Accessing Craters

Design and Experiments with Two Robotic Systems

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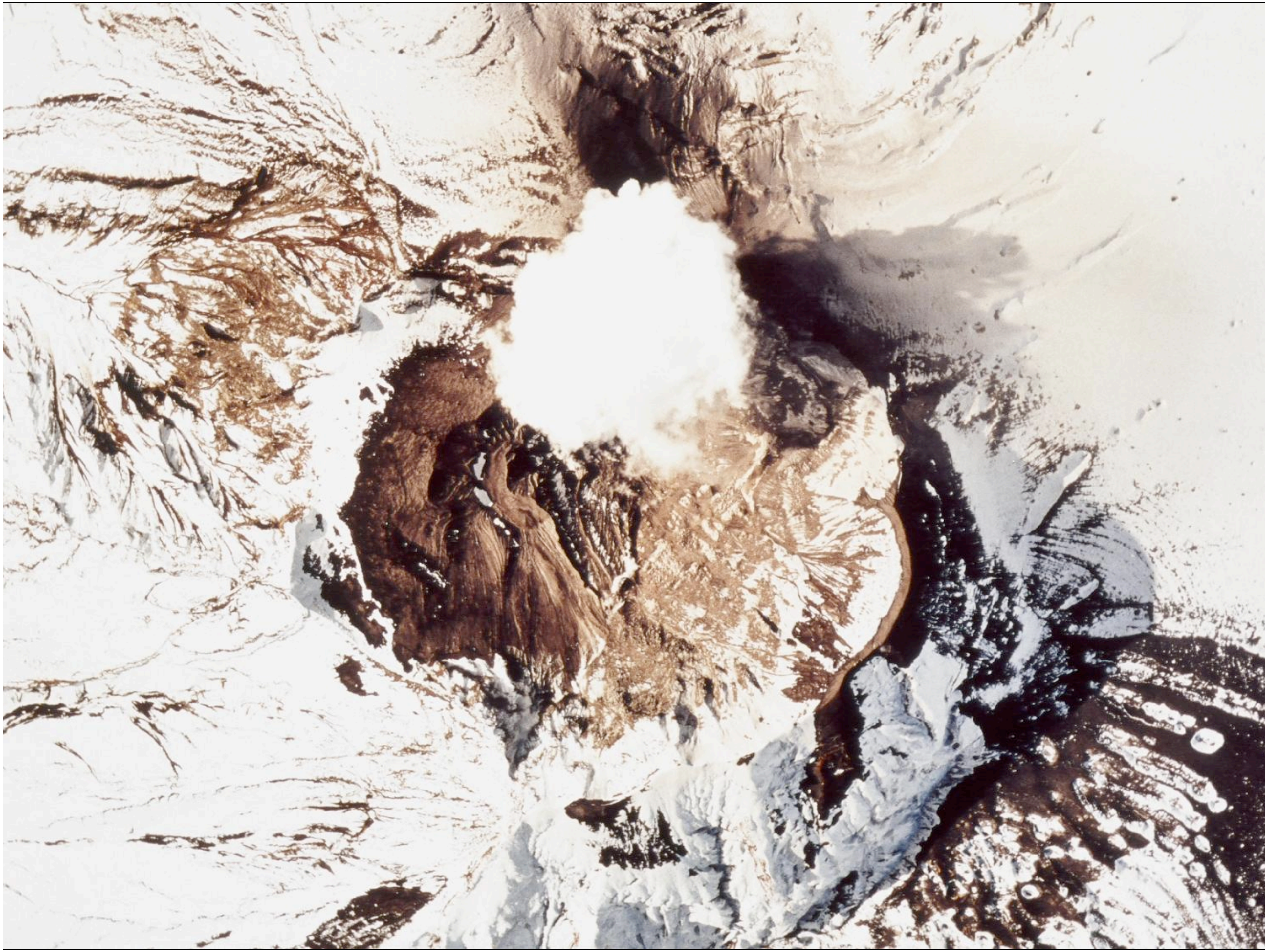
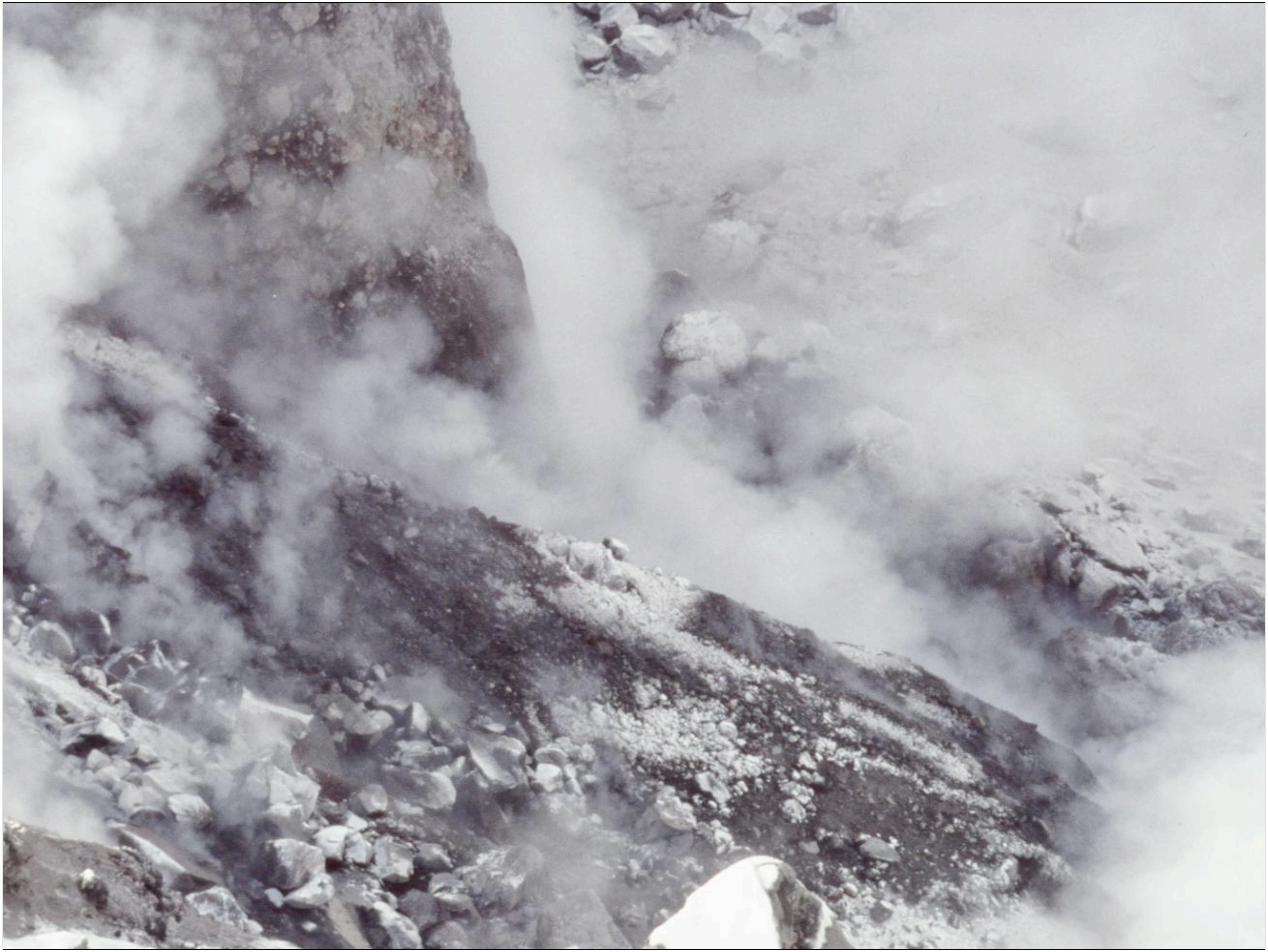
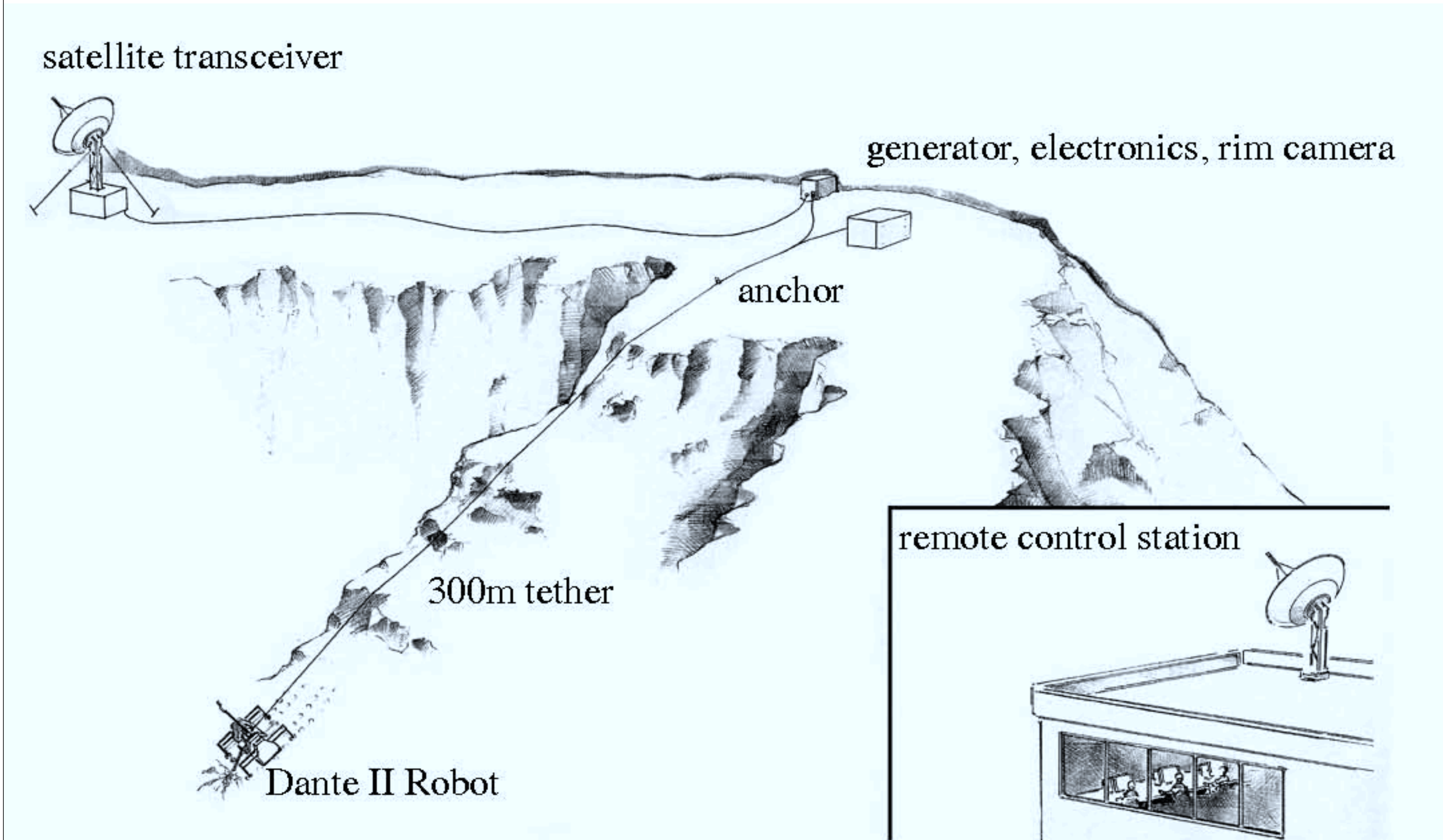
NASA

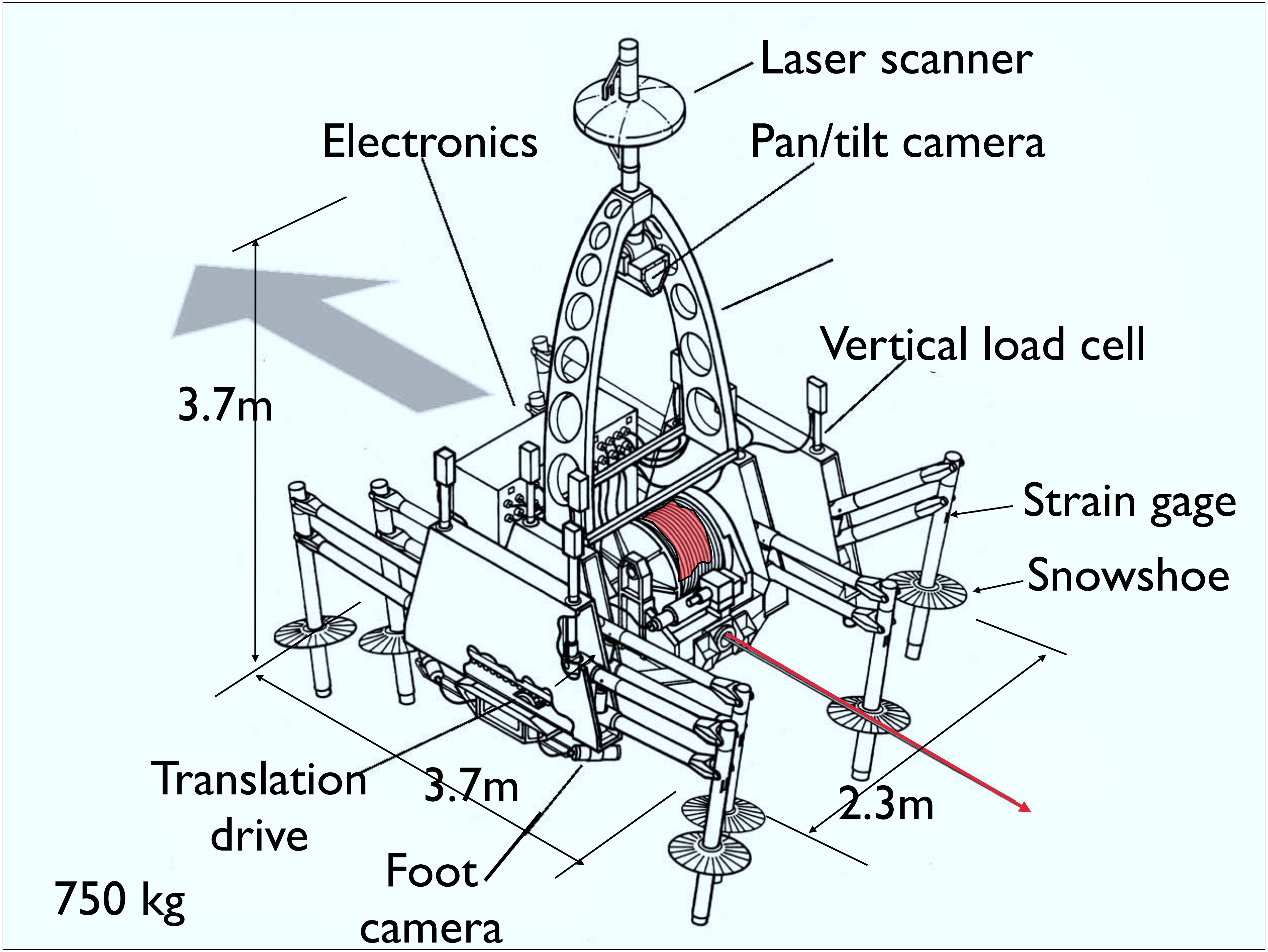

92 8

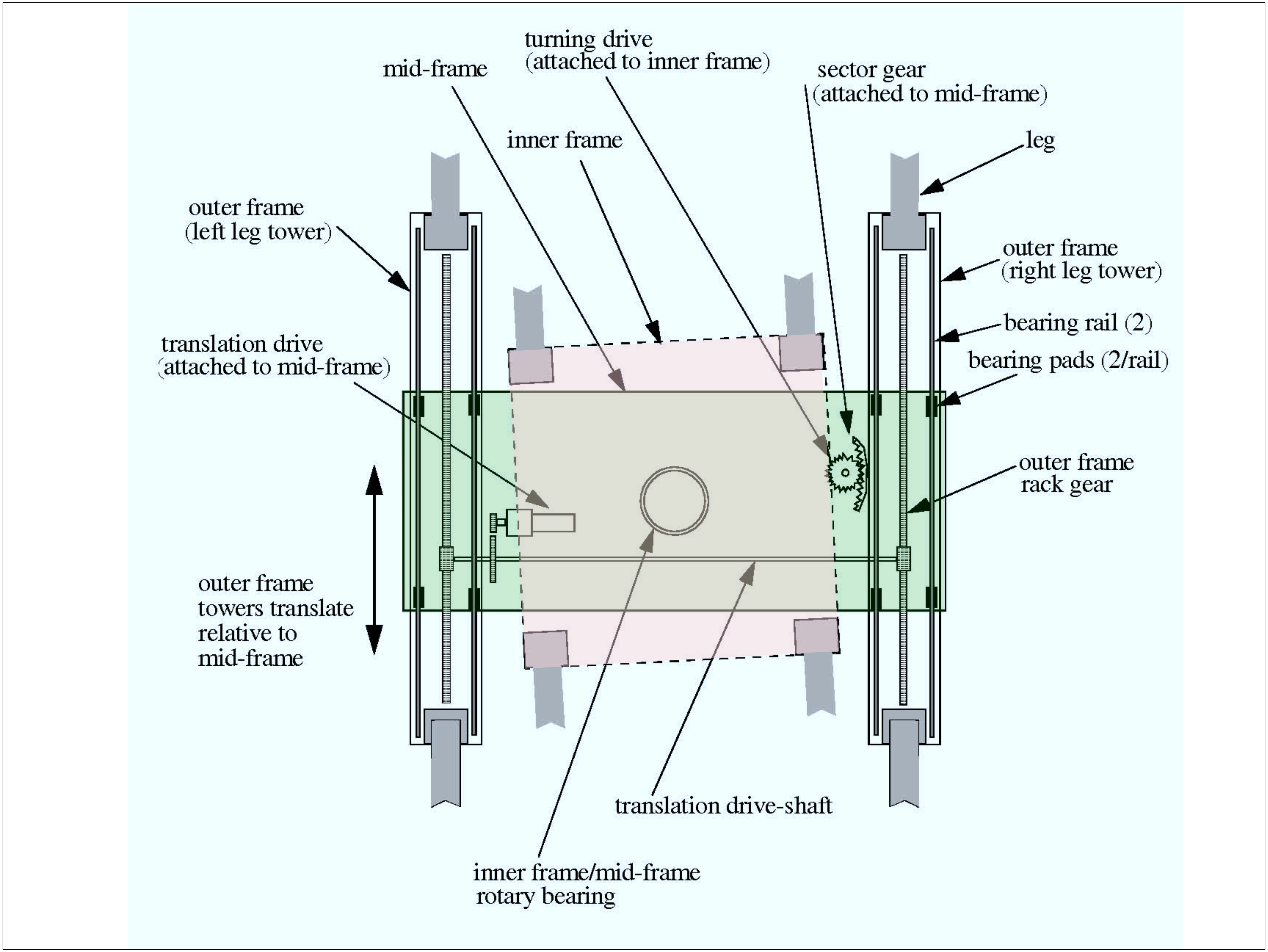




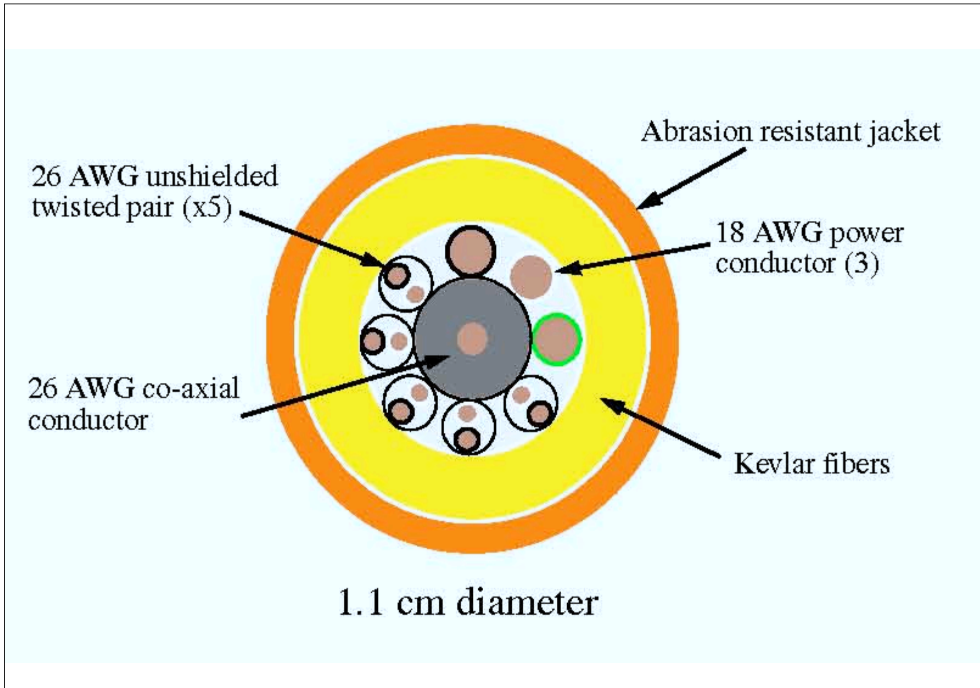


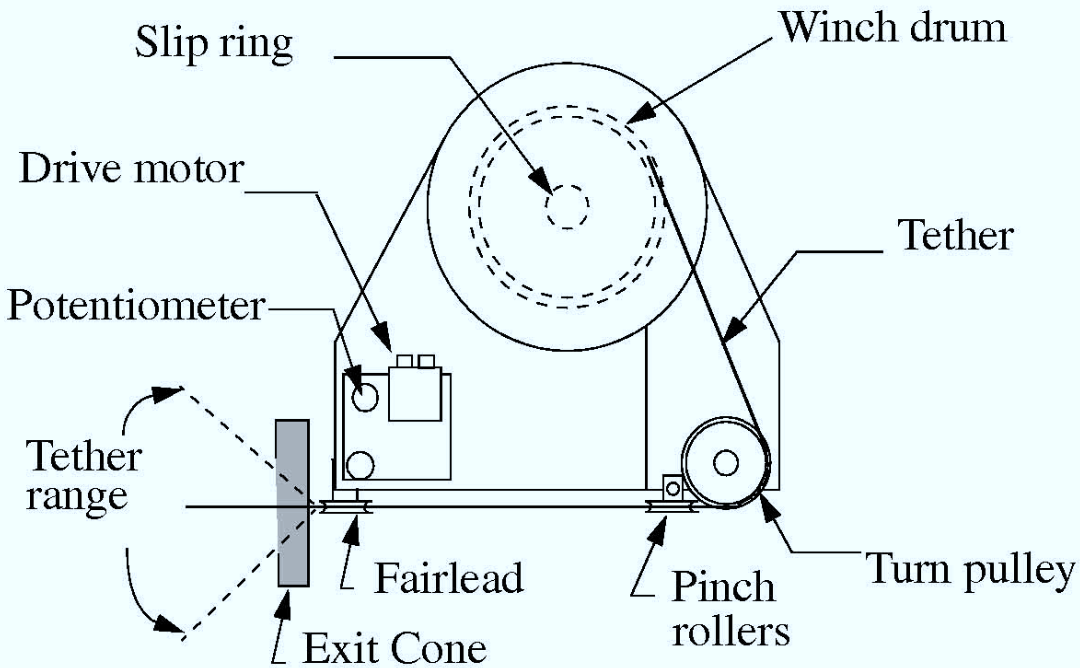
Remote control
120km distant

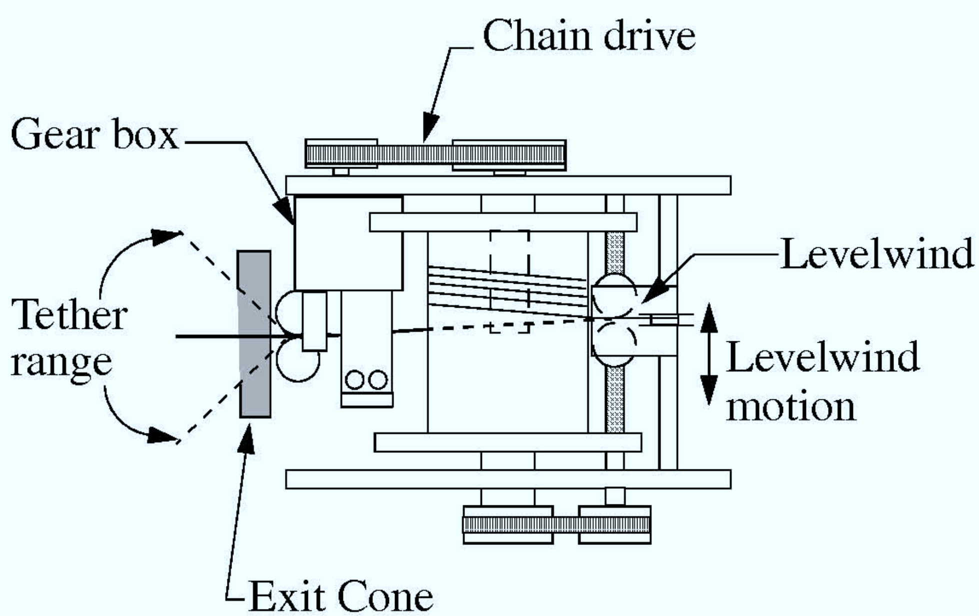

Laser scanner
Electronics
Pan/tilt camera
Vertical load cell
3.7m
Strain gage
Snowshoe
Translation
drive
3.7m
2.3m
Foot
camera
750 kg



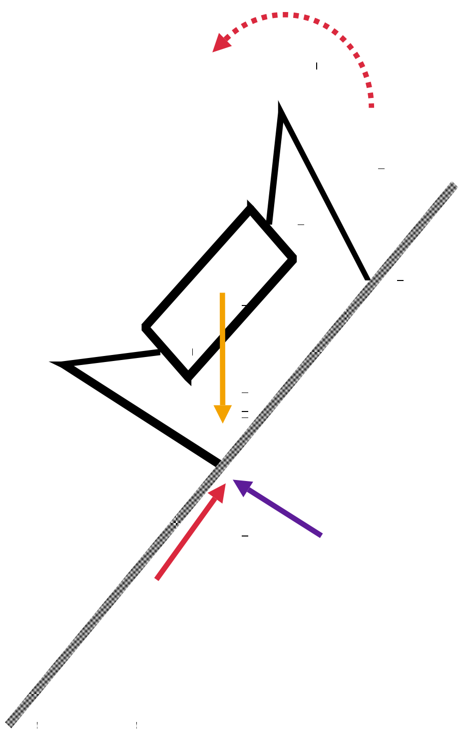
turning drive
(attached to inner frame)
mid-frame
sector gear
(attached to mid-frame)
inner frame
leg
outer frame
(left leg tower)
outer frame
(right leg tower)
bearing rail (2)
translation drive
(attached to mid-frame)
bearing pads (2/rail)
outer frame
rack gear
outer frame
towers translate
relative to
mid-frame
translation drive-shaft
inner frame/mid-frame
rotary bearing


Abrasion resistant jacket
26 AWG unshielded twisted pair (x5)
18 AWG power conductor (3)
26 AWG co-axial conductor
Kevlar fibers
1.1 cm diameter

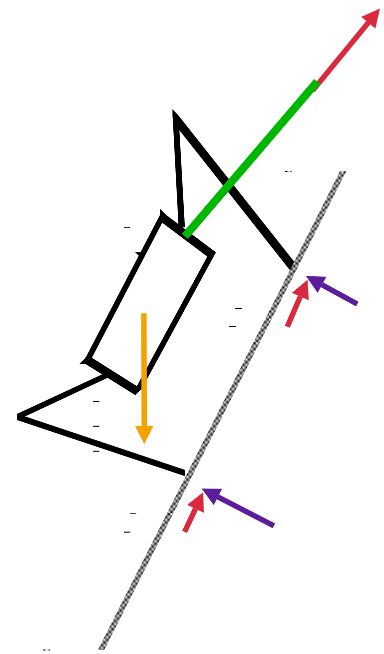

Slip ring
Winch drum
Drive motor
Tether
Potentiometer
Tether
range
Fairlead
Pinch
rollers
Turn pulley
Exit Cone


Chain drive
Gear box
Levelwind
Tether
range
Levelwind
motion
Exit Cone

Rappelling Concept

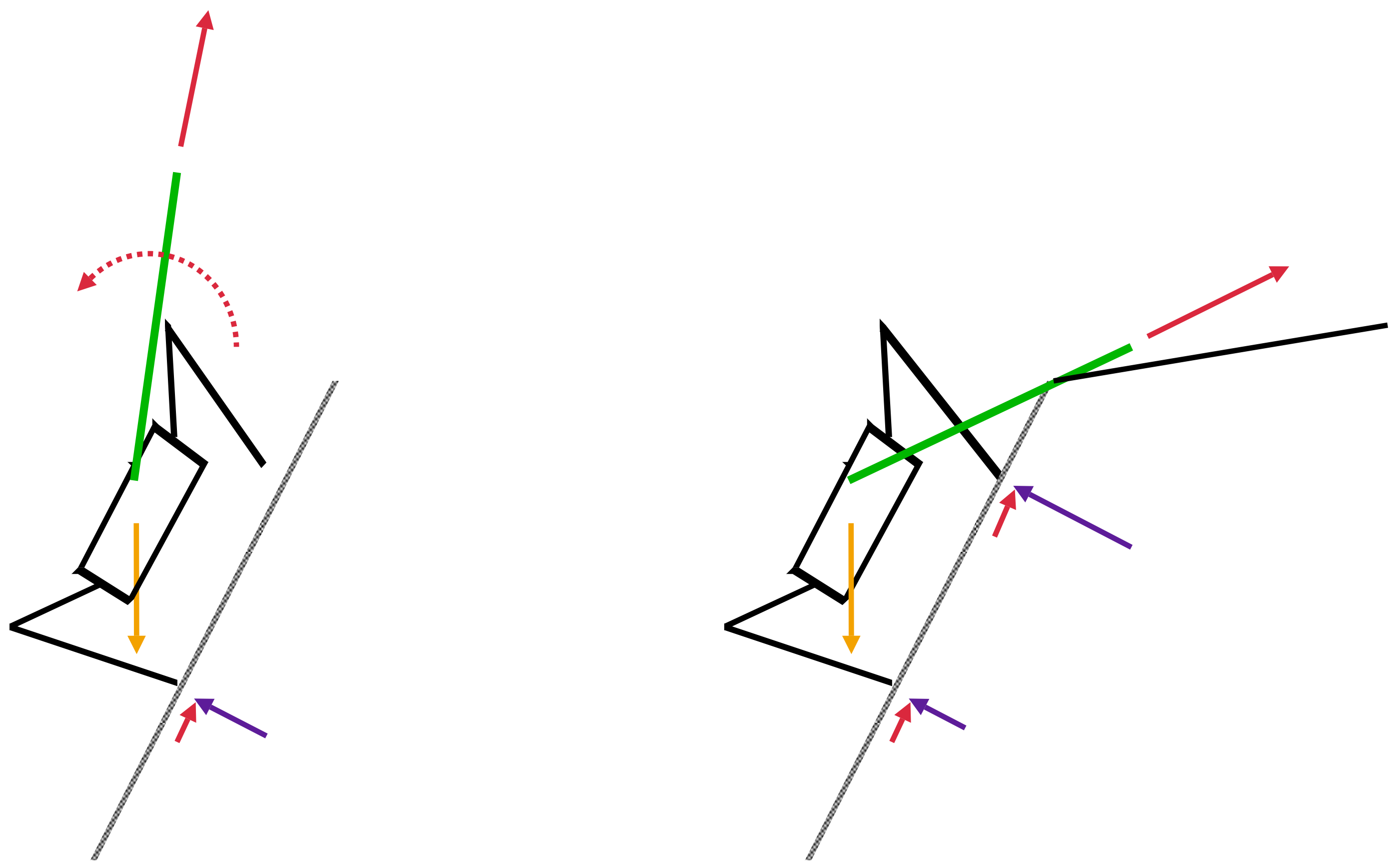


Large downhill leg shearing & normal forces



Tether tension adjusted to eliminate shear forces, distribute normal forces

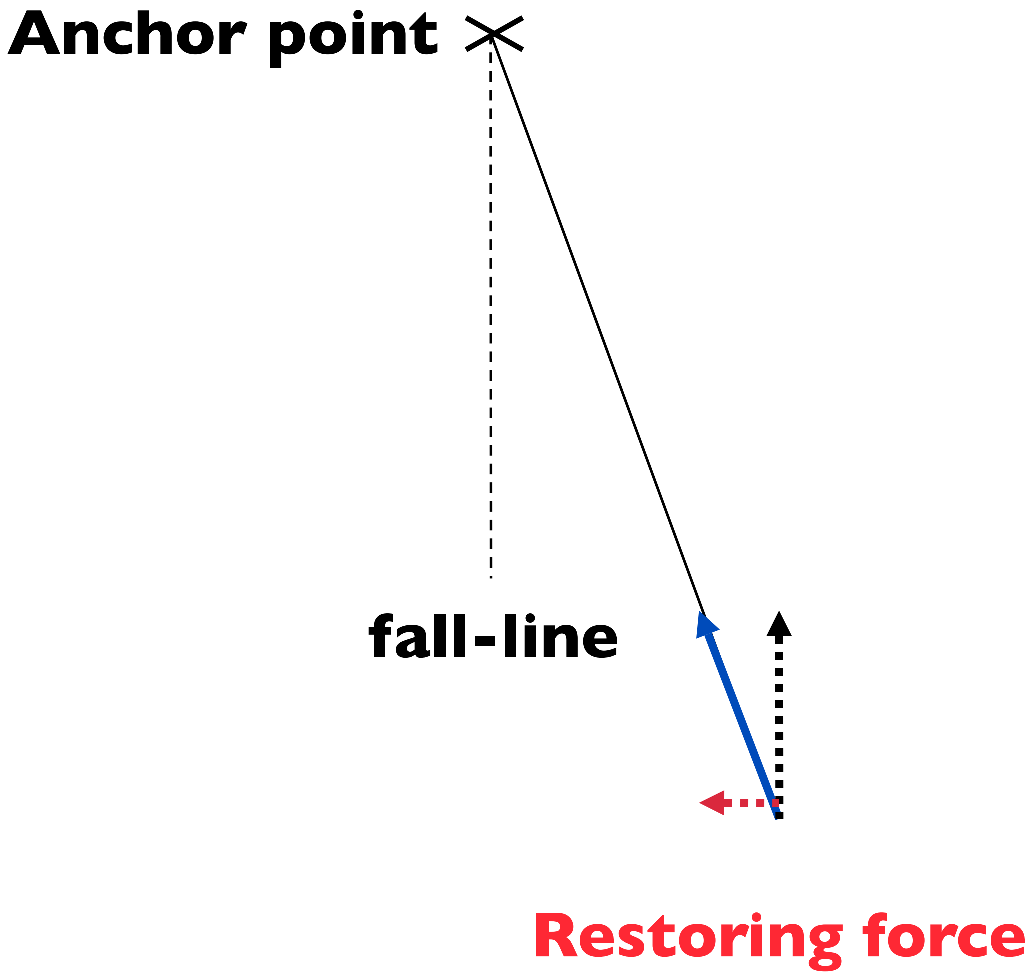
Rappelling Limitations

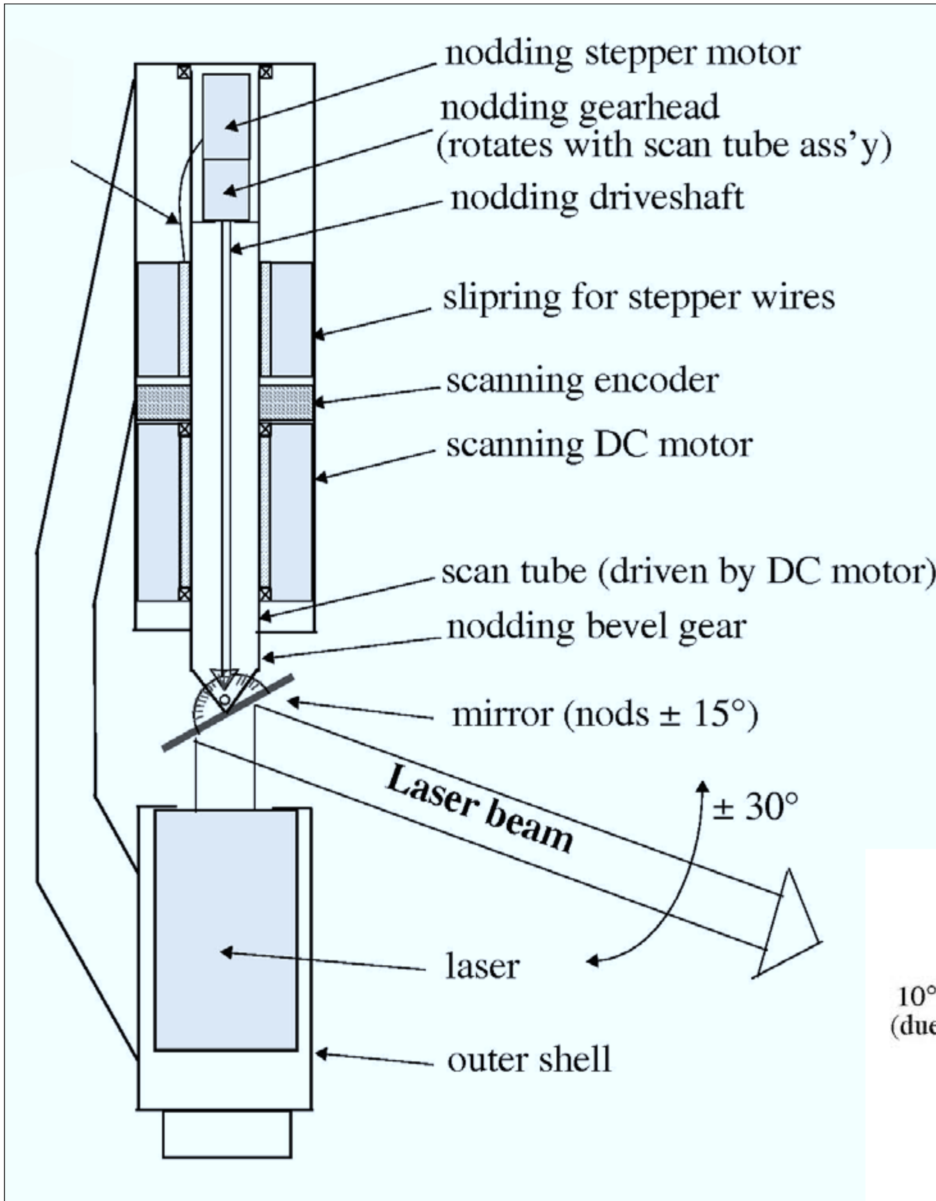


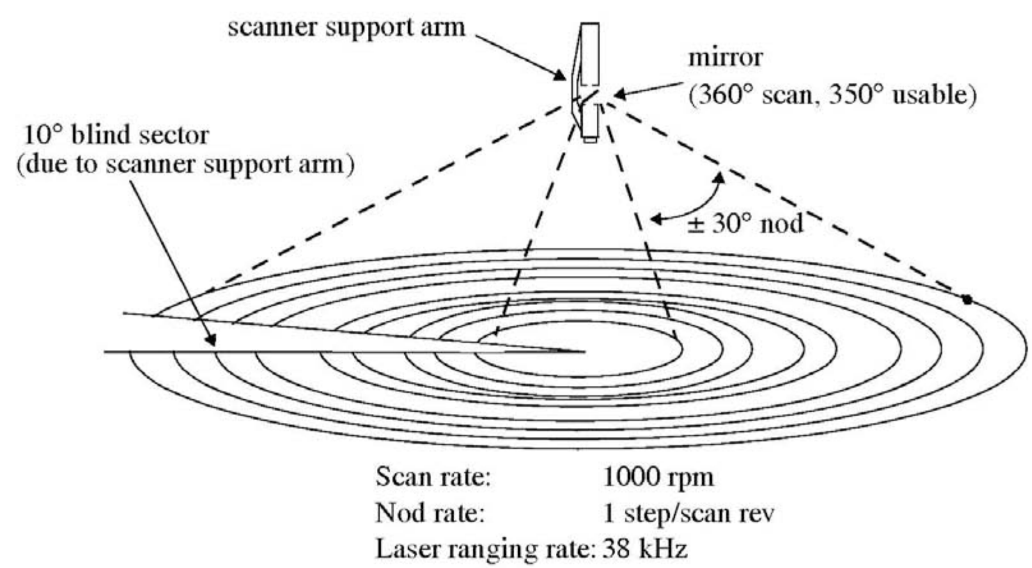
Upwards tether pull tends to destabilize

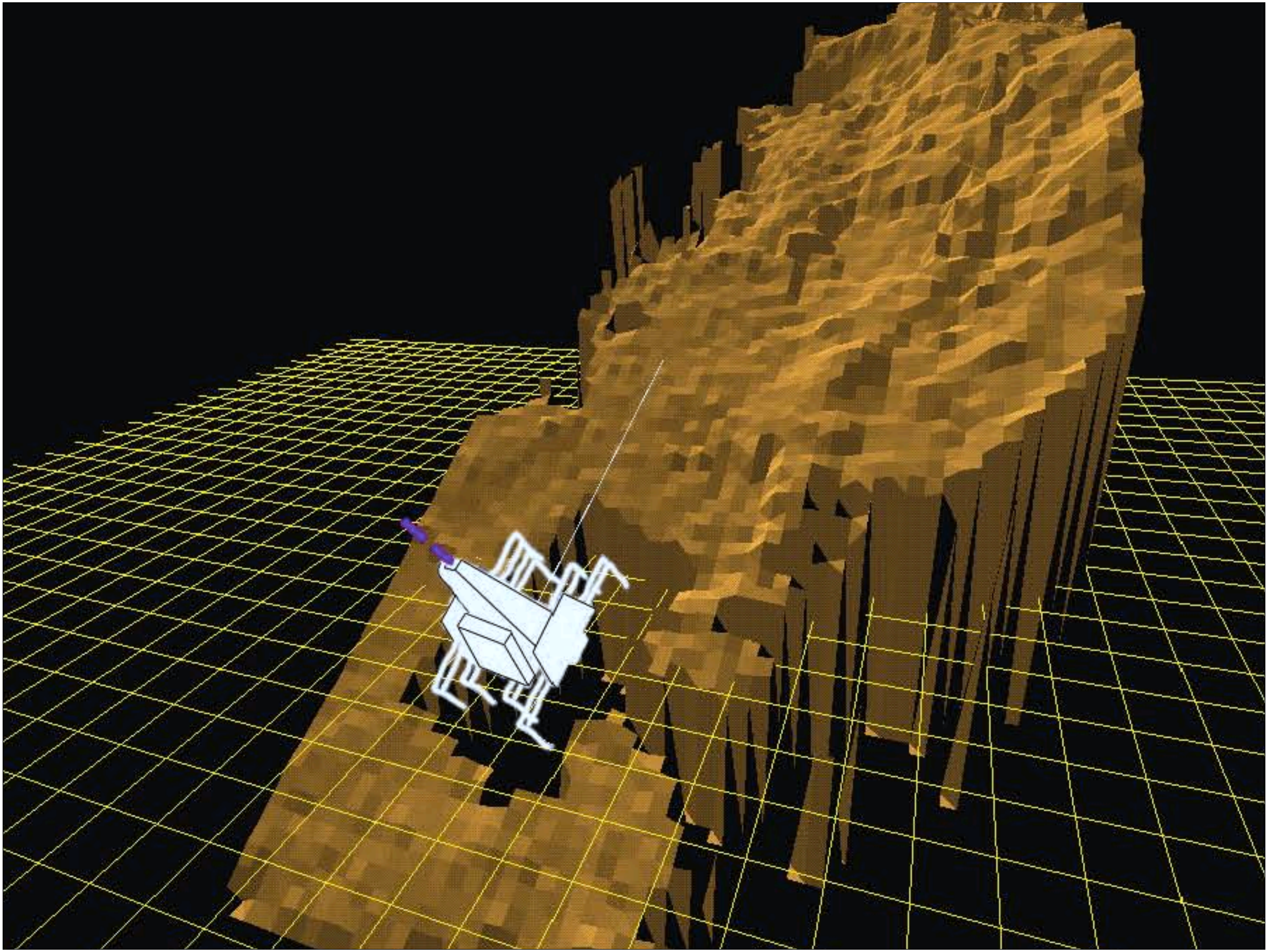
Downward tether pull increases uphill leg loading

Rappelling Limitations

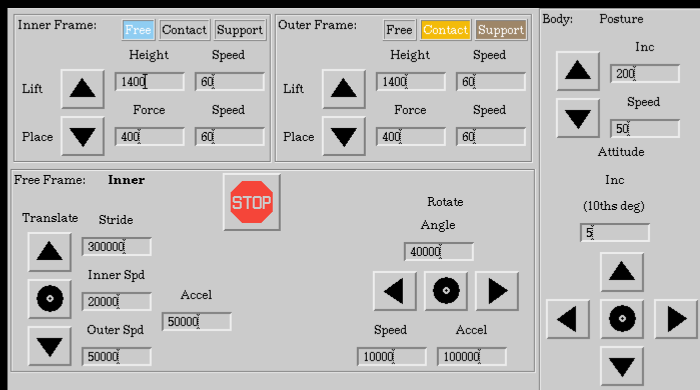


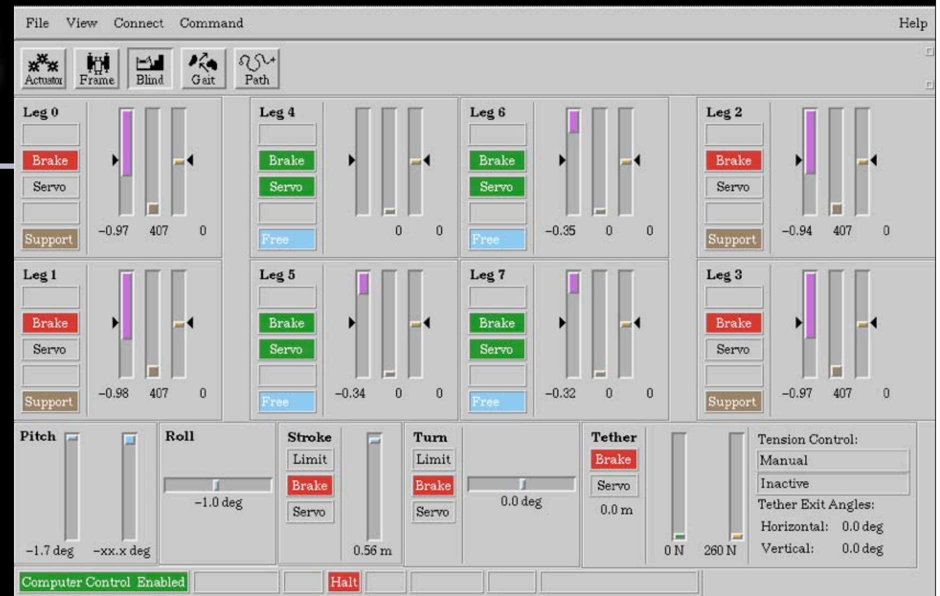

nodding stepper motor
nodding gearhead
(rotates with scan tube ass'y)
nodding driveshaft
slipring for stepper wires
scanning encoder
scanning DC motor
scan tube (driven by DC motor)
nodding bevel gear
mirror (nods ± 15°)
Laser beam
± 30°
laser
outer shell


scanner support arm
mirror
(360° scan, 350° usable)
10° blind sector
(due to scanner support arm)
± 30° nod
Scan rate: 1000 rpm
Nod rate: 1 step/scan rev
Laser ranging rate: 38 kHz

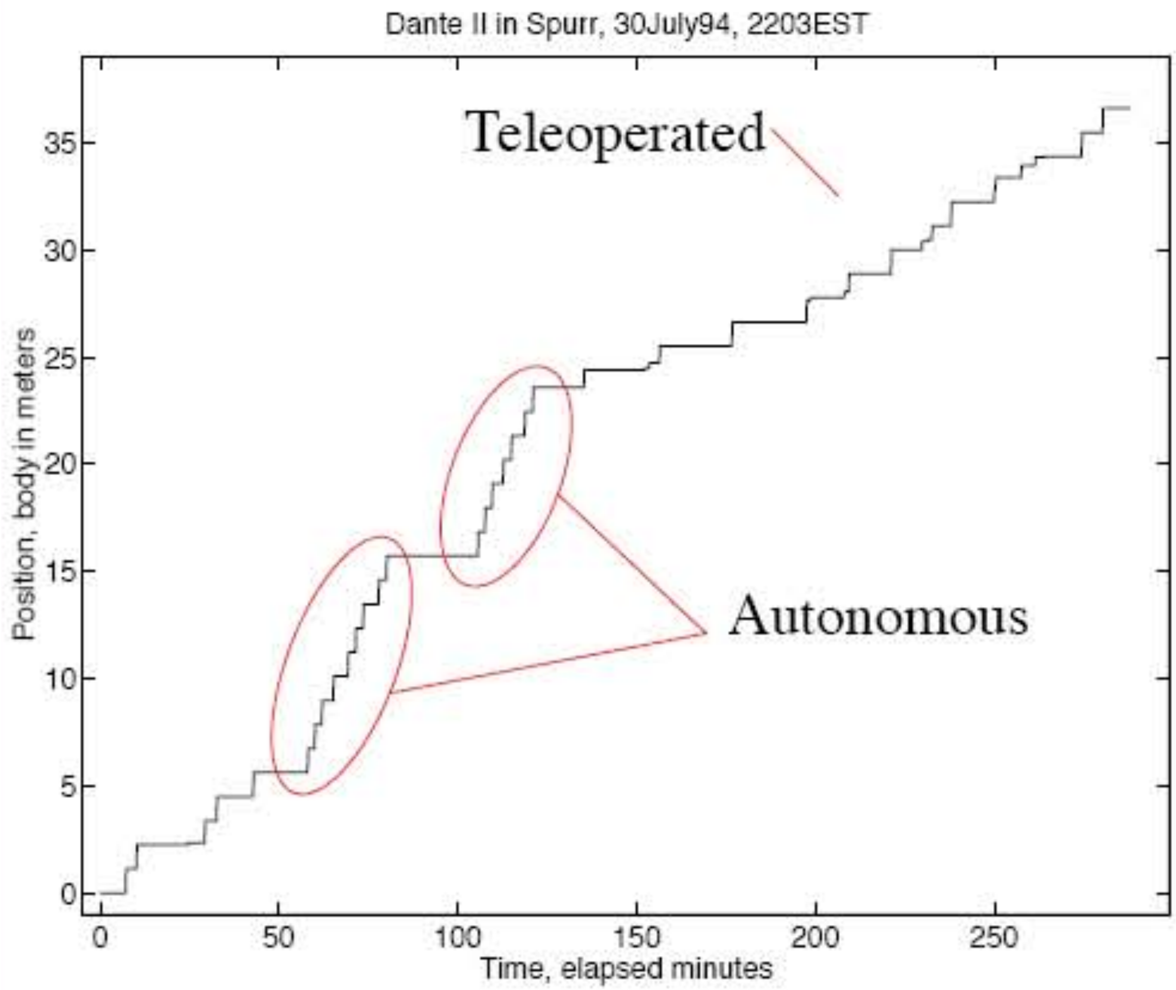


Operational Contexts



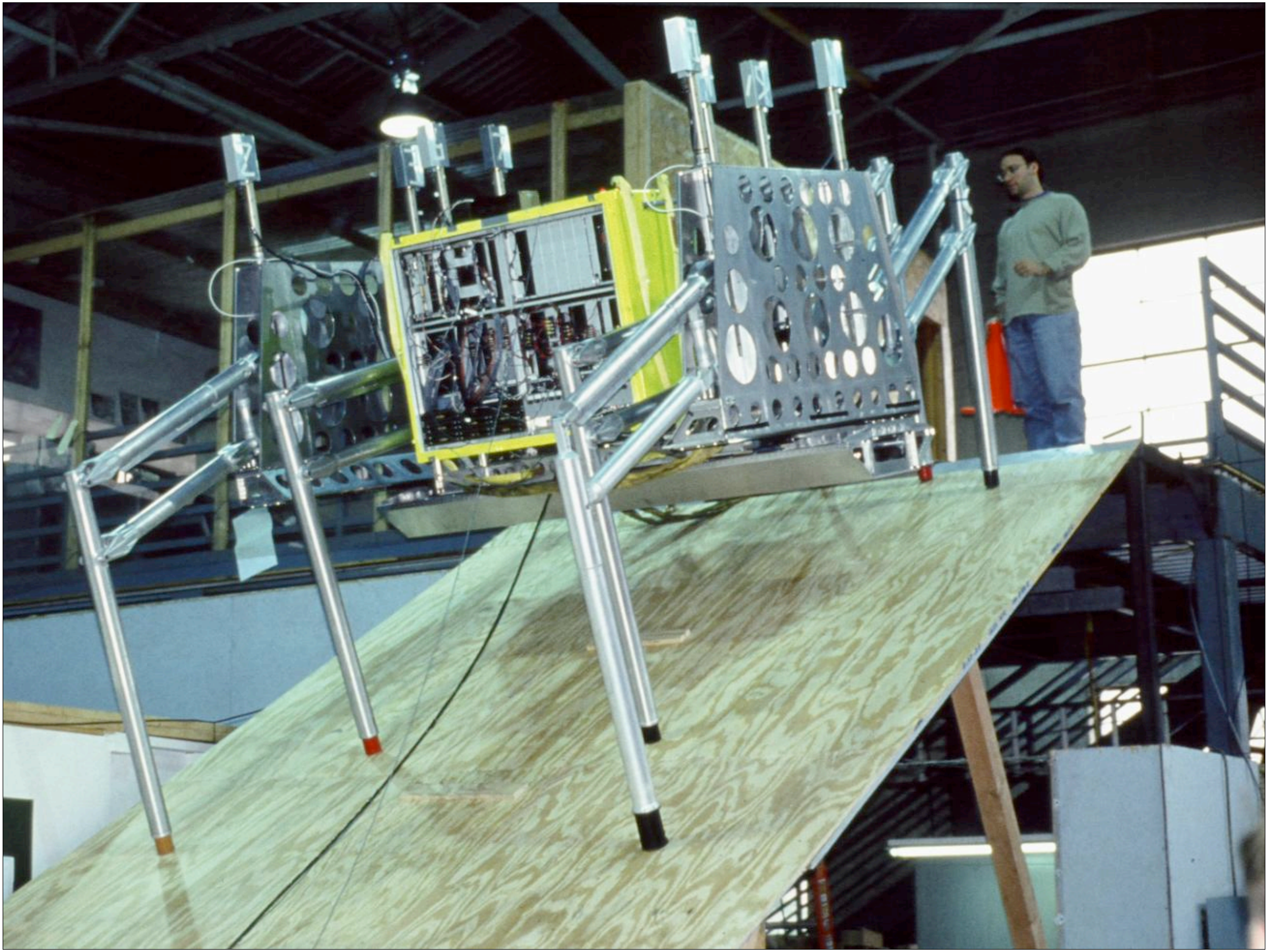


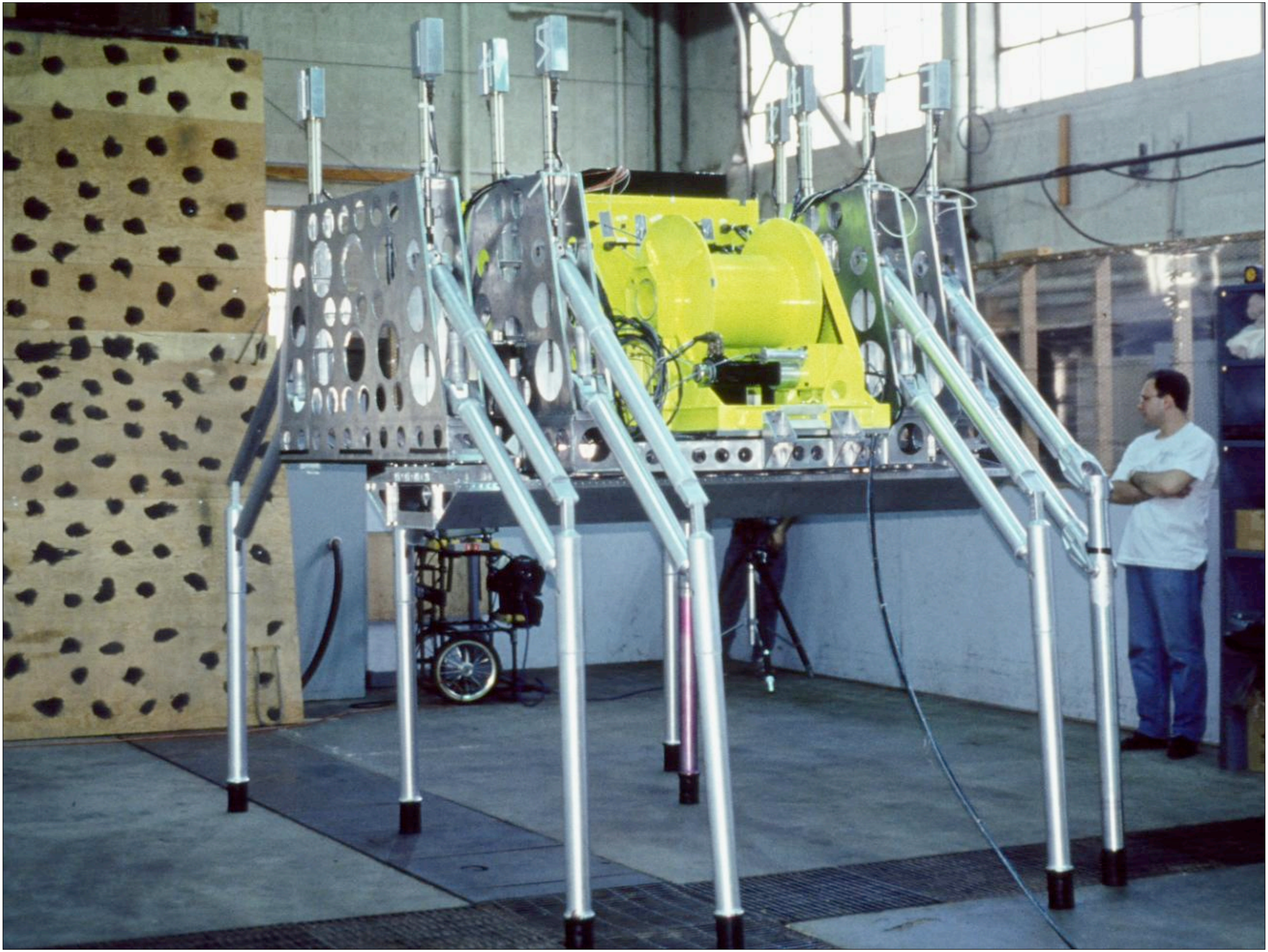
Control Function	Indiv. Actuator Context	Frame Context	Behavior Context	Gait Context	Path Context
Servo tether					
Coordinate leg motions					
Maintain body height					
Maintain posture					
Adjust leg step					
Surmount obstacles					
Perceive terrain					
Determine step height					
Determine body height		**Operator Control**		**Automatic Control**	
Determine posture					
Determine stride					
Correct leg placement					
Generate path					
Determine heading					
Avoid obstacles					



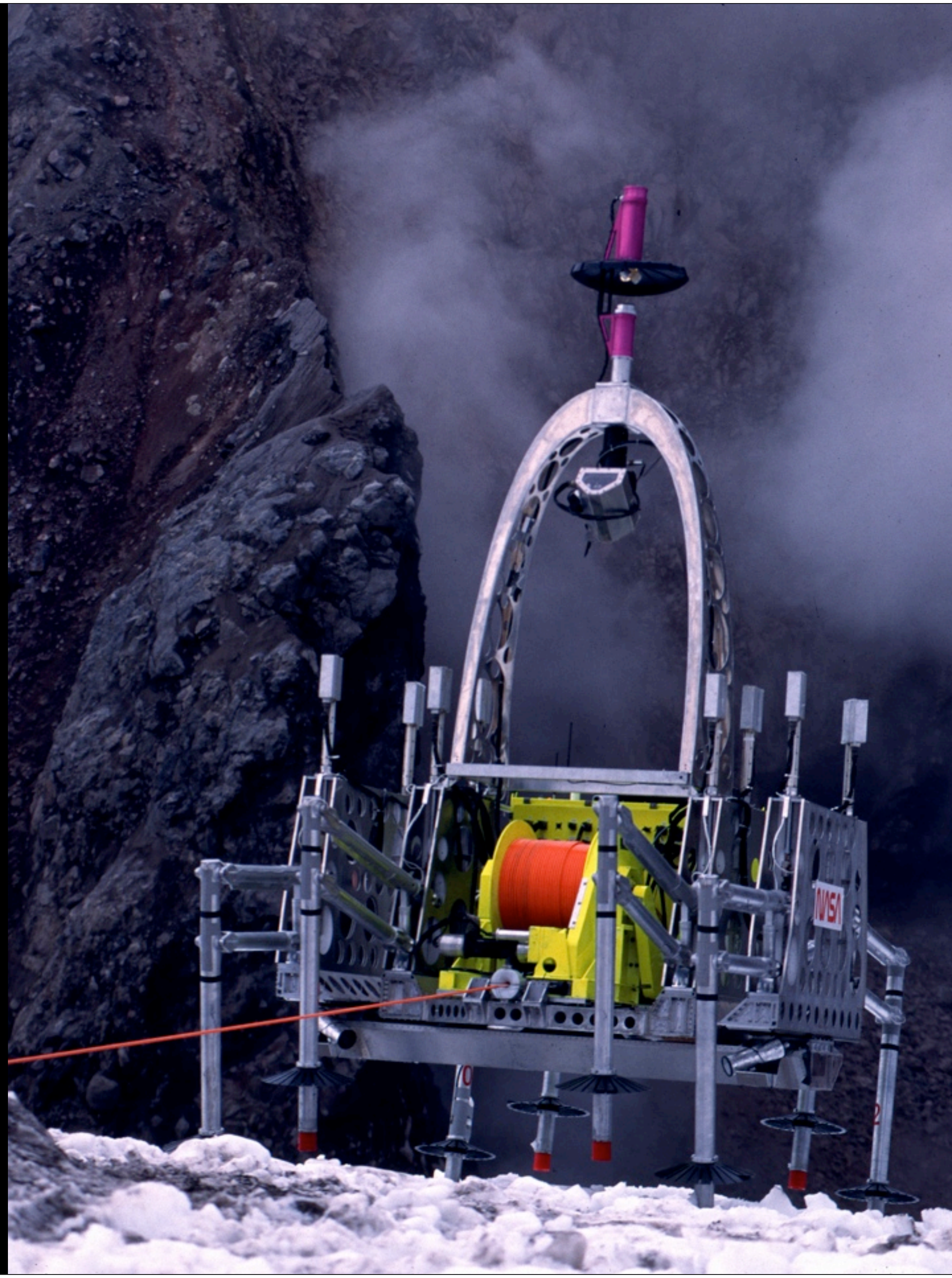
Descending in Mount Spurr

Autonomous: 0.49m/min, Teleop: 0.22m/min

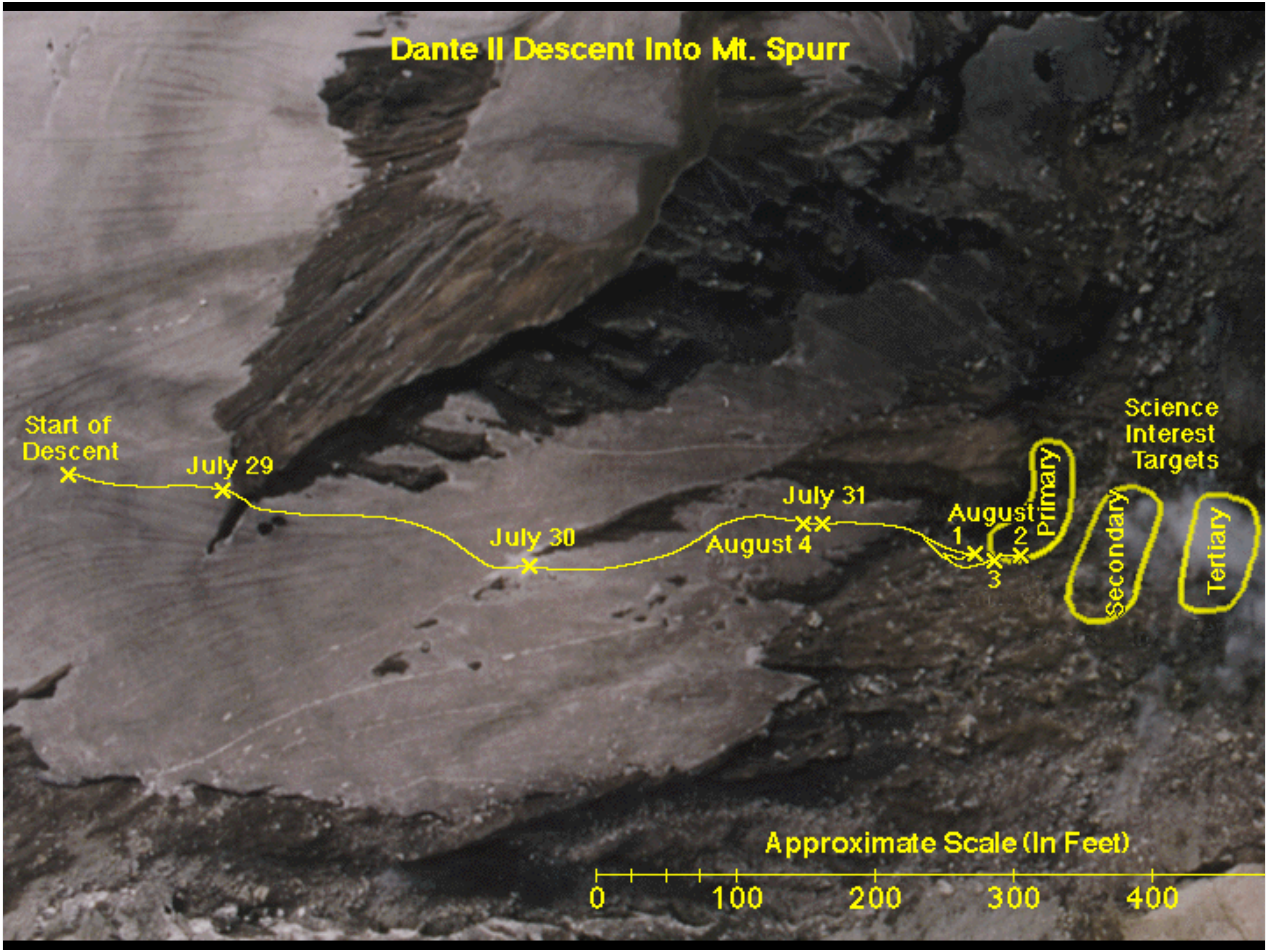





UNITED STATES ARMY




Generator
Dante II
Rim Station
Satellite Dish
Rim Camera
Descent
Route
CRATER PEAK (looking east)



Dante II Descent Into Mt. Spurr
Start of Descent
July 29
July 30
July 31
August 4
August
1
2
3
Primary
Secondary
Tertiary
Science Interest Targets
Approximate Scale (In Feet)
0
100
200
300
400

Mount Spurr Stats

Distance travelled	276m
Number of steps	2900
Number of laser scans	70
Average and steepest slope	32, 40 deg
Cross slope range	20-35 deg
Days of unattended operation	5
Typical power draw (robot and rim equip)	2 kW
Satellite bandwidth (robot to ctrl station)	1 Mb/s
% Distance using behavioral control	15%
% Distance using teleop w/3D interface	75%

Results and Lessons

- Rappelling can work
- Anchoring limits maneuvering and imposes forces
- Constant oversight (teleoperation) is impractical
- Reflexes and behaviors enable autonomy
- Self-righting is systemic requirement
- Harsh field experiments drive program (80/20)


NASA

Specifications

Mass (w/o payload): 280 kg

Weight: 460 N ☽ 2750 N ⊕

Power (driving): 200 W (peak) ⊕

Power (posing): 380 W (peak) ⊕

Power (idle): 78 W

Speed: 5.0 cm/s (6.0 cm/s max)

Height (with drill tower): 2.2 m high stance, 1.6 m low stance

Width (wheelbase): 1.4 m

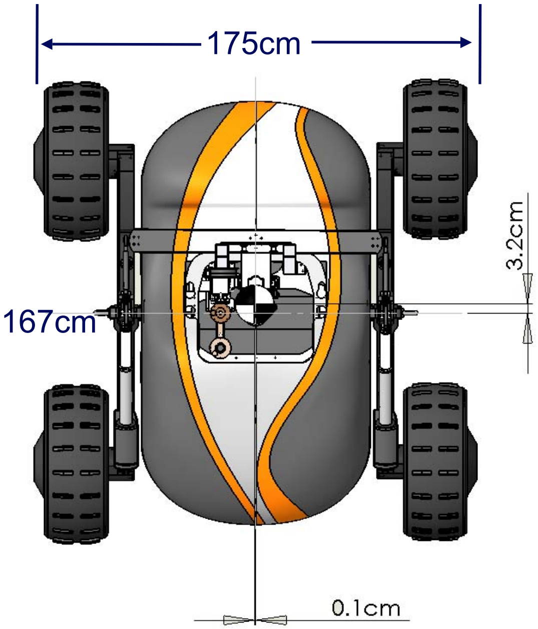
Length (wheelbase): 0.8 - 1.4 m

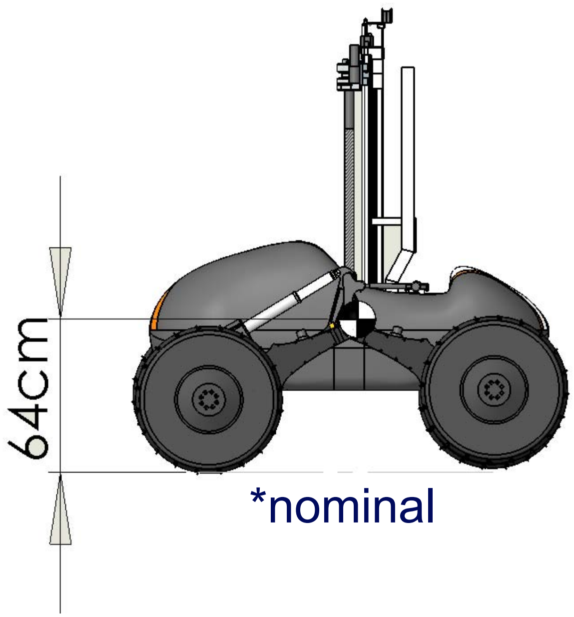
Aspect (track/wheelbase): 1:1 low, 1:1.2 nom, 1:1.7 high

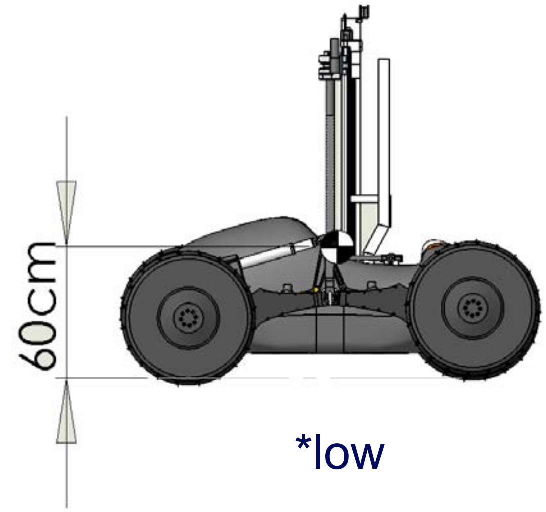
Wheel diameter: 60 cm

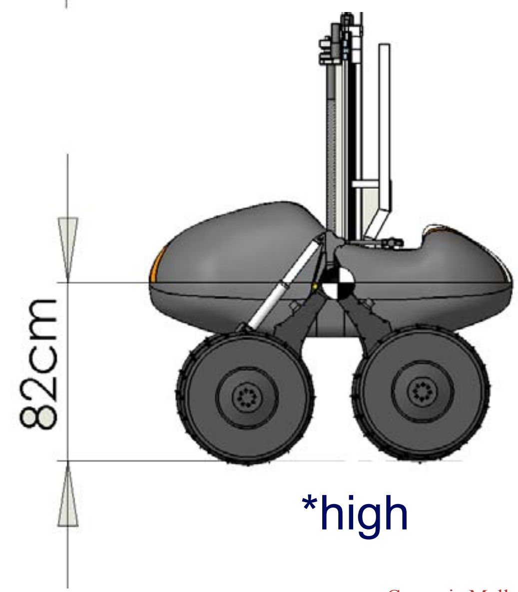
Straddle: 57 cm max, 0 cm min

Scarab Dimensions

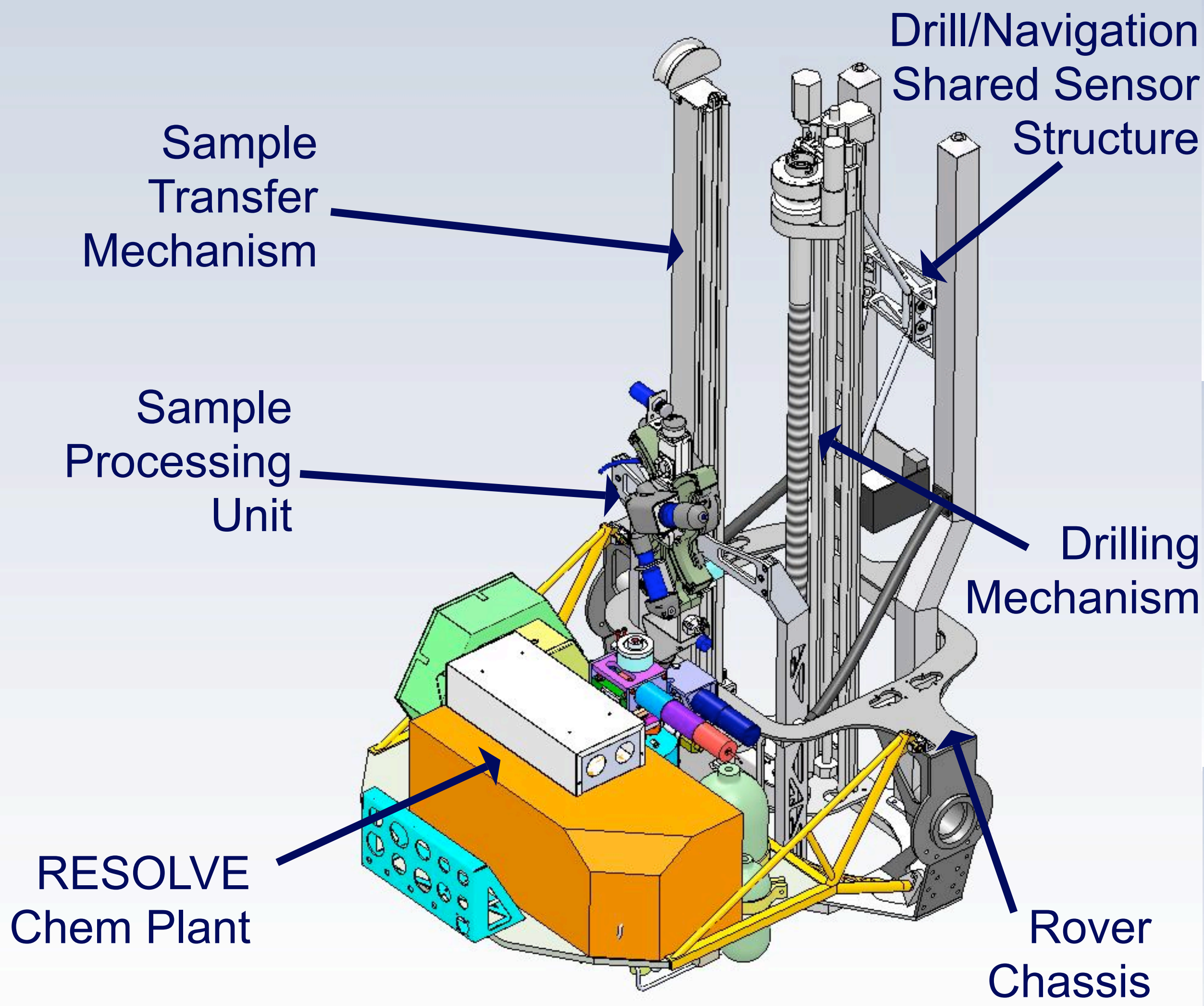


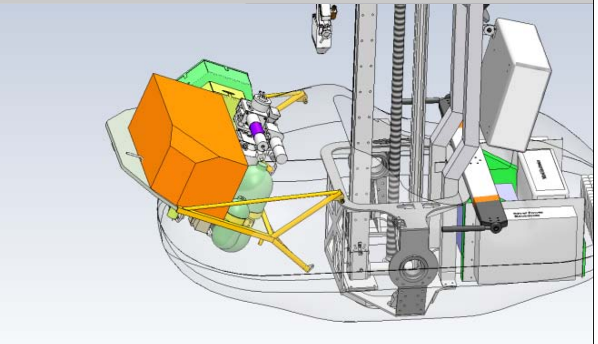




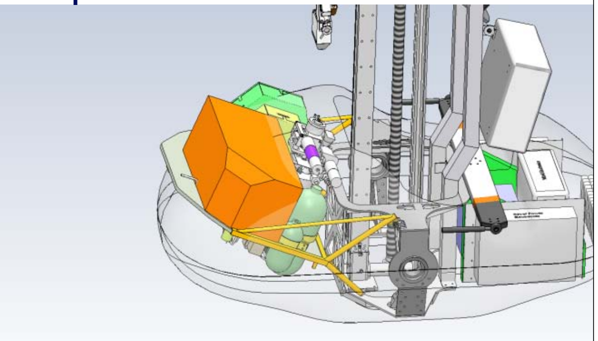


ISRU/RESOLVE Integration

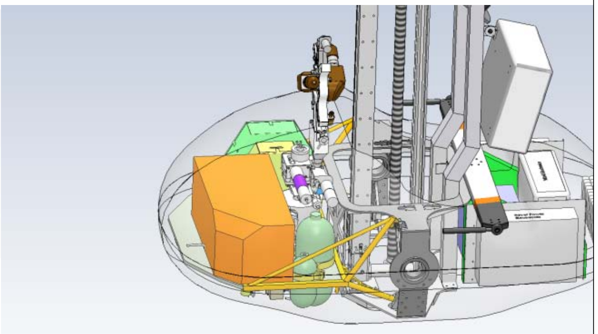




Drop In RESOLVE Chem Plant



Sinch Frame Bolts



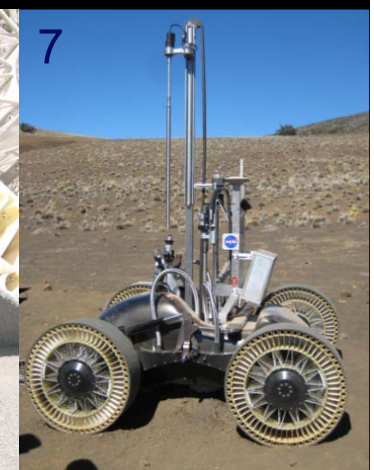
Install Sample Processing Unit

ISRU/RESOLVE Support

•Steep Slope Ascent, 20 ° ash
•Crater access for assay

•Utilize
LIDAR
•Traversability Analysis

•Build 3D Maps
•25 drill sites x 1km distribution



•Remote Operations (PTOC) and Control of Scarab

•Deployment achieved by lowering chassis to ground

•Low risk drilling operations for rover and drilling system

Scarab Objectives

Mobility

- Achieve mobility for lunar-crater analog terrain
- Evaluate the performance of lunar-relevant wheels

Navigation

- Exhibit dark navigation for polar scenarios

Scarab Experiment

Mobility

- Measure: Tractive capability
- Variable: Payload mass
  - Soil properties (size, cohesion)

Scarab Experiment

Mobility

Measure: Slope capability

Variable: Slope angle

Angle of ascent

Vehicle posture

Soil properties (size, cohesion)

Scarab Experiment

Navigation

Measure: Drill emplacement, precise positioning of drill on designated site

Variable: Distance traveled

Terrain complexity

Position accuracy

Scarab Experiment

Navigation

Measure: Long distance dark navigation

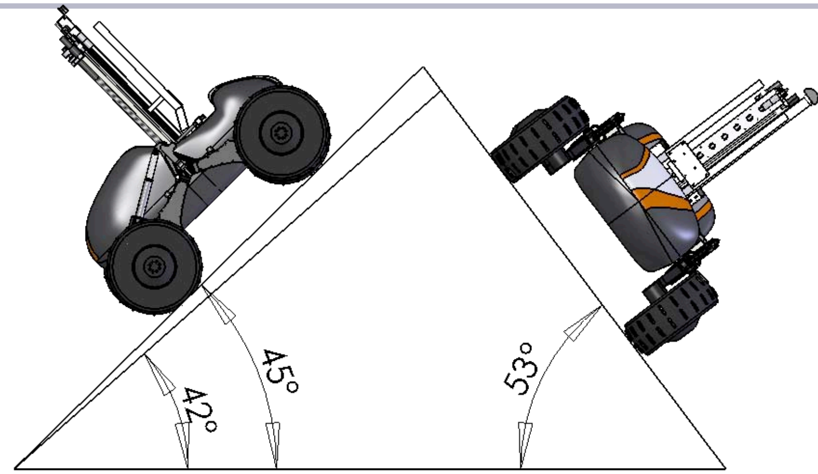
Variable: Distance travel

Terrain complexity

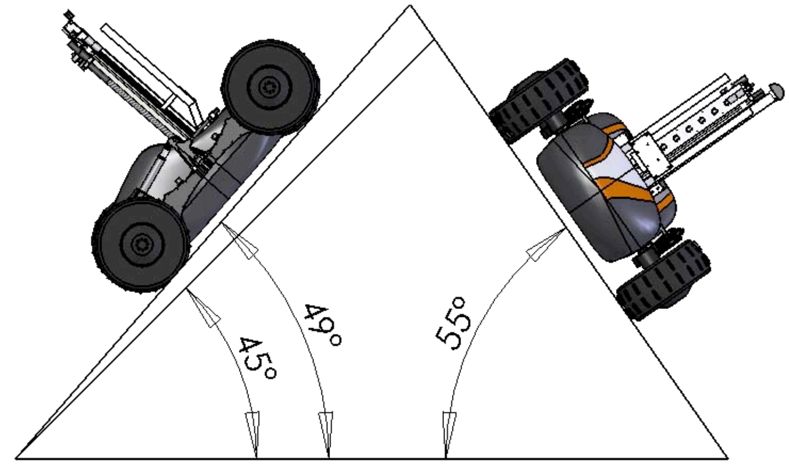
Fault modes

Terrain model fidelity

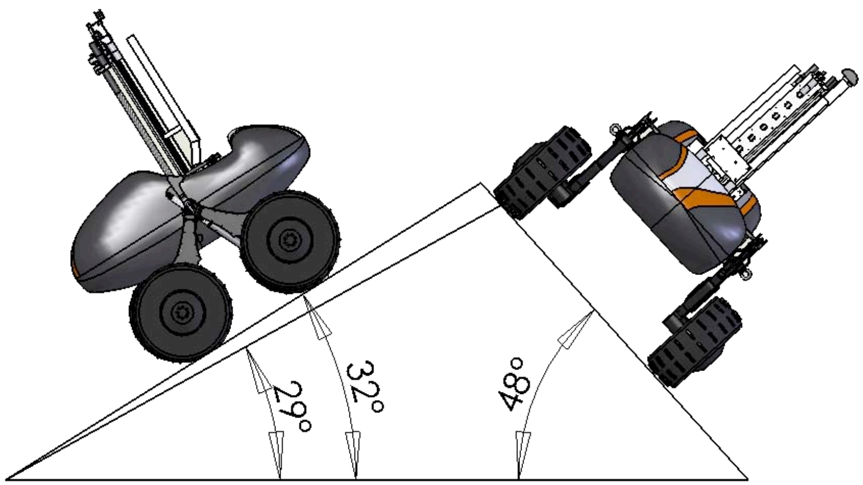
Static Tip-Over Angles



*nominal



*low



*high

(values from tilt-table testing)

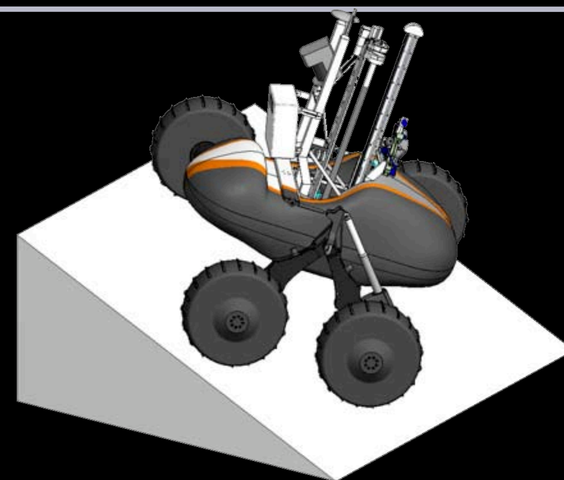
Mobility - Steep Slope Ascent

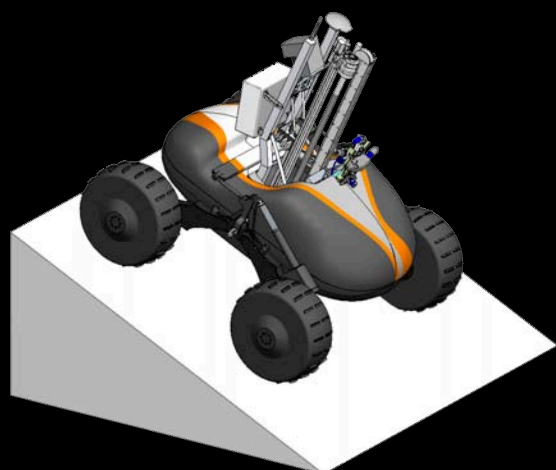
Active Body Roll

•Ascend at ~25-45° angle of attack

•Better distributes pressure amongst wheels

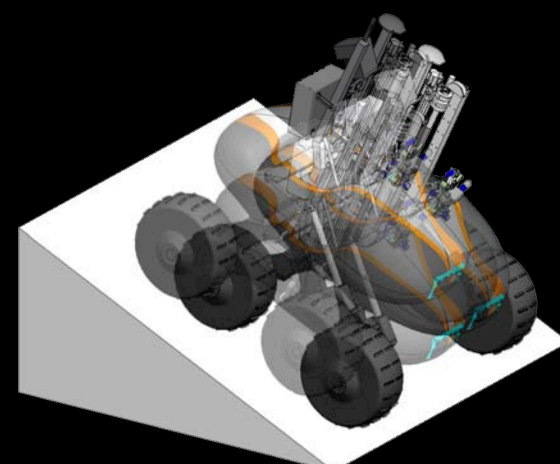
•Can eliminate effect of slope





Conventional Ascent

•Ascend straight up (or angled)



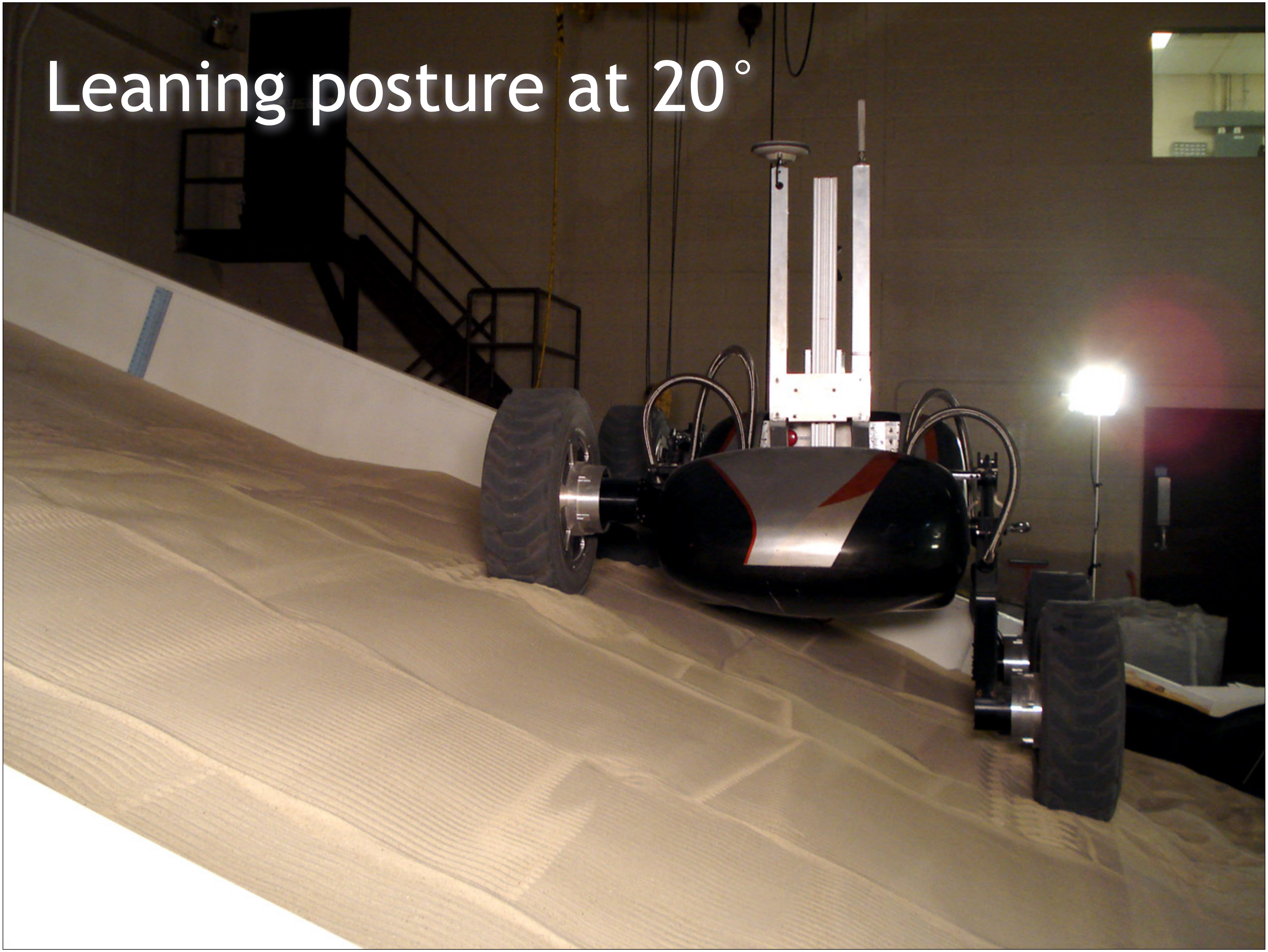
Inchworming

•Peristaltic motion utilized to reduce soil motion resistance

•Resistance eliminated in 2 of 4 wheels leads to net traction increase

•Cyclic raising/lowering, increase/decrease of wheelbase results in motion

Leaning posture at 20°



Cross-slope paths at 20°

Level posture

Leaning posture

Test Procedure

Measurement Equipment

Surveying Total Station

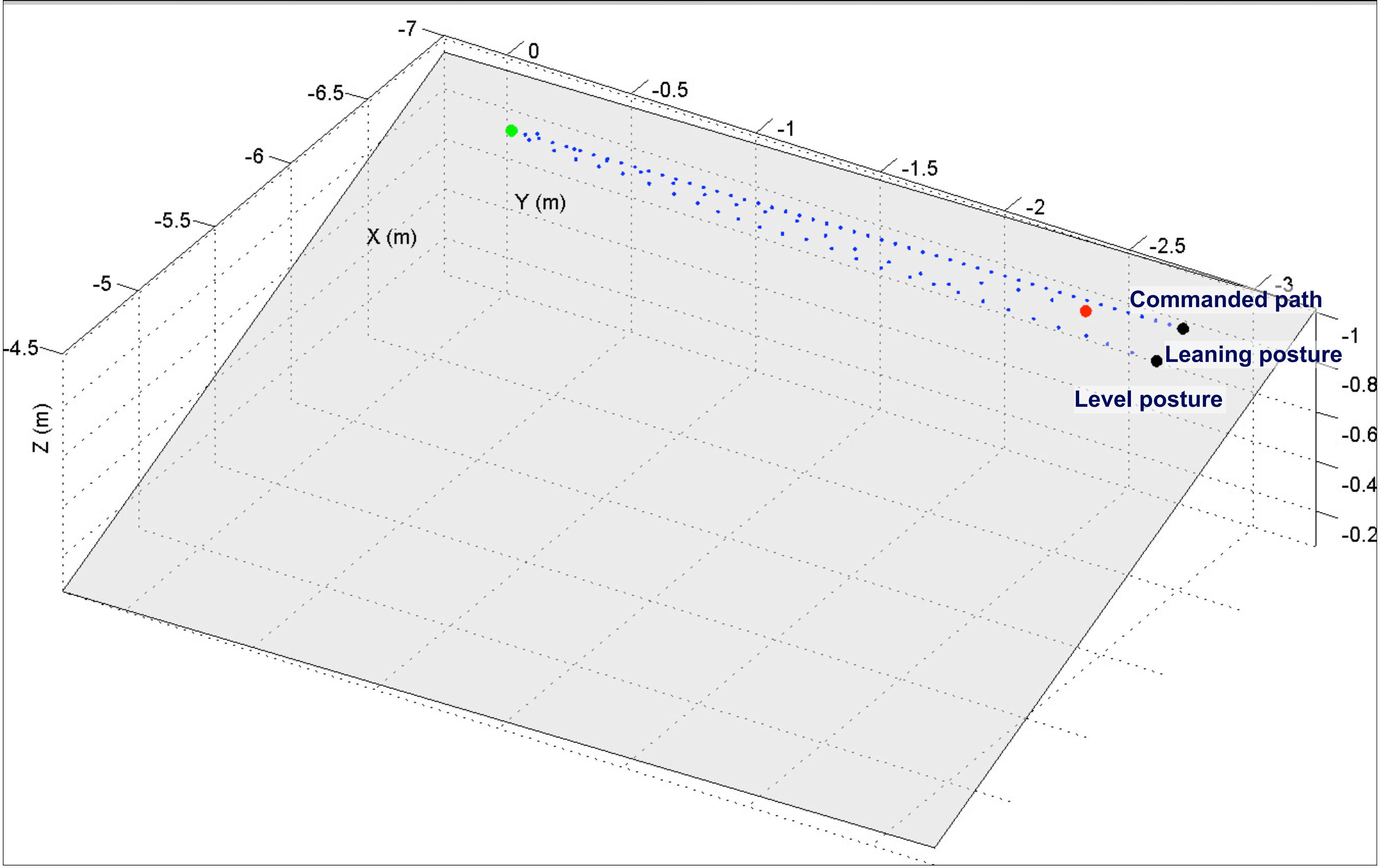
- Tracks rover mounted prism for x-y-z location and slip measurement

Site Parameters

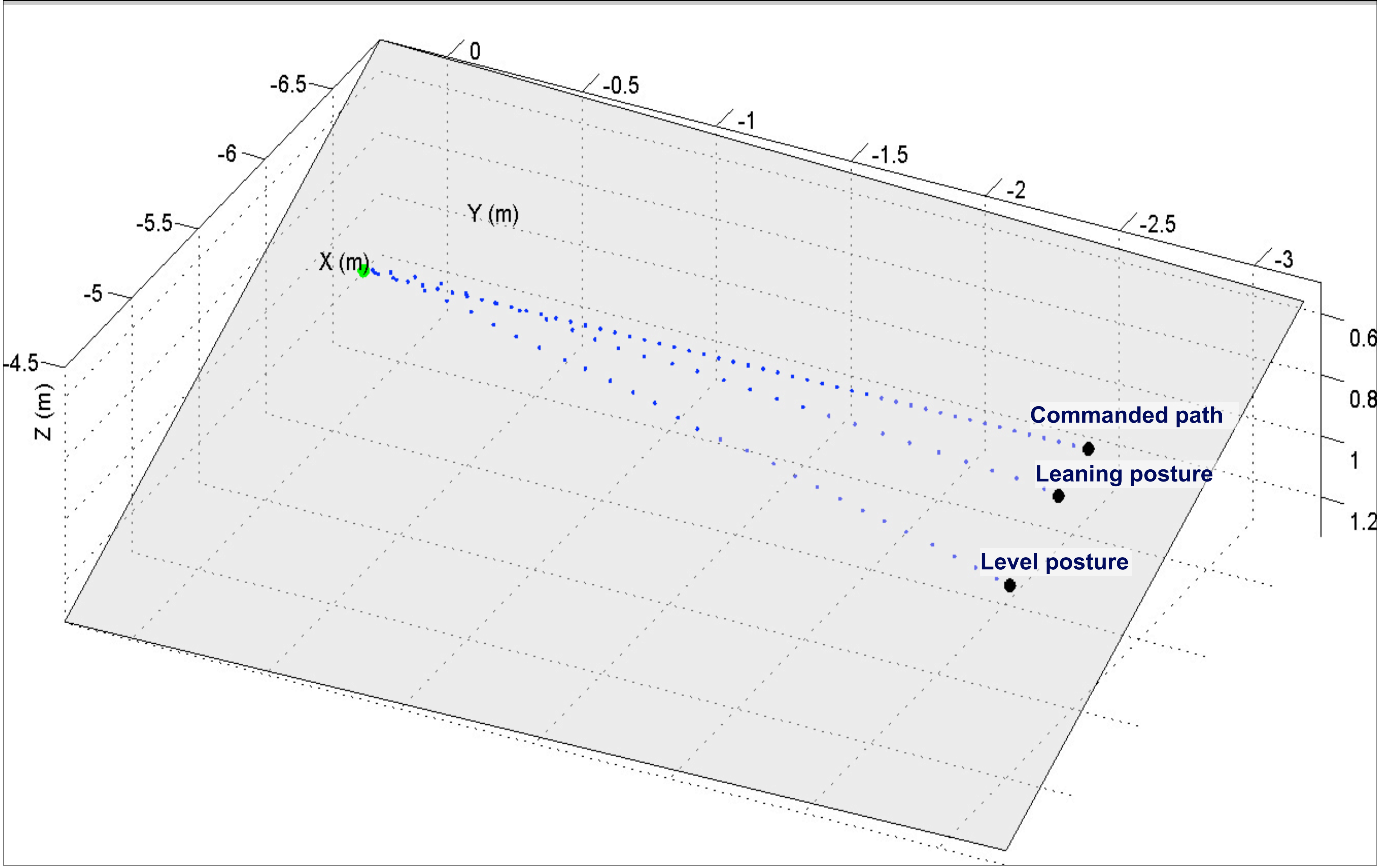
Soil Samples → characterize mechanical properties

Slope measurement

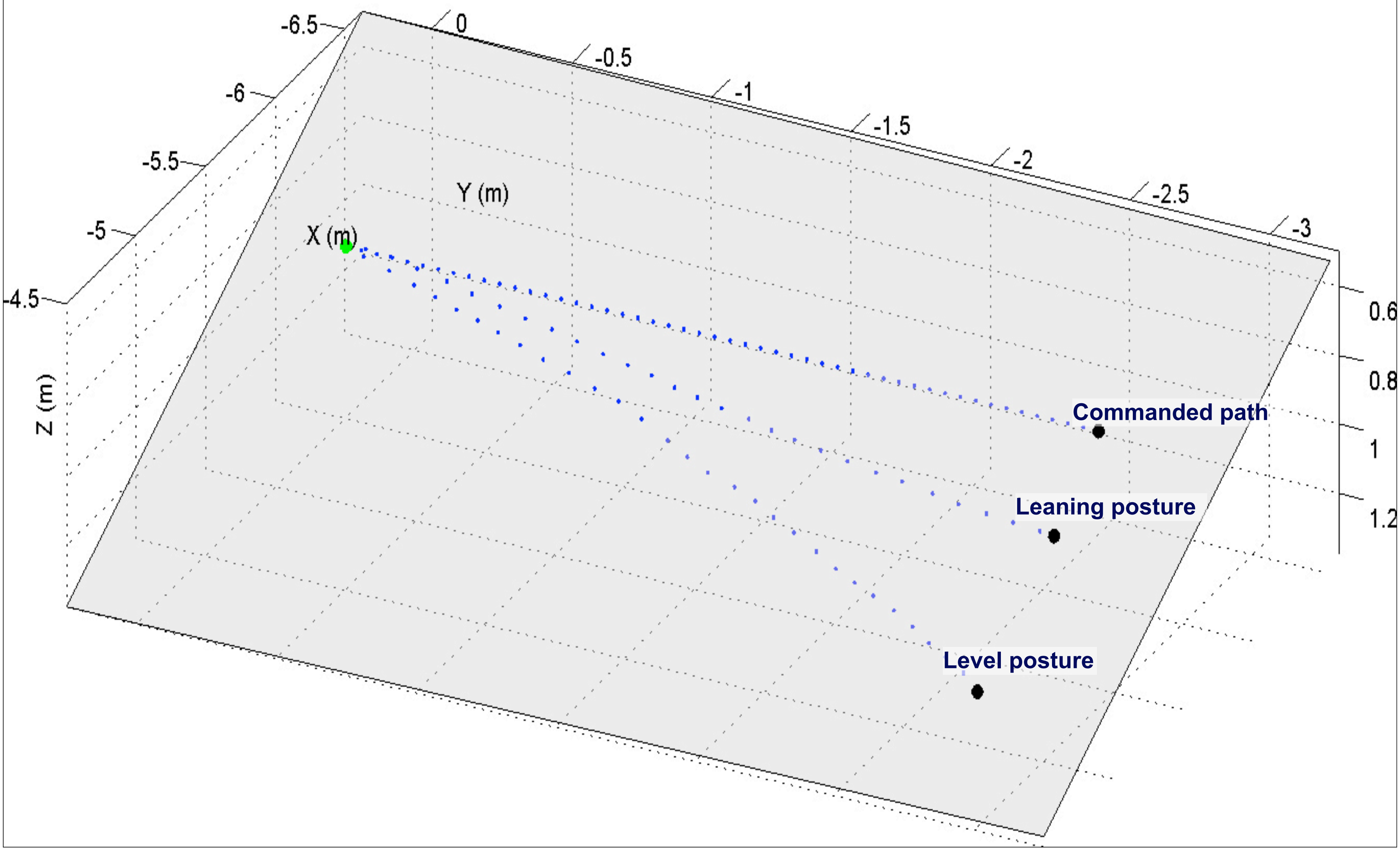
Tilt-Bed at 10˚ Slope



Tilt-Bed at 15˚ Slope



Tilt-Bed at 20˚ Slope



Slope-Bed Results

- 2.75 m straight cross- slope traverse commanded
- Downhill slip recorded as percentage of horizontal distance attempted
- Leaning into slope significantly reduces downhill slip

Downhill Slip

Slope Angle	Level Posture	Leaning Posture	Slip Difference
10°	6%	2%	-4%
15°	22%	8%	-14%
20°	37%	15%	-22%

Mobility - Slope Ascent

Testing Multiple Techniques

- Direct uphill ascent
- Center of mass shifting and varying angle of ascent
- Inchworming

Nine Site Categories

- Varying slope angle and soil strength

Heavy Payload mobility

Mobility - Steep Slope Ascent

Measured Slip

Performance		Wheel		
Soil Strength	Slope Angle	Rubber	Lunar	Lunar with grouser
Low Strength, Loose Dry, Volcanic Ash	20˚	10	80	-
	20˚	30	70	37
Low Strength, Compacted Dry, Volcanic Ash	15˚	10	30	20
High Strength, Compacted rock field	7˚	18	18	-

*slip in commanded direction

Mobility - Steep Slope Ascent

Measured Power of Locomotion

Performance		Power* for Maneuver		
Soil Strength	Slope Angle	Direct	Active CoM Shift**	Inchworm
Low	10			-
	15			-
	20	165W	177W	-
Medium	10			-
	15	140W	130W	TBD
	20	170W	175W	TBD
Medium Strength, Heavy Payload	20	-		-
High	10		125W	-
	15			-
	20			-

***Locomotion power (48V Bus)**

****~25° angle of attack**

Mobility - Steep Slope Ascent

Slope climb ability with Active CoM (center of mass) Shifting
- 28°, medium strength soil, 18% Slip
- 20°, loose soil, 65% slip, 177W locomotion
- 20°, Fine Volcanic Ash, Climbing ability with Lunar Wheel
- Switch-back method to continuously ascend 20˚ demonstrated
- 25 - 30˚ Angle of attack for high slope angles

Slope climb ability with conventional unleveled posture
- 20°, medium strength soil, 45% slip, 170W
- Unable to ascend 20°, low strength soil

Average Power 130-170W, no significant differences

Inchworming climbing technique did not have as favorable results as active CoM shifting.

→Use Inchworming as secondary (alternative) if straight ascent required (33% less slip than conventional uphill ascent)


Dark Navigation

Dark Navigation

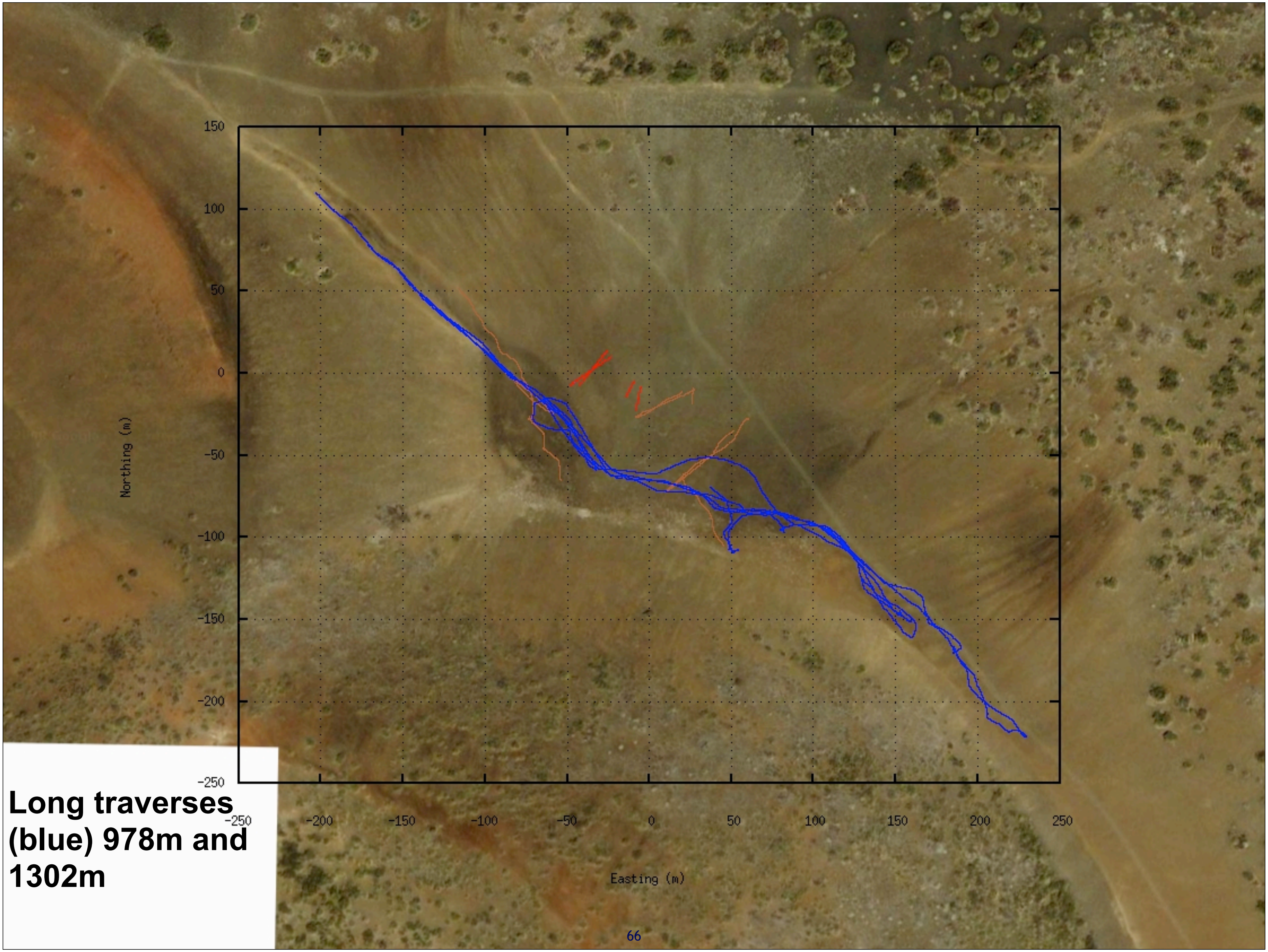
Polar craters require active sensing and navigation in total darkness

Goals

- Multiple 1km continuous autonomous traverses
- Rough terrain navigation
- Linear Velocity Camera test and demonstration

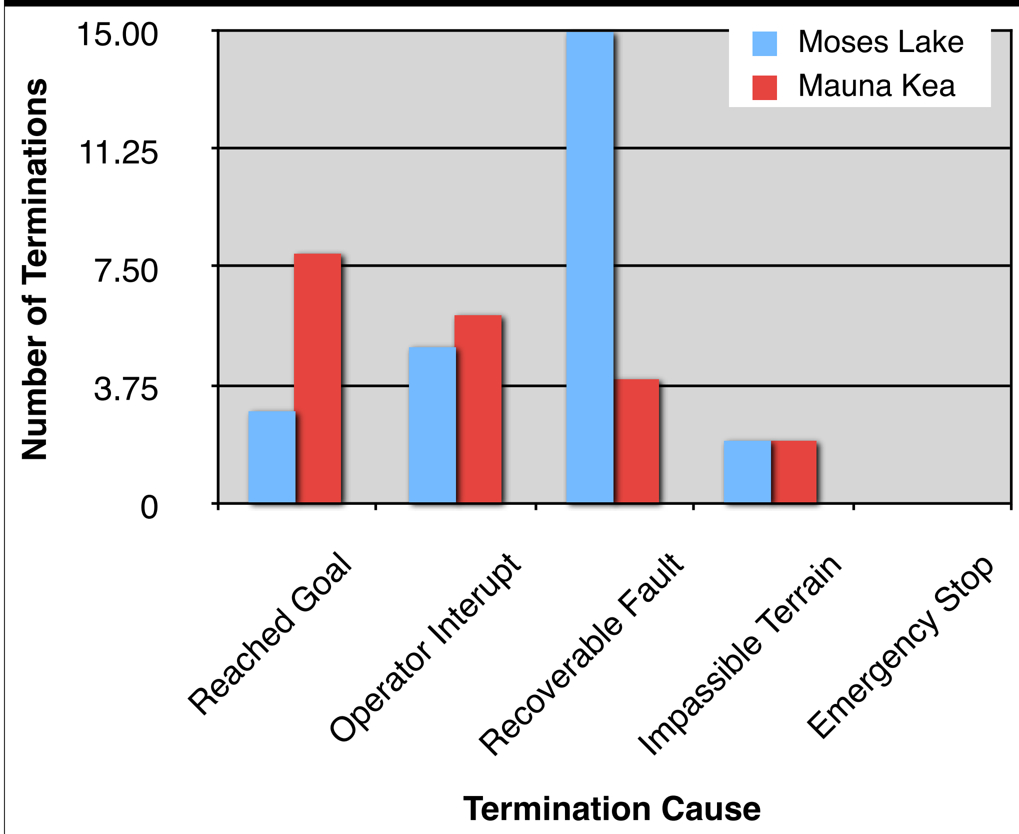
Methods

- Evaluative and Geometric Navigation Algorithms
- TriDAR Laser Scanner



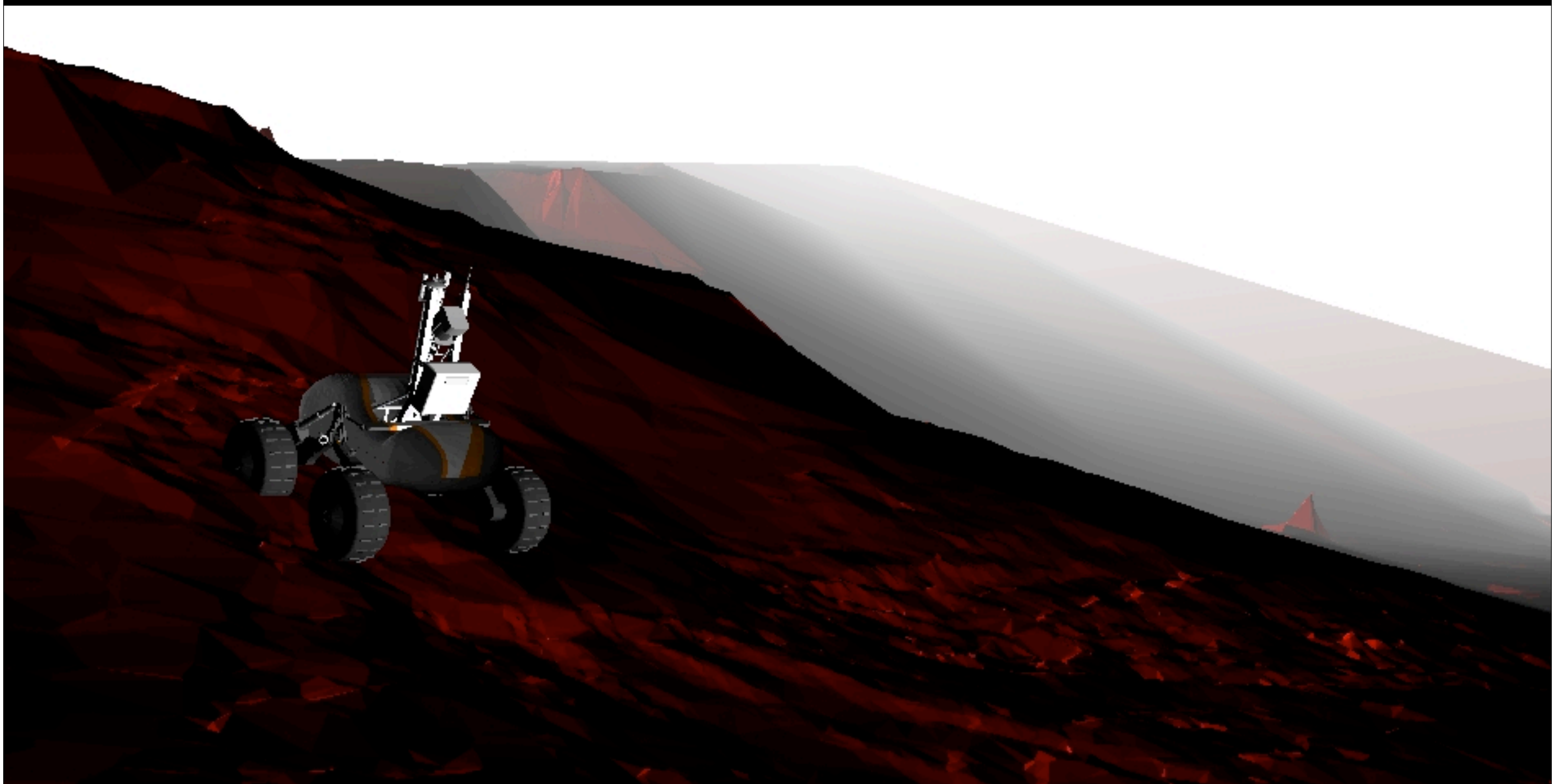
Long traverses (blue) 978m and 1302m

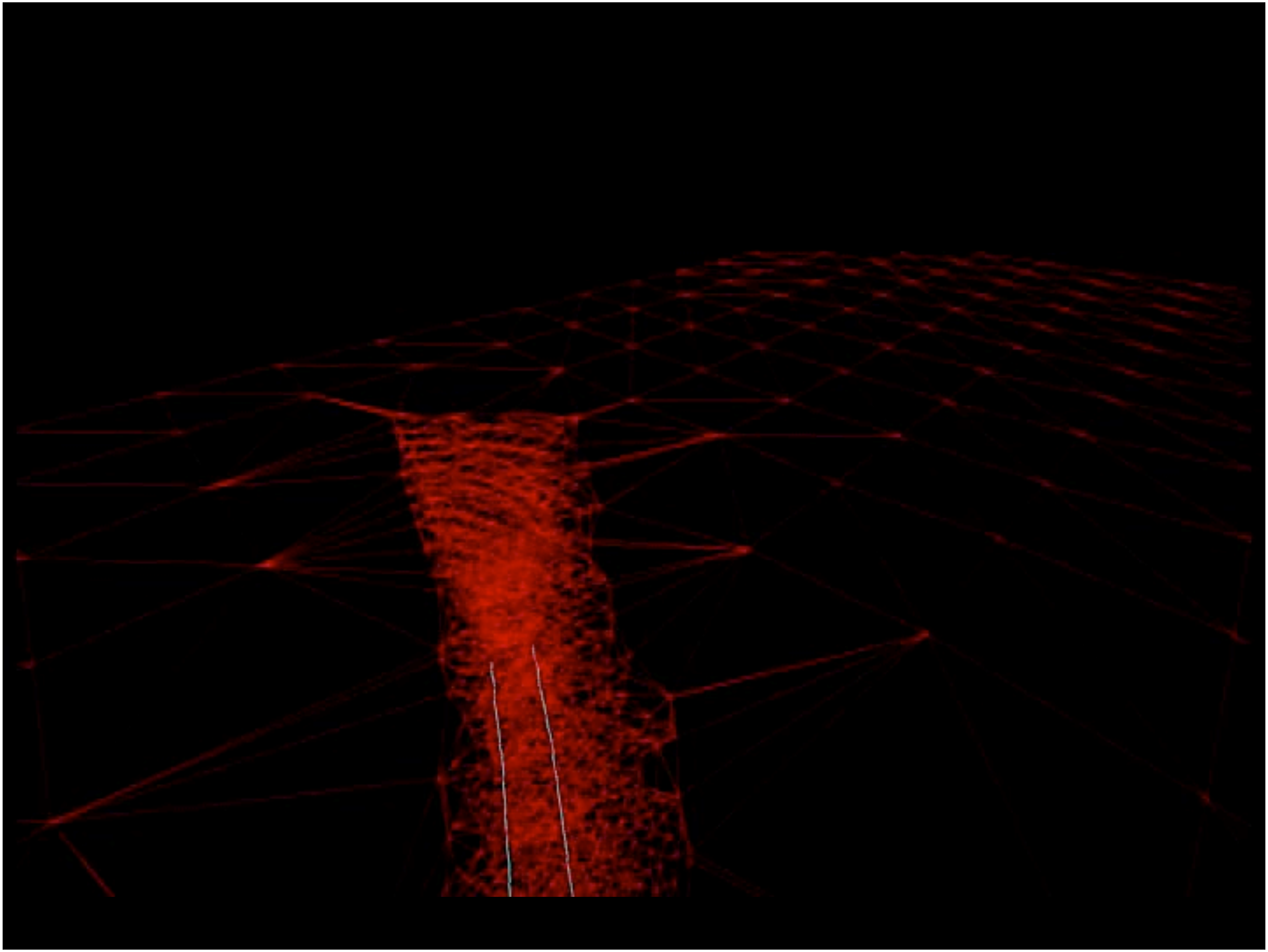
Dark Navigation Results



	Moses Lake	Mauna Kea
Reached Goal	**3**	**8**
Operator Interupt	**5**	**6**
Software Bug	6	3
Sensor Fault	5	0
Operator Error	2	0
Bus Fault	2	1
Recoverable Fault	**15**	**4**
Impassible Terrain	**2**	**2**
Emergency Stop	**0**	**0**
	25	20

Model of Crater Descent





Results and Lessons

- Posture control to enhance stability
- Significant slope performance without tether
- Modeling 3D terrain for navigation is feasible
- Planning ascent/descent currently difficult
- Slip prediction and control is a challenge

Results and Lessons

- Rappelling can work
- Anchoring limits maneuvering and imposes forces
- Constant oversight (teleoperation) is impractical
- Reflexes and behaviors enable autonomy
- Self-righting is systemic requirement
- Harsh field experiments drive program (80/20)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