LSIC Excavation & Construction Focus Group

Lunar Landing & Launch Pads

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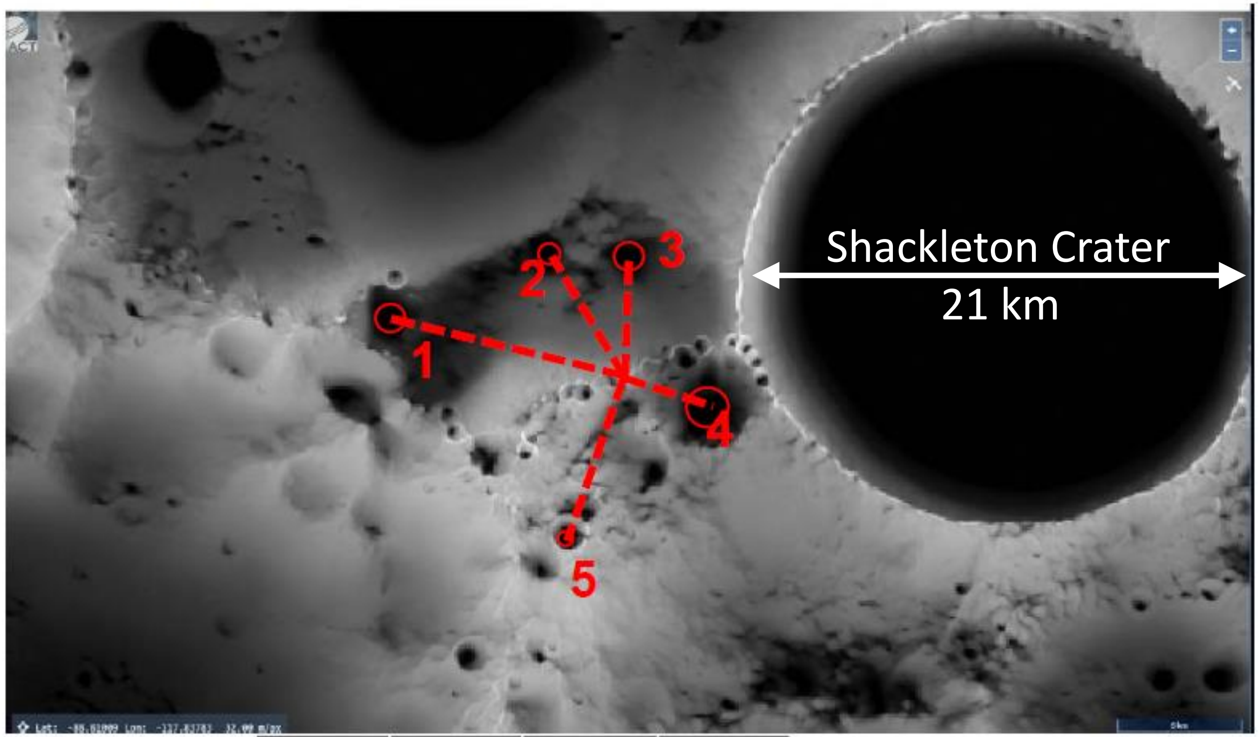
“If you don’t land safely you don’t have a mission”

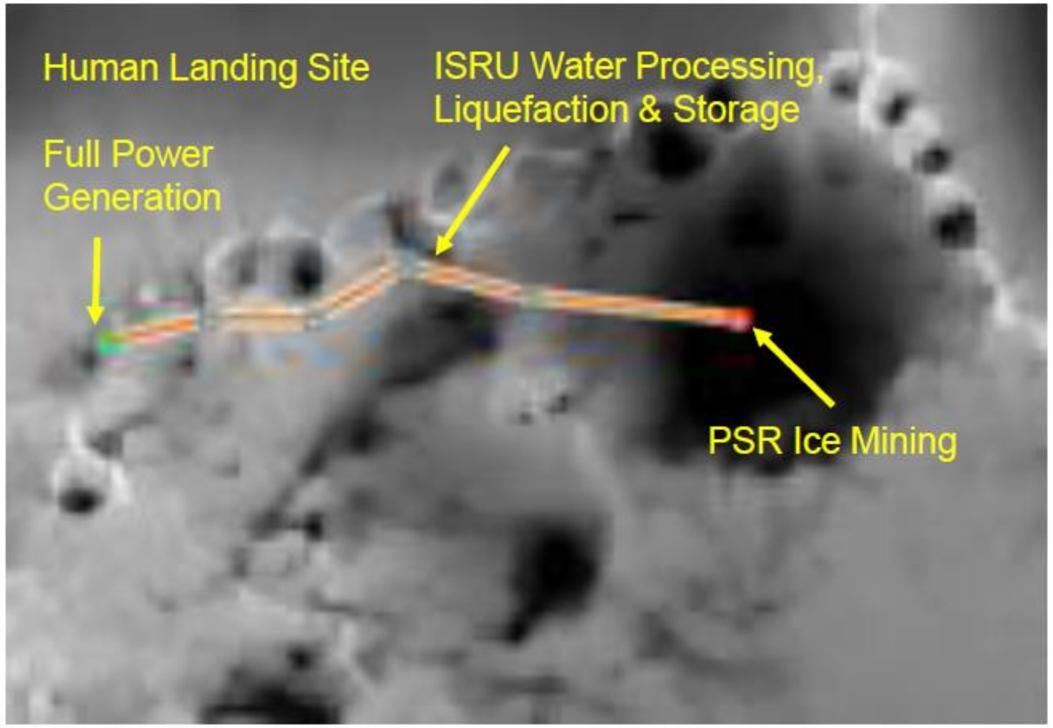
JAXA /Kaguya

We are going to the Lunar South Pole

Landing Hazards

ISRU Ridge Site *Current Baseline





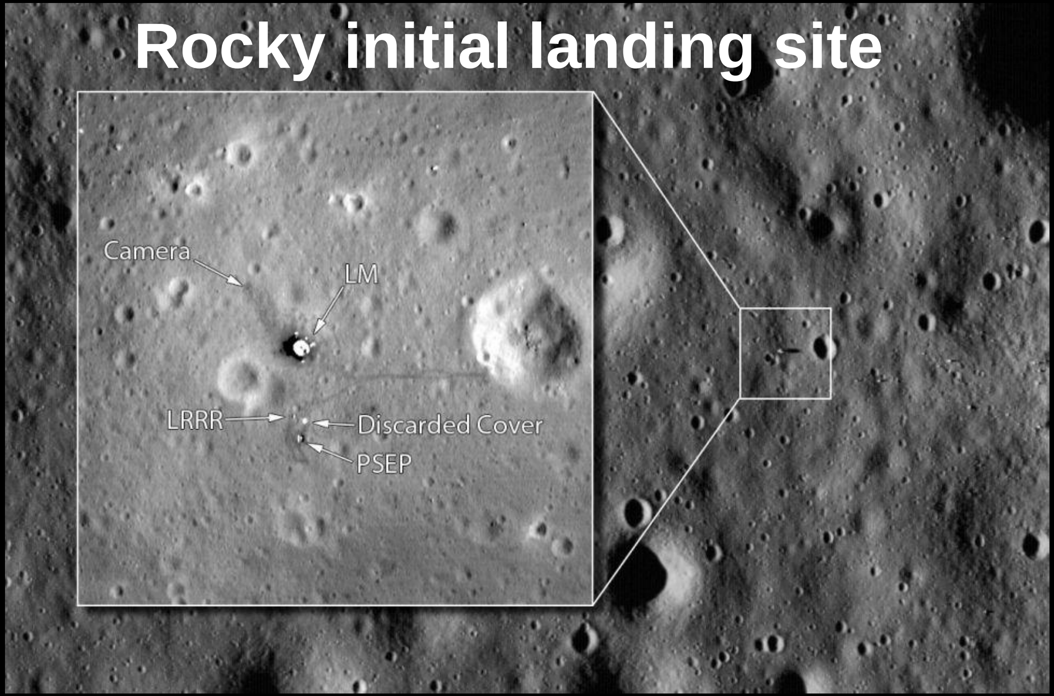
	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m
PSR 1	9105	14	1000
PSR 2	5654	19	500
PSR 3	4737	21	500
PSR 4	3500	16	1500
PSR 5	6688	21	500

	Distance, m	Max Slope, deg	Approx. dia of PSR ice region, m	Ridge Longitude	Ridge Latitude	PSR Longitude	PSR Latitude
PSR 1 straight	6600	20	1000	-137.34 (222.64)	-89.45	-116.94	-89.38
PSR 4 straight	6500	18	1500			-158.79	-89.57
PSR 4 Ridgeline	6850	15	1500			-158.73	-89.58

NASA Oxygen & Water Production Architectures for Early Reusable Lander, Lunar ISRU Workshop, Sanders et al, 7/2019

Apollo 11 - Close Call

Observed Armstrong during the Technical Debrief: "...at something less than 100 feet (30 m); we were beginning to get a transparent sheet of moving dust that obscured visibility a bit. As we got lower, the visibility continued to decrease."



On the very first Apollo landing, the surface features were prominently displayed, just not the right kind in the right place. At 1,500 feet above the Sea of Tranquility Neil Armstrong saw the kind of surface features an Apollo commander does not want to find in his landing zone. Said Armstrong during a 1969 Technical Debrief: "...we were landing just short of a large rocky crater surrounded with a large boulder field with very large rocks covering a high percentage of the surface."

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

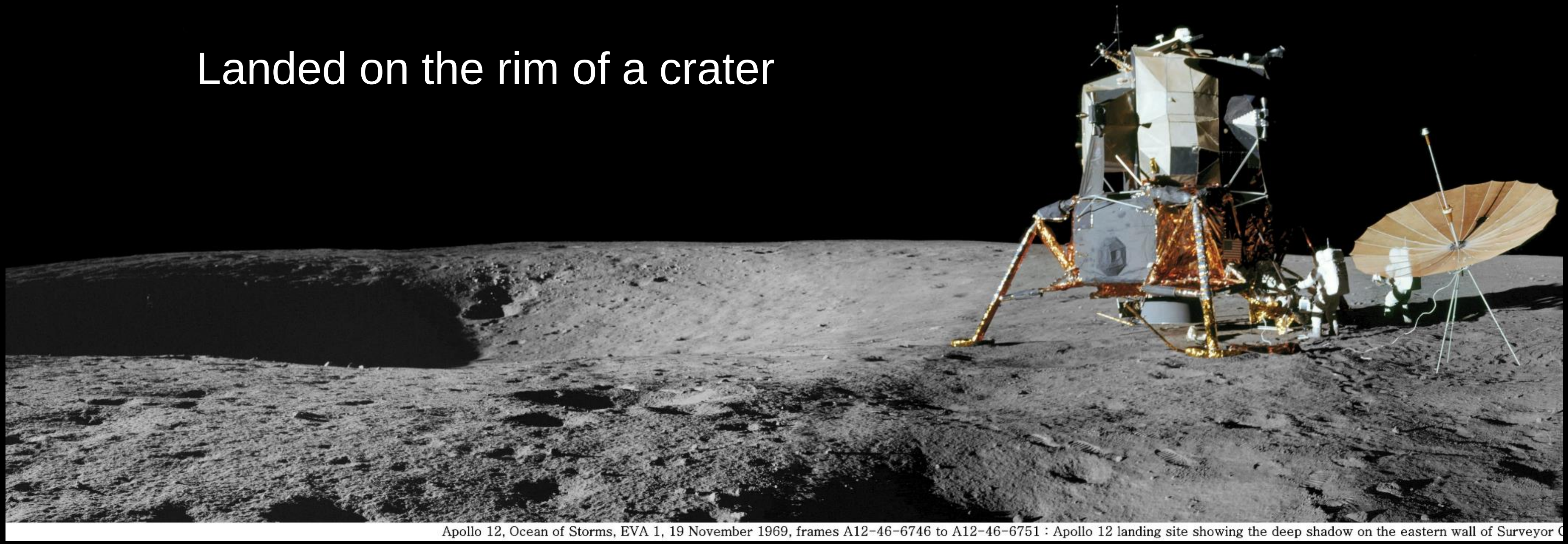
Apollo 11 - Transcripts

https://www.hq.nasa.gov/alsj/a11/a11.landing.html

- 102:45:02 Duke: 60 seconds (of fuel left before the 'Bingo' call). 102:45:17 Aldrin: 40 feet, down 2 1/2. Picking up some dust.
- [Armstrong, from the 1969 Technical Debrief - "I first noticed that we were, in fact, disturbing the dust on the surface when we were something less than 100 feet; we were beginning to get a transparent sheet of moving dust that obscured visibility a little bit. As we got lower, the visibility continued to decrease. I don't think that the (visual) altitude determination was severely hurt by this blowing dust; but the thing that was confusing to me was that it was hard to pick out what your lateral and downrange velocities were, because you were seeing a lot of moving dust that you had to look through to pick up the stationary rocks and base your translational velocity decisions on that. I found that to be quite difficult. I spent more time trying to arrest translational velocity than I thought would be necessary."]
- ["It's only a barnyard calculation, but I probably could not judge 40-foot eye height well with all the blowing dust. But I would certainly prefer that drop to trying to go through the abort sequence at that altitude."]
- [Armstrong - "I was absolutely dumbfounded when I shut the rocket engine off and the particles that were going out radially from the bottom of the engine fell all the way out over the horizon, and when I shut the engine off, they just raced out over the horizon and instantaneously disappeared, you know, just like it had been shut off for a week. That was remarkable. I'd never seen that. I'd never seen anything like that. And logic says, yes, that's the way it ought to be there, but I hadn't thought about it and I was surprised."]

Apollo 12 – Close Call

Landed on the rim of a crater



On Apollo 12, Pete Conrad encountered so much dust that his final descent to the surface was done in the blind. Said Conrad in a 1969 Technical Debrief:

"The dust went as far as I could see in any direction and completely obliterated craters and anything else… I couldn't tell what was underneath me. I knew I was in a generally good area and I was just going to have to bite the bullet and land, because I couldn't tell whether there was a crater down there or not."

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

Apollo 12 – Transcripts

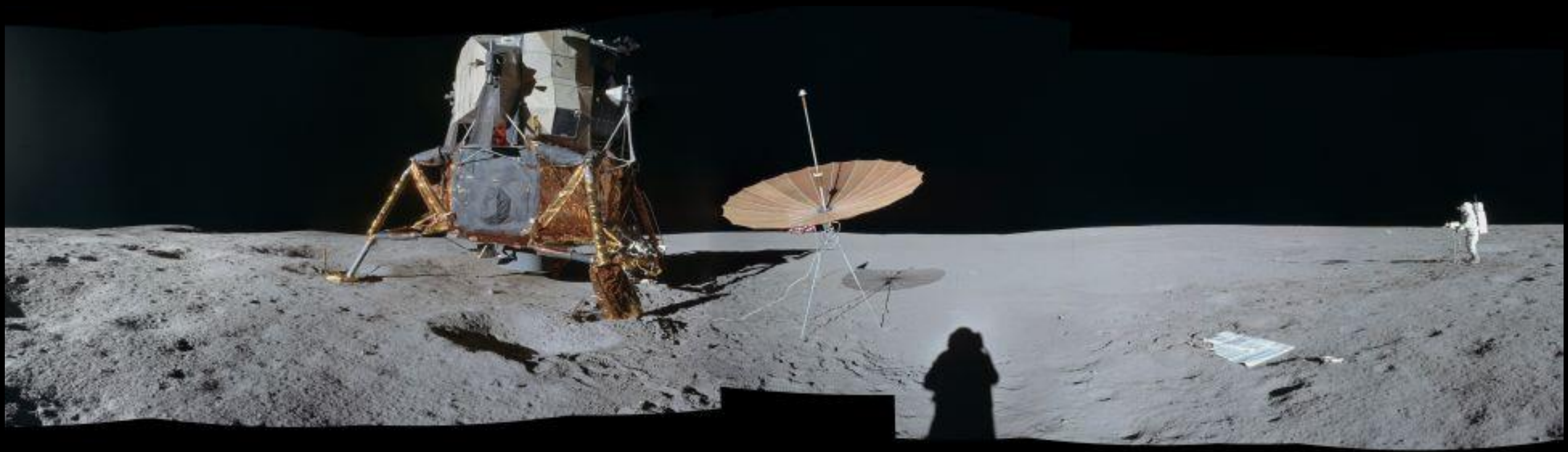
https://history.nasa.gov/alsj/a12/a12.landing.html

- *we picked up a tremendous amount of dust - much more than I had expected. It looked a lot worse than it did in the movies I saw of Neil's landing. It seemed to me that we got the dust much higher than Neil indicated. It could be because we were in a hover, higher up, coming down. I don't know. But we had dust from - I think I called it around 300 feet. I could see the boulders through the dust, but the dust went as far as I could see in any direction and completely obliterated craters and anything else. All I knew was (that) there was ground underneath that dust. I had no problem with the dust, determining horizontal (fore and aft) and lateral (left and right) velocities, but I couldn't tell what was underneath me. I knew I was in a generally good area and I was just going to have to bite the bullet and land, because I couldn't tell whether there was a crater down there or not."]*

Apollo 14 - Close Call

https://www.hq.nasa.gov/alsj/a14/a14.landing.html

7 degree tilt



"In one respect an Apollo lunar module is like a pinball machine -- it doesn't like to tilt," said Epp (JSC Project Manager for ALHAT),"If a lunar module came to rest at an angle beyond 12 degrees tilt the astronauts might not be able to launch themselves off the surface. So if a crew landed on a hill or with a footpad or two on a large rock or in a crater, that could make for a bad day."

https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

Apollo 14 – Transcripts

https://www.hq.nasa.gov/alsj/a14/a14.landing.html

- *108:14:28 Mitchell: If you could land over here; there's some dust, Al; 110 feet. Three feet per second down. You're looking great.*
- *108:14:34 Shepard: (Garbled).*
- *108:14:35 Mitchell: Six percent; there's good dust. You're on your own. (Garbled).*

- *[Shepard, from the 1971 Technical Debrief - ["I believe that we had less problem with dust than they've had before. I think it's because, as we comment later on, the surface of the general area in which we landed was less dusty - that is, exclusive of the dust around the rim of craters. The general area appeared to have less dust and we certainly had no problem with dust at touchdown. I referred to the cross pointers (velocity indicators) during the final stages of the descent at less than 100 feet, but only to assure myself that I had done the best I could as far as cross velocity (left or right) was concerned. The dust was obvious, but you could also see the rocks through the dust. We had no problems here. I think we had a touchdown that was very light, just a little plop when we hit the ground."]*
- *[Mitchell, from the 1971 Technical Debrief - "Right. But, just looking out the window, you can see the dust is no great problem at all."]*

Apollo 15 – Close Call

Below about 60 feet (18 m), Scott could see nothing of the surface because of the quantities of lunar dust being displaced by Falcon's exhaust

Apollo 15's lunar module Falcon came to rest with its rear footpad on the rim of a 20-foot-wide crater. This caused one of the lunar module's footpads to be off the surface entirely and placed the spacecraft at an 11-degree tilt. Stated Scott in the mission's debrief -- "...at the altitudes looking down as we approached the landing, it was very difficult to pick out depressions... as far as the shallow depressions there and the one in which the rear footpad finally rested, I couldn't see that they were really there. It looked like a relatively smooth surface."

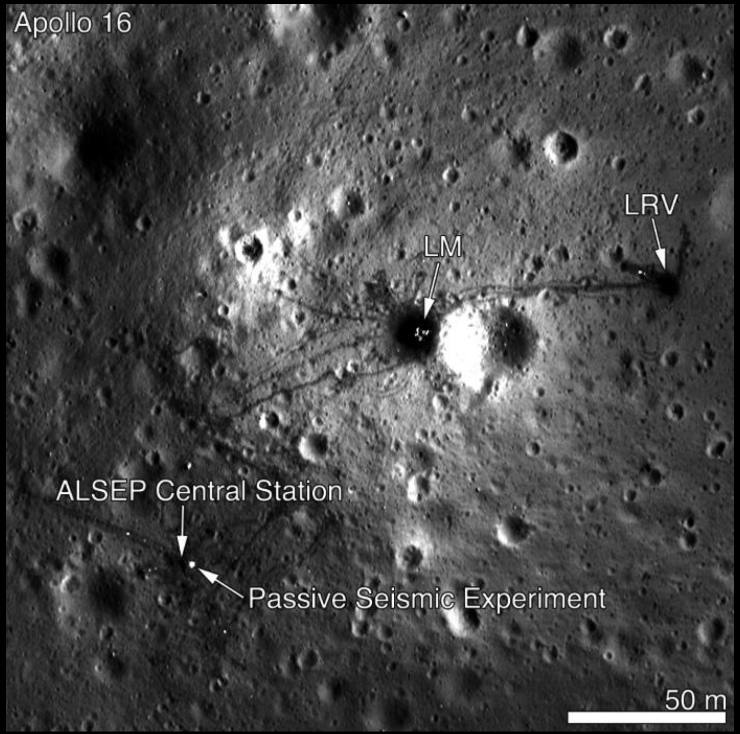
https://www.nasa.gov/topics/moonmars/features/alhat20081223.html

Apollo 15 – Close Call

https://www.hq.nasa.gov/alsj/a15/a15.landing.html

- *[Scott - "There weren't many rocks around, and I don't remember seeing anything. It was just a white-out. I remember totally listening to Jim. I didn't bring my eyes back in, I stayed out there 'cause I was looking for something. I didn't have to bring my eyes back in, because my second pair of eyes were doing the job."]*
- *When you get to the Moon, there's no runway. There's nothing there to tell you how high you are*
- *We landed exactly where I was headed. In spite of the fact that the rear pad was in a crater, that's just where I wanted to land. [In a 1995 letter, Dave commented that he may not have been aware of the crater in which he put the rear pad because "it was shallow and probably had no shadow".]*

Apollo 16 – Slopes & Craters



No issues – but surrounded by craters

Although Apollo 16 lunar module's landing tilt was only 2.5 degrees, <u>if it had come down less than 100 feet in any direction from that point would have placed them on a slope of between 6 and 10-degrees.</u> Apollo 16 commander John Young commented in the mission's Technical Debrief: "I couldn't judge slope out the window worth a hoot, and that's the truth. Even down low. The ground looks flat, but I'm sure it would look flat if it had been a 6 - 8-degree slope too. I don't see any way around that."

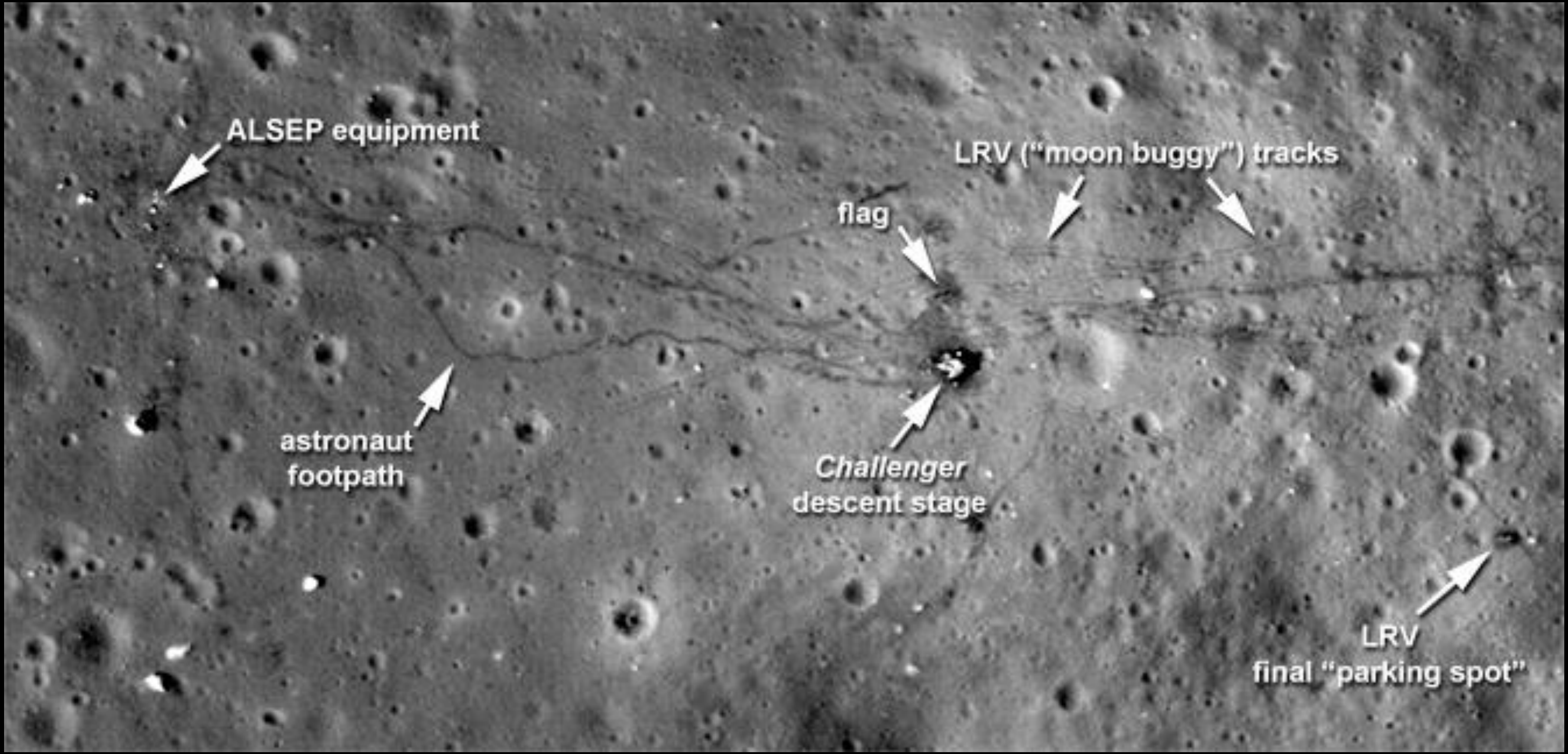
Apollo 16 - Nominal

https://www.hq.nasa.gov/alsj/a16/a16.landing.html

- **104:29:08** Duke: Okay, 80 feet, down at 3. Looking super. There's dust. (Pause) Okay, down at 3. 50 feet, down at 4. Give me one click up. You're backing up slightly. (Pause)

  Young, from the 1972 Technical Debrief - "Yes, 80 feet. Certainly it started there and it got a lot worse, but you could still see the rocks all the way to the ground. The surface features - even the craters - which really surprised me. I was expecting two things: either the dust would be so bad (as on Apollo 12) we couldn't see anything, or there probably wouldn't be as much dust as there was. Possibly, it's the 15-degree sun angle that did all that. Because there's certainly plenty of dust down there to blow, and there's nothing thin about that regolith around the LM."]

Apollo 17 - Nominal



- No issues – but surrounded by craters

Apollo 17 – Nominal

https://www.hq.nasa.gov/alsj/a17/a17.html

13:01:15 Schmitt: Moving forward a little. 90 feet. Little forward velocity. 80 feet; going down at 3. Getting a little dust. We're at 60 feet; going down about 2. Very little dust. Very little dust, 40 feet, going down at 3.

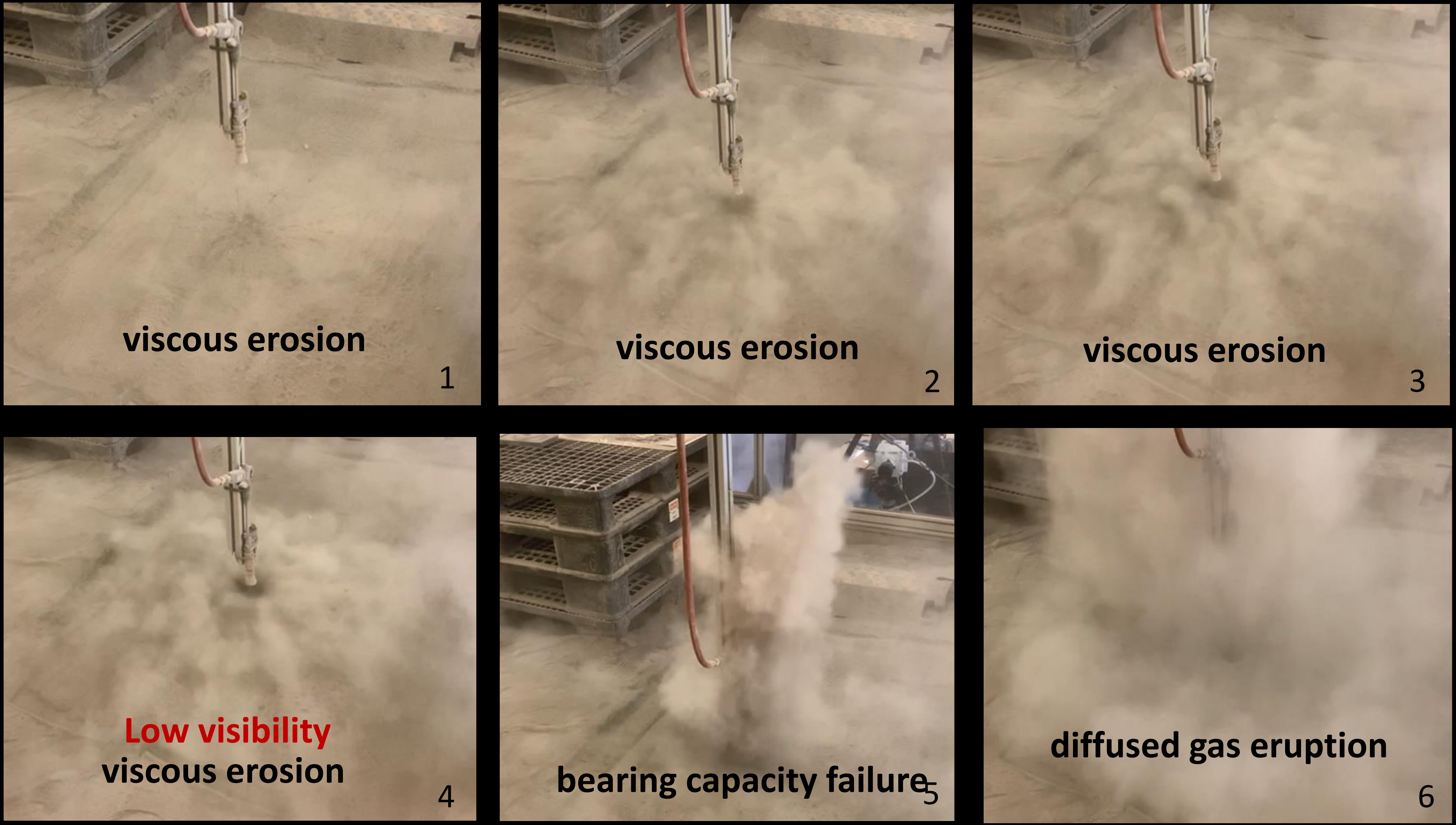
[In the landing film, dust becomes easily visible at about 113:01:38; but, by this time, Gene knows exactly where he is going to land. Even in the film, rocks and small craters are visible until the last few seconds. The 16-mm camera is mounted in Jack's window.]

113:01:42 Cernan: Stand by for touchdown.

113:01:43 Schmitt: Stand by. 25 feet, down at 2. Fuel's good. 20 feet. Going down at 2. 10 feet. 10 feet.

113:01:58 Schmitt: Contact. (Pause)

Cold Gas Testing Video: GMRO* lab - KSC



*Granular Mechanics & Regolith Operations (GMRO)

~100 psi (689.5 kPa) compressed air

Cold Gas Testing Crater: GMRO* lab - KSC

After the Test

*Granular Mechanics & Regolith Operations (GMRO)

Collimated Plume during Morpheus Flight at Kennedy Space Center

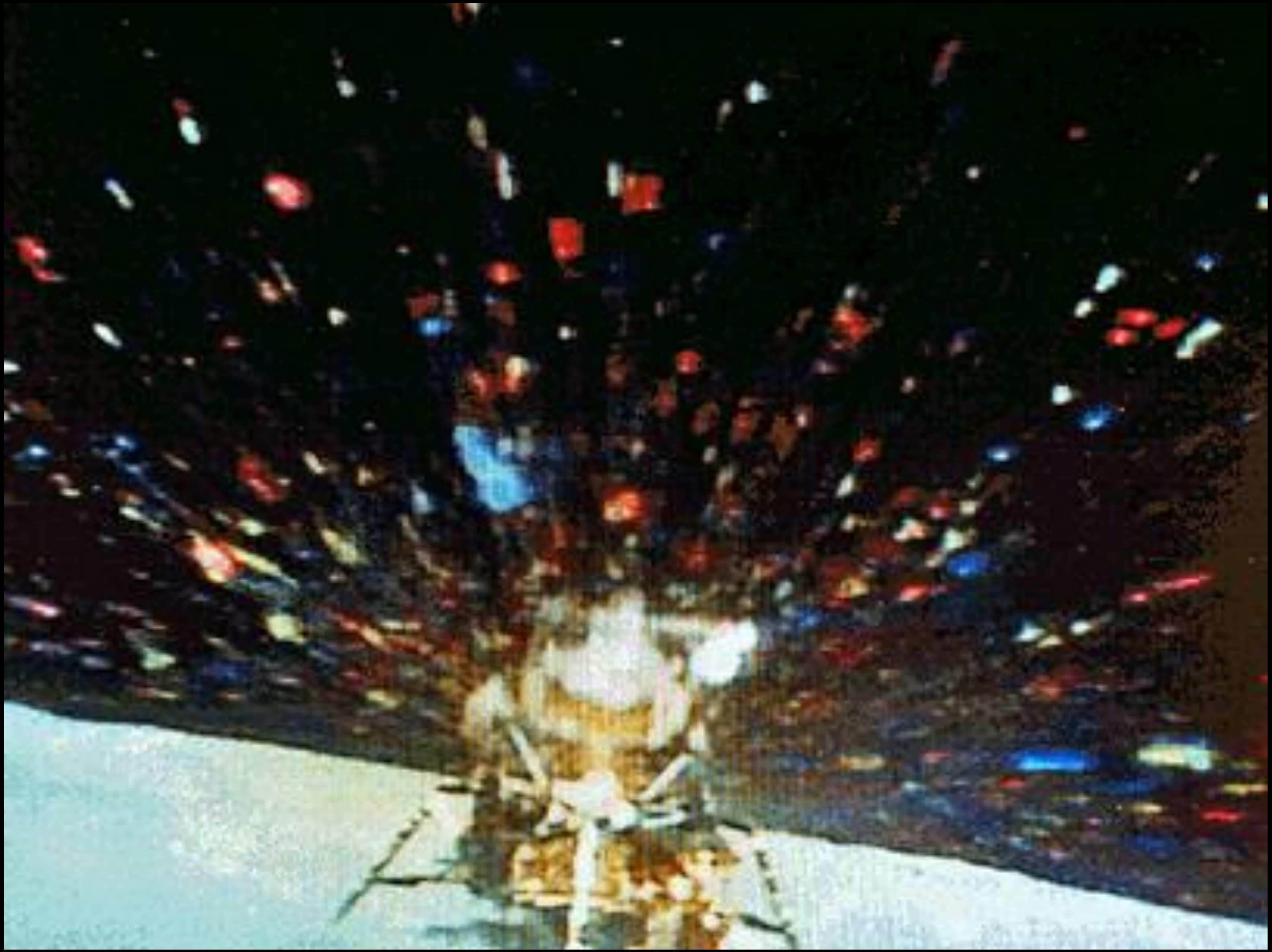
Collimated Plume during Morpheus Launch at Kennedy Space Center

Falcon 9 plume
with under-expanded
nozzle in upper
atmosphere

Source: SpaceX

Rocket Plume during Starship Lunar Landing in Vacuum (Artist's concept)

Source: SpaceX



Apollo 16 Launch
(NASA PHOTO: s72-35613)

44.5 kN (10,000 lb) Thrust Rocket Engine Analysis – Mach 5 - Lunar Vacuum

(Regolith cohesive stress is 100 Pa and the friction angle is 30°, 30 micron dust particles)

TABLE 1. Maximum shear stress computed from Robert's theory and DPLR.

Altitude [m]	Max. Shear Stress - Roberts [Pa]	Max. Shear Stress - DPLR [Pa]
5	1542	2995
10	385	590
15	171	190

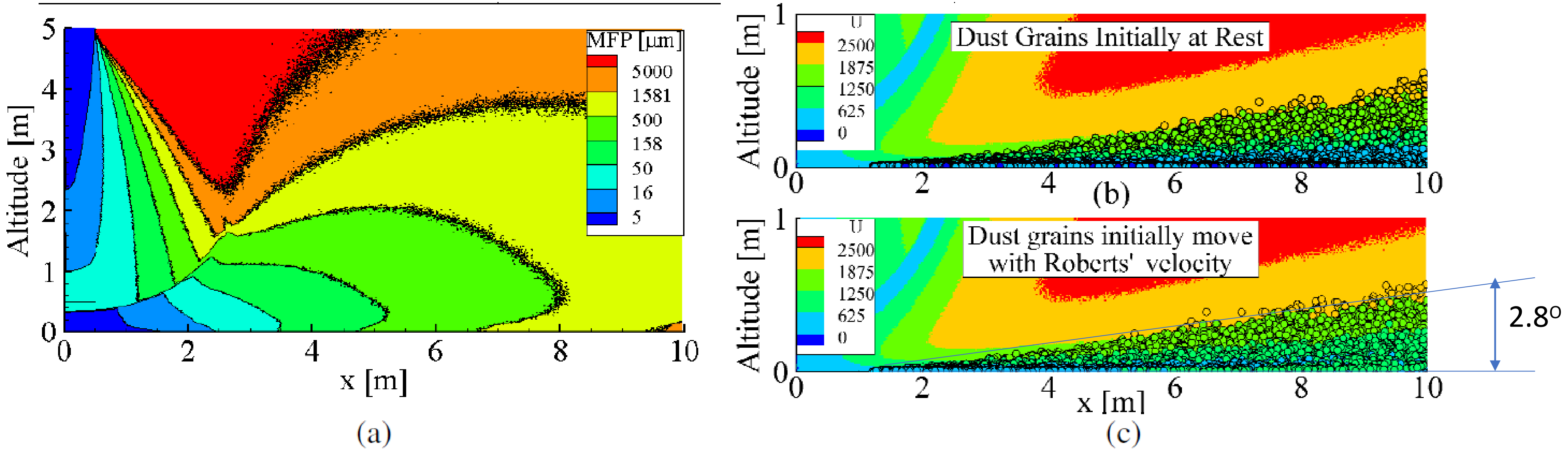


FIGURE 5. (a) 30 micron diameter dust particles overlaid upon the gas mean free path. (b) Horizontal velocity of gas and dust grains. The dust grains are initially at rest. (c) Dust grains are initially ejected with a velocity determined by Roberts' theory.

Morris, A. B., et al. "Plume impingement on a dusty lunar surface." *AIP Conference Proceedings*. Vol. 1333. No. 1. American Institute of Physics, 2011.

Lunar Landing Considerations

- **Topography** (tipping angle, hazards, craters, boulders, rocks, ejecta shielding)
- **Lighting** (Pilot view, camera sensor view)
- **Regolith Reflectance** (LIDAR, RADAR)
- **Thermal** (long shadows, CTE stresses)
- **Seismic** (structural integrity of landing site)
- **Geotechnical** (regolith conditions, bearing strength, surface dust)
- **Over Flight Path** (cannot fly over base for safety)
- **Navigational Aids** (Visual targets, retro-reflectors, active beacons)
- **Rocket engine thrust** (mass of lander, landing conops, height from surface, duration of operation)
- **Plume Surface Impingement Ejecta** (landing visibility, damage to base assets & orbital assets)
- **Plume Surface Impingement Cratering** (hazard to vehicle, liberates regolith & dust)
- **Plume Surface Impingement Blast Ejecta** (Explosion Ejecta)
- **Proximity to Regions of interest** (Science, ISRU)
- **Proximity to Habitat / Base** (Commuting burden)
- **Access via traverses** (EVA and mobility platforms, direct vs. distance made good)
- **Artemis Accords** (principle of due regard, safety zones, de-confliction)

Lunar Landing / Launch Pads

Goal: Mitigate lunar surface hazards

Pad Solution: Prepare the landing site to remove rocks & grade surface

Goal: Eliminate liberation of regolith dust particles & avoid surface cratering

Pad Solution: Emplace a rocket engine gas plume barrier on the regolith surface

Lunar Landing / Launch Pads (LLP) Notional Preliminary Requirements (To be Reviewed)

- The LLP terrain shall have a slope of < 5^{o}
- The LLP terrain shall be cleared of rocks > 20 cm diameter
- The LLP shall withstand gas temperatures of 3,000^{o} – 4,000^{o} C
- The LLP shall withstand gas velocities of 2,000 – 3,000 m/s
- The LLP shall withstand a maximum shear stress of 3000 Pa
- The LLP shall support landing within 100m of a given point
- The LLP shall have good visibility for pilots and sensors before and during landing
- The LLP shall withstand the launch environment during ignition

Lunar Landing / Launch Pads Trade Criteria

Preparation and Staging Phase	Construction Phase	Operations and Maintenance Phase
Up-Mass of Construction Materials and Systems	Constructability	Performance as a Landing/Launch Surface
Difficulty of Insitu Materials Collection, Handling, and Processing	Versatility	Expected Life
Effort of Site Preparation/Staging Time	Construction Time	Ease of Repairability
Reliance on other Surface Assets	Reliance on other Surface Assets	Reliance on Lunar, Gateway and Earth Crew Interaction
Reliance on Lunar, Gateway and Earth Crew Interaction	Reliance on Lunar, Gateway and Earth Crew Interaction	Robotics and Autonomy
Robotics and Autonomy	Robotics and Autonomy	Required Power
Robustness of process	Robustness of process	Lifecycle cost
Current Technology Readiness Level	Current Technology Readiness Level	
Required Power	Required Power	
	Ability to Verify As-Built Performance	

Off Earth Landing and Launch Pad Construction – A Critical Technology for Establishing a Long-Term Presence on Extraterrestrial Surfaces
Nathan J. Gelino, Robert P. Mueller, Robert W. Moses, PhD, James G. Mantovani, PhD, Philip T. Metzger, PhD, Brad C. Buckles, Laurent Sibille, PhD
To Be pubished at ASCE Earth & Space Conference, April 2021 (COVID-19 delay)

Lunar Landing / Launch Pads Concepts

LLP Structure Concepts
Minimal Preparation
Existing Topography
Compacted Regolith Surface
Bedrock Surface
Ice Surface
Rock Piles
Surface Stabilization Applications
Regolith Bags
Ice Bladders
Pavers
Metallic Plates
Deployable Structures
Direct Emplacement of Sintered Structures
Direct Emplacement of Polymer Concretes
Direct Emplacement of a Concrete Pad

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Conclusions

- Lunar launch and Landing must be safe to have a successful mission
- There are many hazards on the lunar surface
- These hazards must be mitigated to ensure a safe landing and launch
- Site Preparation can shape the topography by moving regolith
- Regolith and rocks can be moved by robotic mobility with implements
- A landing/launch pad can prevent rocket plume regolith ejecta and cratering
- The Artemis accords may require a landing/launch pad