Human-robot teaming for space exploration

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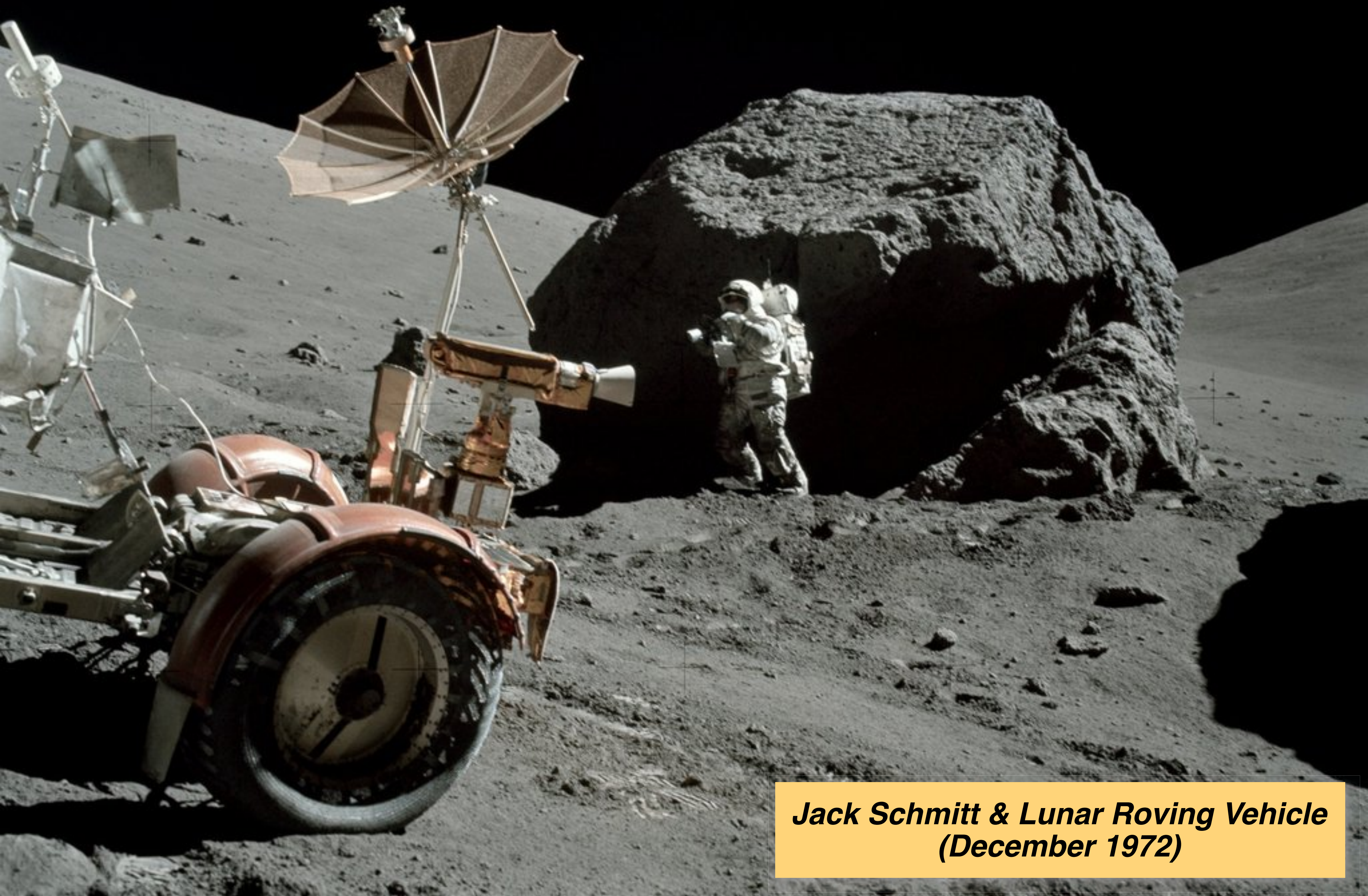
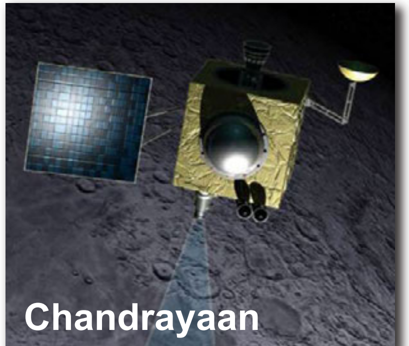
Apollo 17 surface operations

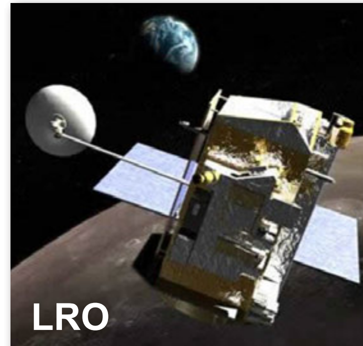


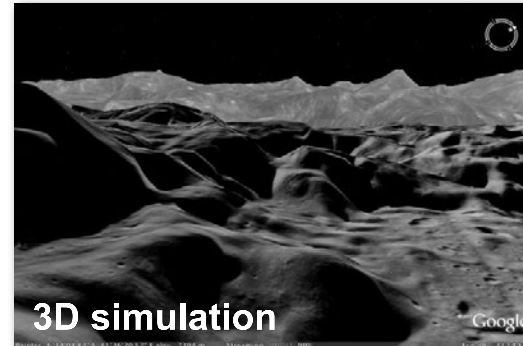
Jack Schmitt & Lunar Roving Vehicle (December 1972)

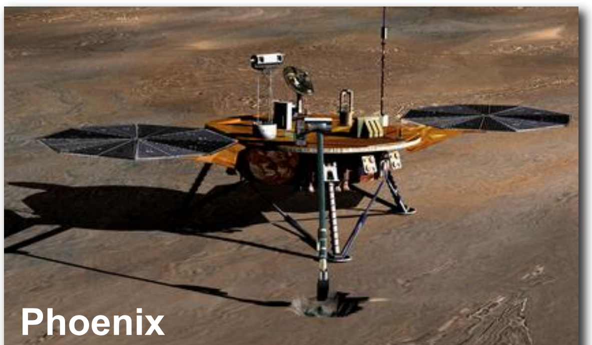
What’s changed since Apollo?


Kaguya


Chandrayaan


LRO


3D simulation


Phoenix


Dante II


Zoë

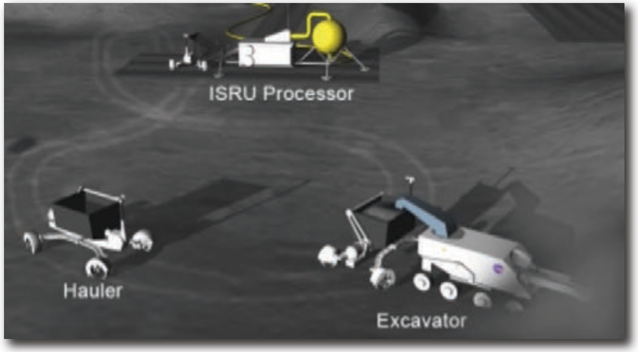

MER, Sojourner, MSL


ATHLETE, K10, Chariot

Robots for human exploration

Robots before crew

- Prepare for subsequent human mission
- Scouting, prospecting, etc.
- Site preparation, equipment deployment, infrastructure setup, etc.



Robots after crew

- Perform work following human mission
- Follow-up work
- Close-out tasks, maintenance, etc.

Robots and crew

- Extend and enhance human reach
- Parallel activities and remote operations
- Inspection, mobile camera, etc.

NASA Robotic Recon Experiment

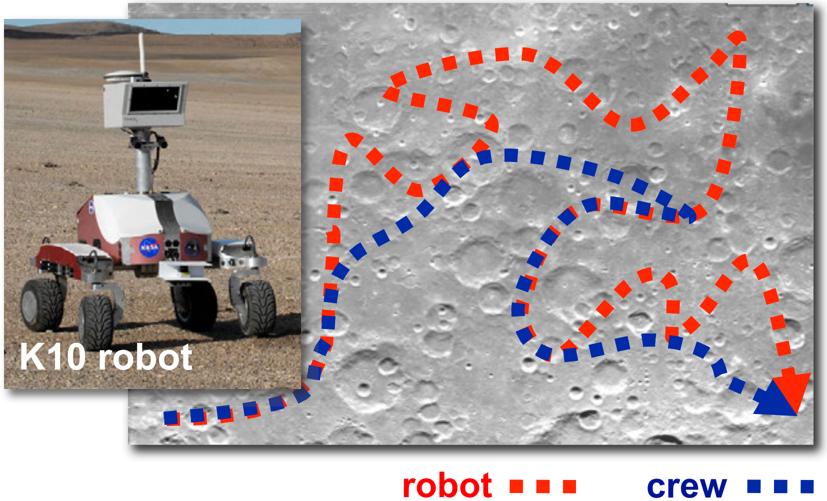
Objectives

- Test coordinated human-robot field exploration
- Robot scouts ahead of crew
- Fold lessons learned into lunar surface science ops concepts

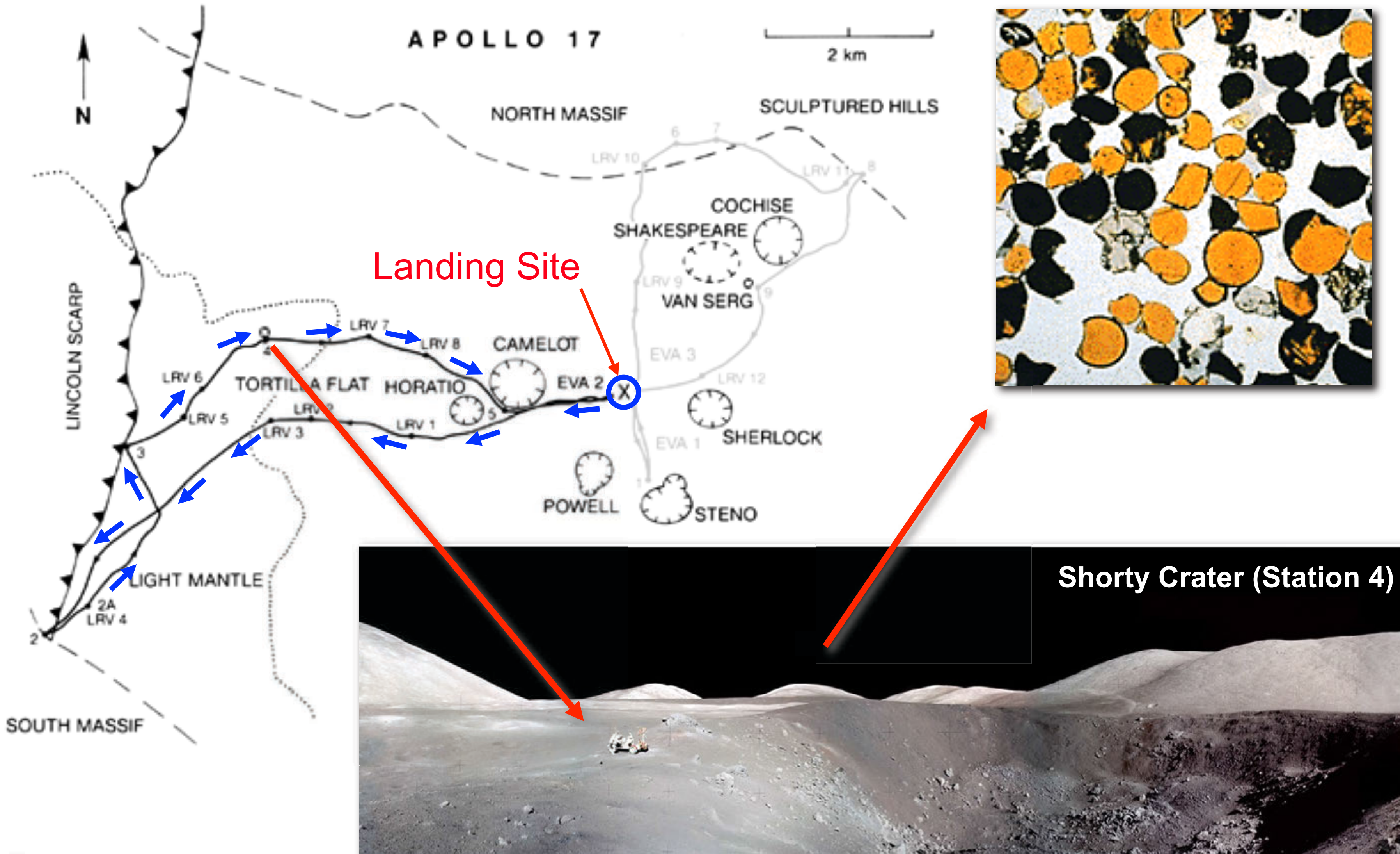
Results

- Identified requirements (instruments, comm, nav, etc.) for robotic recon
- Assessed impact of robotic recon on traverse planning & crew productivity
- Learned how to improve human productivity & science return

M. Bualat et al. (2011). Robotic recon for human exploration: method, assessment, and lessons learned. GSA Special Paper.

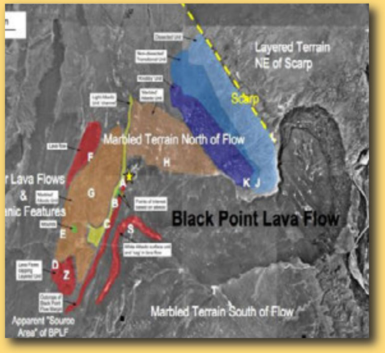


Why is reconnaissance useful?



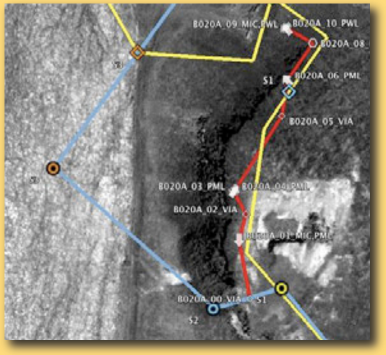
Field experiment (2009)

Mission Planning



Robot Mission

Re-planning



Crew Mission

Mar 1 – June 1
- Satellite images
- Geologic map

June 14 – June 26
- K10 at Black Point
- Ground control at NASA Ames

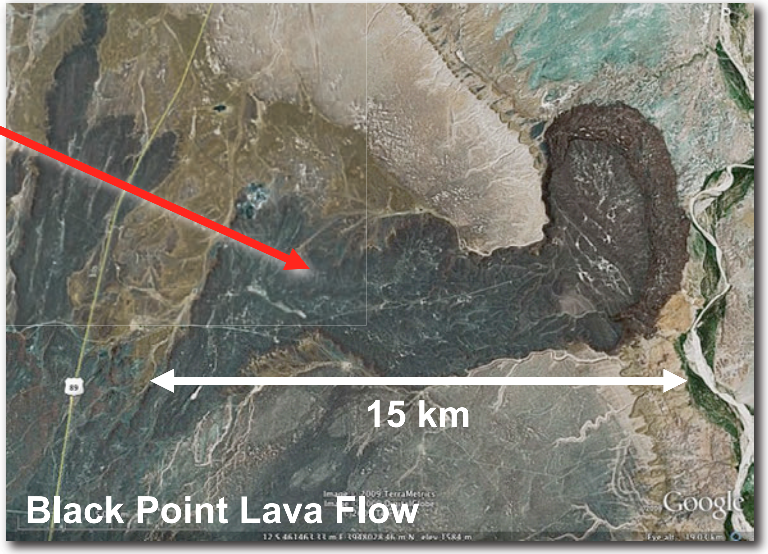
July 1 – Aug 15
- Recon images
- Terrain models

Aug 29 – Sep 3
- LER at BPLF
- Science back-room at BPLF

Lunar analog site

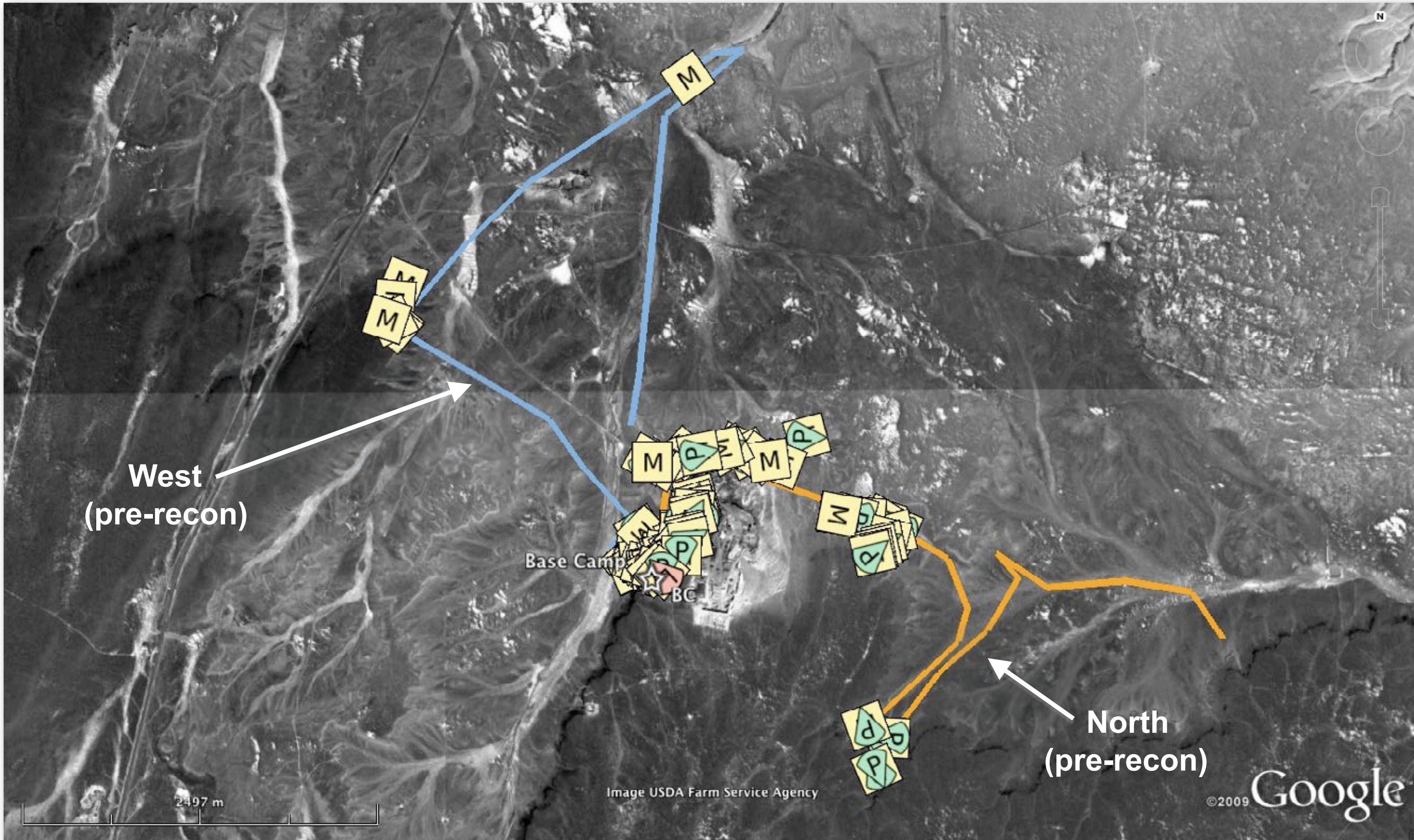
Black Point Lava Flow

- 65 km N of Flagstaff, AZ
- Analog of the "Straight Wall" (Mare Nubrium / Rupes Recta)



Robot mission (June 2009)

Collected recon data

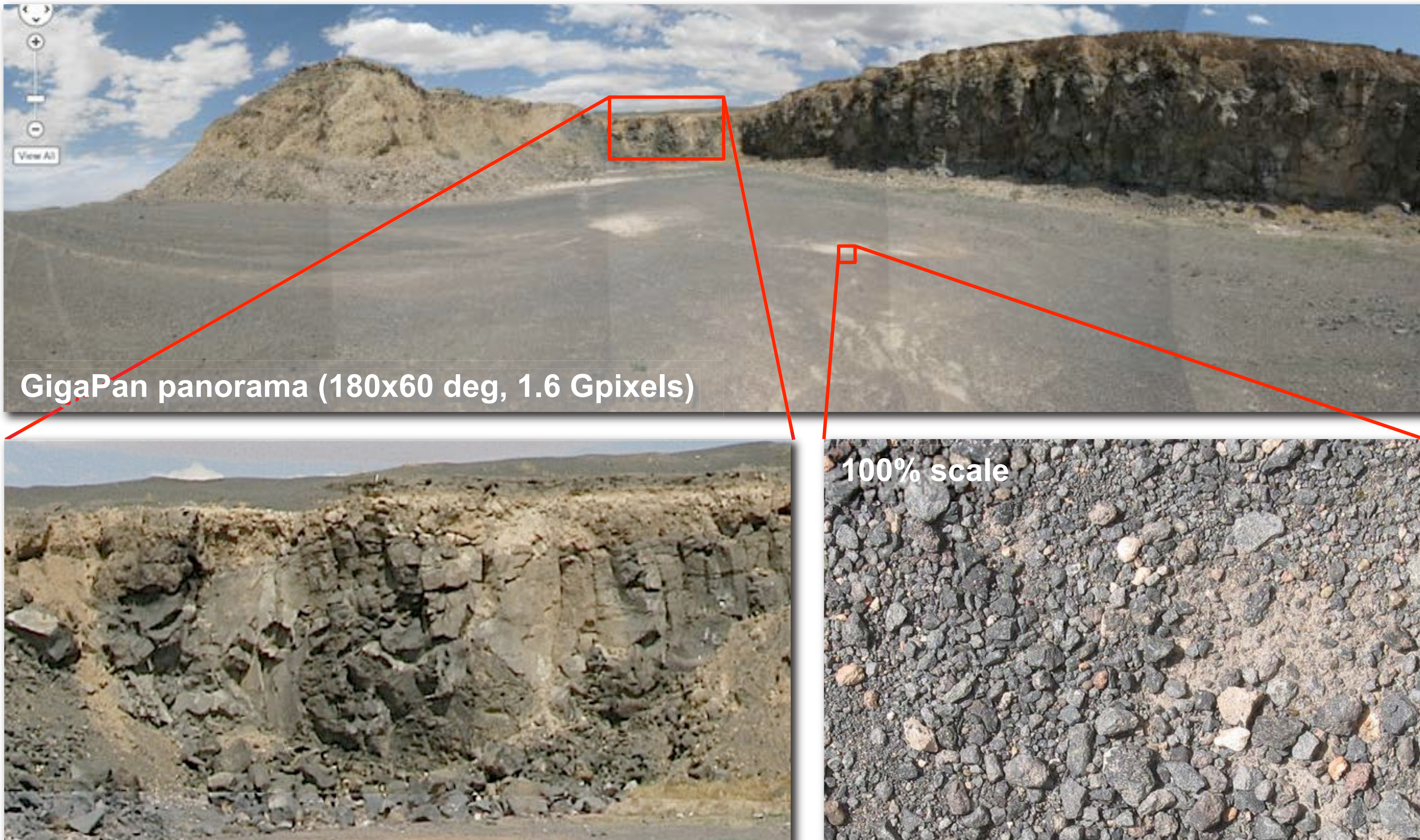


8.5 GB data collected (52 hrs of robotic recon operations)
39 LIDAR scans, 75 GigaPan, and 95 terrain images

Orbital data

Digital Globe QuickBird (60 cm/pixel)

Surface data



GigaPan panorama (180x60 deg, 1.6 Gpixels)

GigaPan panorama close-up

Terrain image (55 microns / pixel)

Surface data

3D scanning LIDAR (250 m range, 3 mm depth resolution)

Crew mission (September 2009)

Space Exploration Vehicle (SEV)

- Prototype pressurized crew vehicle for lunar operations
- Two “suit ports” for rapid (15 min) egress and ingress
- 20 km/hr max, active suspension
- 3.5 x 5 m (wheelbase x length)

Crew A

- Mike Gernhardt & Brent Garry
- W1 (pre-recon) + N2 (post-recon) traverses

Crew B

- Andy Thomas & Jake Bleacher
- N1 (pre-recon) + W2 (post-recon) traverses

Space Exploration Vehicle

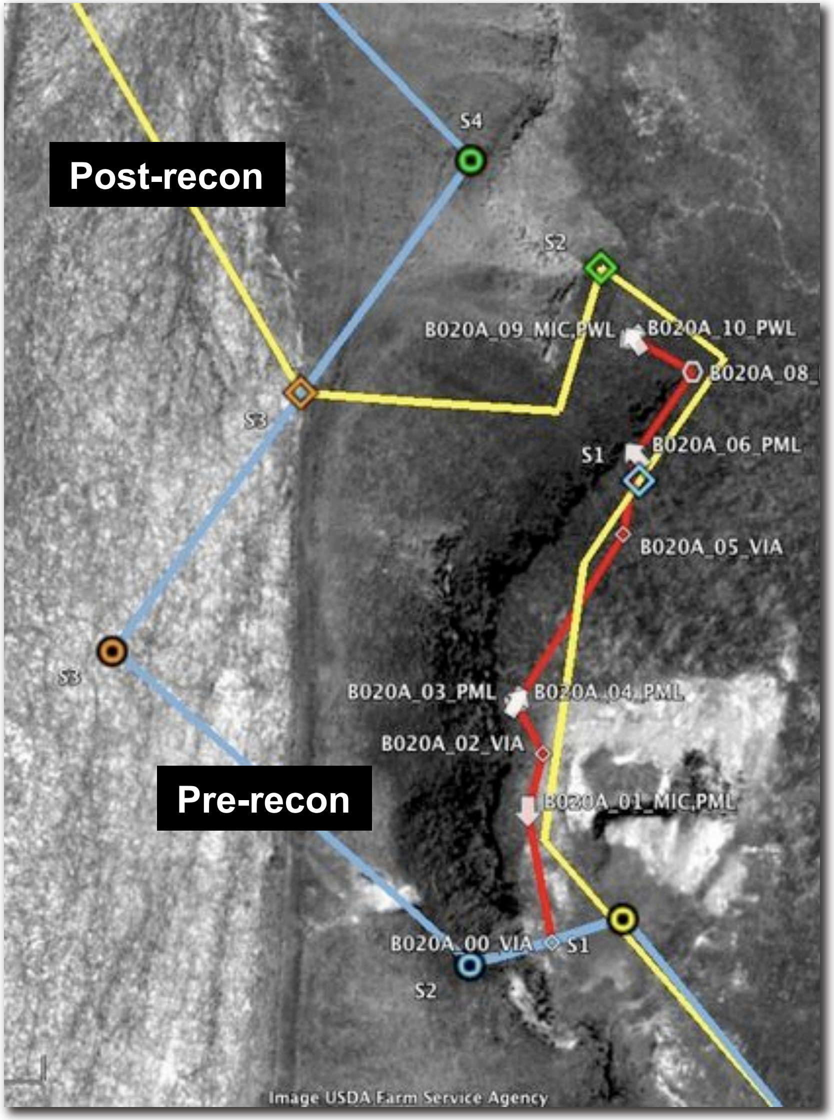
Crew mission (September 2009)

Field experiment results

"West" region

- Pre-recon traverse plan was designed like Apollo
  - Assume single visit to each site
  - Rapid area coverage (cover multiple geologic units)
- Post-recon plan ended up being **significantly different**
  - More flexible & adaptable
  - Recon data supports real-time replanning
- Impact of recon
  - Reduced science uncertainty
  - Improved target prioritization

T. Fong et al. (2010). Assessment of robotic recon for human exploration of the Moon. Acta Astronautica 67 (9-10)



NASA Robotic Follow-up Experiment

An exploration problem

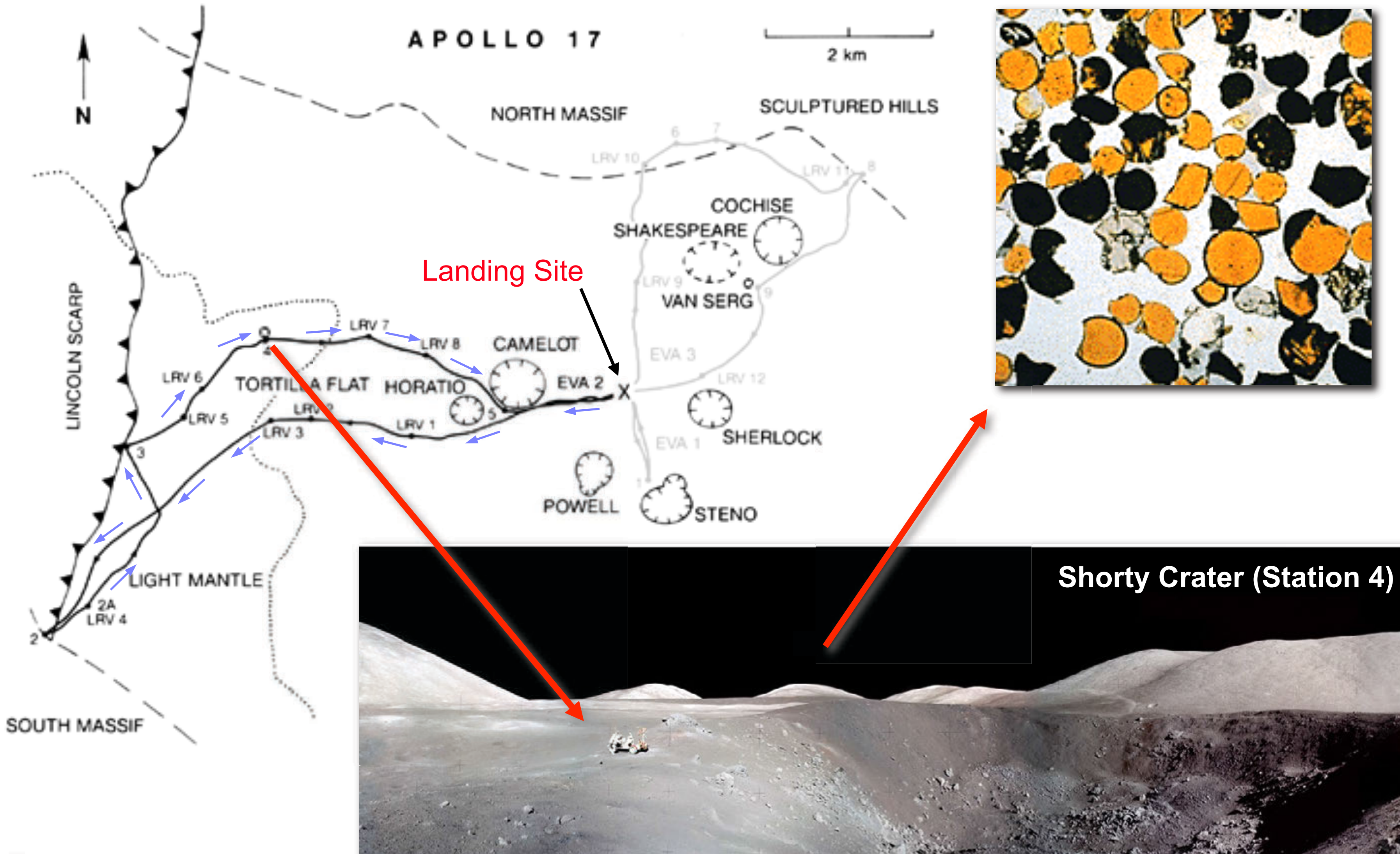
- Never enough time for field work
- "If only I could have…"
  - More observations
  - Additional sampling
  - Complementary & supplementary work

The solution

- Use robots to "follow-up" after humans
- Augment human field work with subsequent robot activity
- Use robots for work that is tedious or unproductive for humans to do

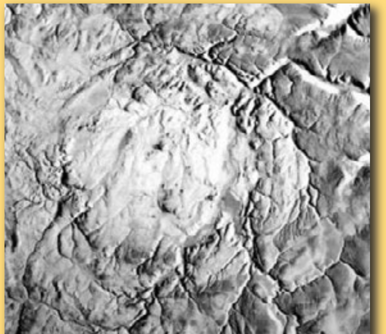
M. Deans et al. (2011). Field testing robotic follow-up for exploration field work. Proc. of the Lunar & Planetary Science Conf.

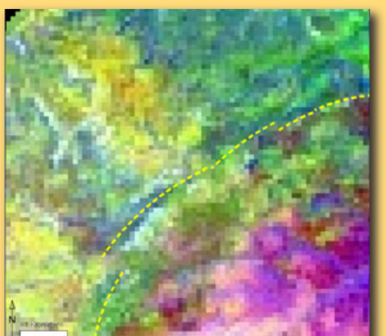
Why is “follow-up” useful?



Field experiment

Mission Planning



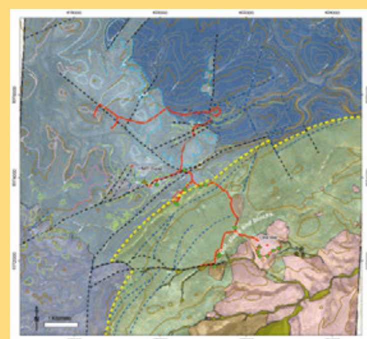


June 2009
- Satellite images
- ASTER, DEM, etc.

Crew Mission

July 2009
- Two crews at Haughton Crater

Follow-up Planning

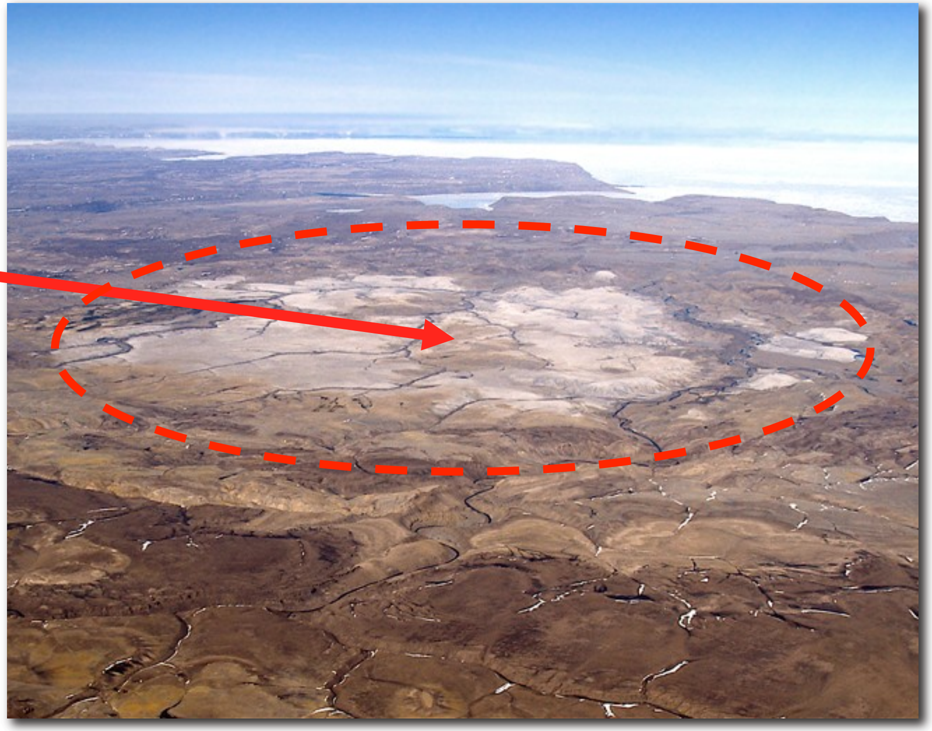


October 2009
- Field data
- Observations and mission logs

Robot Mission

July 2010
- K10 at Haughton
- Science operations at NASA Ames

Lunar analog site



Haughton Crater

- 20 km diameter impact structure
- ~39 million years ago (Late Eocene)
- Devon Island: 66,800 sq. km (largest uninhabited island on Earth)

Crew mission (July 2009)

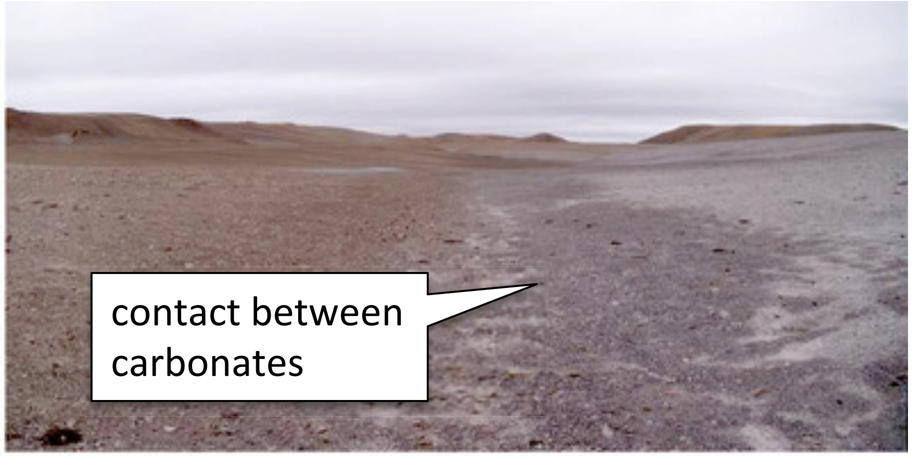
Geologic Mapping

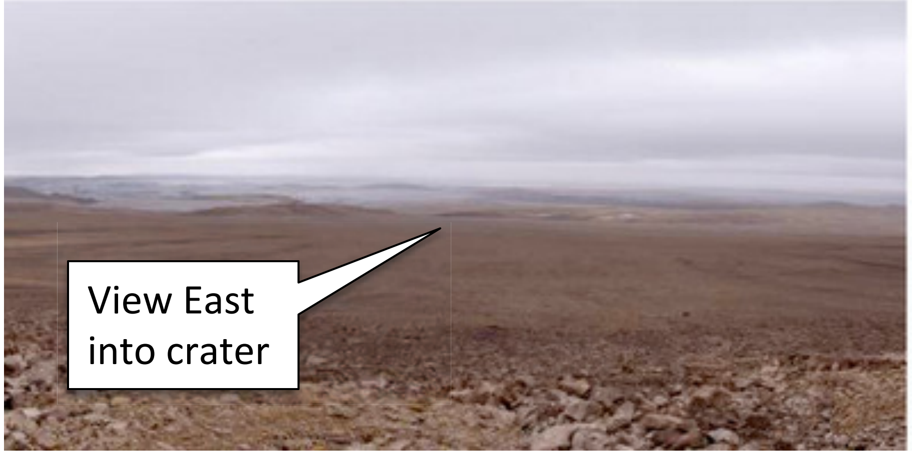
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

Geophysical Survey

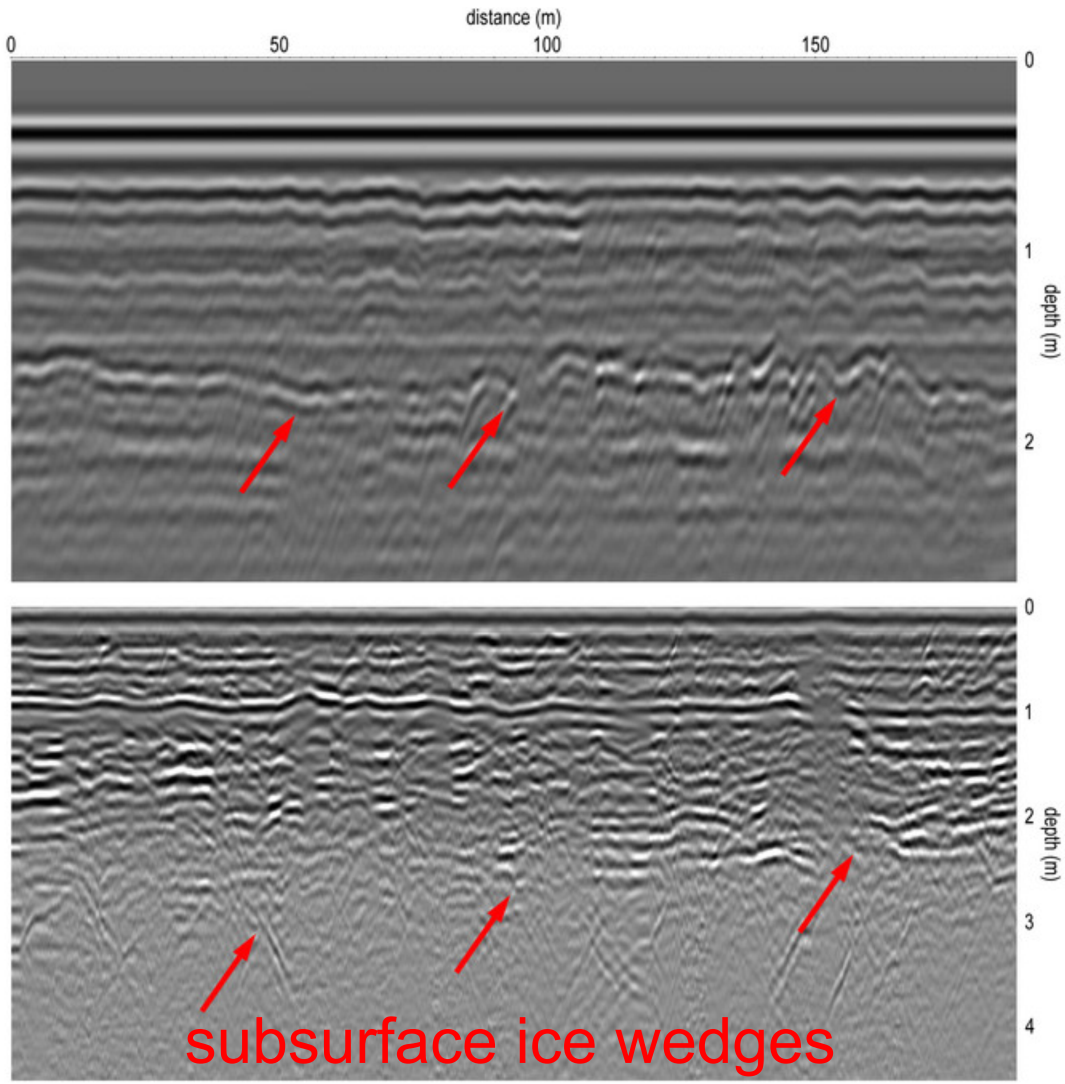
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz

Geologic mapping results

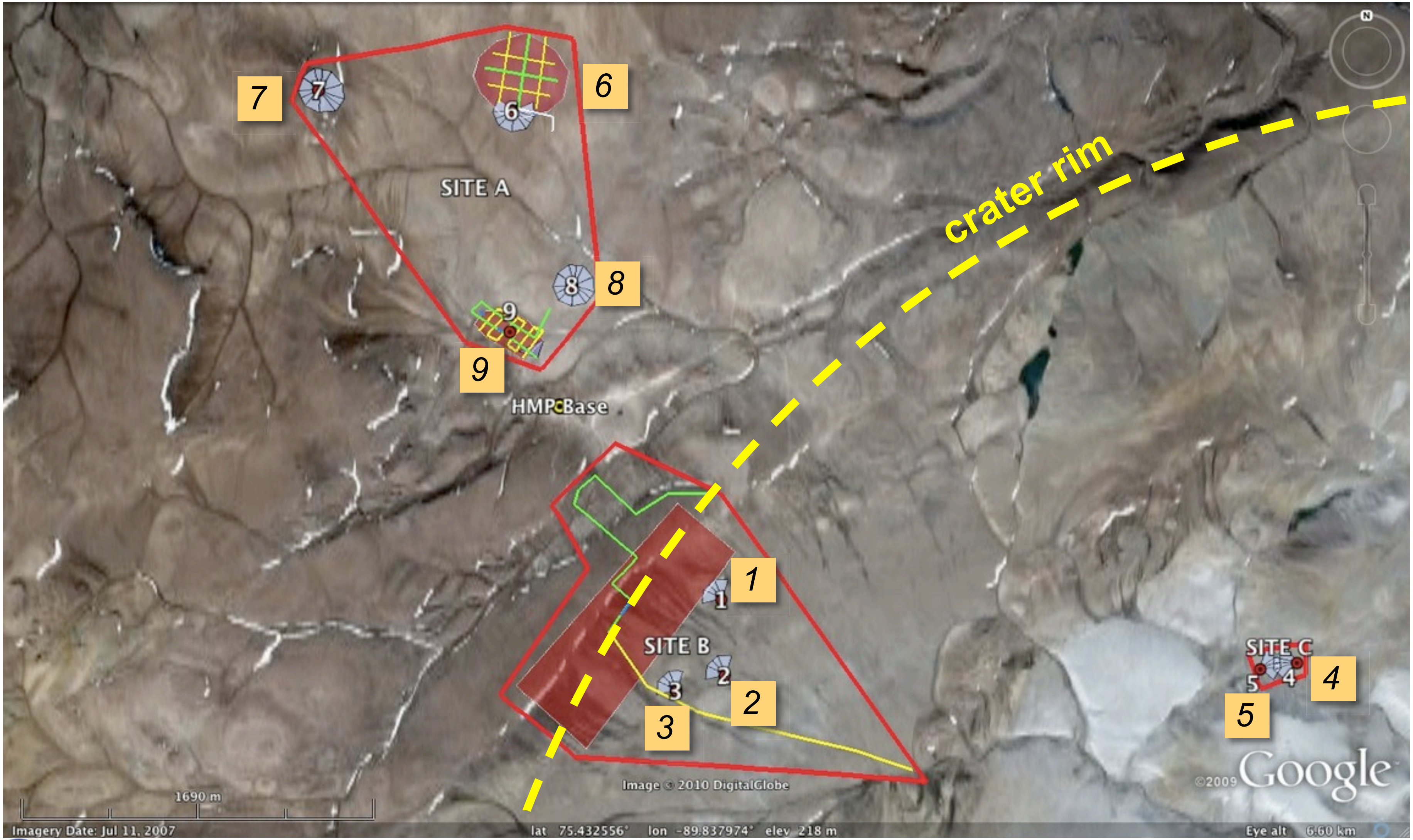




Geophysical survey results



Robotic follow-up plan



Robot mission (July 2010)

Field experiment results

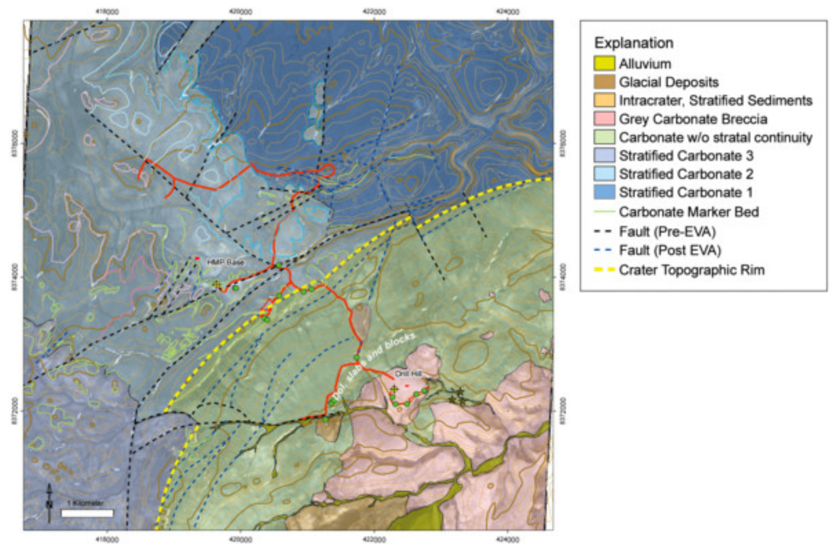
Geologic Mapping

- **Verified the geologic map** in multiple locations (revisited and confirmed geologic units)
- **Amended the geologic map** in multiple locations (added detail to long-range crew observations)

Geophysical Survey

- **Detail study of "polygons"** (correlated surface & subsurface features identified by crew)
- **Measured average depth** of subsurface ice layer (refined observations from crew)

T. Fong et al. (2010). Robotic follow-up for human exploration. AIAA-2010-8605. Proc. of AIAA Space 2010.



Real-time human-robot collaboration

Our focus

- Study how **humans can remotely support robots**
- Address the many **anomalies**, **corner cases**, and **edge cases** that require unique solutions, which are not currently practical to develop, test, and validate under real-world conditions
- Humans provide high-level guidance (not low-level control) to assist when autonomy is inadequate, untrusted, etc.

Crew-controlled surface telerobotics

Future exploration architecture study teams have made assumptions about how crew can remotely perform work on a planetary surface …

Candidate Exploration Missions

- **L2 Lunar Farside**. Orion MPCV mission to Earth-Moon L2 point
- **Near-Earth Asteroid**. NEA dynamics and distance make it impossible to manually control robot from Earth
- **Mars Orbit**. Crew must operate surface robot from orbit when circumstances (contingency, etc.) preclude Earth control

(NASA GSFC)

Assumptions

- Productivity of crew-control (decision making, efficiency, etc.)
- Existing technology gaps (and how these can be bridged)
- Operational risks (proficiency, performance, failure modes)

NASA Surface Telerobotics Project

Key Points

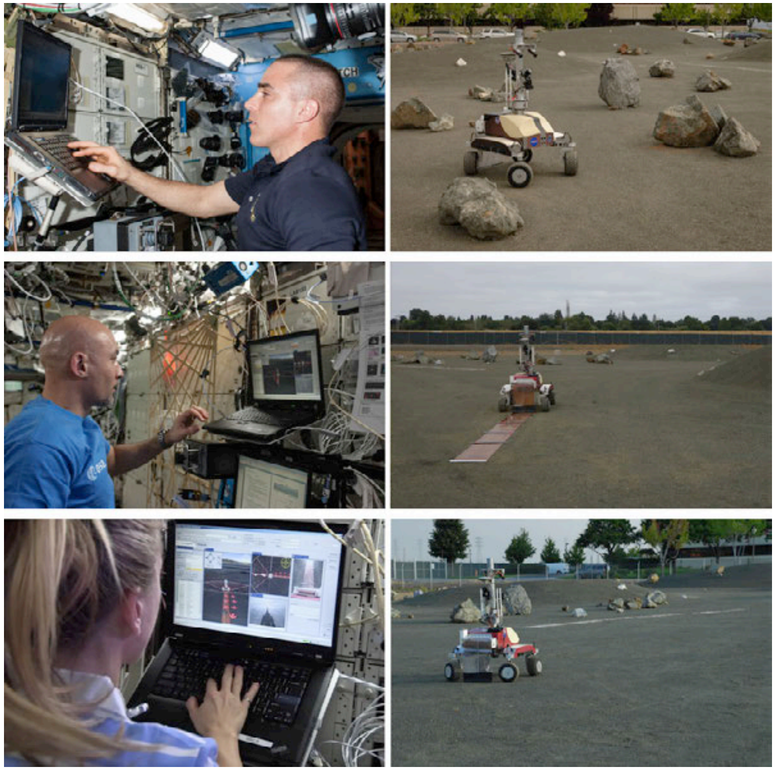
- Demo crew-control of planetary rover from orbiting spacecraft
- Test human-robot conops for future exploration mission
- Obtain baseline engineering data (robot, crew, data comm, task, etc)

Implementation

- Lunar libration mission simulation
- Astronaut on Space Station
- K10 rover in NASA Ames Roverscape

Expedition 36 testing

- June 17, 2013 – C. Cassidy, survey
- July 26, 2013 – L. Parmitano, deploy
- Aug 20, 2013 – K. Nyberg, inspect



SURVEY

DEPLOY

INSPECT

- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** (“just in time” training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete commands) and supervisory control (task sequence)

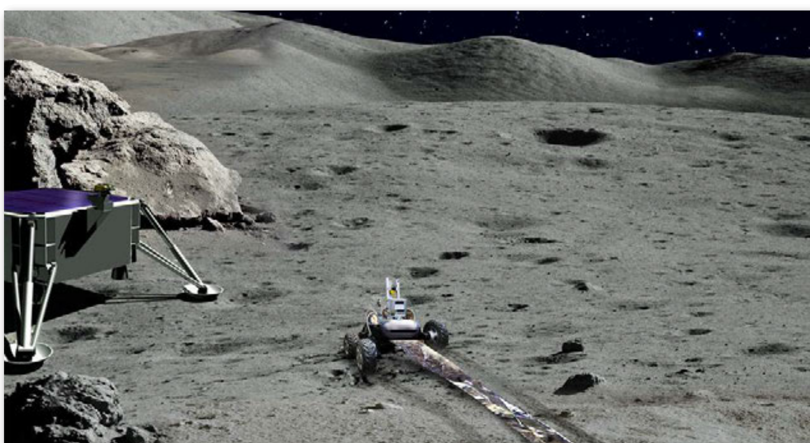
“Fastnet” Lunar Mission Concept

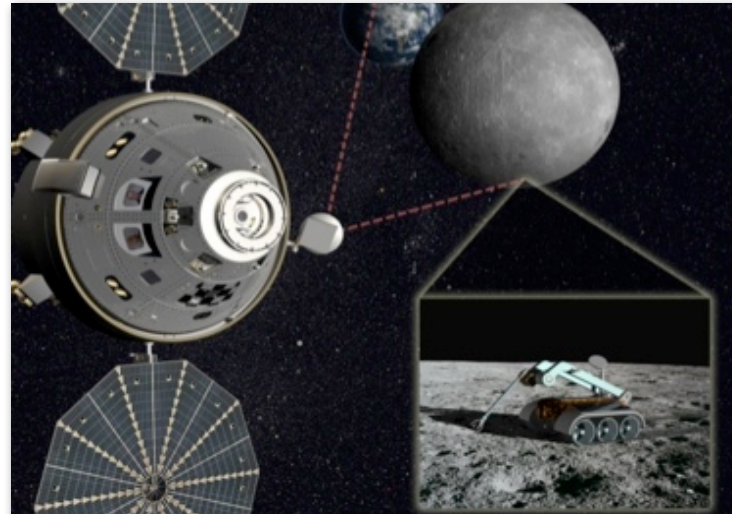
Orion MPCV at Earth-Moon L2

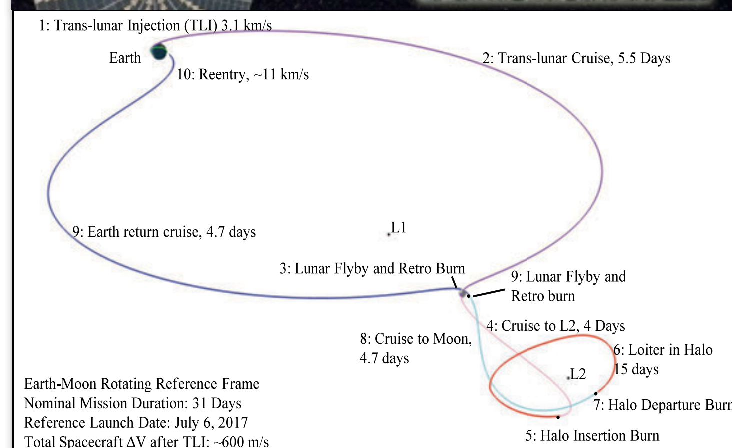
- 60,000 km beyond lunar farside
- Crew remotely operates robot
- Does not require human-rated lander

Lunar farside telescope

- Lunar farside provides radio quiet zone for low-freq measurements
- Requires surface survey, telescope deployment, and inspection







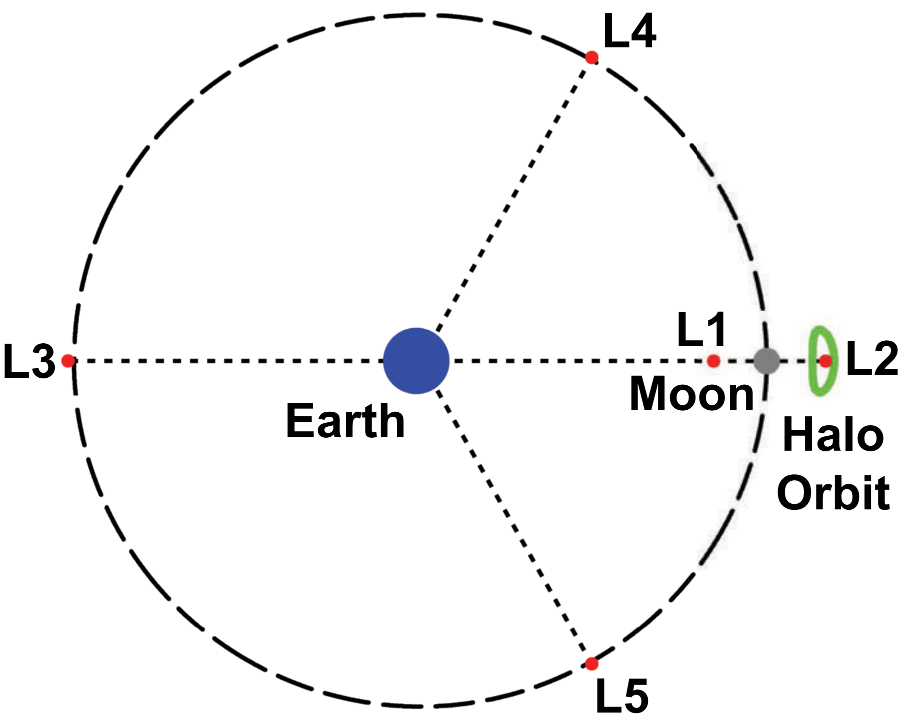
Credit: Lockheed Martin / LUNAR

J. Burns, D. Kring, *et al.* 2013, ***Advances in Space Research***, 52, p. 306-320.

Why the EM-L2 Lagrange Point?

EM-L2 is well situated for exploration of the Moon

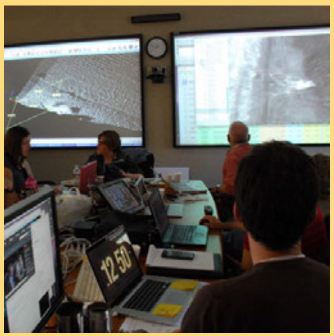
- Direct (line-of-sight) data communications to the lunar farside
- Direct observation of lunar farside
- ΔV can be lower than EM-L1
- Demonstrate capability for deep space operations in trans-lunar space
- Potential location for a “Deep Space Gateway”– staging point for future missions, cis-lunar science facility, etc.



"Fastnet" mission simulation

ISS Expedition 36

Pre-Mission Planning



Ground teams plan out telescope deployment and initial rover traverses.

Spring 2013

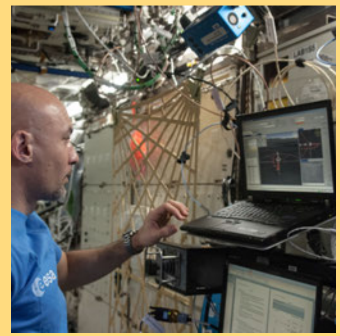
Surveying

Crew gathers information needed to finalize the telescope deployment plan.

17 June 2013

Chris Cassidy

Telescope Deployment

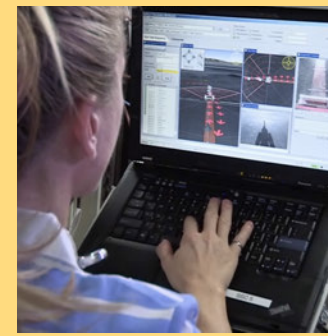


Crew monitors the rover as it deploys each arm of the telescope array.

26 July 2013

Luca Parmitano

Telescope Inspection

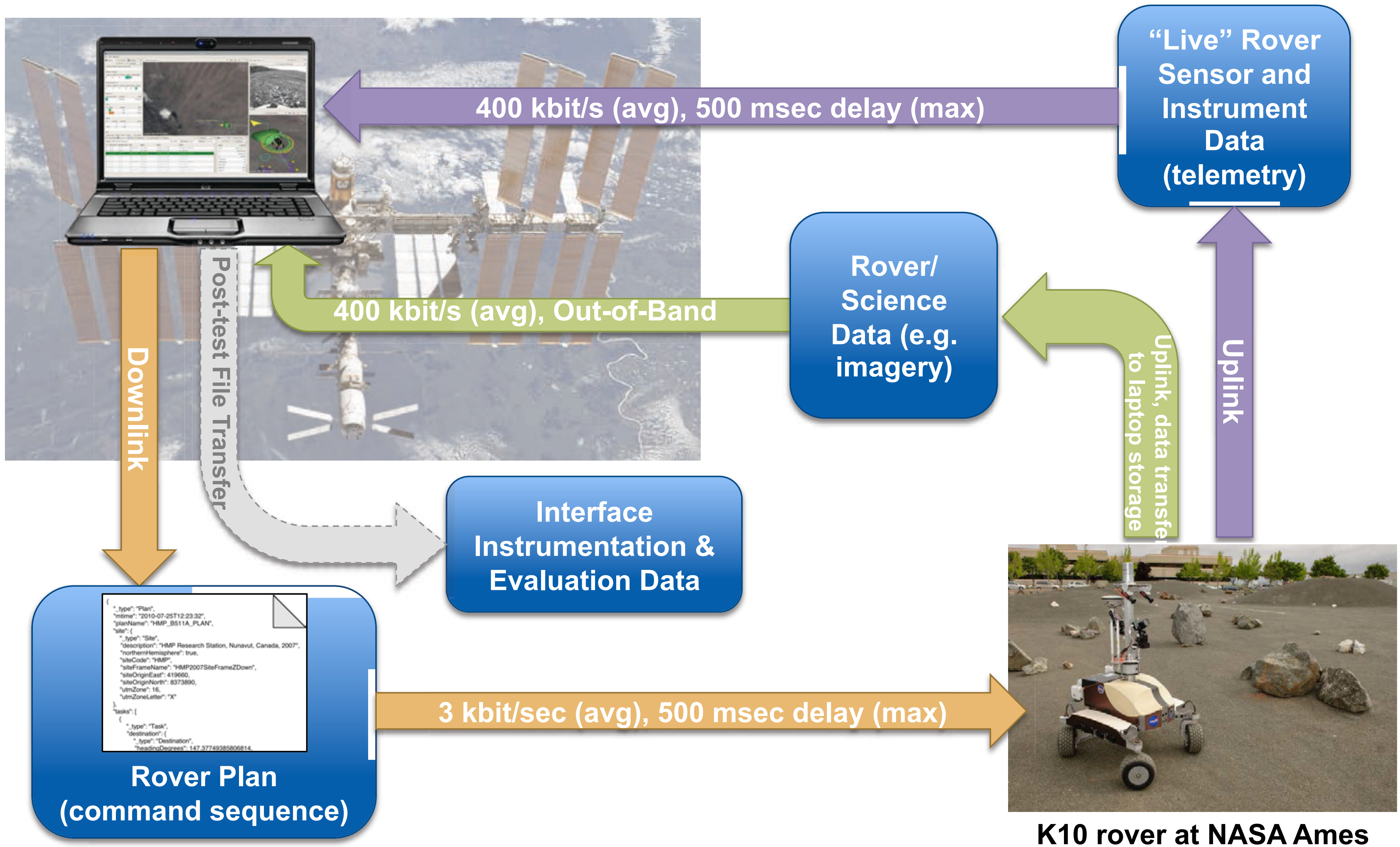


Crew inspects and documents the deployed telescope for possible damage.

20 August 2013

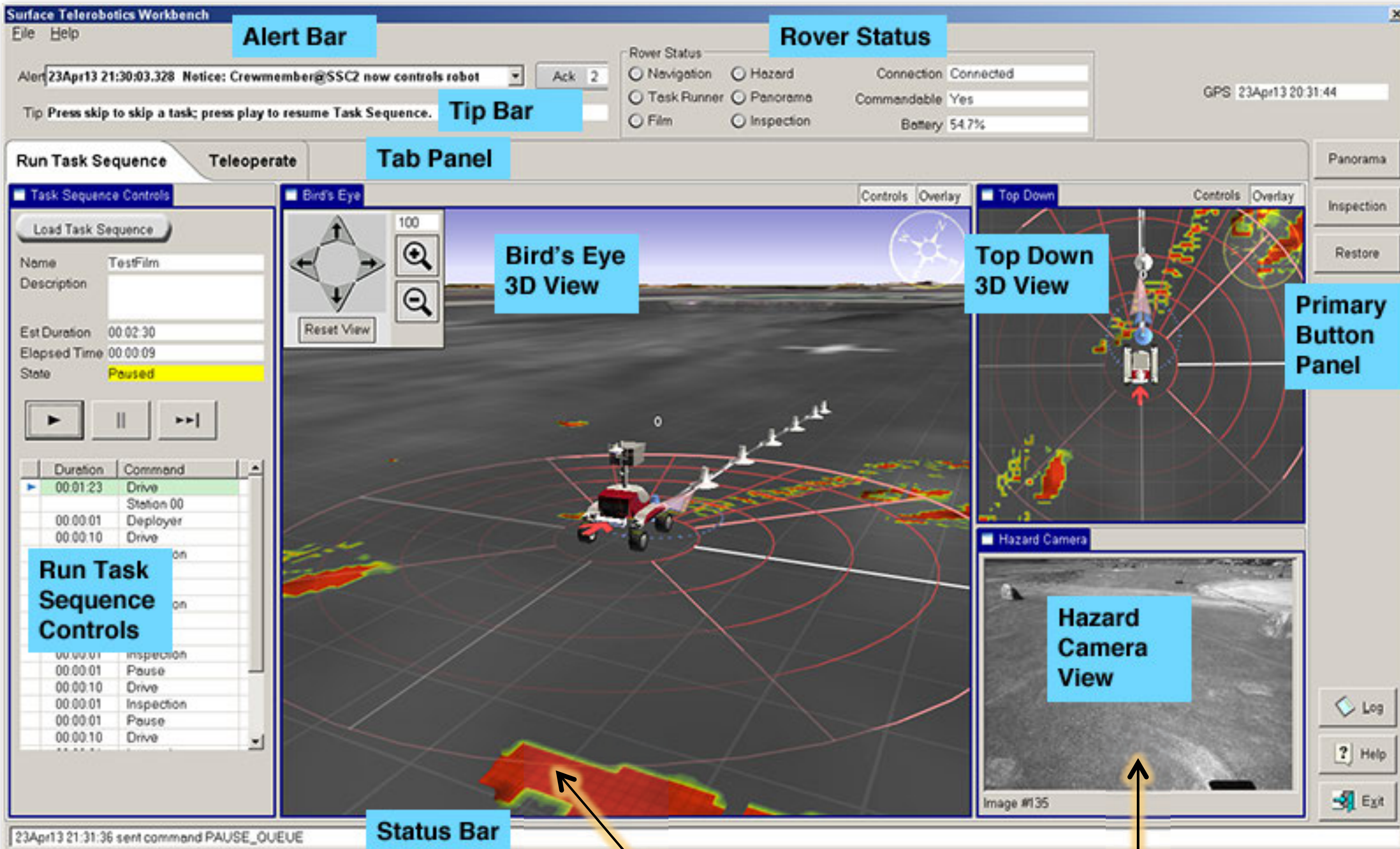
Karen Nyberg

Space Station test setup



User interface (supervisory control)

Task Sequence

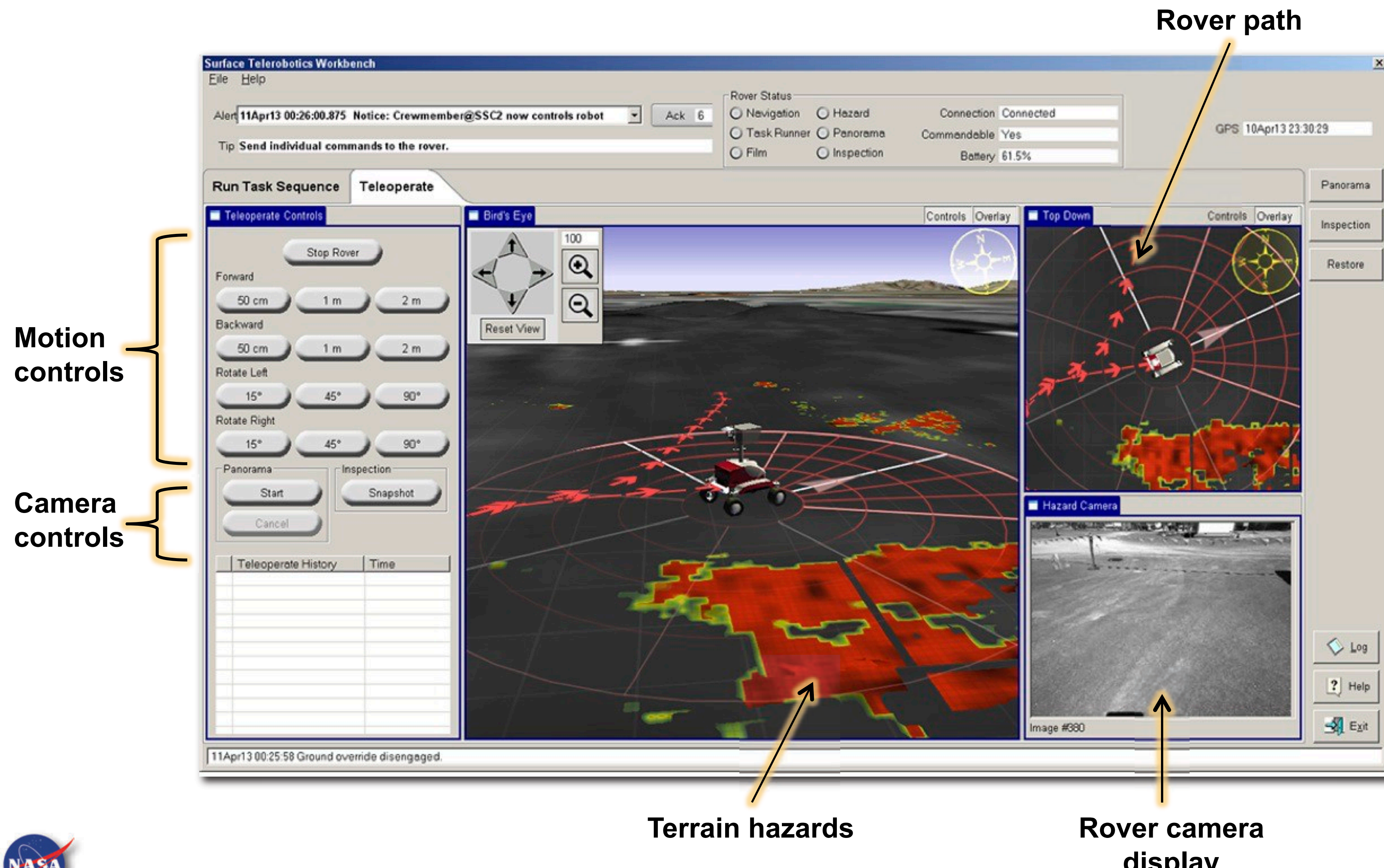


Duration	Command
00:01:23	Drive
	Station 00
00:00:01	Deployer
00:00:10	Drive
00:00:01	Pause
00:00:10	Drive
00:00:01	Inspection
00:00:01	Pause
00:00:10	Drive

Terrain hazards

Rover camera display

User interface (manual control)

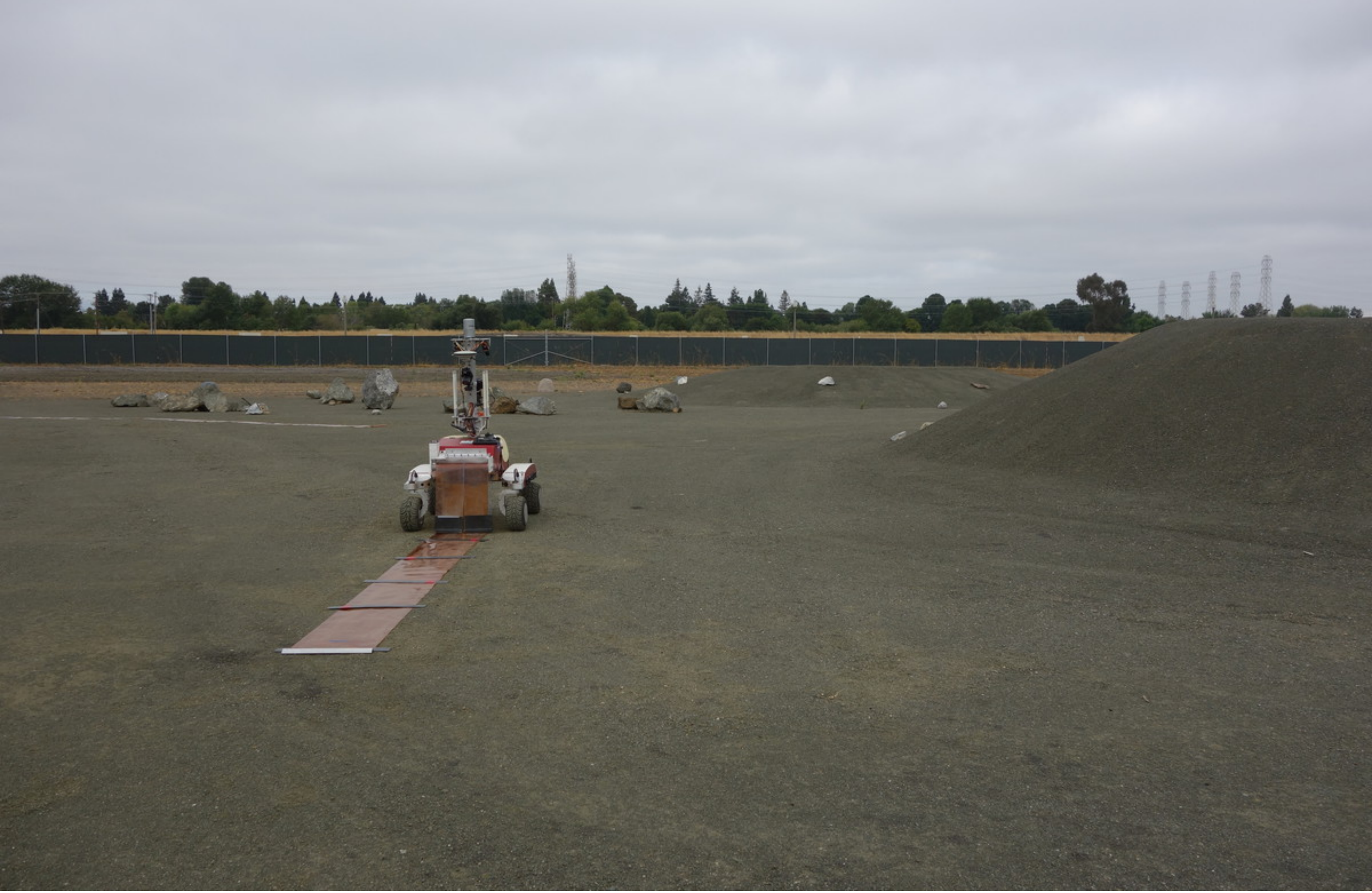


Astronaut in space / Robot on Earth

Chris Cassidy remotely operates K10 from the ISS to perform site survey (2013-06-17)

K10 performing surface survey

Luca Parmitano works with K10 to deploy simulated polymide antenna (2013-07-26)



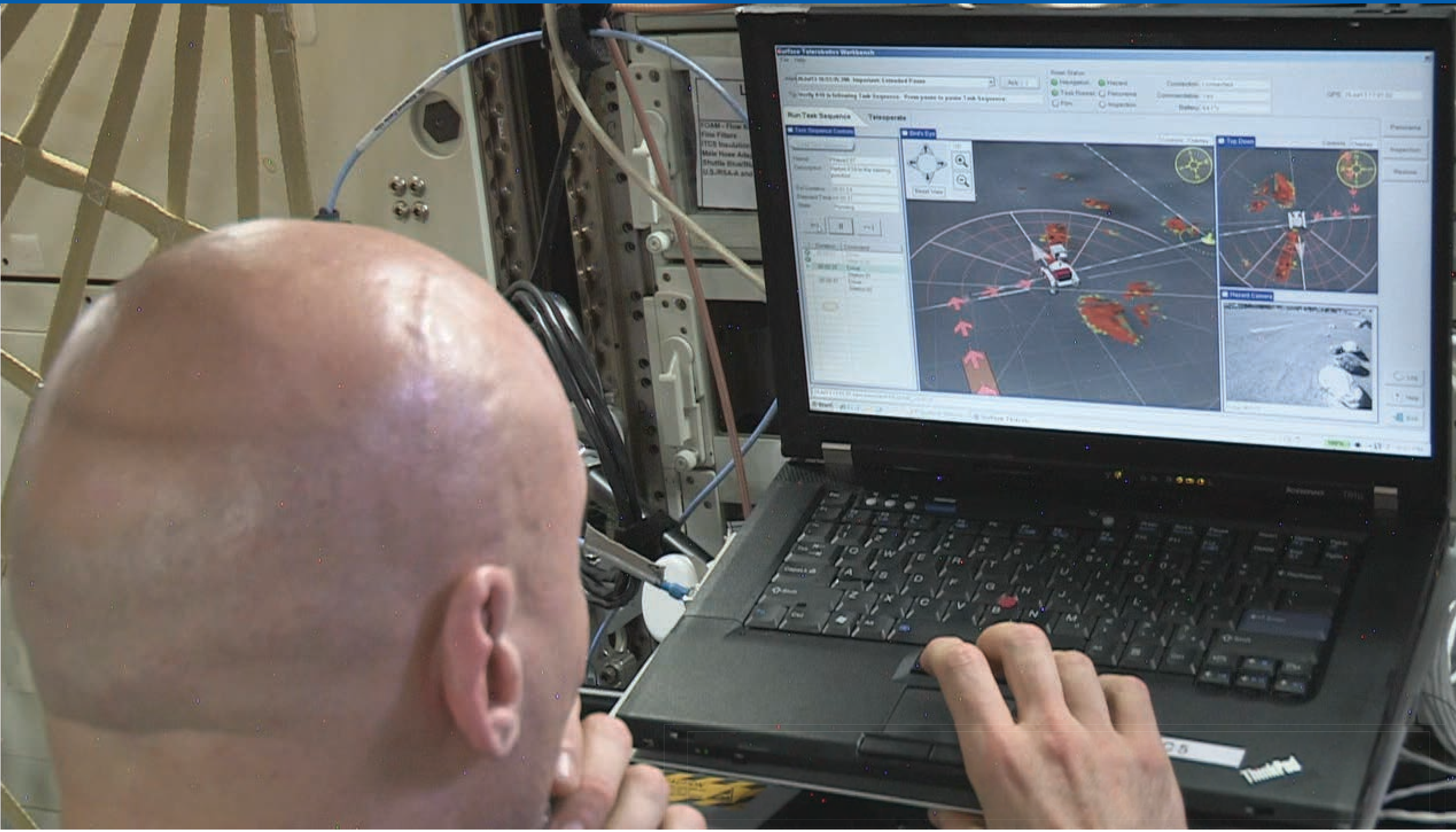
K10 deploying simulated polymide antenna

Deployed simulated polymide antenna (three "arms")

Karen Nyberg works with K10 to document deployed simulated antenna (2013-08-20)

K10 documenting simulated polymide antenna

Crew control of K-10 rover



Assessment Approach

Metrics

- **Mission Success:** % task sequences: completed normally, ended abnormally or not attempted; % task sequences scheduled vs. unscheduled
- **Robot Utilization:** % time robot spent on different types of tasks; comparison of actual to expected time on; did rover drive expected distance
- **Task Success:** % task sequences per session and per task sequence: completed normally, ended abnormally or not attempted; % that ended abnormally vs. unscheduled task sequences
- **Contingencies:** Mean Time To Intervene, Mean Time Between Interventions
- **Robot Performance:** expected vs. actual execution time on tasks

Data Collection

automatic

- **Data Communication:** direction (up/down), message type, total volume, etc.
- **Robot Telemetry:** position, orientation, power, health, instrument state, etc.
- **User Interfaces:** mode changes, data input, access to reference data, etc.
- **Robot Operations:** start, end, duration of planning, monitoring, and analysis
- **Crew Questionnaires:** workload (Bedford Scale), situation awareness (SAGAT)

M. Bualat, D. Schreckenghost, et al. (2014) **"Results from testing crew-controlled surface telerobotics on the International Space Station"**. Proc. of 12th I-SAIRAS (Montreal, Canada)

Keck Institute for Space Sciences study

Low-Latency Telerobotics

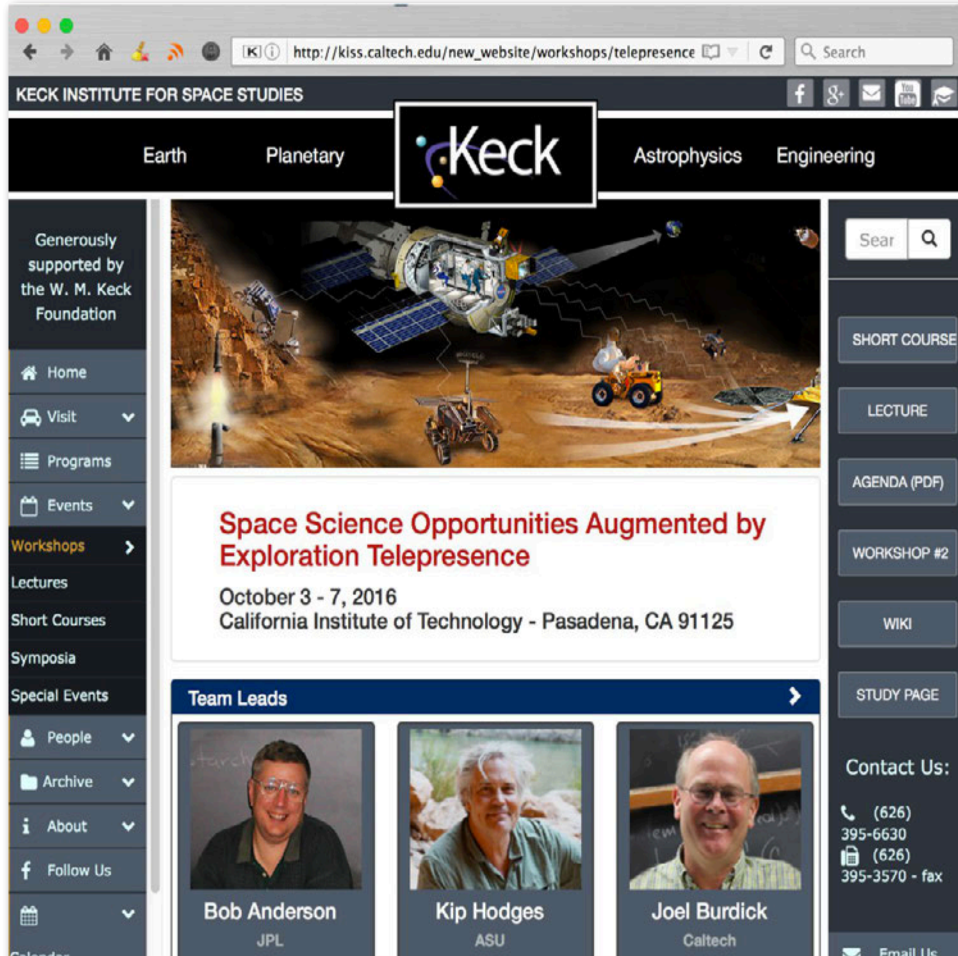
- Astronauts use robots as avatars to be remotely present at a field site
- Focus on field science (emphasis on geology)

Workshop #1: October 2016

- Reviewed state-of-the-art
- Discussed pros and cons
- Identified science goals

Workshop #2: July 2017

- Developed research roadmap
- Identified key research and studies to be performed
- Outlined summary report



http://kiss.caltech.edu/new_website/workshops/telepresence/telepresence.html

Conclusion

Many forms of human-robot teaming

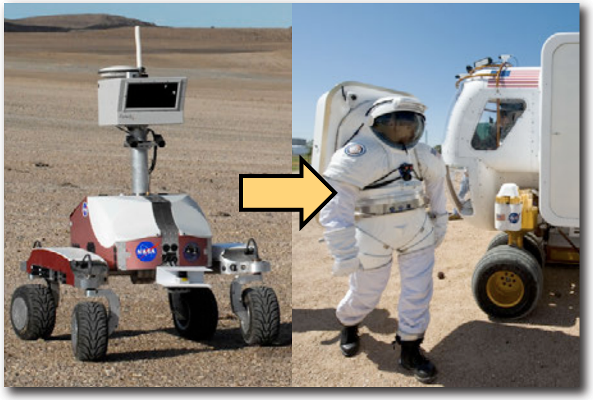
- “Robot as tool” is only **one** model
- Not just co-located or line-of-sight
- ▸ **Humans & robots can support each other**

Concurrent, interdependent operations

- Human-robot interaction is still **slow** and **mismatched** (compared to human teams)
- Easy for robots to impede the human
- ▸ **Loosely-coupled teaming may be best**

Distributed teams

- Require **coordination** and **info exchange**
- Require understanding of (and planning for) each teammate’s **capabilities**
- ▸ **Effective protocols and tools are critical**



Questions?

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