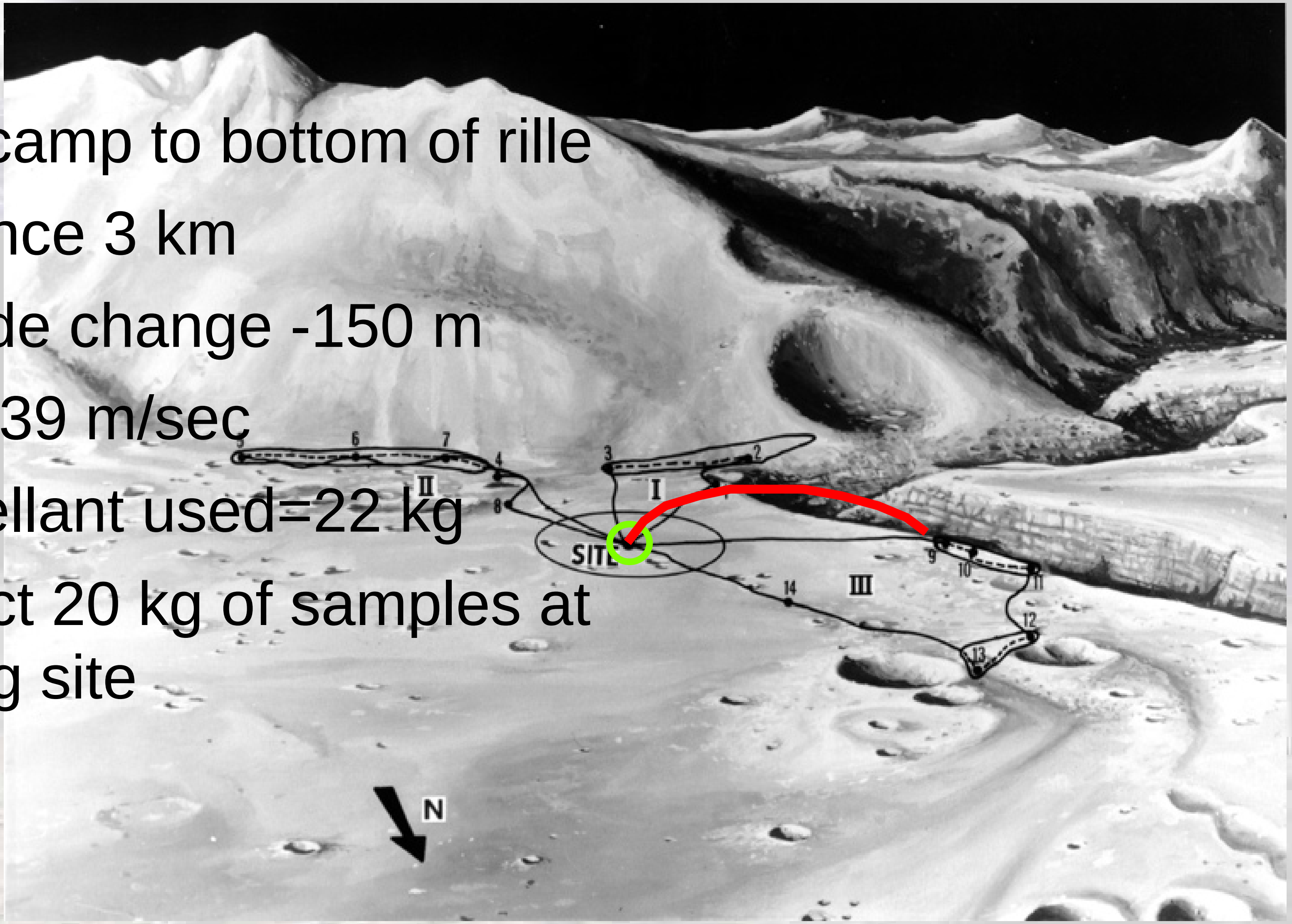
Apollo 15 Revisited: LFV Sortie

Basic assumptions

- Vehicle inert mass=300 kg
- Crew mass=150 kg
- Science package=100 kg
- Total propellant=130 kg



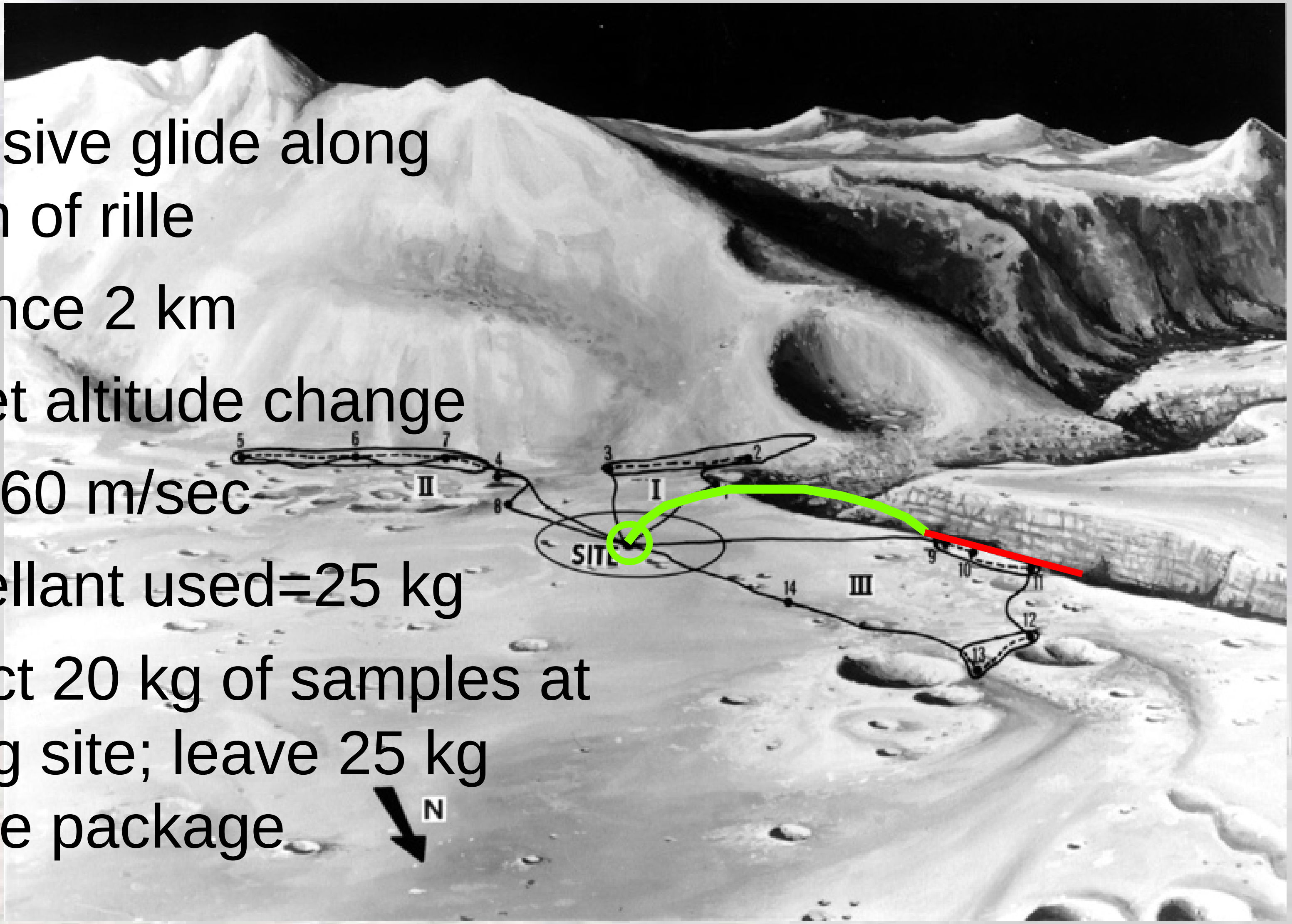
Apollo 15 Revisited: Leg 1



Base camp to bottom of rille

- Distance 3 km
- Altitude change -150 m
- ΔV=139 m/sec
- Propellant used=22 kg
- Collect 20 kg of samples at landing site

Apollo 15 Revisited: Leg 2



Propulsive glide along bottom of rille

- Distance 2 km
- No net altitude change
- ΔV=160 m/sec
- Propellant used=25 kg
- Collect 20 kg of samples at landing site; leave 25 kg science package

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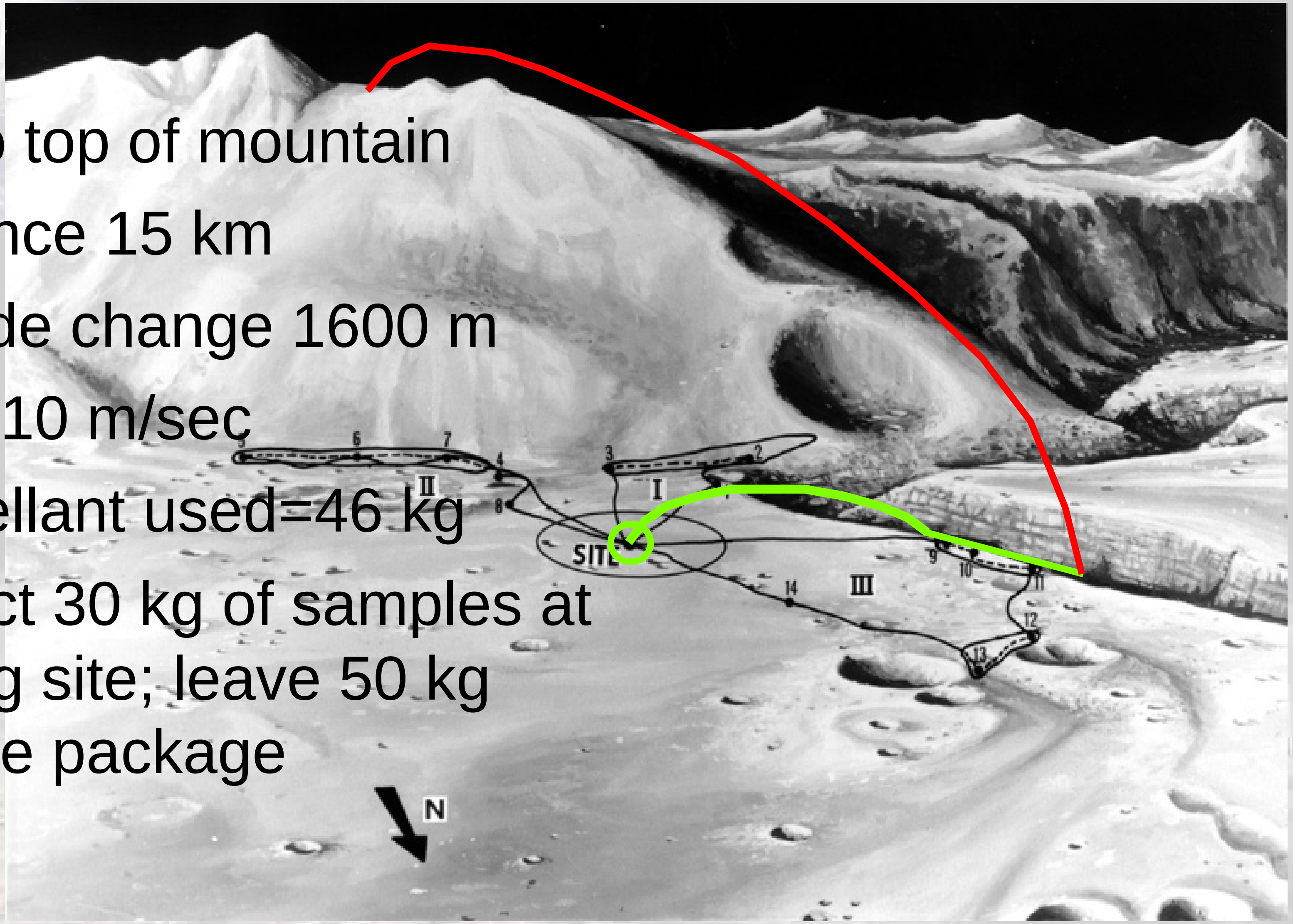
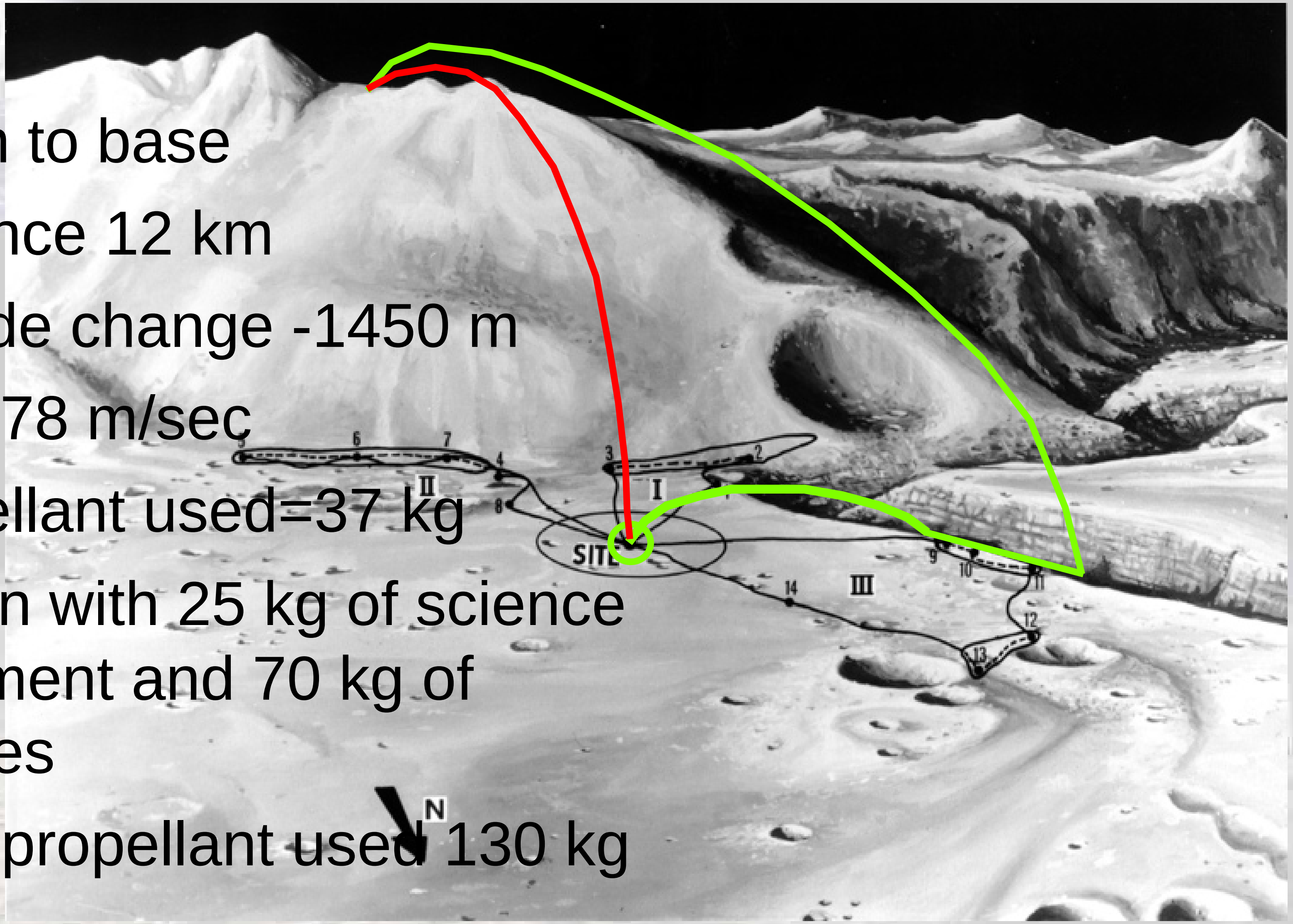
Apollo 15 Revisited: Leg 3

Hop to top of mountain

- Distance 15 km
- Altitude change 1600 m
- ΔV=310 m/sec
- Propellant used=46 kg
- Collect 30 kg of samples at landing site; leave 50 kg science package



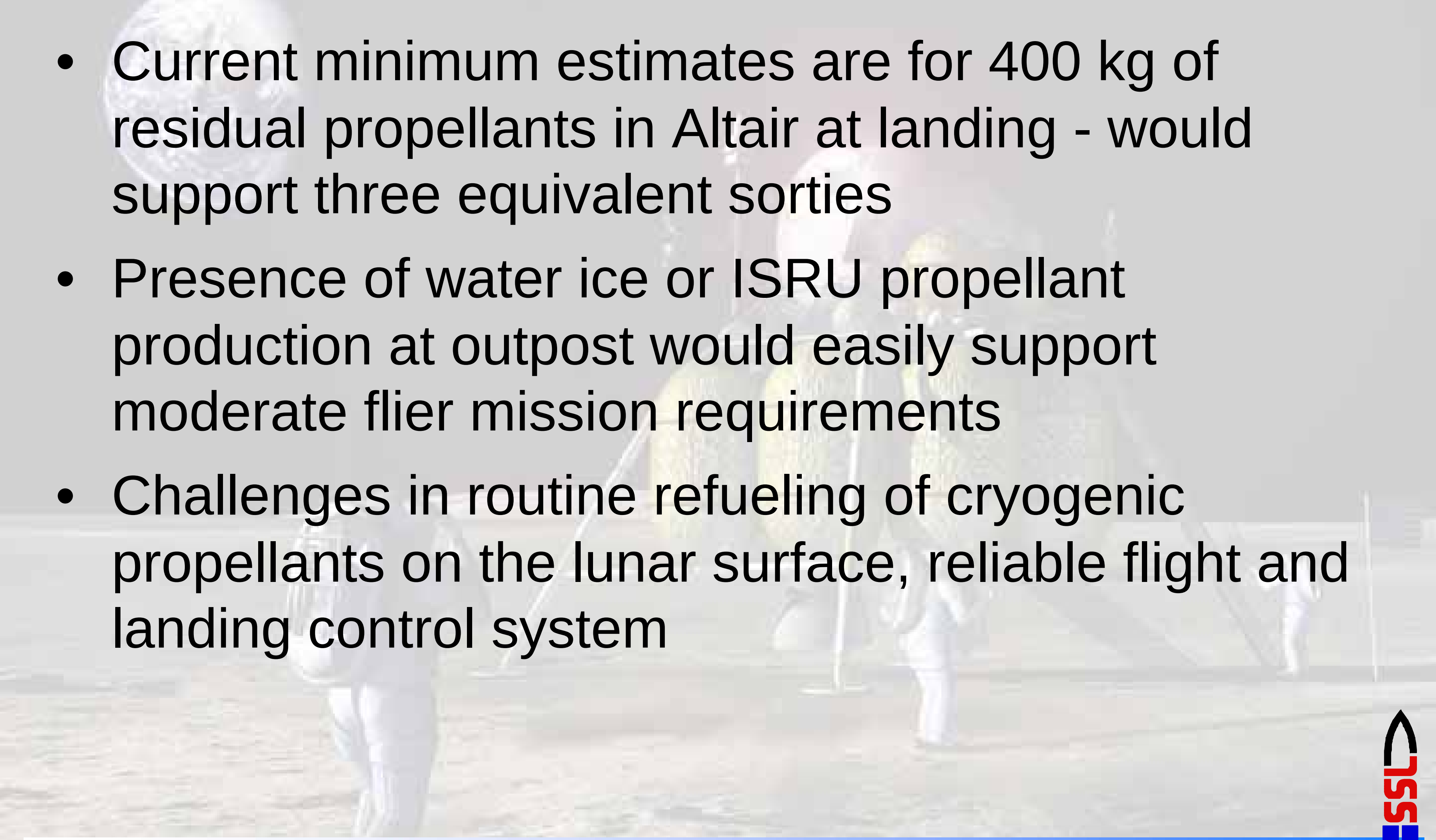
Apollo 15 Revisited: Leg 4



Return to base

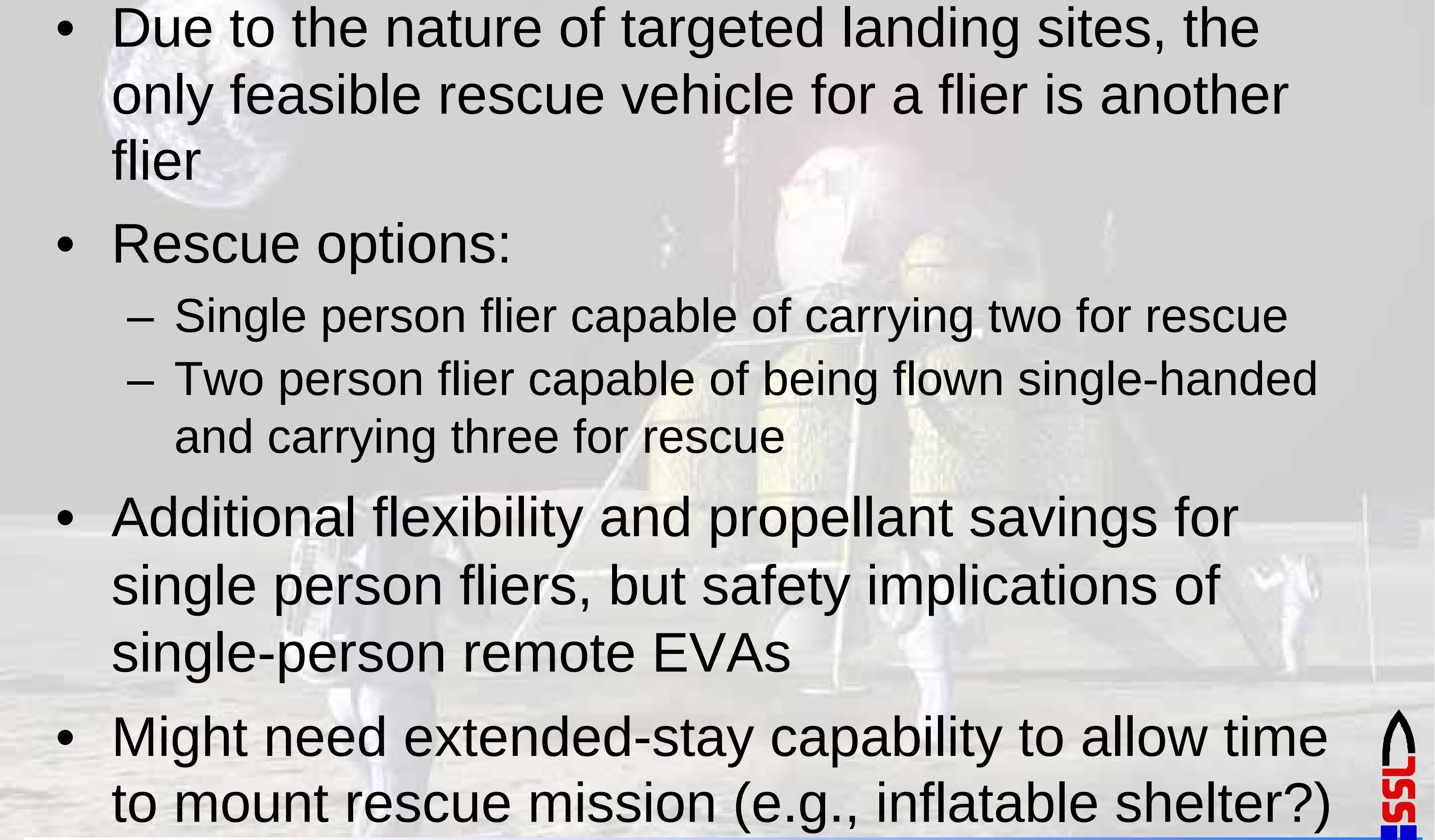
- Distance 12 km
- Altitude change -1450 m
- ΔV=278 m/sec
- Propellant used=37 kg
- Return with 25 kg of science equipment and 70 kg of samples
- Total propellant used 130 kg

Apollo 15 Revisited: Discussion



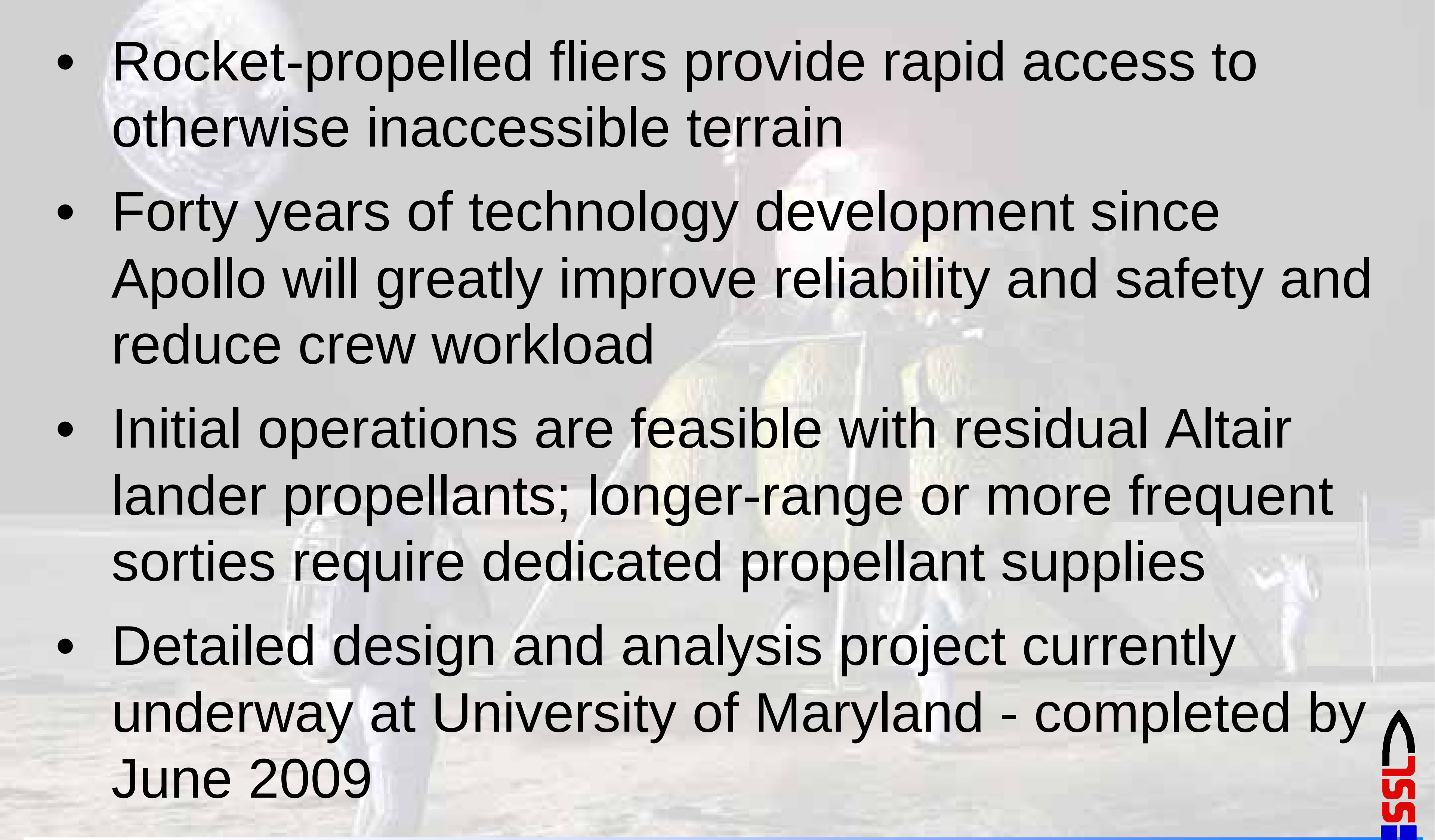
- Current minimum estimates are for 400 kg of residual propellants in Altair at landing - would support three equivalent sorties
- Presence of water ice or ISRU propellant production at outpost would easily support moderate flier mission requirements
- Challenges in routine refueling of cryogenic propellants on the lunar surface, reliable flight and landing control system

LFV System Safety



- Due to the nature of targeted landing sites, the only feasible rescue vehicle for a flier is another flier
- Rescue options:
  - Single person flier capable of carrying two for rescue
  - Two person flier capable of being flown single-handed and carrying three for rescue
- Additional flexibility and propellant savings for single person fliers, but safety implications of single-person remote EVAs
- Might need extended-stay capability to allow time to mount rescue mission (e.g., inflatable shelter?)

Lunar Flying Vehicles - Conclusions



- Rocket-propelled fliers provide rapid access to otherwise inaccessible terrain
- Forty years of technology development since Apollo will greatly improve reliability and safety and reduce crew workload
- Initial operations are feasible with residual Altair lander propellants; longer-range or more frequent sorties require dedicated propellant supplies
- Detailed design and analysis project currently underway at University of Maryland - completed by June 2009