From the Moon to the Earth:

Planetary exploration to self-driving cars

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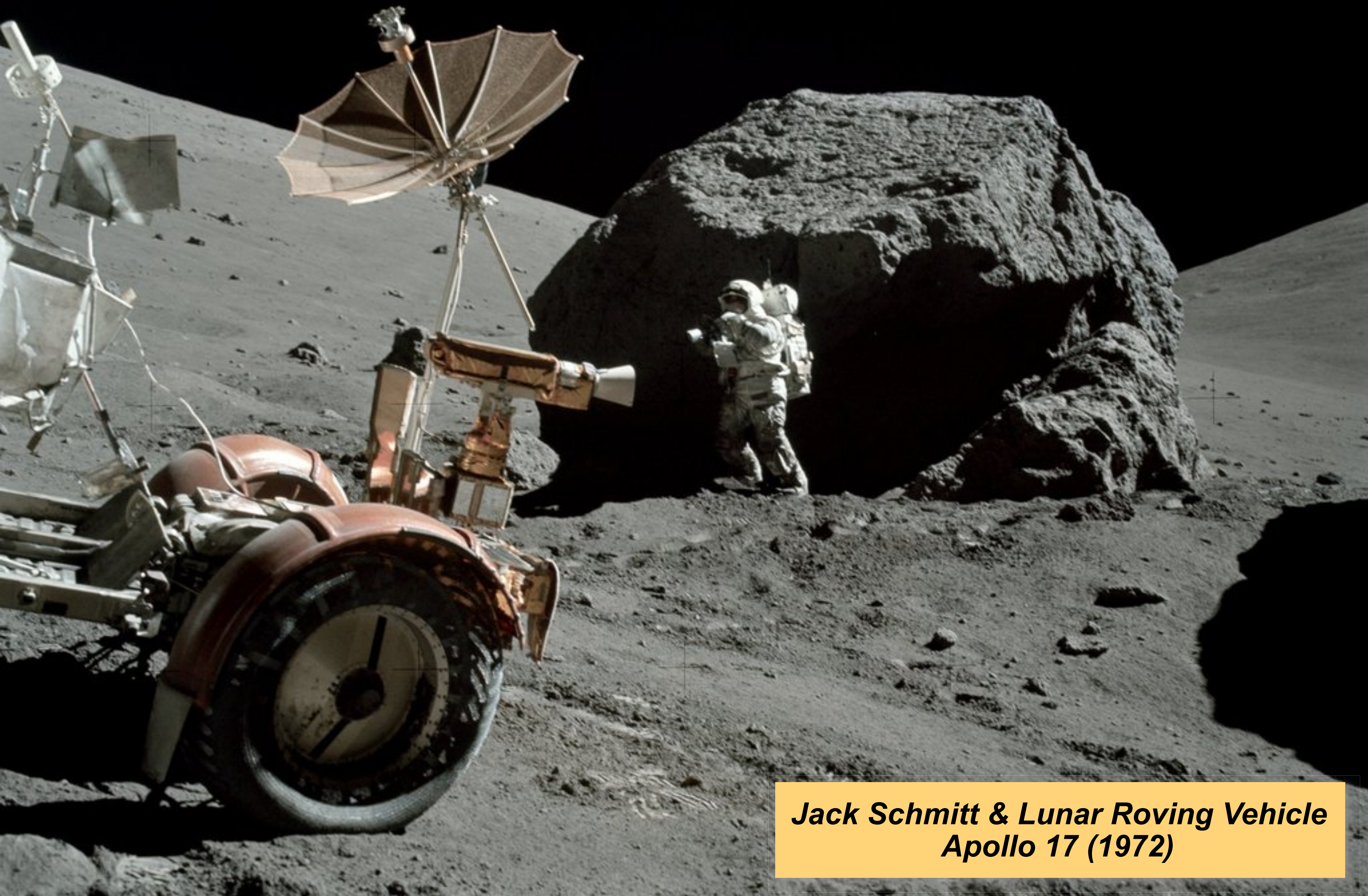
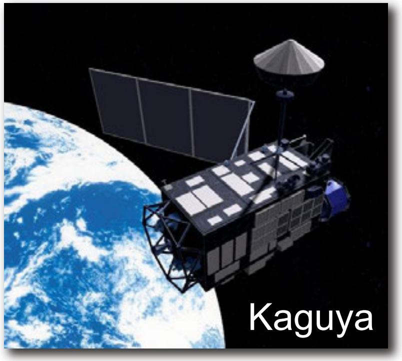
Human planetary exploration

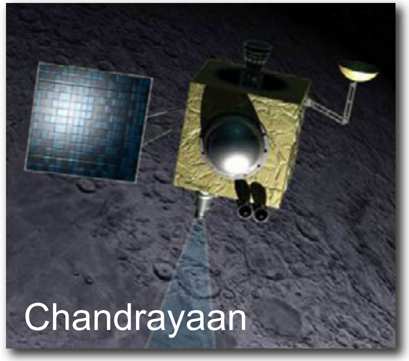


Jack Schmitt & Lunar Roving Vehicle
Apollo 17 (1972)

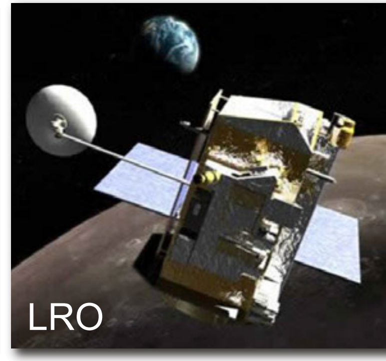
What’s changed since Apollo?



Kaguya

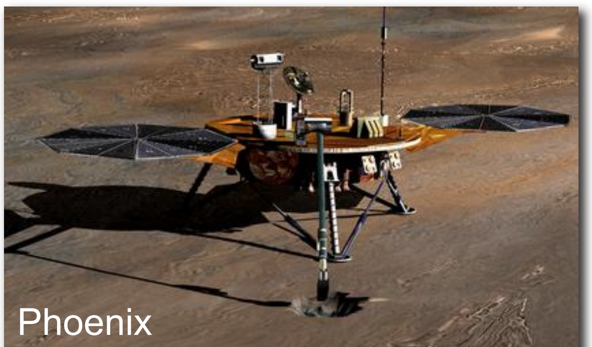


Chandrayaan



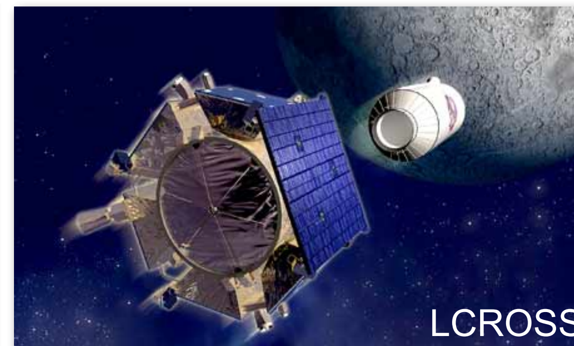
LRO

Space Station

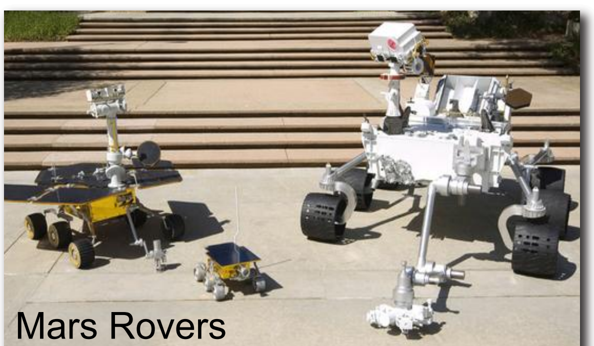


Phoenix

Robonaut 2



LCROSS



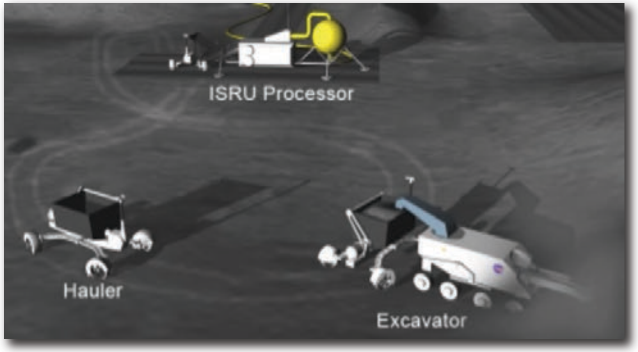
Mars Rovers

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 supporting crew

- Parallel activities and real-time support
- Inspection, mobile camera, etc.
- Heavy transport & mobility

Robots after crew

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

Robotic "Follow-up" Project

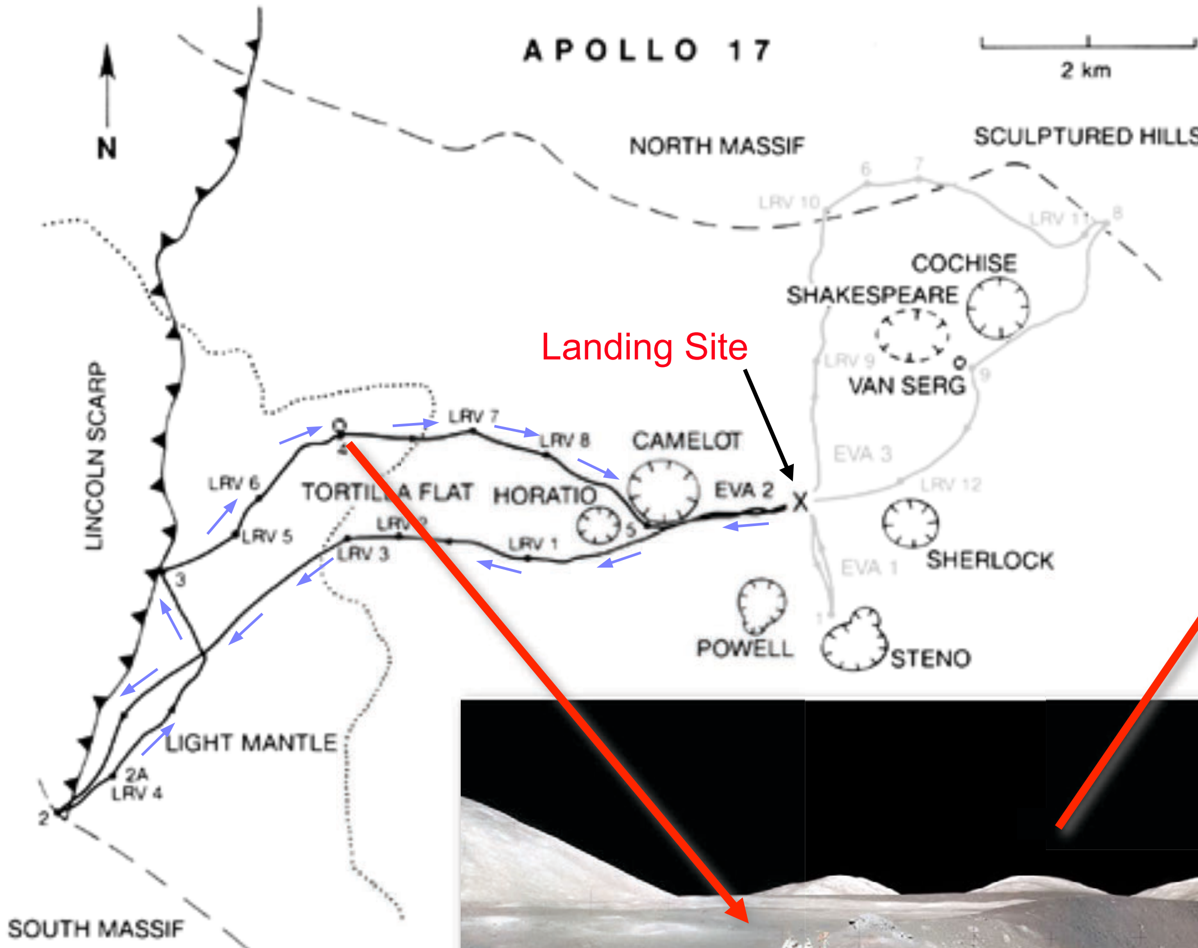
The problem

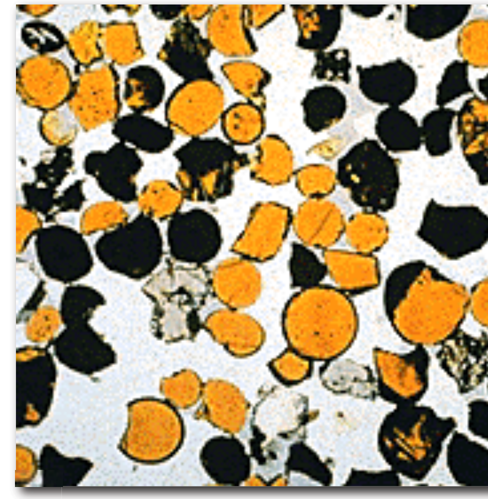
- Never enough time for field work
- "If only I could have…"
  - More observations
  - Additional sampling
  - Complementary & supplementary work

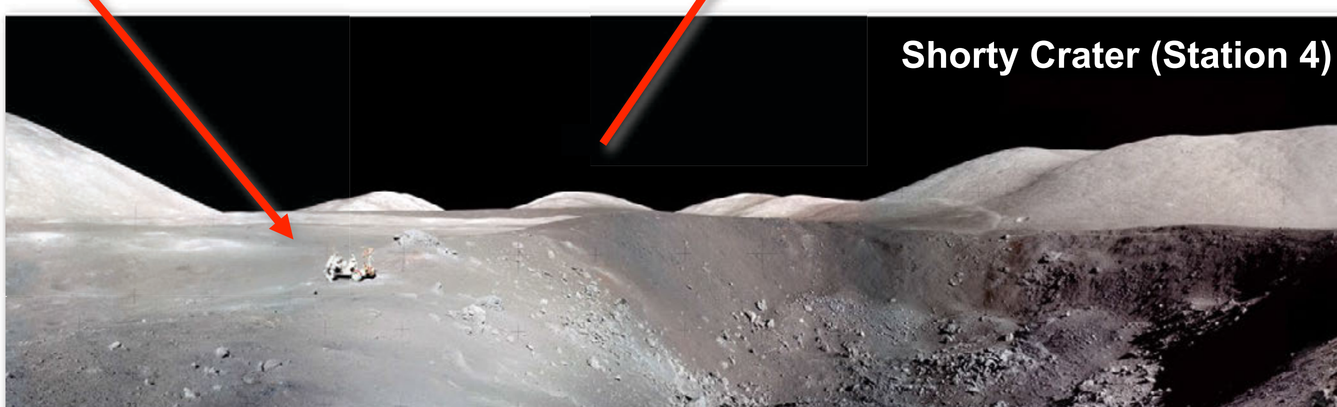
The solution

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

Why is follow-up useful?







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)

Astronaut mission

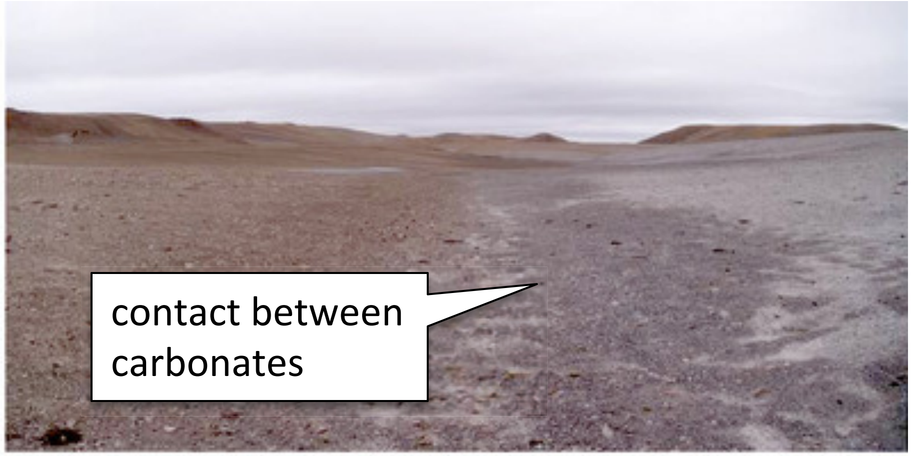
Geologic Mapping

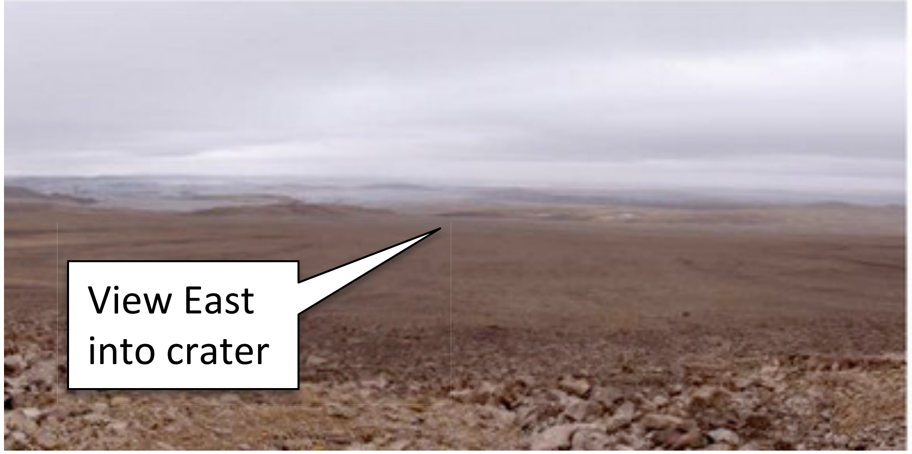
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

Geophysical Survey

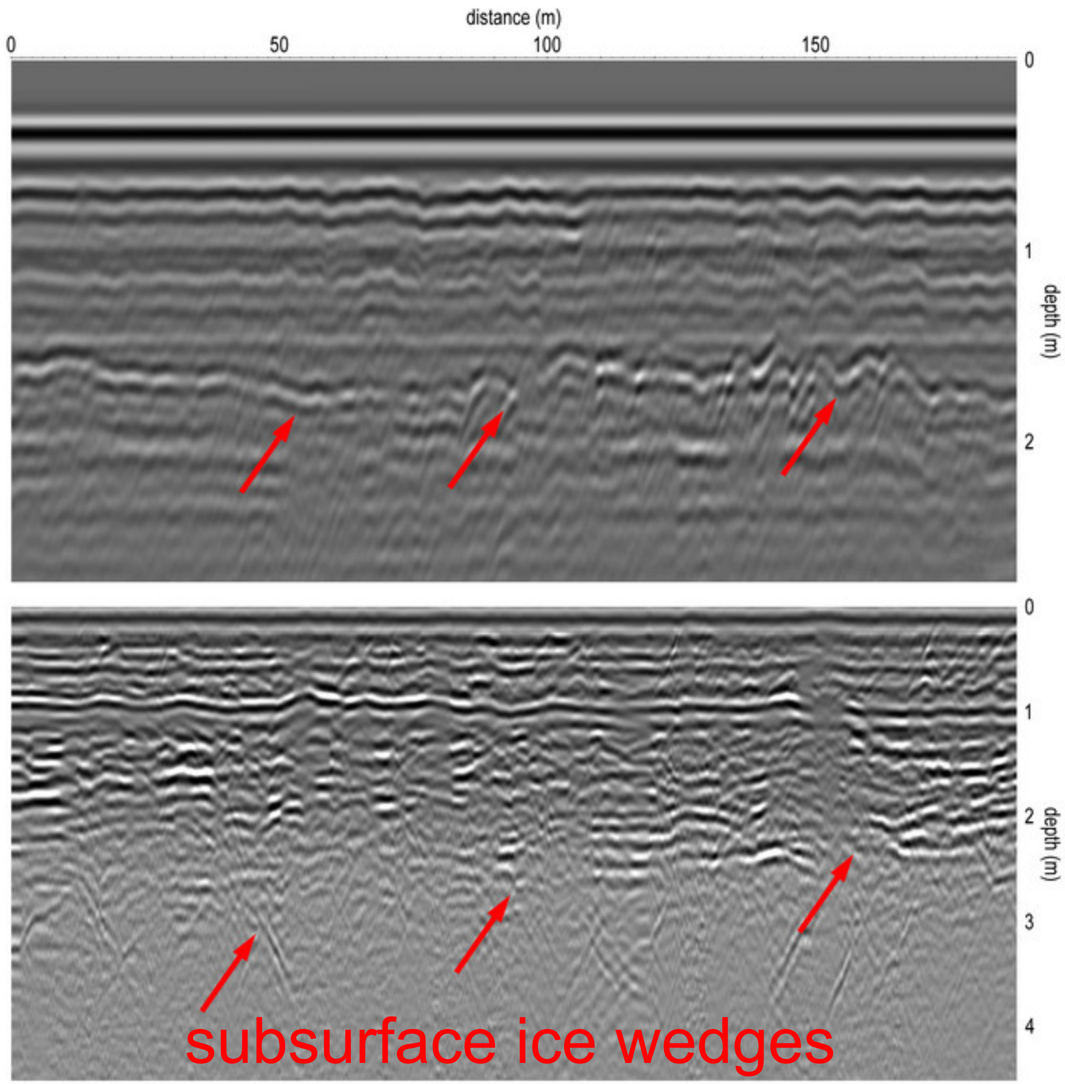
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz

Geologic mapping results

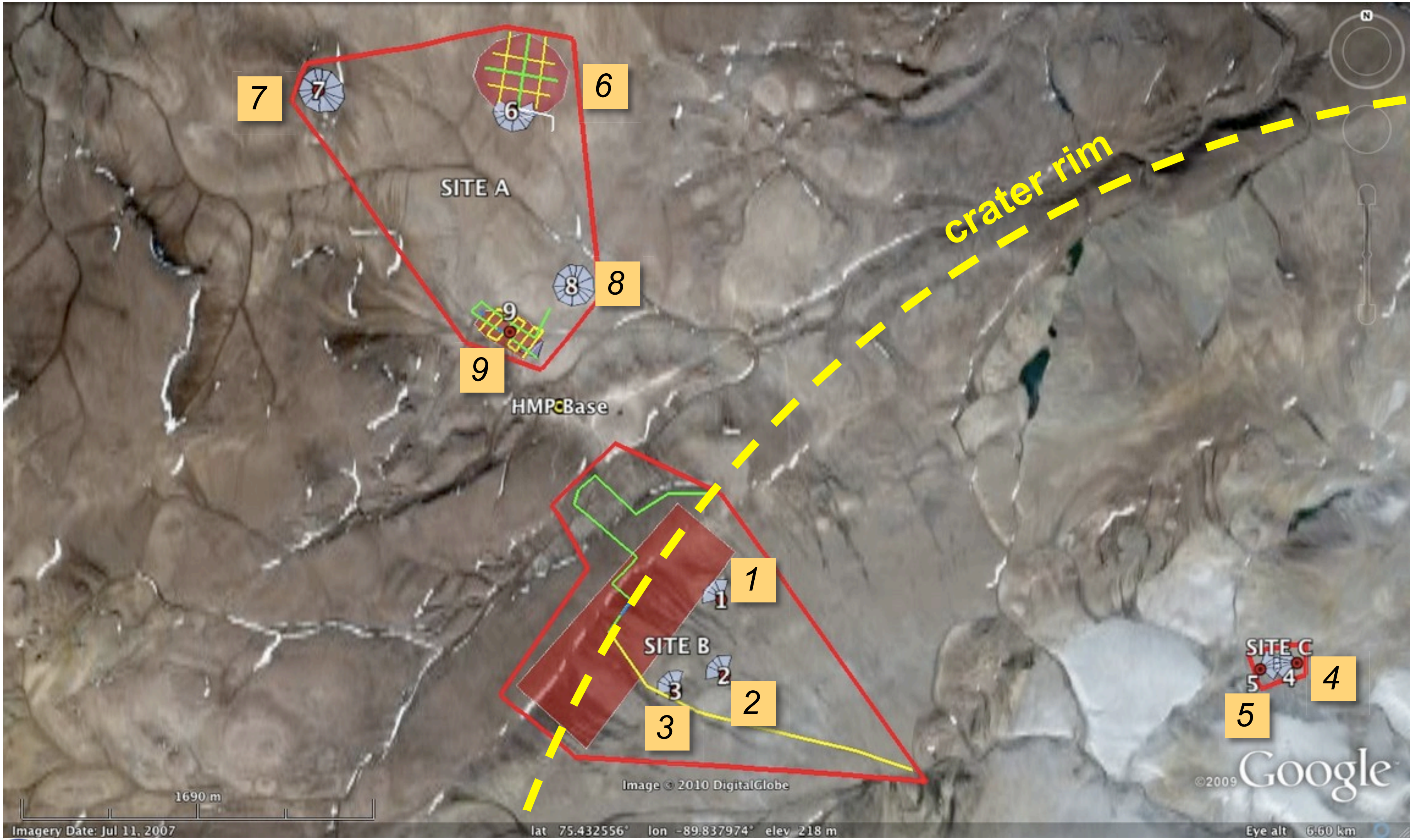




Geophysical survey results



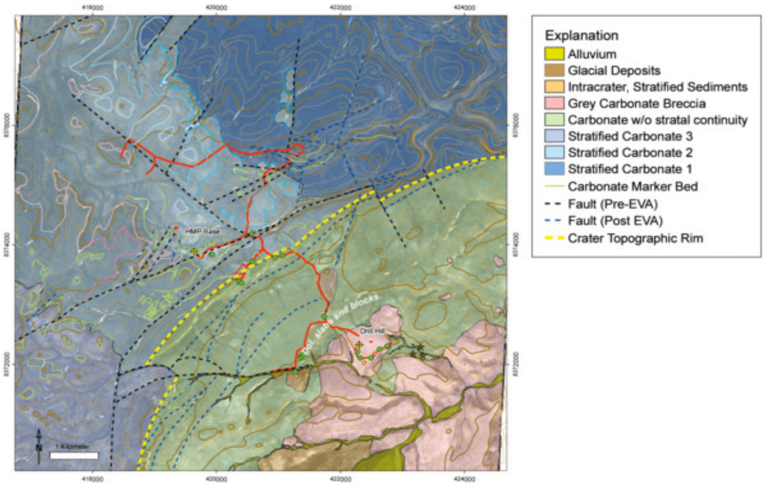
Robotic follow-up plan



Robotic follow-up 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, M. Bualat, et al. (2010) **"Robotic follow-up for human exploration"**. AIAA Space Conf.

Human-robot collaboration

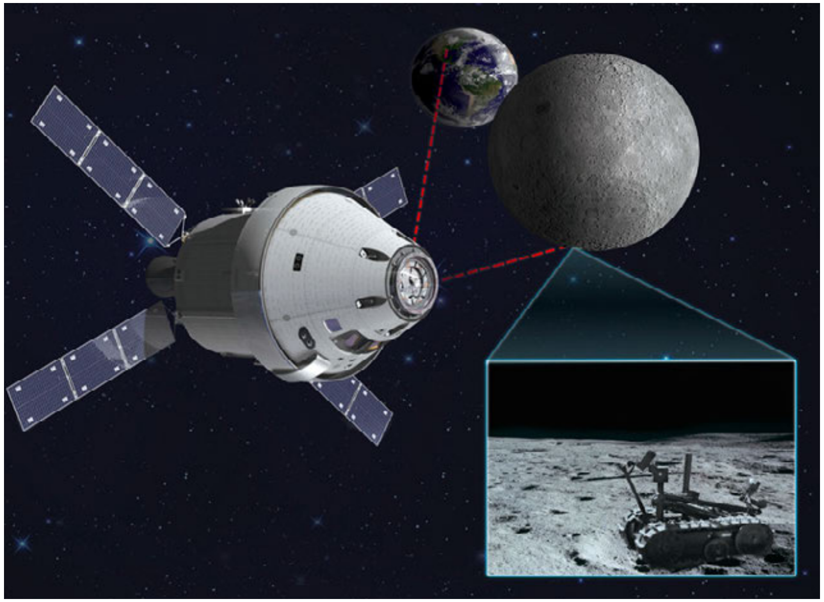
Our focus

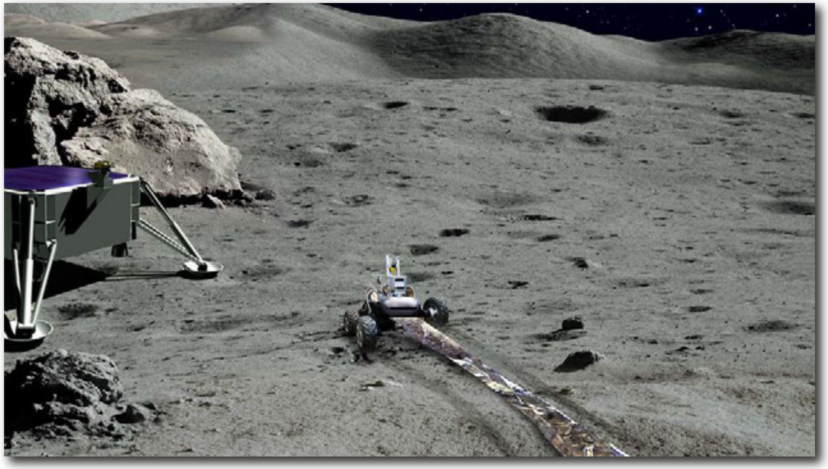
- Study how **humans can remotely support robots**
- Address the many **anomalies**, **corner cases**, and **edge cases** that require unique solutions, which are not currently practical to develop, test, and validate under real-world conditions
- Humans provide high-level guidance (not low-level control)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

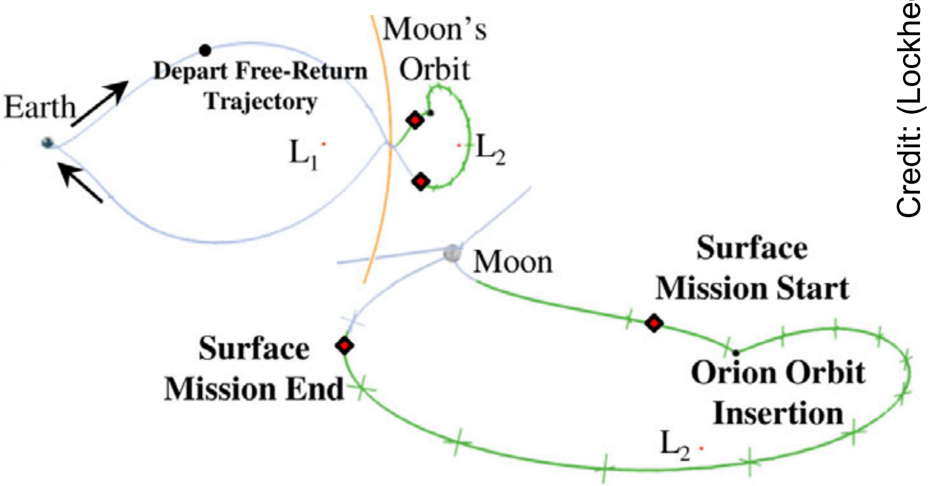
Lunar Mission Concept

Orion at Earth-Moon L2 Lagrange

- 60,000 km beyond lunar farside
- Allows station keeping with minimal fuel
- High-bandwidth, low-latency data communication to the lunar surface
- Astronaut remotely operates lunar rover from orbiting spacecraft – ***AVATAR in real-life!***
- Does not require human-rated lander







Credit: (Lockheed Martin / LUNAR)

Surface Telerobotics Project

Key Points

- Demo **crew-control** surface telerobotics (planetary rover controlled from space)
- 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

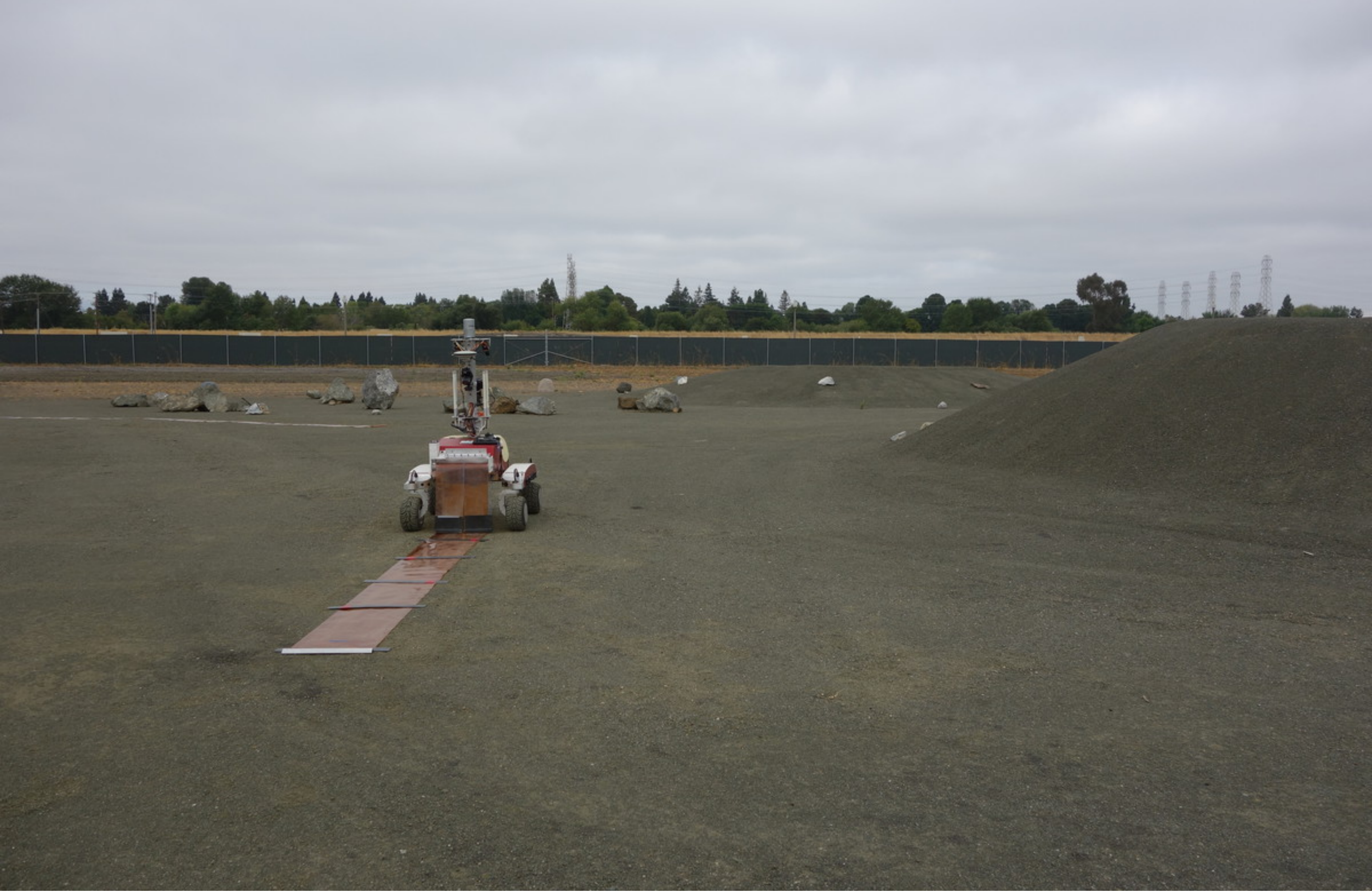
- **Human-robot mission sim**: site survey, telescope deployment, and inspection
- **Telescope proxy**: Kapton polyimide film roll (no antenna traces, electronics, or receiver)
- **3.5 hr per crew session** ("just in time" training, system checkout, ops, & debrief)
- **Robot ops**: manual control (discrete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

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)



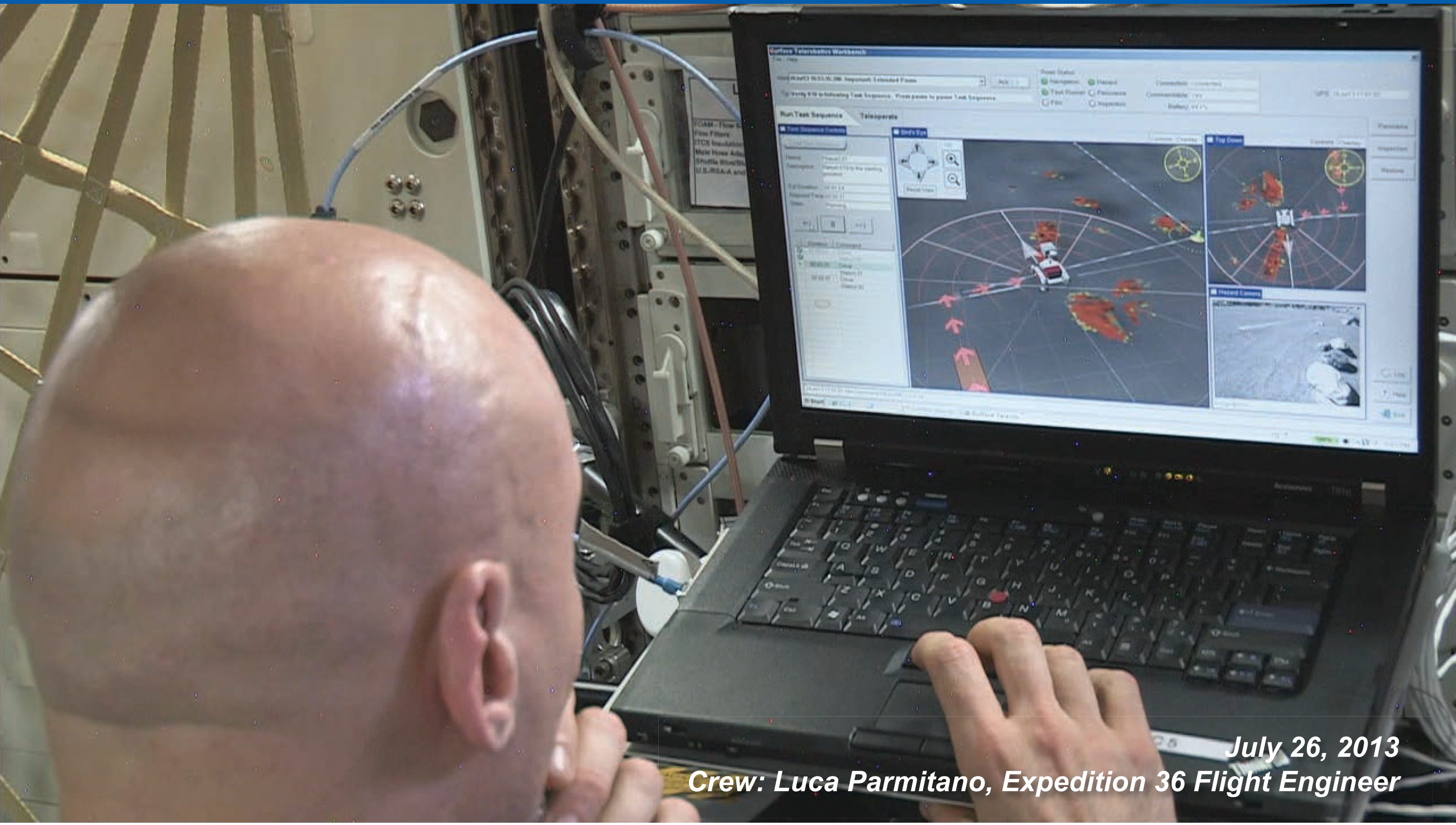
K10 deploying simulated polymide antenna

Deployed simulated polymide antenna (three "arms")

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

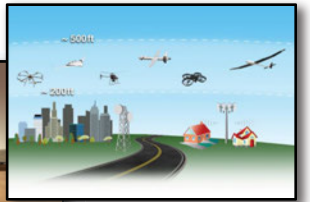
K10 documenting simulated polymide antenna

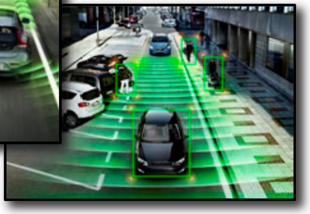
Crew control of K-10 rover



July 26, 2013
Crew: Luca Parmitano, Expedition 36 Flight Engineer

NASA and self-driving cars





NASA Missions

Planned human-machine interaction

Natural and time delayed environments

Aerial, space, and planetary navigation

On-board and ground control autonomy

Cyber-security for "one-off" systems

…

Common Technologies

Autonomy
Advanced Planning & Scheduling Algorithms, etc.

Human-Autonomy Teaming
Robotic Supervision including Human/Robotic Interactions, etc.

Networked Operations
Remote Vehicle Management, etc.

Prognostics / Diagnostics
Including State Management, etc.

Sensors and Perception
Data Processing / Fusion Methodologies, etc.

Verification and Validation
Methodologies & Application Experiences, etc.

Self-Driving Cars

Diverse human-machine interaction

Structured environment

GPS & map-based navigation

Distributed and cloud-based autonomy

Cyber-security for consumer product

…

Self-driving cars at NASA Ames

Public/private partnerships

- **Google** (2014-15): collaborative testing of sensors and vehicles
- **Nissan** (2014-17): cooperative software development

NASA interest

- Expand knowledge of commercial autonomous systems
- Develop protocols and best practices for safe testing of real-world autonomy
- Transfer NASA technology to terrestrial applications

Technology maturation

- Safe testing in urban environment
- Leverage NASA expertise in autonomy, robotics, safety critical systems, and vehicle systems

Nissan Leaf at Ames

Google Prius at Ames

Imperfect vehicle autonomy

Edge cases, corner cases, and anomalies

- When a construction worker uses hand gestures to provide guidance, or direction, no autonomous car today can reliably make the right decision.
- When the sun is immediately behind a traffic light, most cameras will not be able to recognize the color of the signal through the glare.
- If we see children distracted by the ice cream truck across the street, we know to slow down, as they may dash toward it.

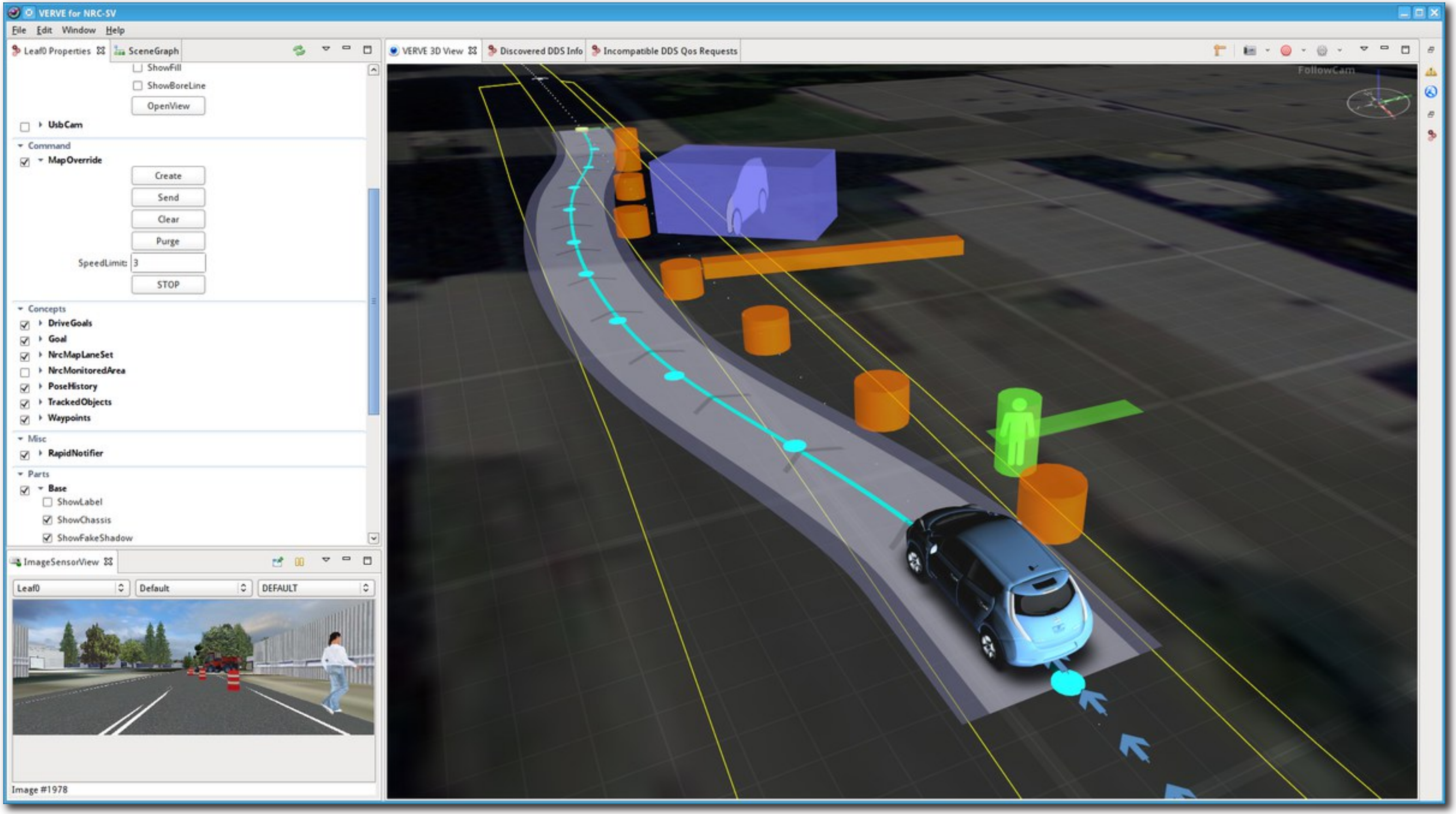
– Andrew Ng (Wired, 3/15/2016)

Astronaut helping planetary rover

Mobility manager helping self-driving cars

Vehicle assist: Situation assessment

Vehicle assist: High-level guidance

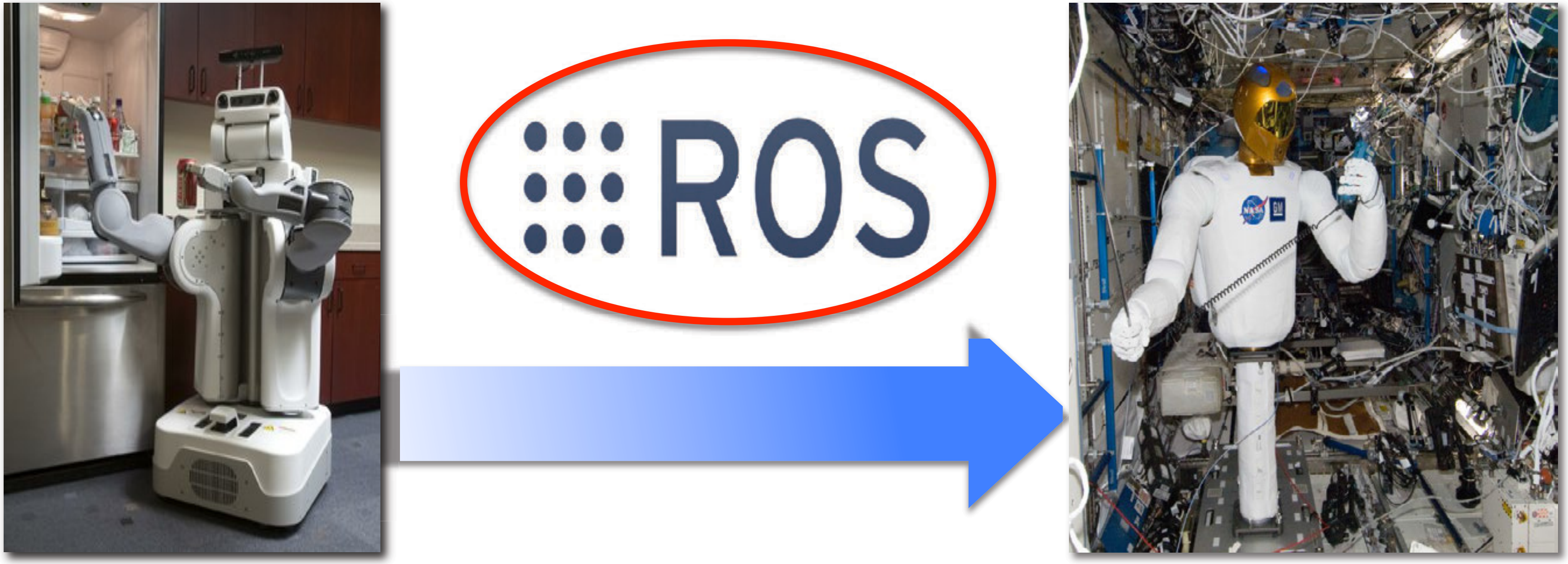


Consumer Electronics Show (2017)

Working with NASA: Small Business

SBIR / STTR program   sbir.nasa.gov

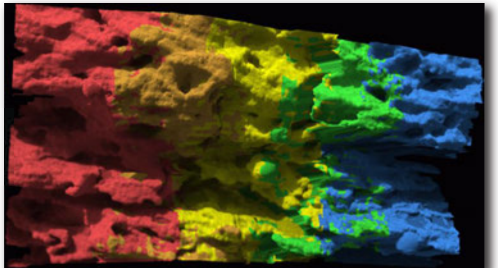
- **Adapt** and **mature** terrestrial robotics technology for space use
- **Identify** and **transition** low-TRL technology from academia
- Build commercial products for **economies of scale** & **sustainability**
- Help NASA move beyond “one-off” components and systems
- Next solicitation: **January 2018**

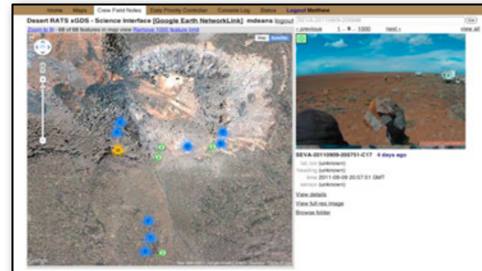


Working with NASA: Software Licensing

Vision Workbench

Apache 2



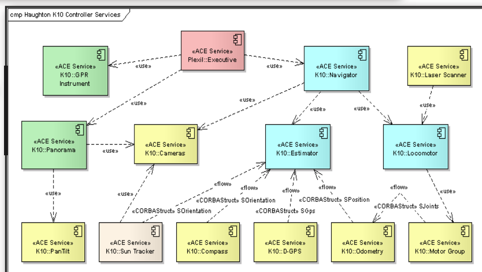


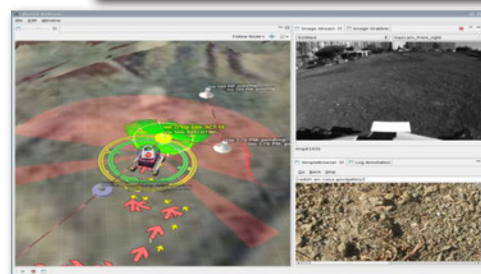
Exploration Ground Data Sys. (xGDS)

Apache 2

RoverSW

NOSA 1.3





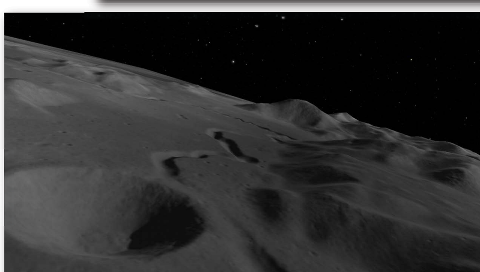
Visual Environment for Remote Virtual Exploration (VERVE)

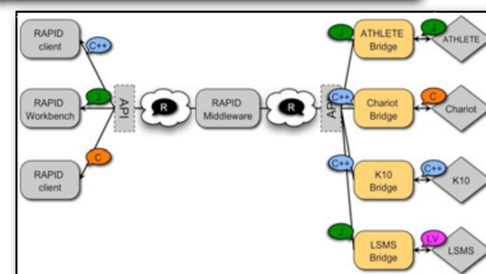
Apache 2

Neo Geography Toolkit

(Ames Stereo Pipeline)

Apache 2





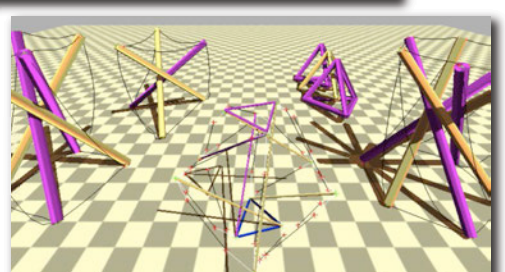
RAPID

(NASA robot middleware)

Apache 2

NASA Tensegrity Robotics Toolkit

Apache 2



Astrobee Robot Software

Apache 2

Working with NASA: Partnerships

Academic

- The Robotics Institute
- Leland Stanford Junior University (1891)
- Vanderbilt University
- MIT
- Case Western Reserve University, Est. 1826
- Berkeley, University of California
- Rutgers, The State University of New Jersey
- University of Idaho
- USC
- Brigham Young University (BYU), Founded 1875, Provo, Utah
- Wisconsin, University of Wisconsin–Madison
- Cornell University
- Universiteit Gent
- SETI Institute
- KAIST, Korea Advanced Institute of Science and Technology, 한국과학기술원

Commercial

- Google
- Nissan
- Astrobotic
- SSL
- Energid, Robotics and Machine Vision
- Otherlab
- Altius Space Machines
- ProtoInnovations
- TRACLabs

Government

- DARPA
- Marine Corps Warfighting Lab, "Semper Fidelis"
- SPAWAR
- NPS, Praestantia per Scientiam, 1909
- Naval Research Laboratory, Washington, DC
- USGS, science for a changing world

Questions?

Intelligent Robotics Group
Intelligent Systems Division
NASA Ames Research Center

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