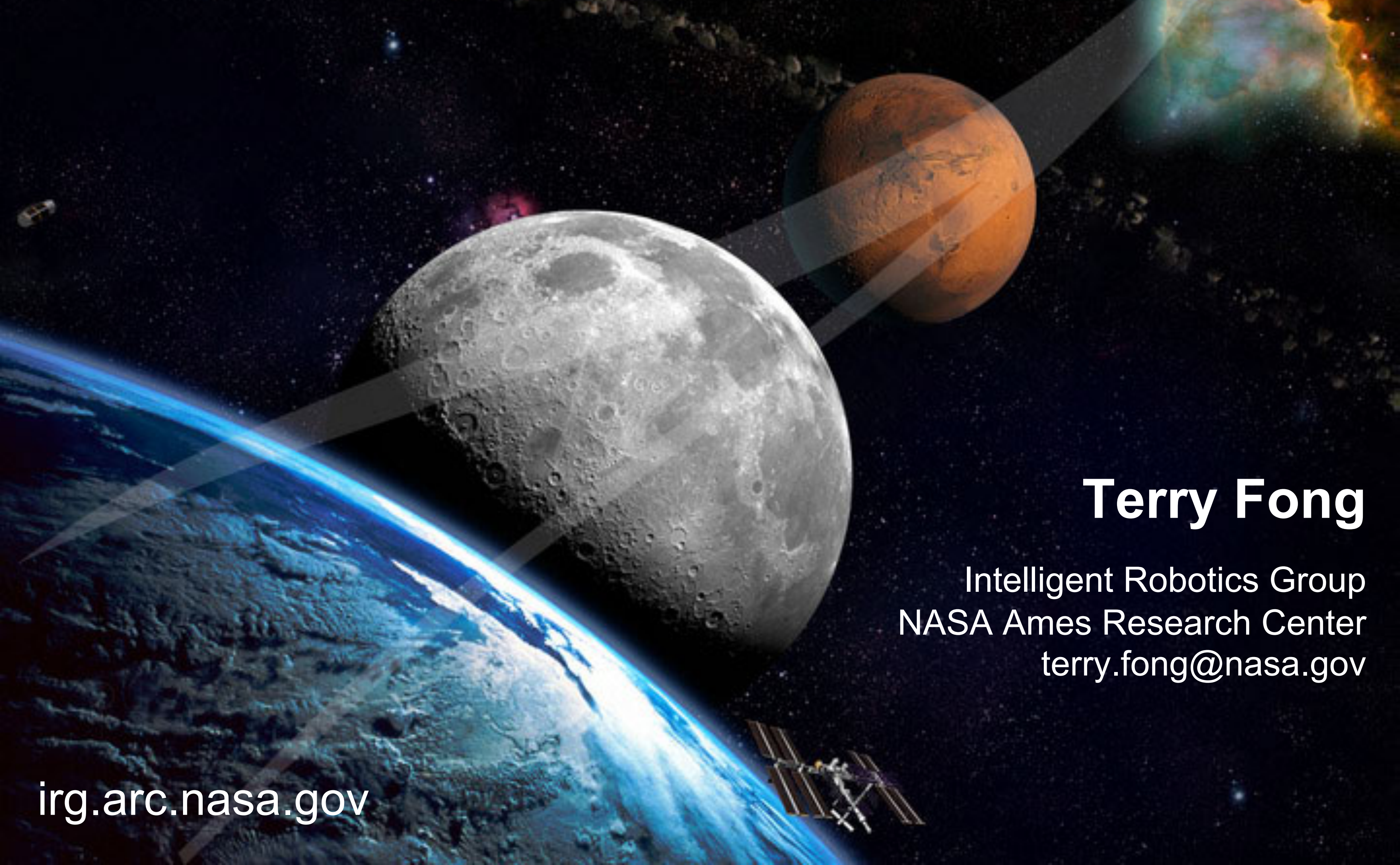
Planetary Exploration *REBOOTED* !

New ways of exploring the Moon, Mars, & beyond

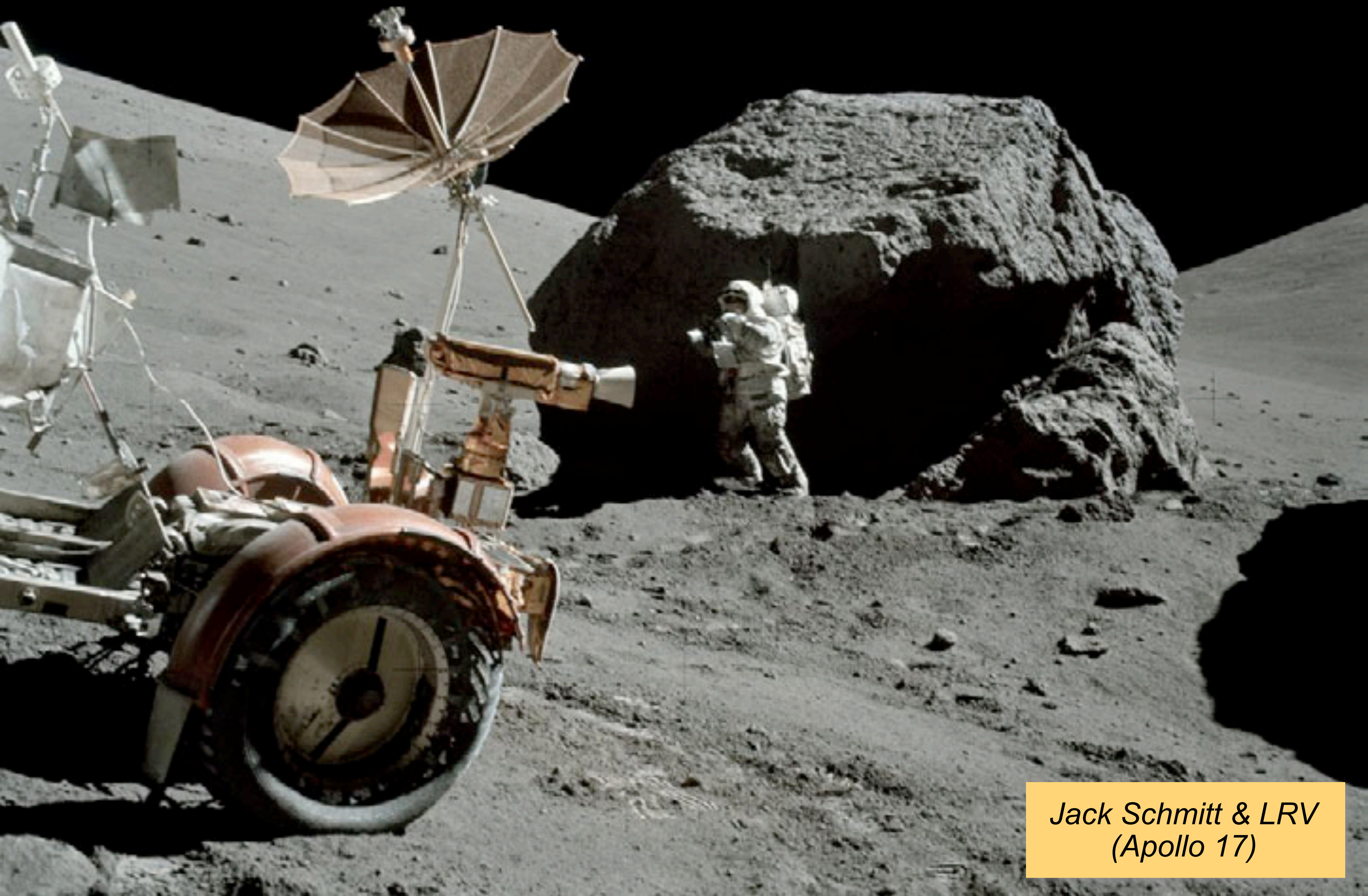


Terry Fong

Intelligent Robotics Group
NASA Ames Research Center
terry.fong@nasa.gov

irg.arc.nasa.gov

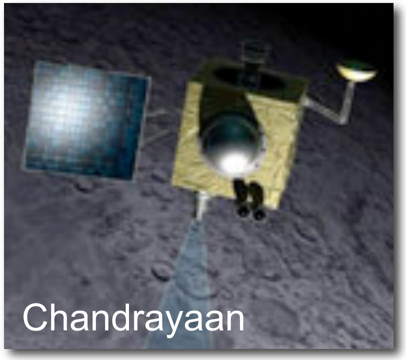
Apollo Surface Operations

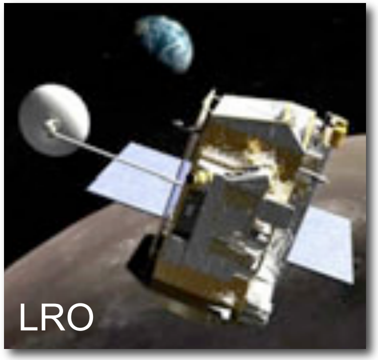


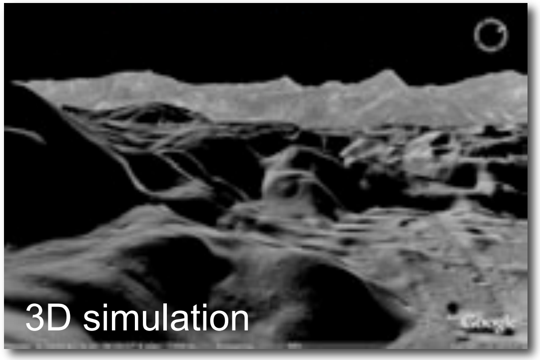
Jack Schmitt & LRV
(Apollo 17)

What’s Changed Since Apollo?


Kaguya


Chandrayaan


LRO


3D simulation


Phoenix


Dante II


Zoë


MER, Sojourner, MSL


ATHLETE, K10, Chariot

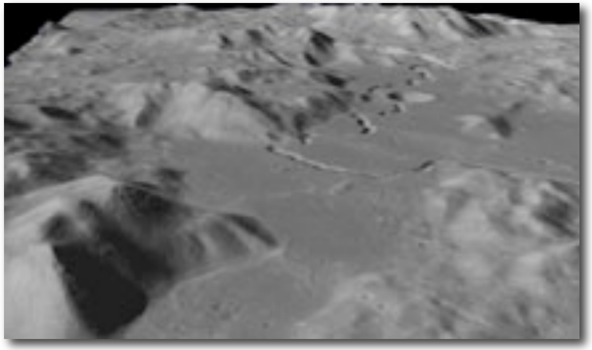
New Ways of Exploring

Part 1: Robots for human exploration

- Improve planning for crew missions
- Off-load “unproductive” tasks
- Before, during, & after

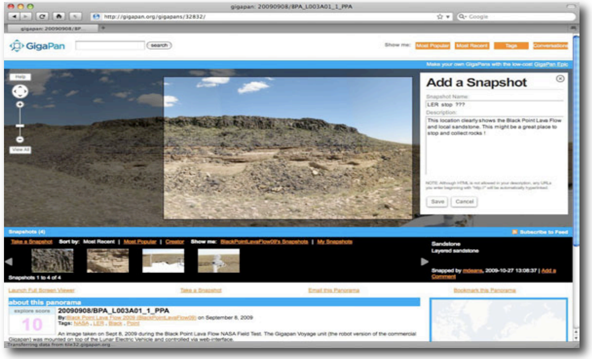
Part 2: Automated planetary mapping

- Image base maps
- 3D terrain reconstruction (DEM’s)
- Very rapid updates



Part 3: Participatory exploration

- Public involvement in missions
- Neo-geography & Web 2.0 tools
- Citizen science & education



Part 1: Robots for Human Exploration

Purpose

- Improve mission planning and crew productivity
- Off-load “unproductive” tasks (tedious, repetitive, long-duration)

Before crew

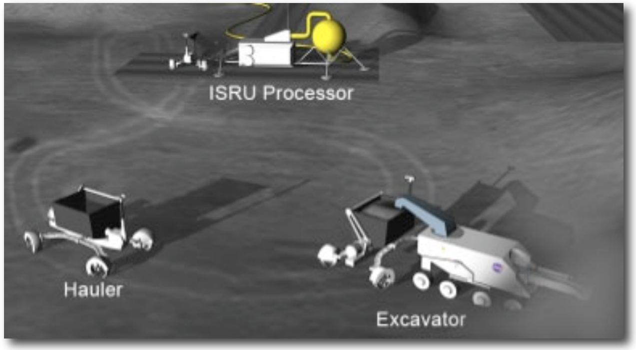
- Recon (scouting) & prospecting
- Site prep, deploy equipment, etc.

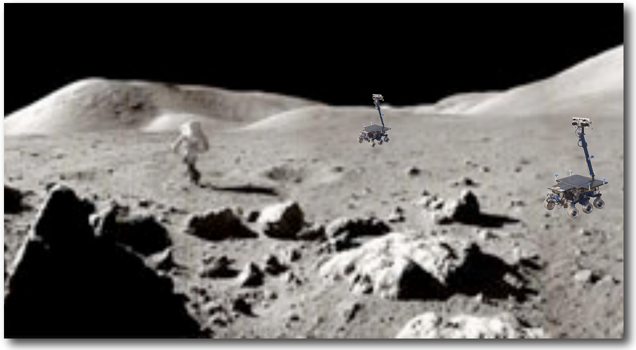
Supporting crew

- Inspection, mobile camera, etc.
- Heavy transport & mobility

After crew

- Follow-up & close-out work
- Site survey, supplementary tasks, etc.





NASA Human-Robotic Systems Project

Research areas

Surface mobility

- Crew
- Habitat
- Robots

Handling

- Cargo
- Payloads
- Resources

Human-robot interaction (HRI)

Primary objectives

- Address key technical challenges for lunar surface operations
- Develop requirements & mature systems for lunar surface operations
- Perform trade studies in laboratories and analog environments

NASA Centers: ***ARC****, GRC, GSFC,* ***JPL****,* ***JSC****, KSC, LaRC*

HRS Field Testing

Test and validate

- Technologies, systems, & protocols
- Integrated mission simulations

Analogs are never 100% perfect

- No place on Earth is exactly the Moon
- Many factors to consider

Factors and fidelity

Applications	Science; Exploration
Functions	Learn; Test; Train; Engage
Fidelity	Low; Medium; High; N/A
Value	Applications; Functions; Aspects; Fidelity; Cost-Effectiveness

Aspects
- Climate
- Geology
- Biology
- Terrain
- Logistics
- Other


Meteor Crater


Haughton Crater


Black Point Lava Flow

2006 Meteor Crater Field Test

3-16 September 2006

- Coordinated human-robot operations
- ARC, JSC, JPL, & LaRC
- Co-located with Desert RATS (shared infrastructure)

Lunar Short Stay Mission Simulation

1 ATHLETE positions Pressurized Rover Compartment (PRC)

2 Crew drive unpressurized rover to worksite

3 Crew dismount and walk to PRC to recharge suits

4 Centaur removes sample box (time-delayed teleop via satellite from Houston)

5 K10 performs autonomous "walkaround" (for remote visual inspection)

Visual Inspection

Robot-based imaging

- Autonomous approach & inspection photography
- HDR gigapixel panorama
- Crew (IVA or ground) analyzes images for problems

K10 inspection of SCOUT
Meteor Crater Field Test, Sept. 2006

M. Bualat, L. Edwards, et al. (2007)
"Autonomous robotic inspection for lunar surface operations"
Field & Service Robotics

Basic Panorama

HDR Panorama

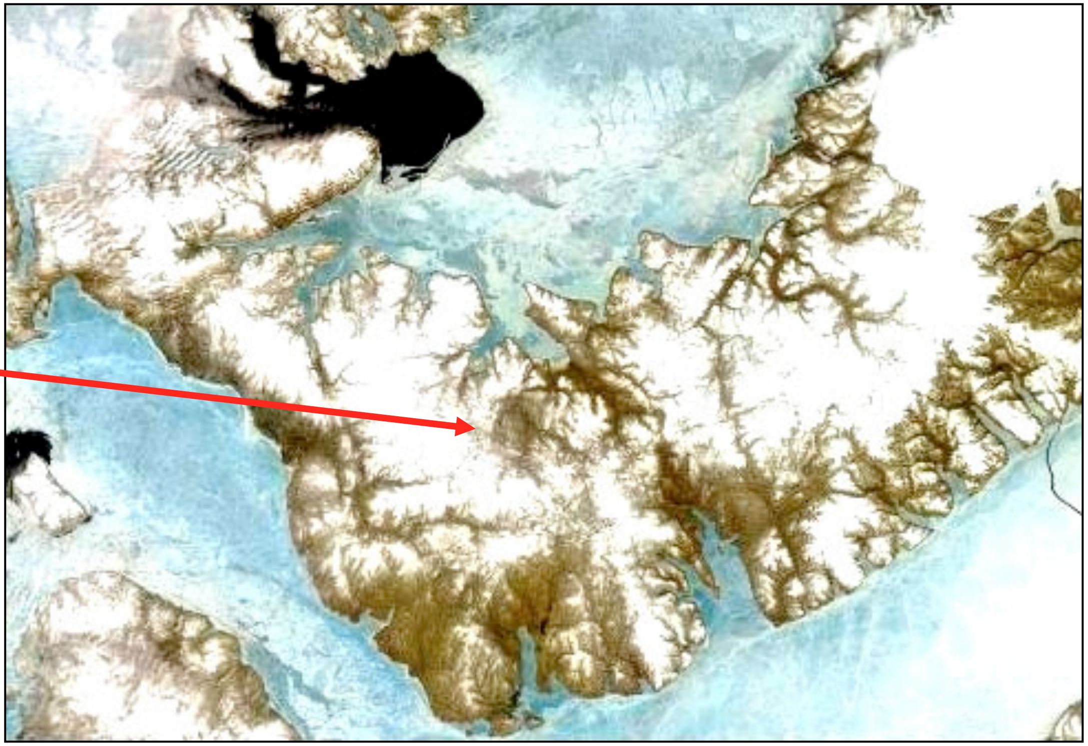
2007 Haughton Crater Field Test

10 July – 3 August 2007

- **Systematic site survey** with two K10 robots
  - 3D scanning lidar for topographic mapping
  - Ground-penetrating radar for resource prospecting
- Multiple lunar analog sites at Haughton Crater
- Remote (habitat & ground control) robot operations

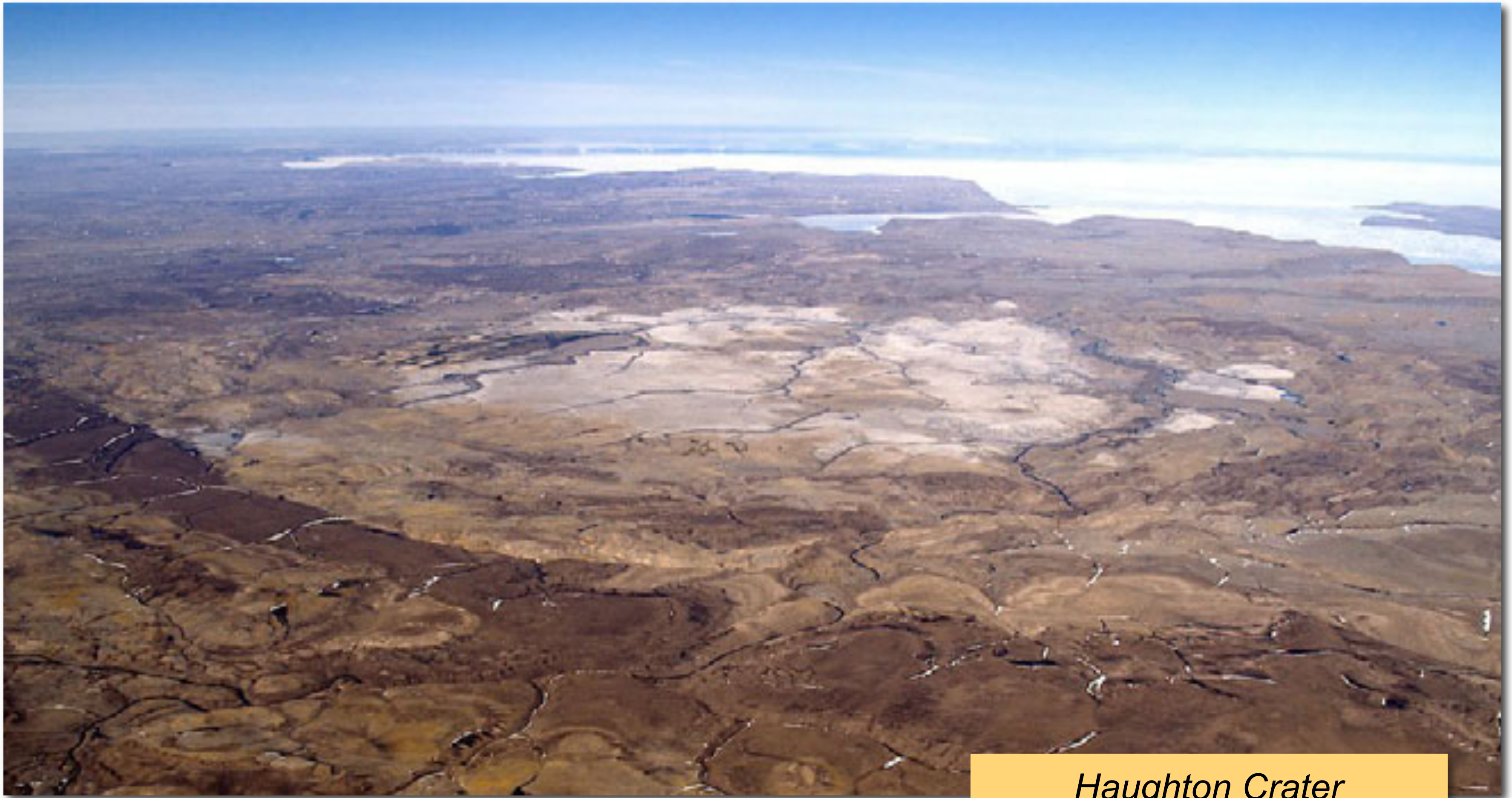
T. Fong, M. Allan, et al. (2008)
"Robotic site survey at Haughton Crater"
Intl. Symposium on AI, Robotics, & Automation in Space

Haughton Crater



- Devon Island: 66,800 sq. km
- Largest uninhabited island on Earth
- Haughton Crater: ~20 km (diameter), ~39 Ma (Late Eocene)

Haughton Crater

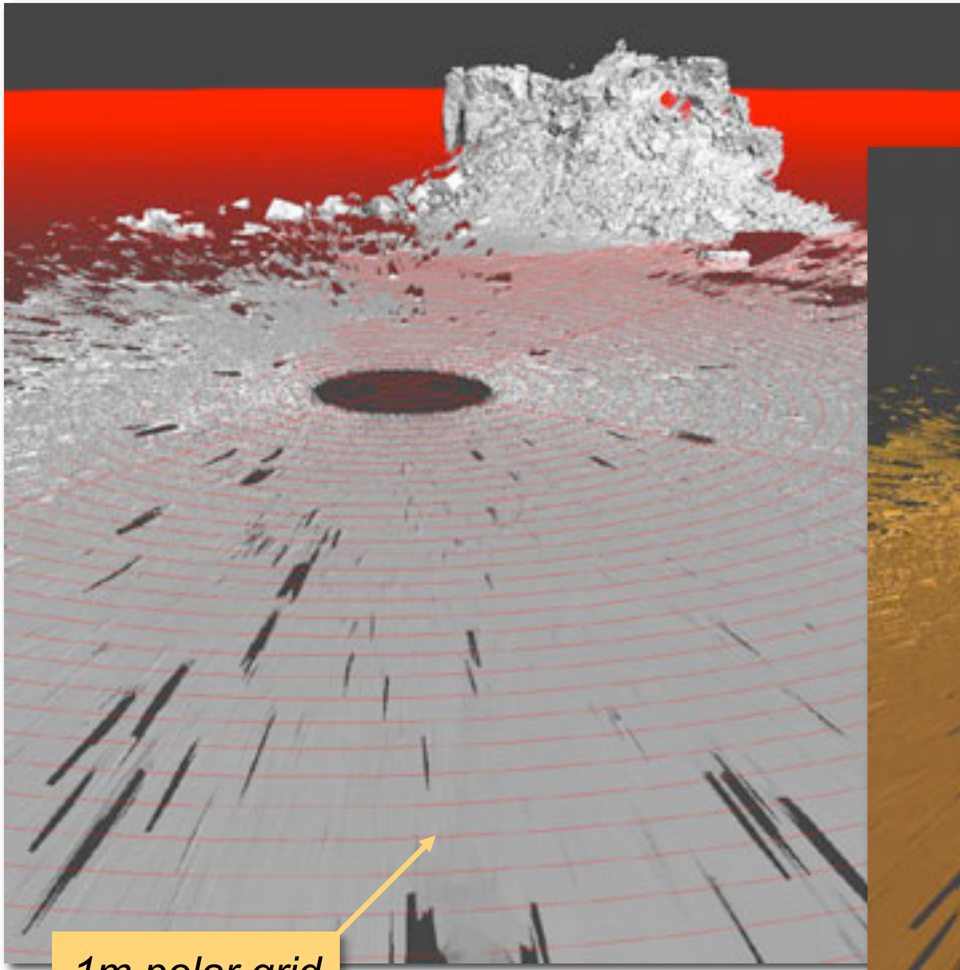


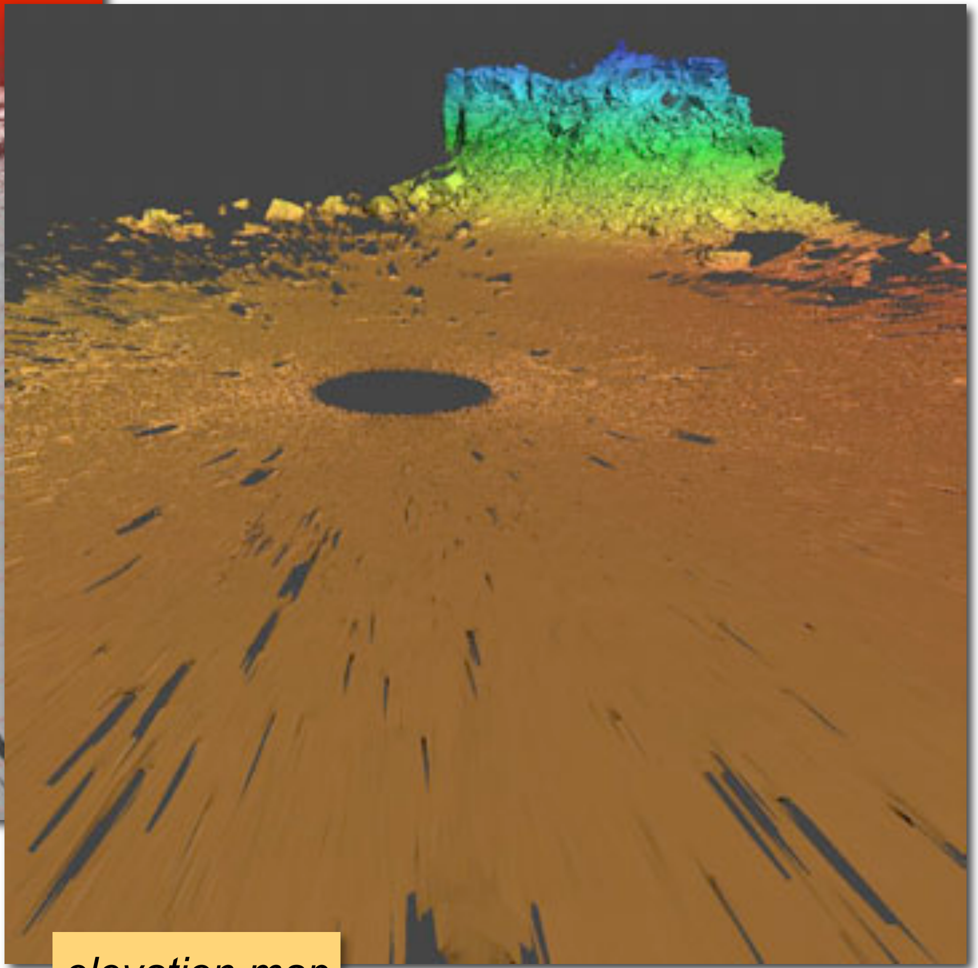
Haughton Crater
75º 22' N, 89º 41' W

2007 Haughton Crater Field Test

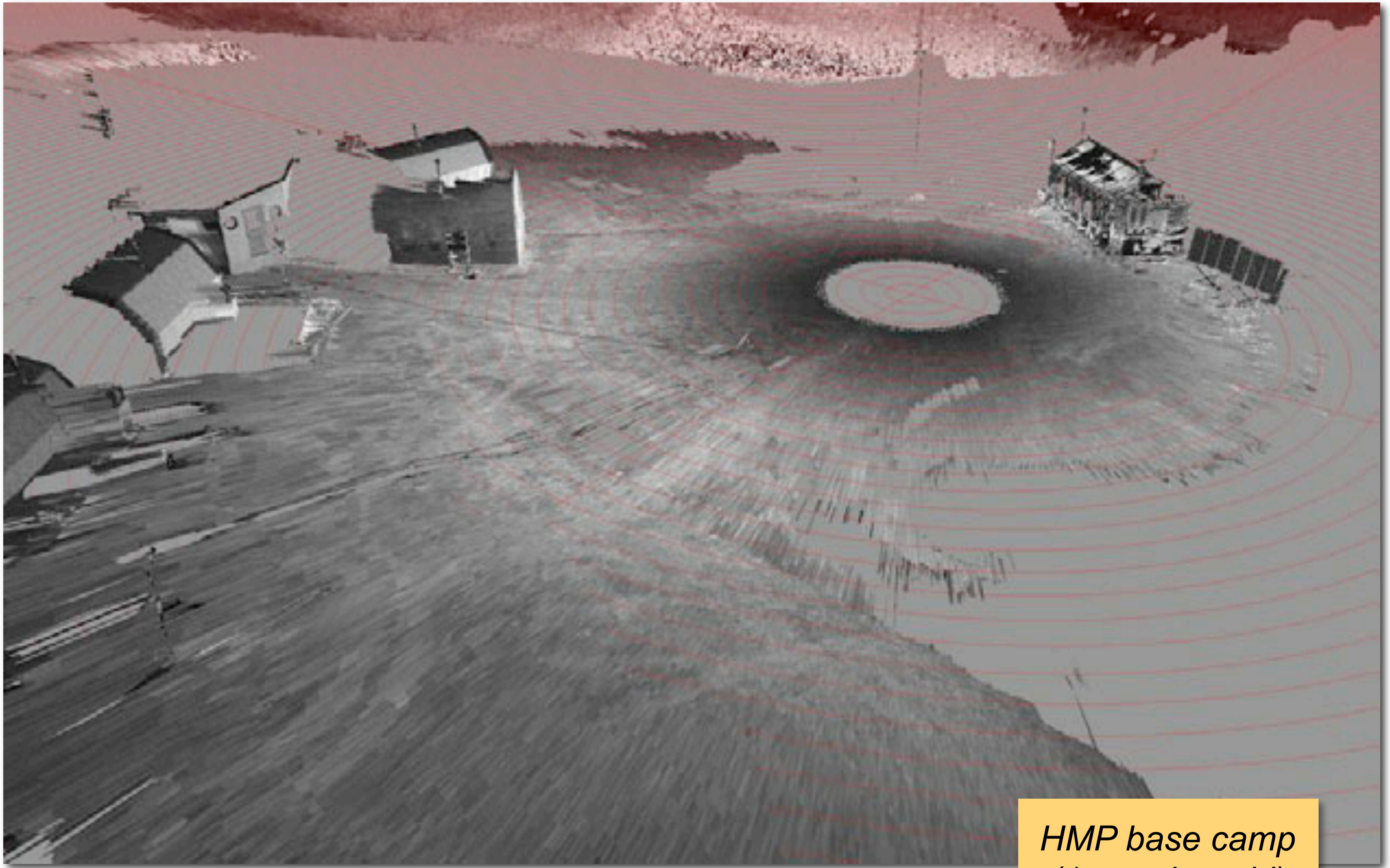
3D Mapping (Terrain)

3D Mapping (Terrain)



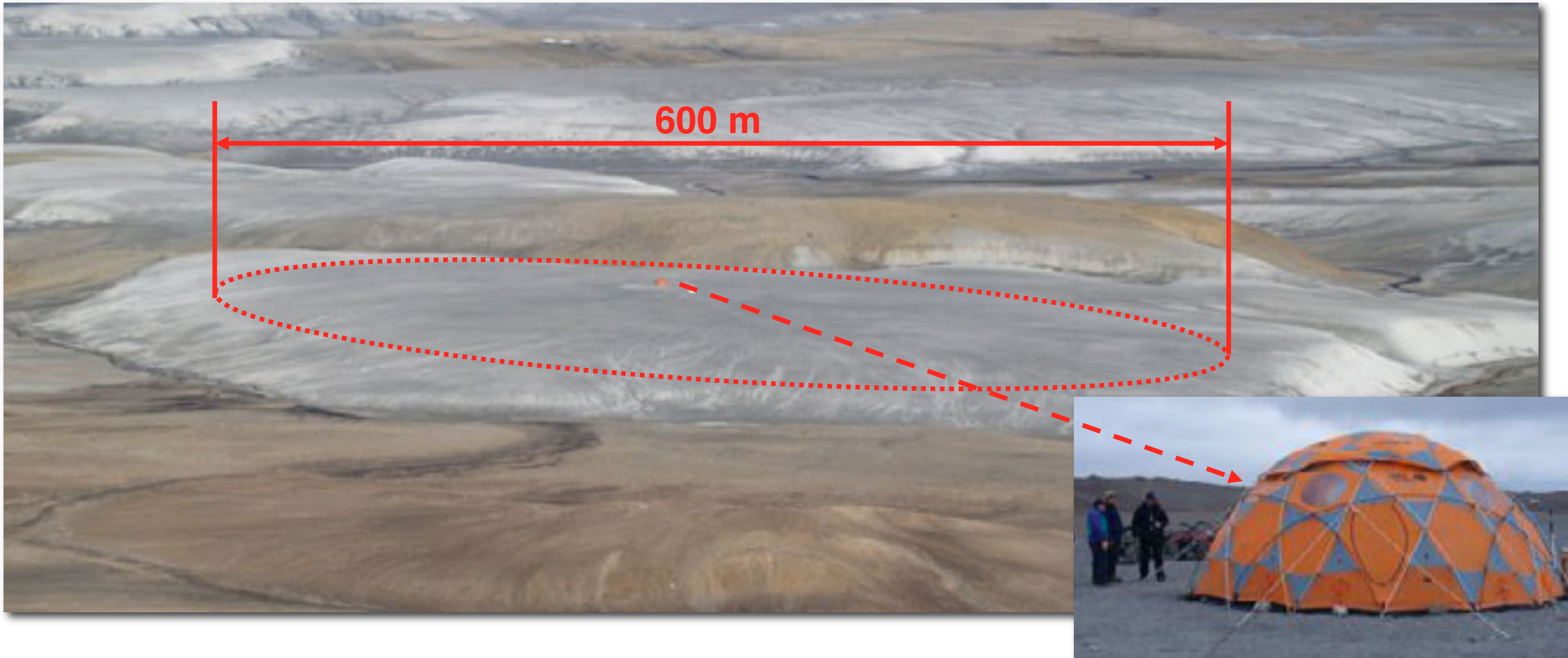


3D Mapping (Structures)



HMP base camp
(1 m polar grid)

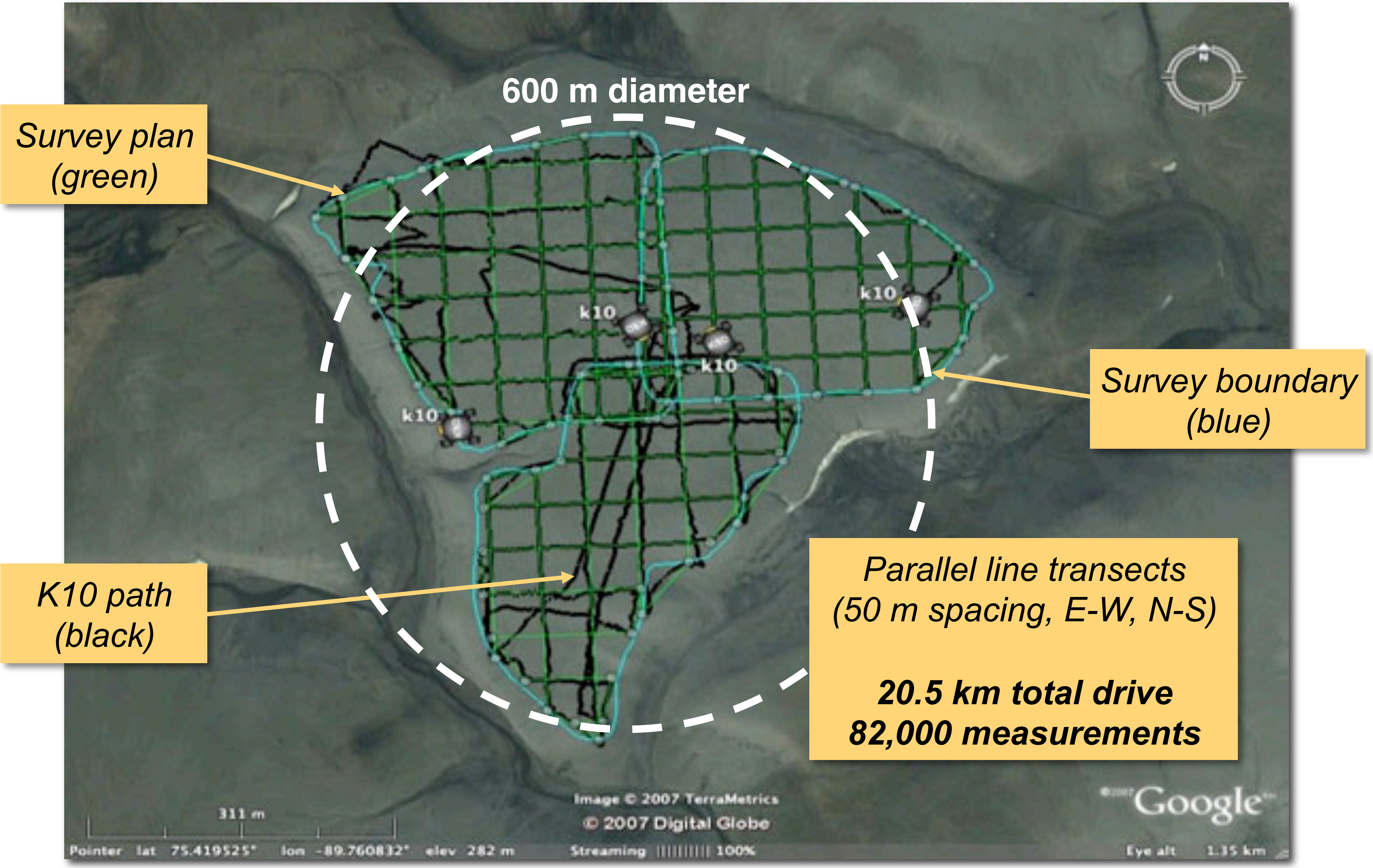
"Drill Hill" Subsurface Survey



Ground Penetrating Radar survey

- Resource prospecting: subsurface scans for buried water ice
- Parallel transects (lawnmower pattern) with 50 m spacing, E-W & N-S
- Survey speed limited by sensor data acquisition rate !

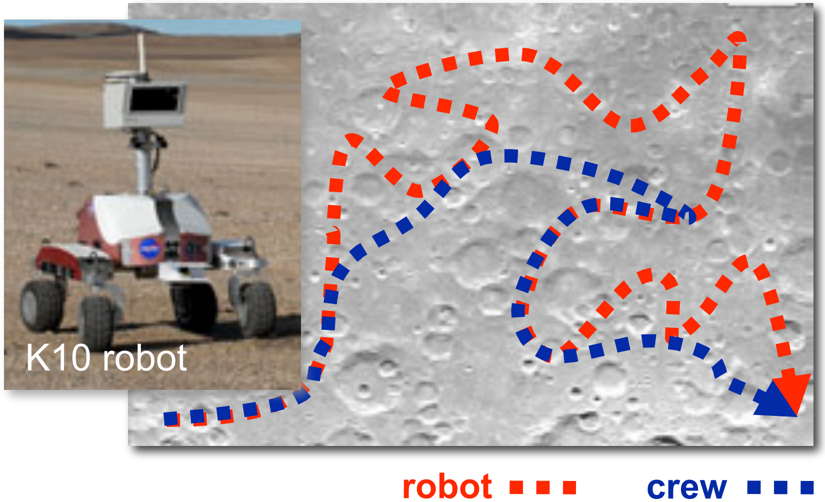
"Drill Hill" Survey



2009 Robotic Recon Experiment

Focus

- Test robotic recon in advance of crew (LER-based mission)
- Test coordinated human-robot field exploration technique
- Improve productivity & science during human exploration missions

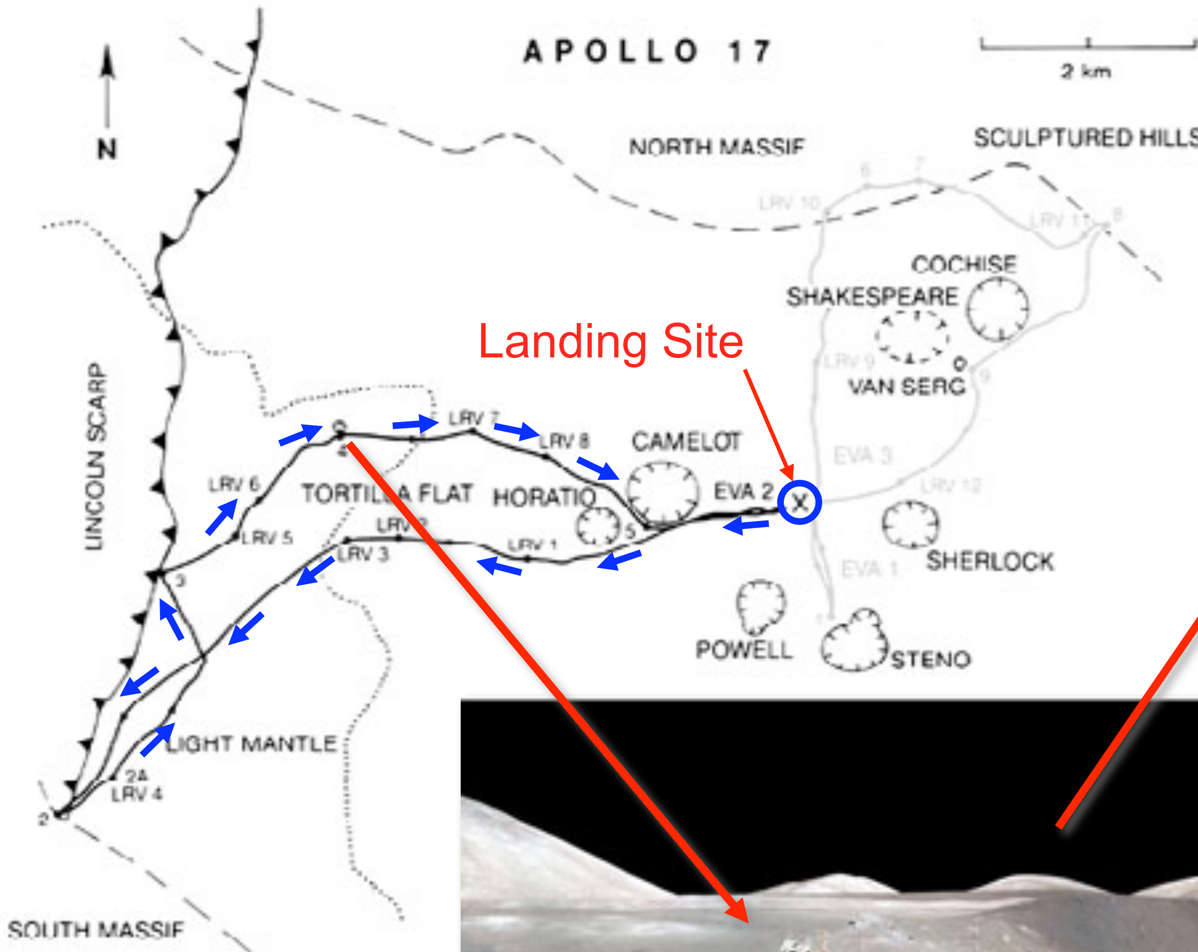


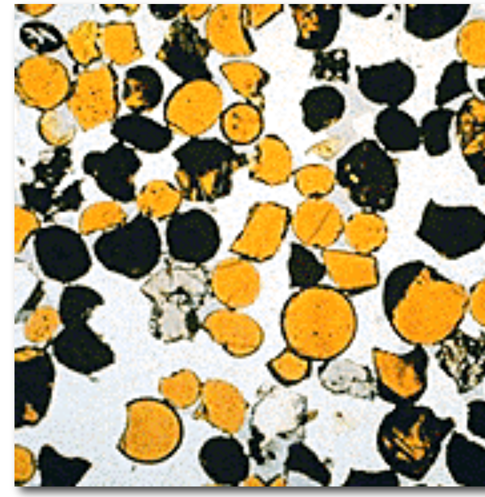
Objectives

- Assess effect of robotic recon on traverse planning & crew productivity
- Capture requirements (instruments, comm, nav, etc.) for robotic recon
- Provide recommendations to lunar architecture and exploration planning

M. Deans, T. Fong, et al. (2009)
"Robotic scouting for human exploration"
AIAA Space (AIAA-2009-6781)

Why Is Recon Useful?



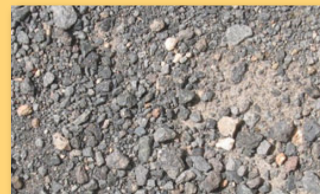


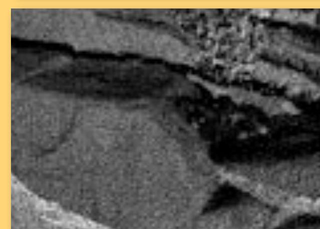
2009 Robotic Recon Experiment

Pre-Recon

Robotic Recon Mission

Pre-Crew





Crew Mission

Mar 1 – June 1
- Satellite images (LRO equiv.)
- Geologic map

June 14 – 26
- K10 at BPLF
- Ground control at NLSI

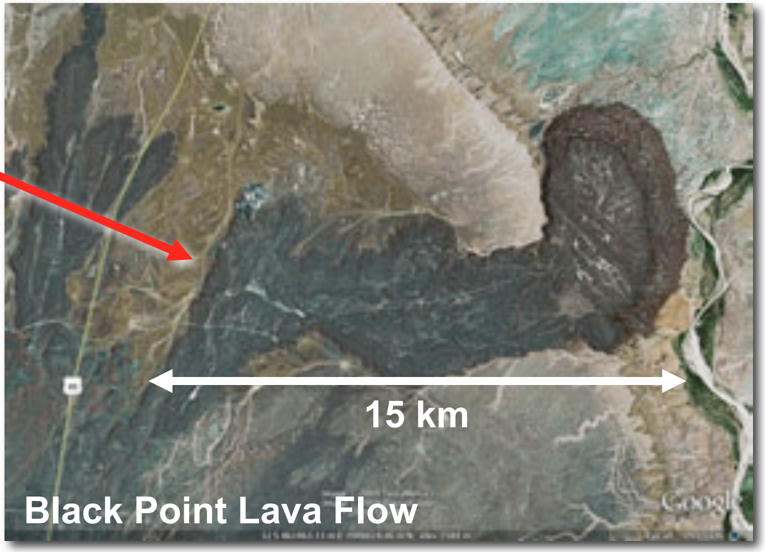
July 1 – Aug 15
- Satellite images
- K10 recon data (images, lidar)

Aug 29 – Sep 3
- LER at BPLF
- Science backroom at BPLF

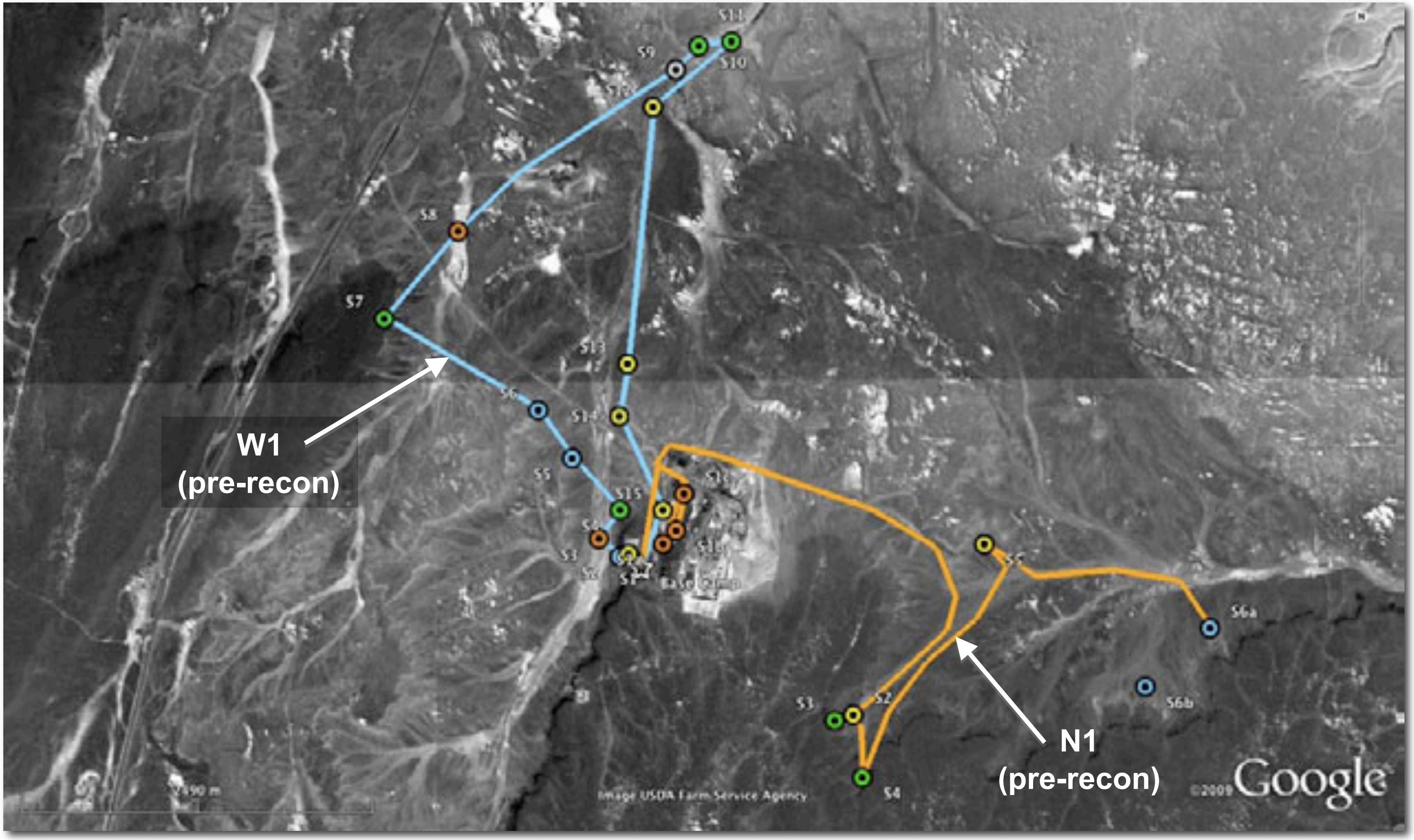
Lunar Analog Site

Black Point Lava Flow

- 65 km N of Flagstaff, AZ
- Analog of the “Straight Wall” (Mare Nubrium / Rupes Recta)
- Basaltic volcanic rocks & unit contacts



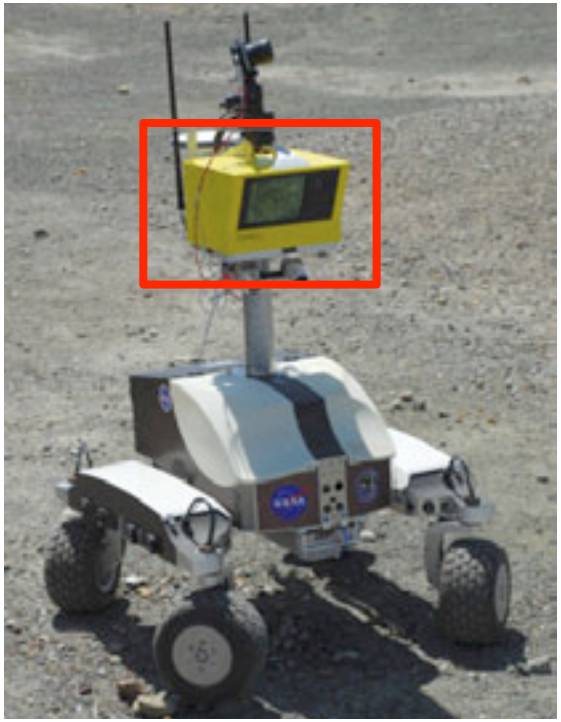
Preliminary Crew Traverses



Robotic Recon Mission (June 2009)

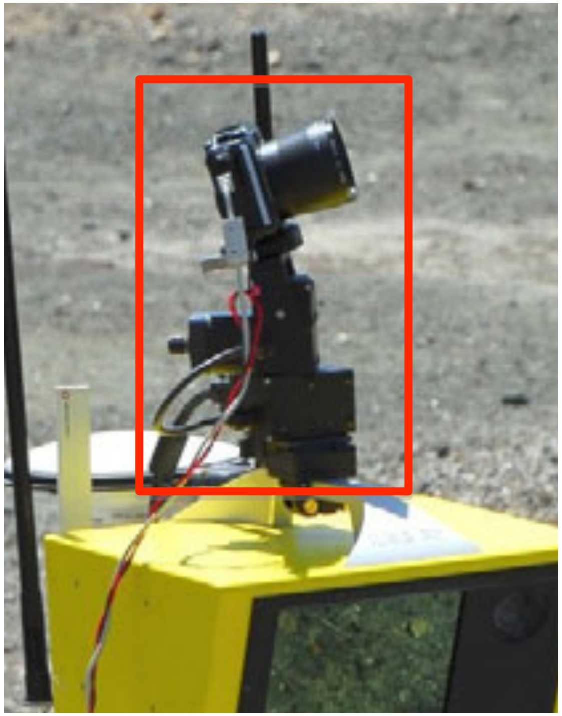
lunarscience.nasa.gov/roboticrecon

Robotic Recon Instruments



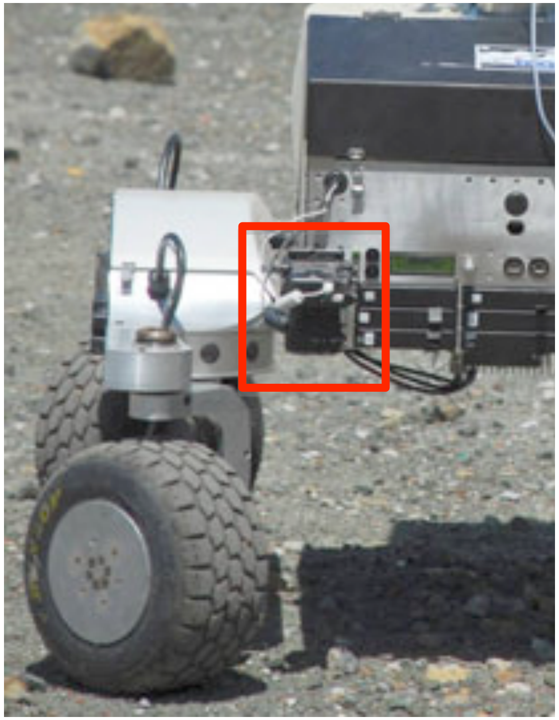
3D scanning LIDAR

- 3D topography measurements
- 5mm @ 500m
- Oblique views not possible from orbit



GigaPan

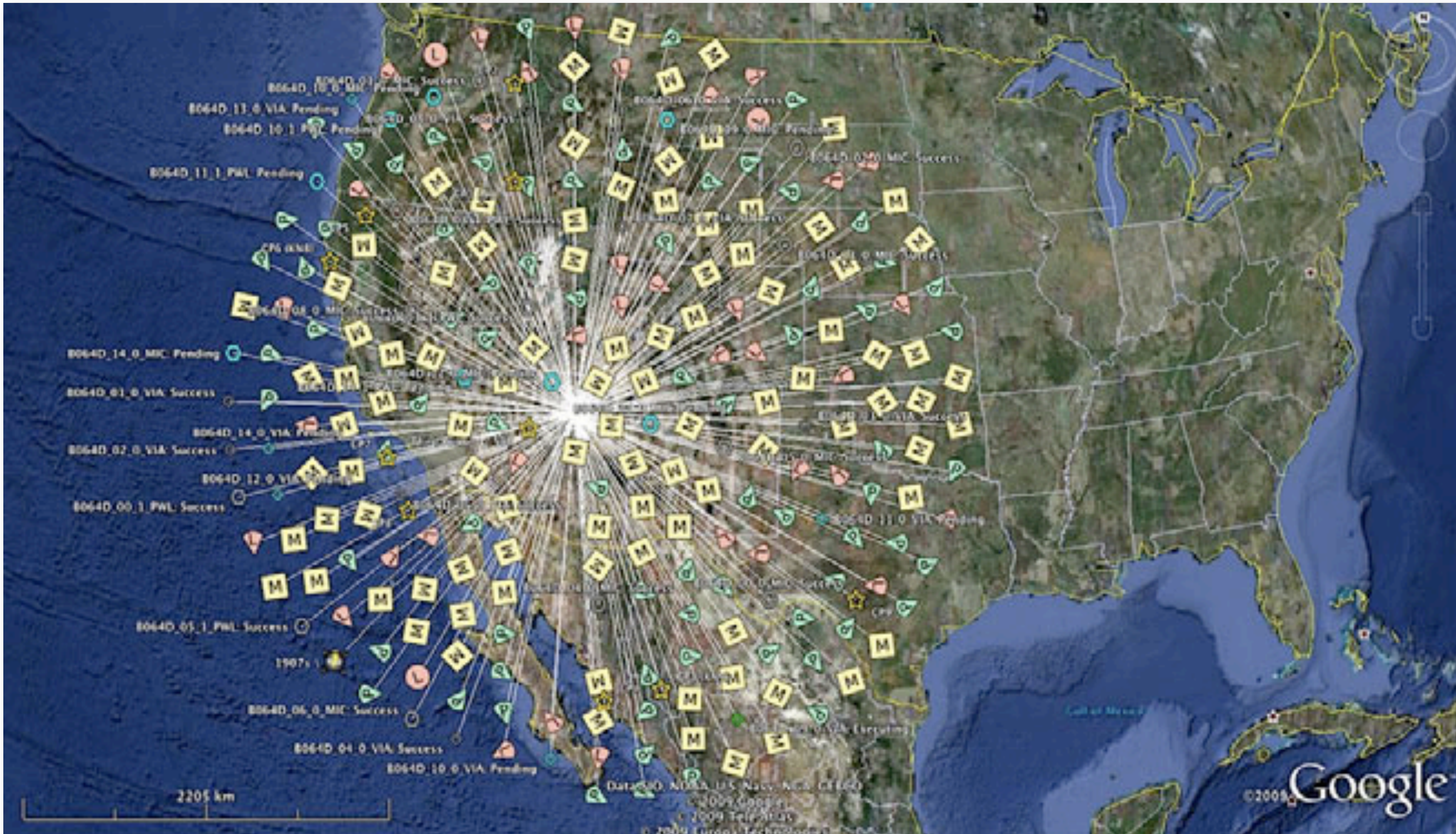
- Oblique, wide-angle, color, context views
- 60x180 deg
- >100x resolution of LRO LROC-NA



Microscopic Imager

- High-res, close-up, color, terrain views
- 72 micron / pixel
- >7,000x resolution of LRO LROC-NA

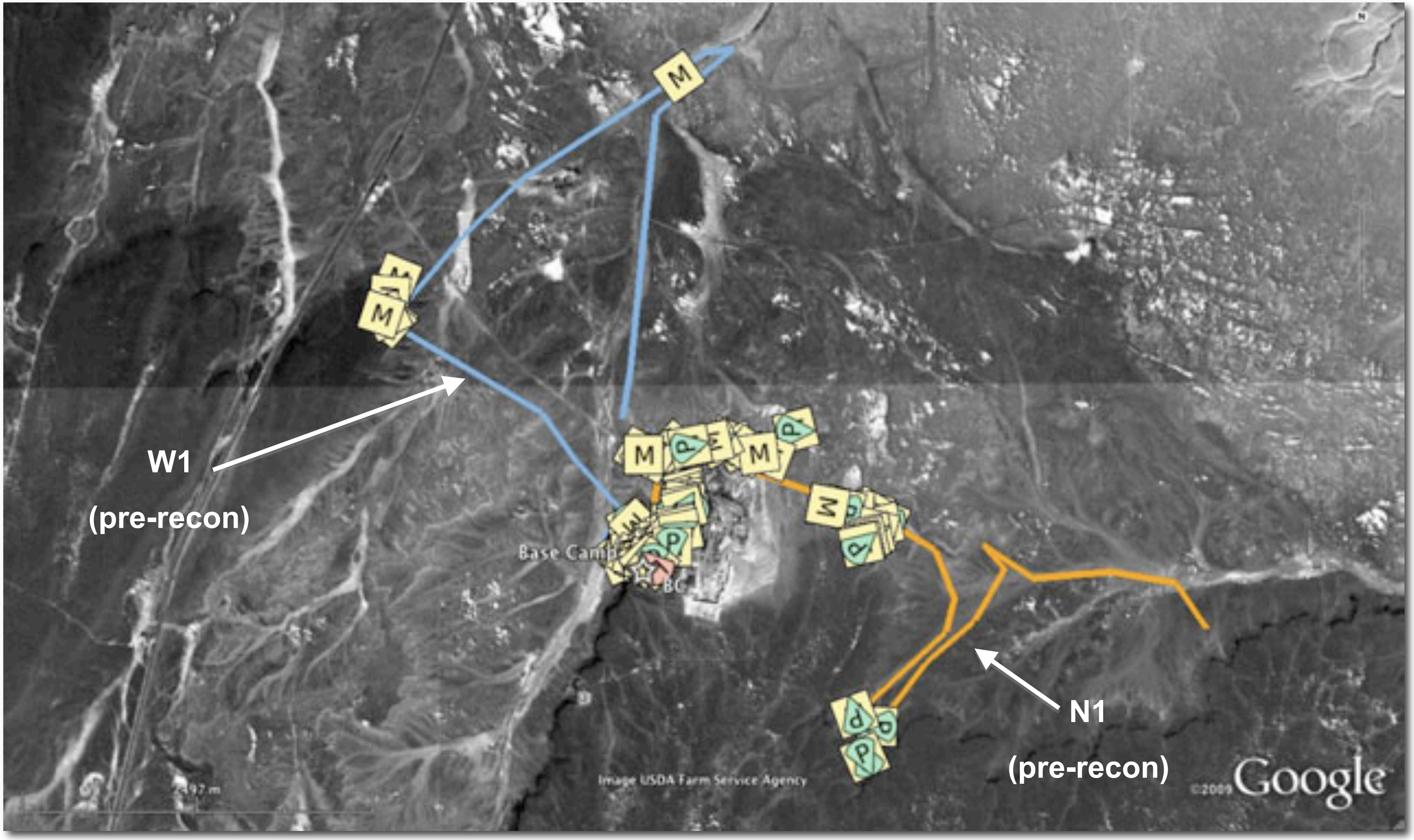
Collected Recon Data



8.5 GB data collected (52 hrs of robotic recon operations)

39 LIDAR scans, 75 GigaPan, and 95 terrain images

Collected Recon Data



Orbital Data

Digital Globe QuickBird (60 cm/pixel)

Surface Data

GigaPan panorama close-up

Terrain image (55 microns / pixel)

Crew Mission (September 2009)

Lunar Electric Rover (LER)

- 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

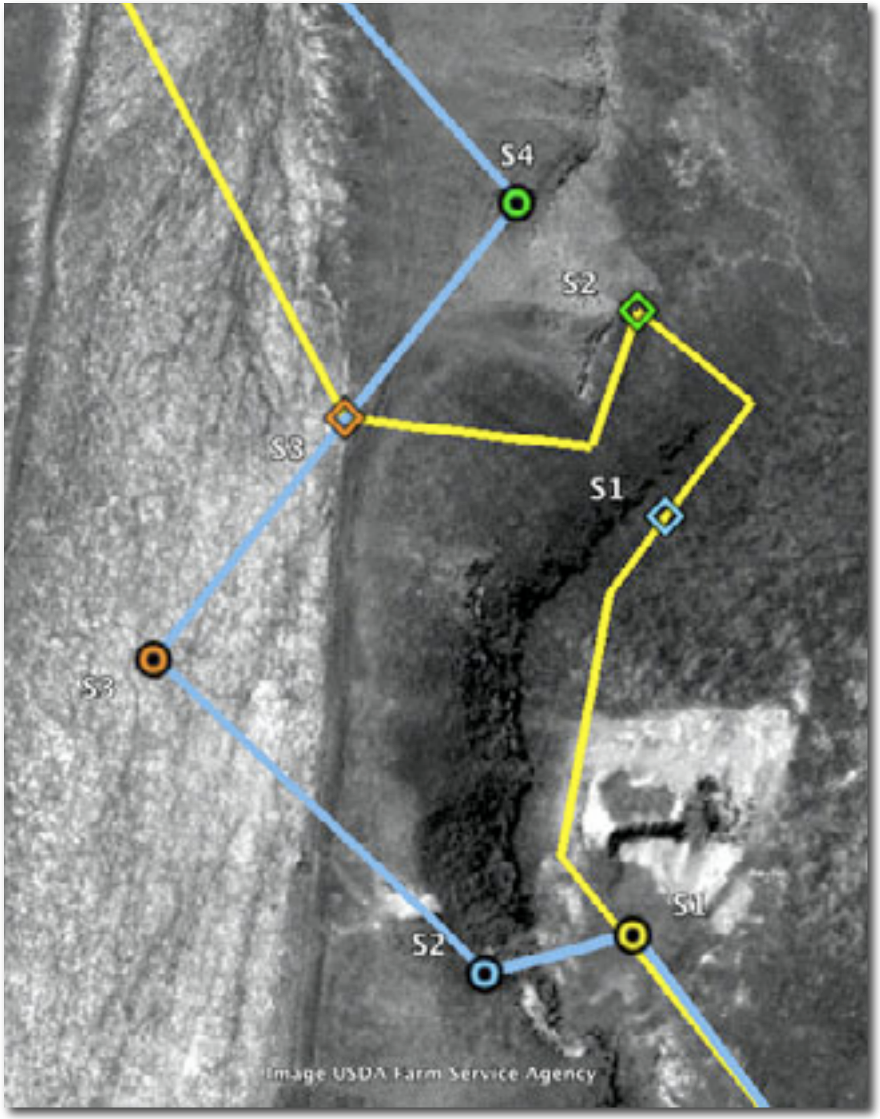
- Andy Thomas & Jake Bleacher
- N1 (pre-recon) + W2 (post-recon) traverses

Crew Mission (September 2009)

Impact on Traverse Planning

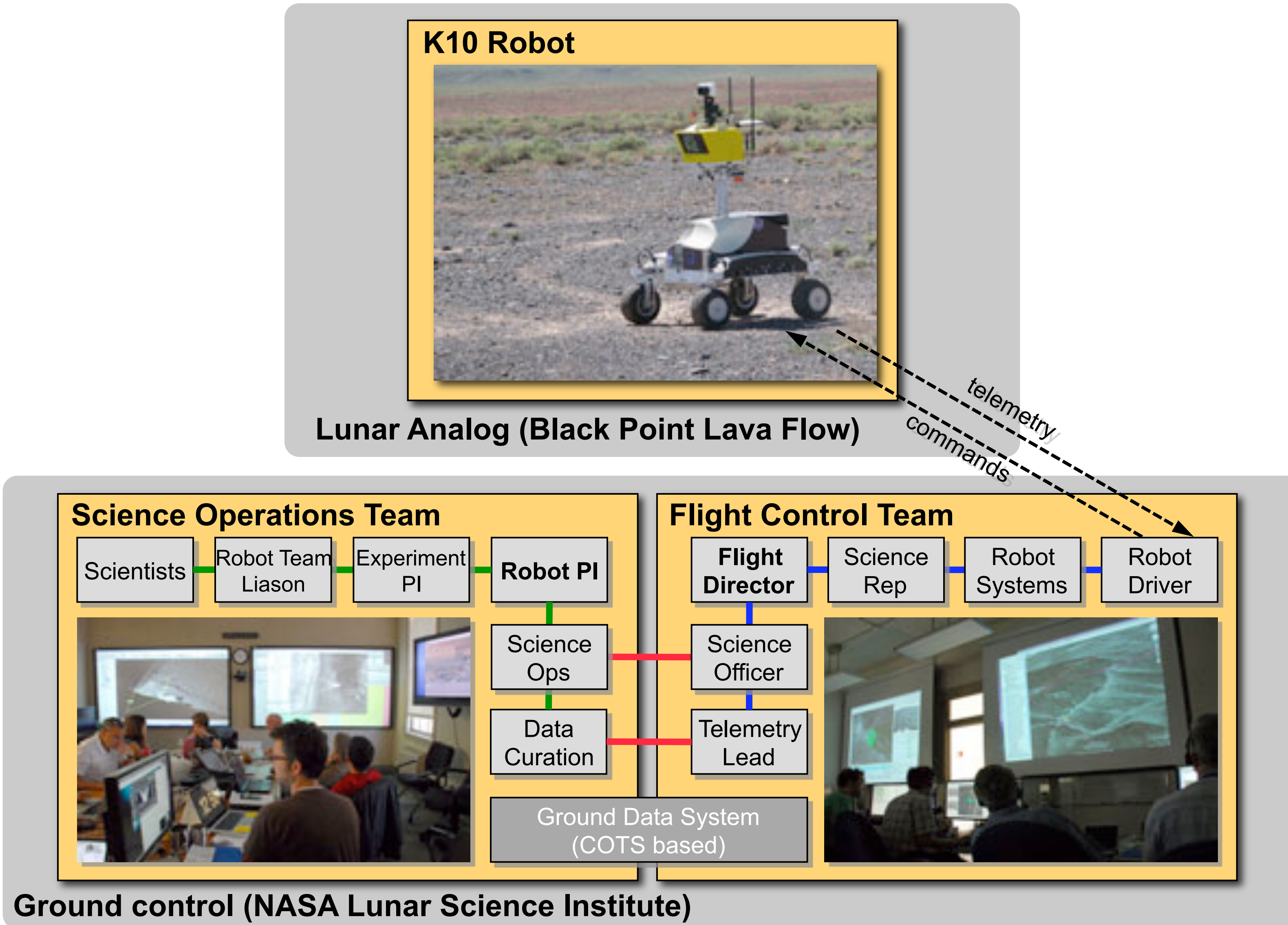
"West" region

- W1 (pre-recon) plan was Apollo-like exploration
  - Rapid area coverage (visit 5 geologic units)
  - Assumed single visit
- W2 (post-recon) plan was significantly different than W1
  - Improved target prioritization
  - Recon data supported real-time replanning



T. Fong, A. Abercromby, et al. (2009)
"Assessment of robotic recon for human exploration of the Moon"
International Astronautical Congress

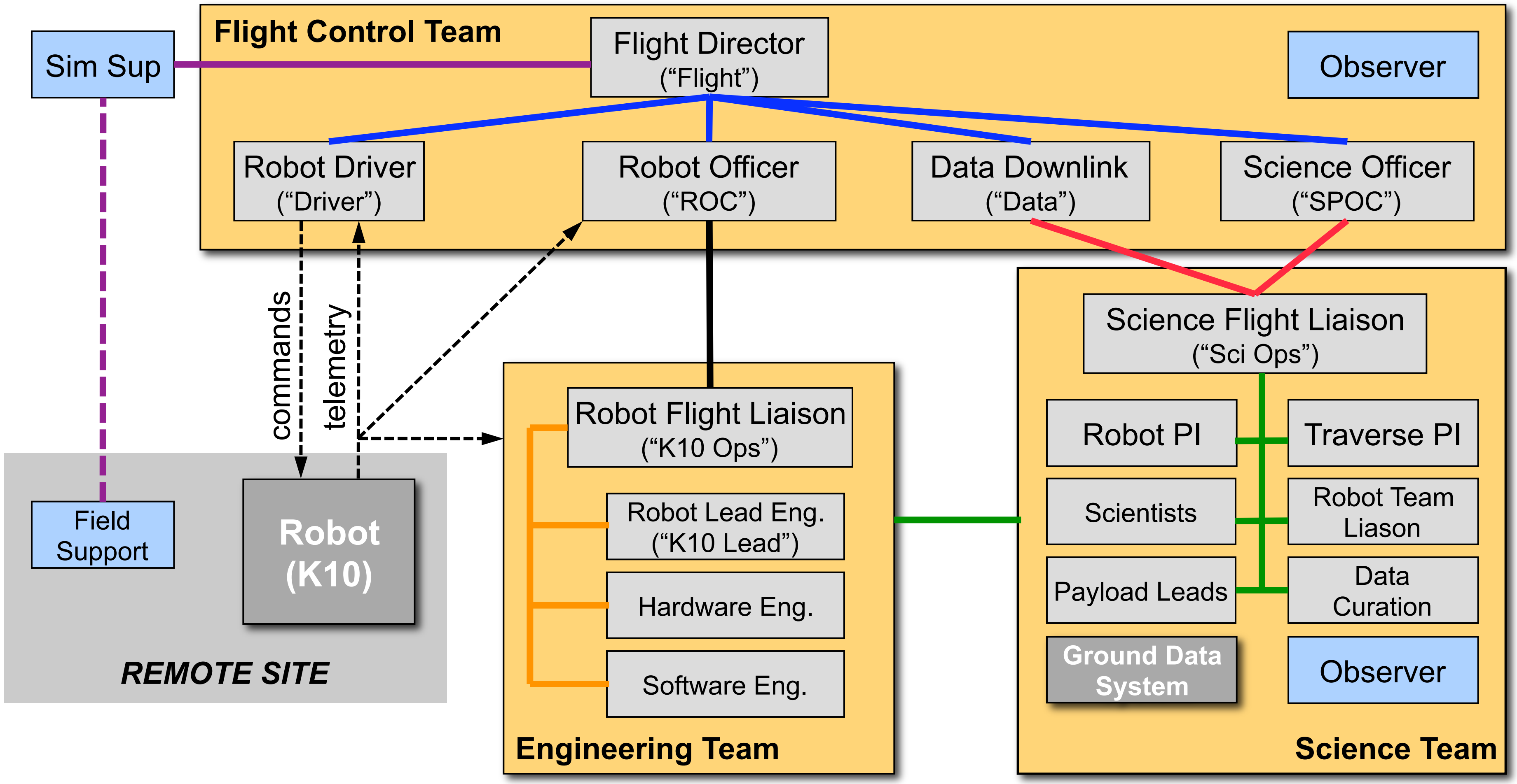
Interactive Planetary Robotics



Ops Drivers

	Lunar Robot	Apollo	Shuttle & Station	MER
Surface ops	✔	✔		✔
24 hour daylight	✔	✔	✔	
Asynchronous solar cycle	✔			✔
Continuous, DTE comm	✔	✔	✔	
Low latency	✔	✔	✔	
High bandwidth	✔	✔	✔	
Three ops shifts	✔	✔	✔	
Unstructured/Unpredictable	✔	✔		✔
Robot only	✔			✔
No crew sleep	✔			✔
Solar powered	✔		✔	✔
Around the clock activity	✔		✔	

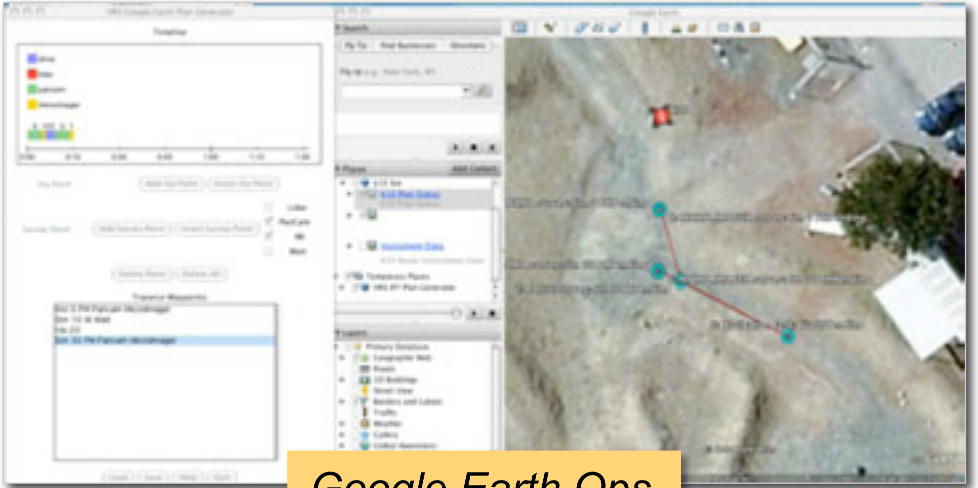
Ground Control Structure



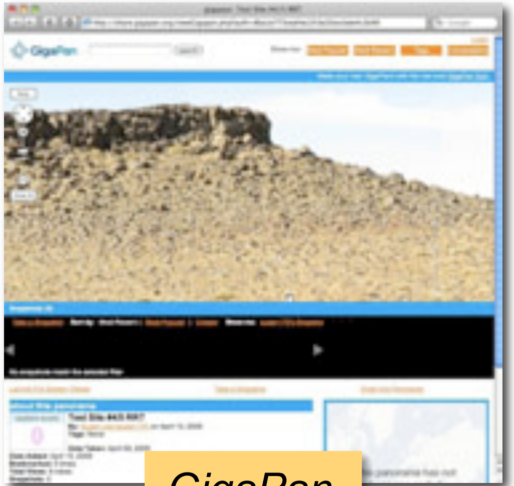
T. Fong, M. Bualat, et al. (2008)
"Field testing of utility robots for lunar surface operations"
AIAA Space (AIAA-2008-7886)

K10 Ground Data System

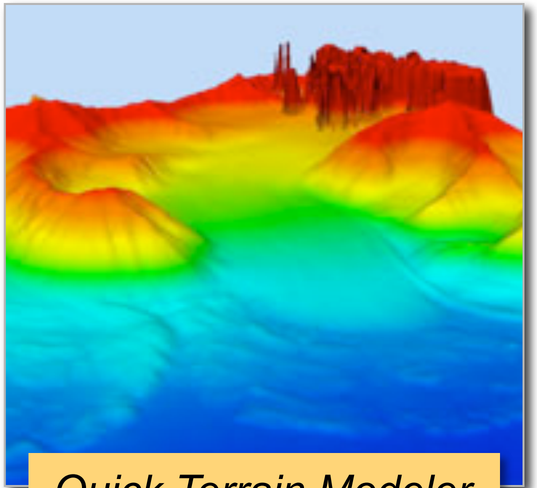
Viz



Google Earth Ops



GigaPan



Quick Terrain Modeler

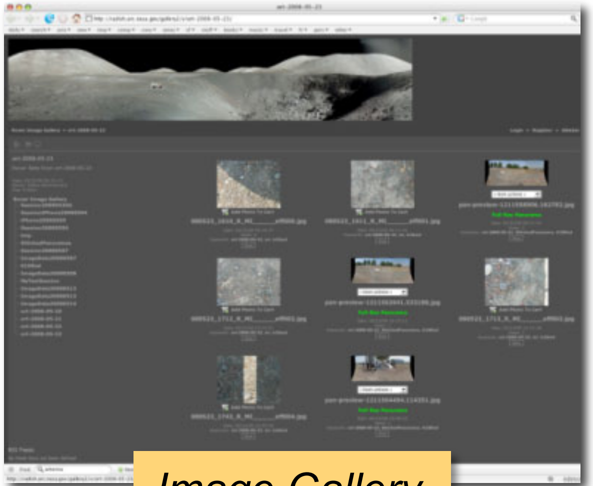
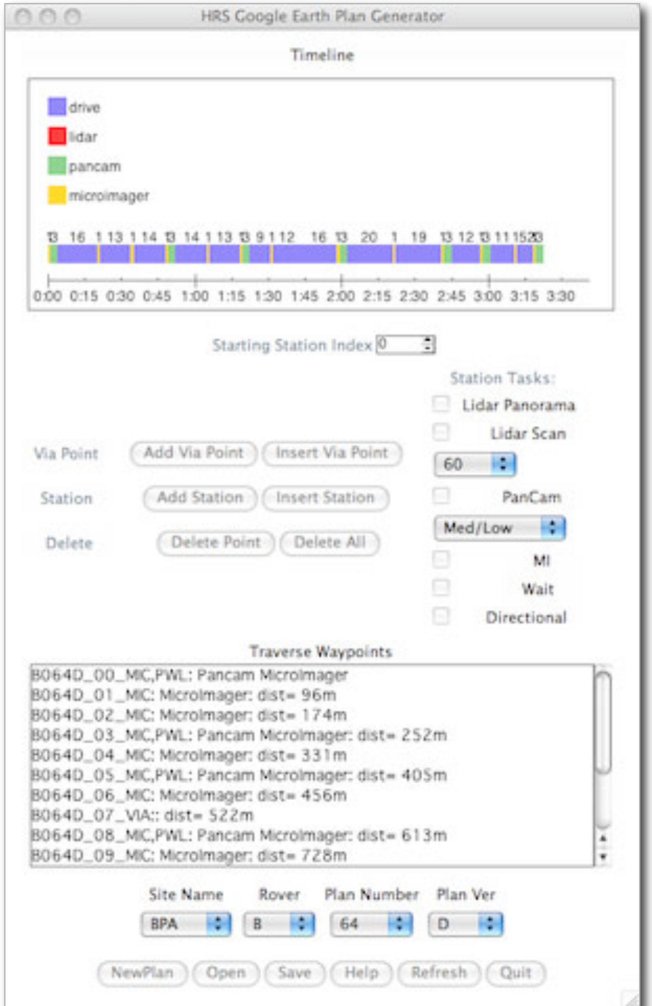


Image Gallery

Google Earth Traverse Planning



Google Earth Monitoring & Data Viz

In-Line Performance Metrics

Continuous robot monitoring

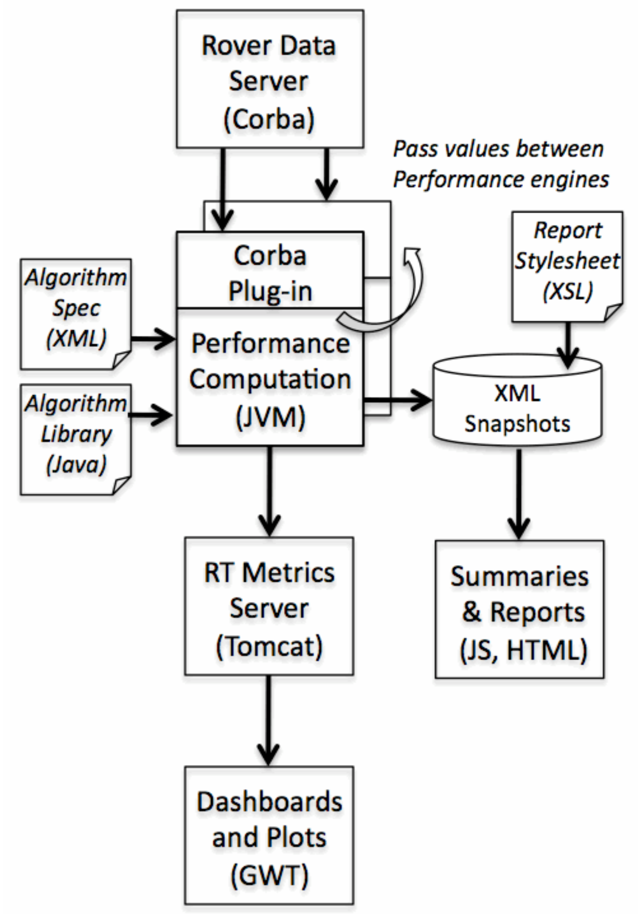
- Monitor robot telemetry
- Compute task & system metrics
- Web-based displays for flight control

Metrics for flight control

- Plan timers (planned, elapsed, etc.)
- Instrument timers (data acquisition)
- Loss of Signal

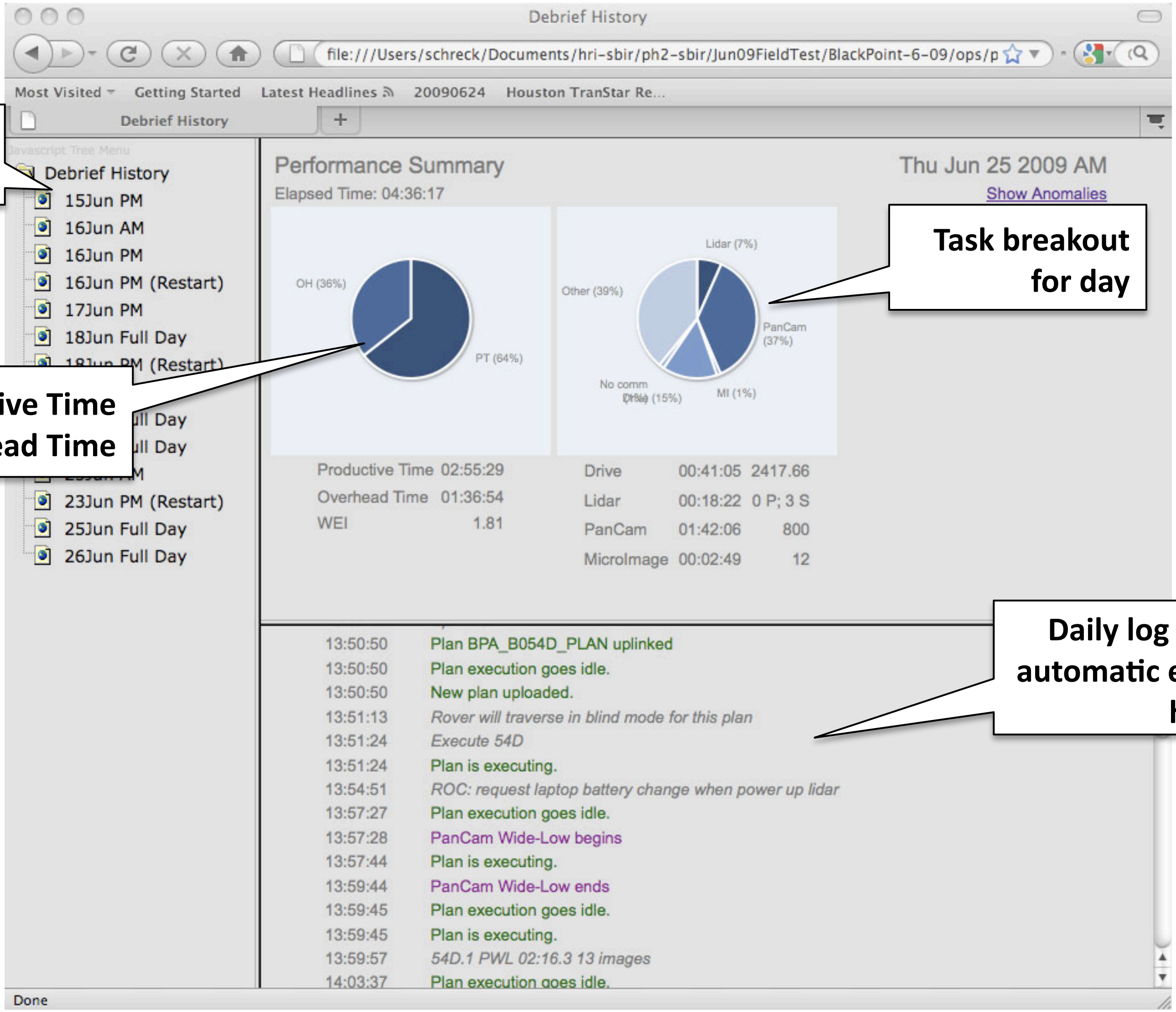
Metrics for shift debrief

- Productivity (WEI, % time on task)
- Reliability (MTTI, MTBI, interventions)
- Loss of Signal



D. Schreckenghost, T. Fong, et al. (2009)
"Measuring robot performance in real-time for NASA robotic recon operations"
Performance Metrics for Intelligent Systems Workshop

Performance Displays (Shift Debrief)



Debrief Summary for each day

Ratio: Productive Time to Overhead Time

Task breakout for day

Daily log interleaves automatic events with human logs

Part 2: Automated Planetary Mapping

Purpose

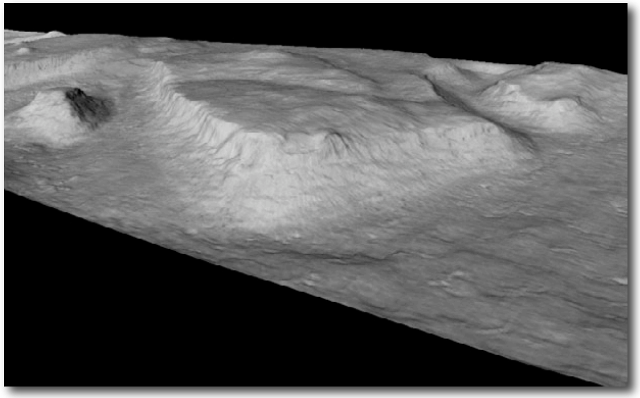
- High-quality digital maps
- On-line access
- Very rapid updates

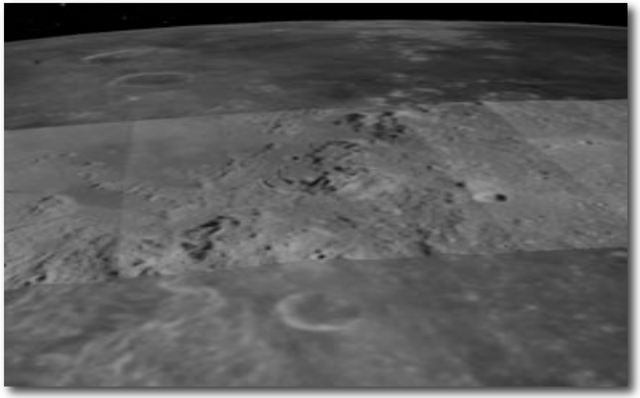
Data processing

- Orbital imagers (Moon, Mars, etc.)
- Image base maps
- 3D terrain reconstruction (DEM's)

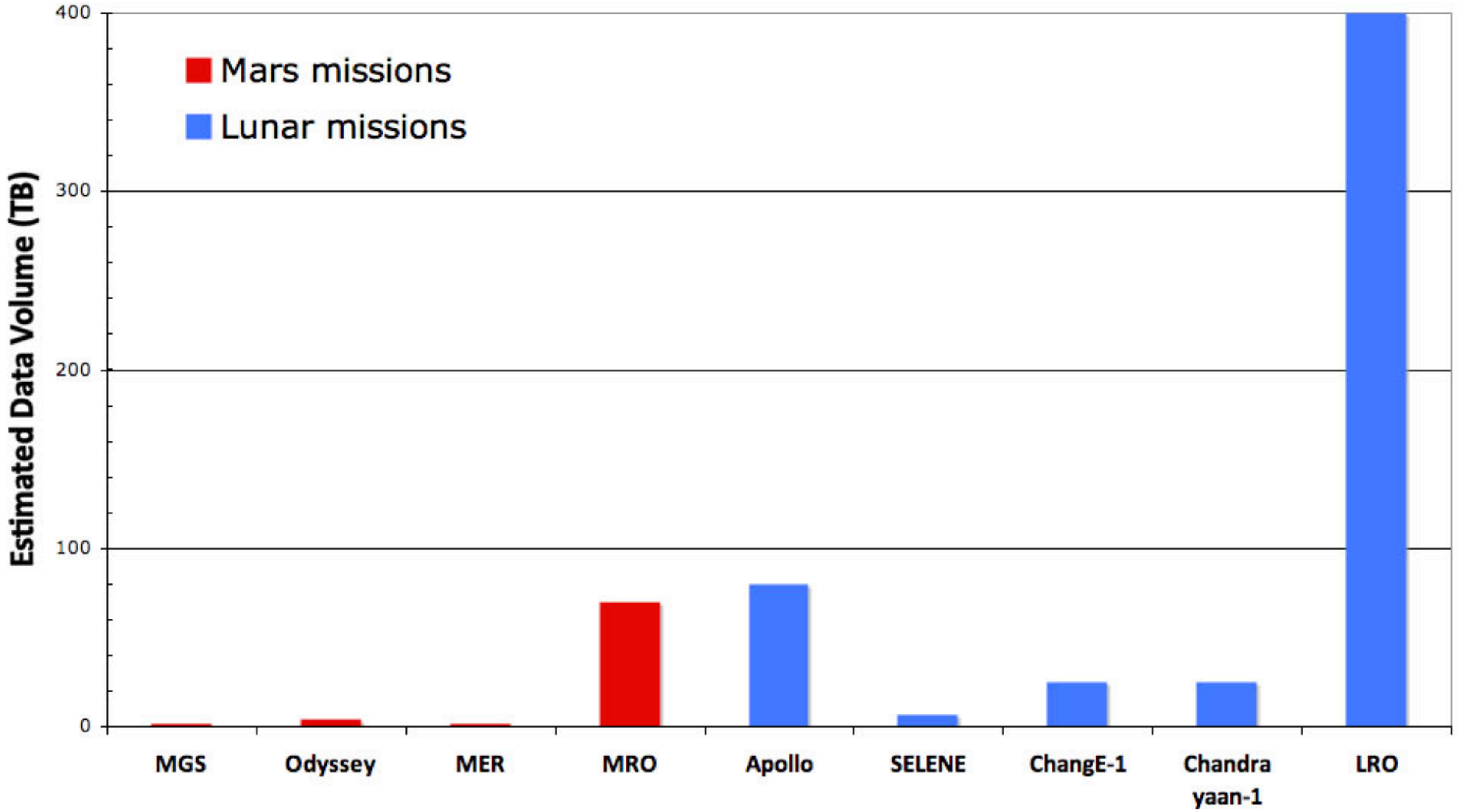
Data fusion & retrieval

- OGC standards (WMS, WFS)
- Geobrowser markup (KML, WTML)
- Image metadata (GeoTIFF, etc.)





Planetary Data Firehose



Source: B. Archinal, L. Gaddis, et al. (2007)
"Urgent Processing and Geodetic Control of Lunar Data"
Workshop on Science Associated with the Lunar Exploration Architecture

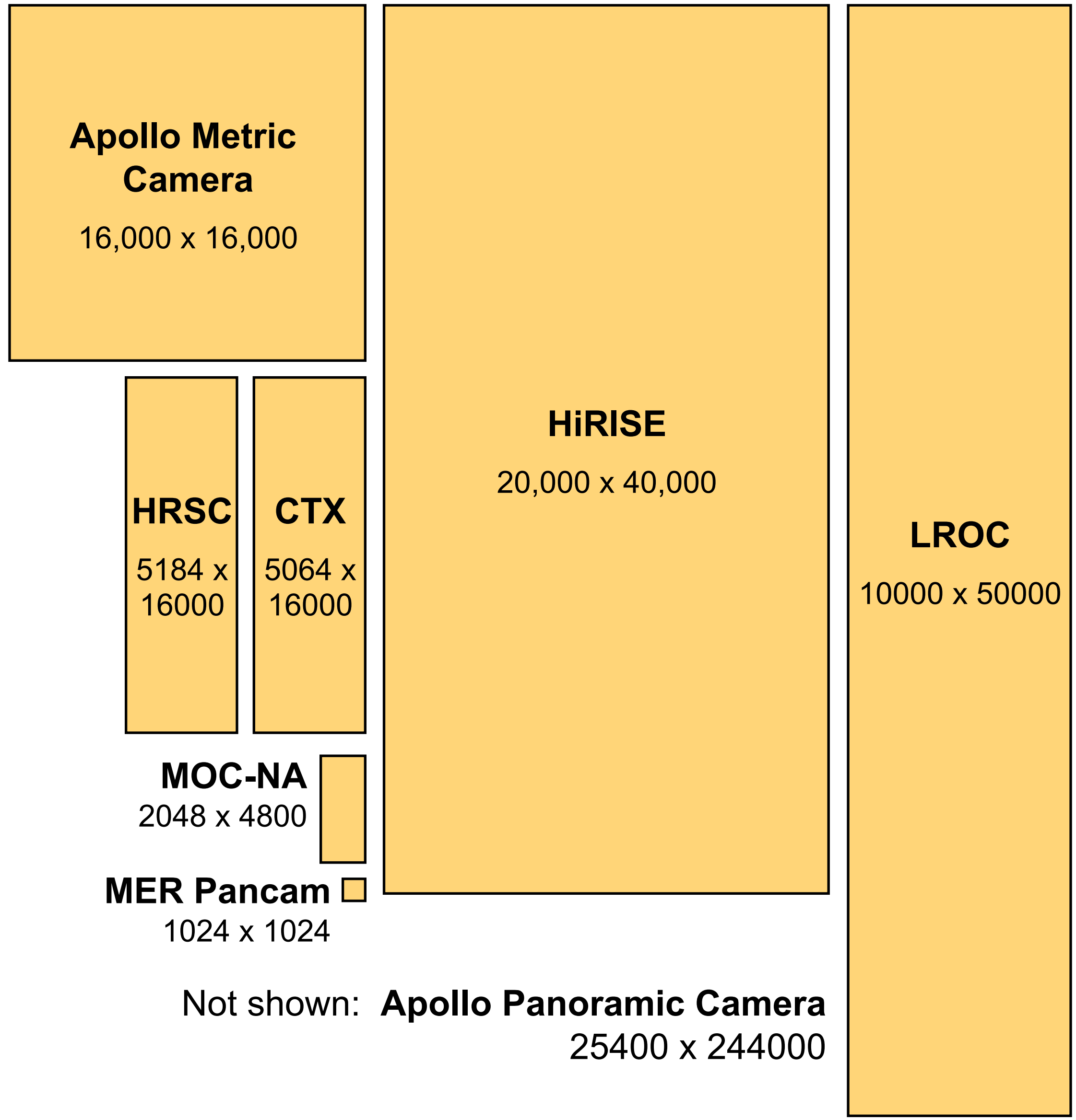
Planetary Data Firehose

Traditional mapping

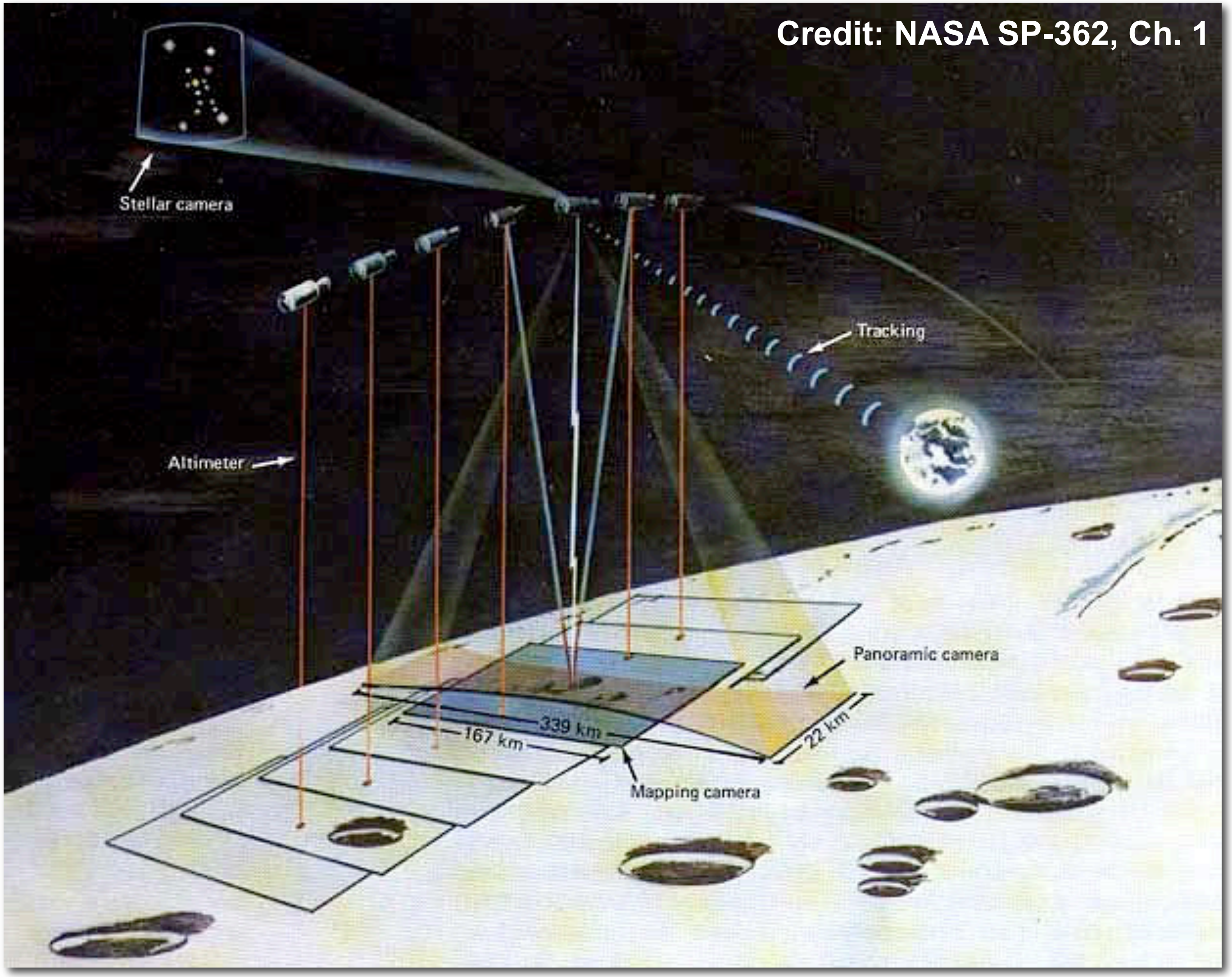
- Human-intensive cartography
- Manual control & error analysis
- Maps take years to complete

Image resolution

- Imagers keep getting better
- High-res digital scans of old film



Automated Stereo Image Processing



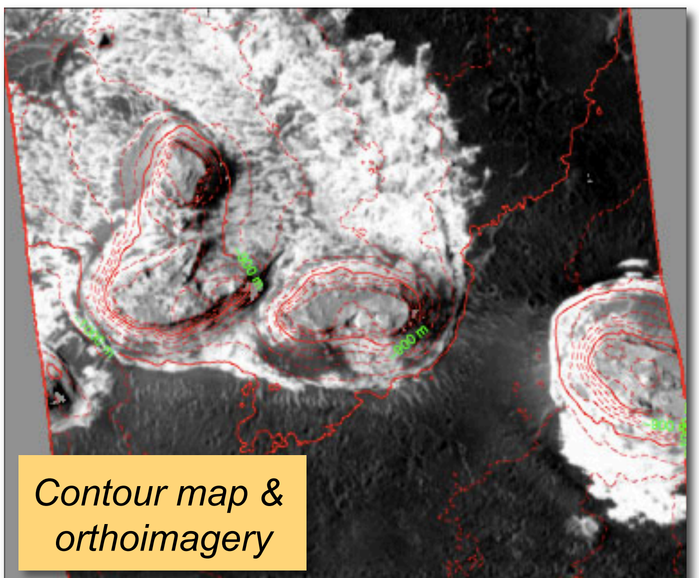
Automated Stereo Image Processing

Problem

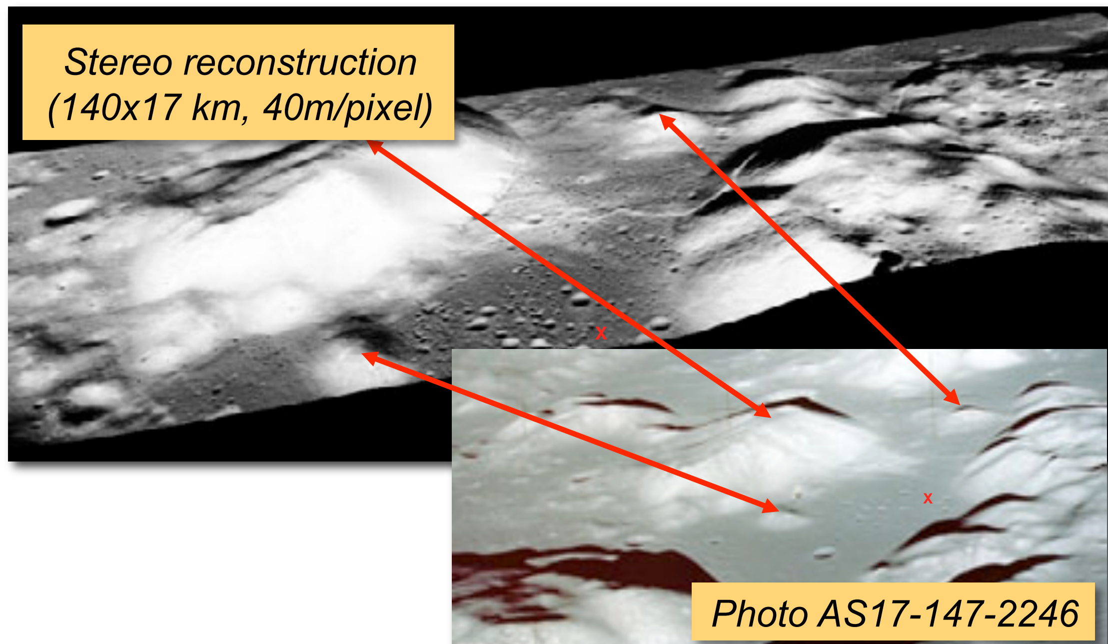
- Multiple images from different viewing angles
- Compute 3D terrain model with no human intervention

Open-source C++ packages

- NASA Ames Stereo Pipeline
- NASA NeoGeography Toolkit
- NASA Vision Workbench



Contour map & orthoimagery

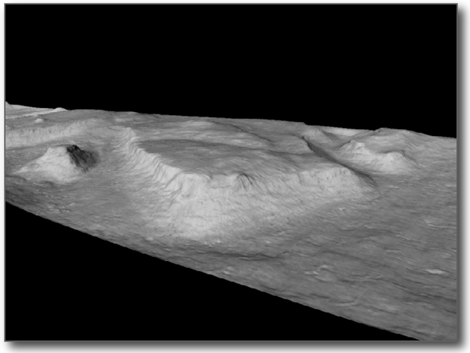


Stereo reconstruction (140x17 km, 40m/pixel)

Photo AS17-147-2246

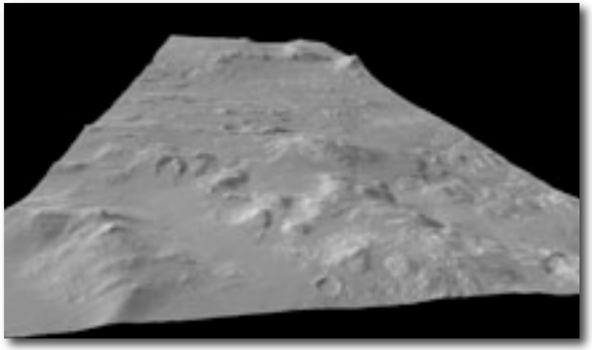
M. Broxton and L. Edwards (2008)
"The Ames Stereo Pipeline: Automated 3D surface reconstruction from orbital imagery"
Lunar and Planetary Science Conference

Mars Terrain Models

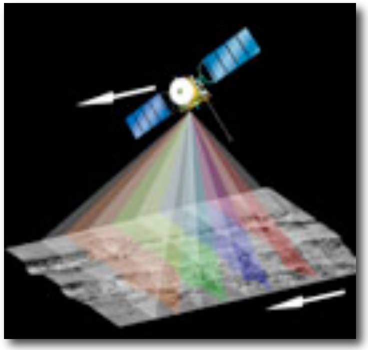
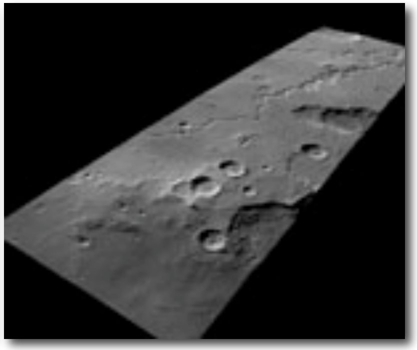
MGS MOC Narrow Angle

- Collaboration with Malin Space Science Systems
- Adapted Ames Stereo Pipeline to orbital images




MRO Context Imager (CTX)

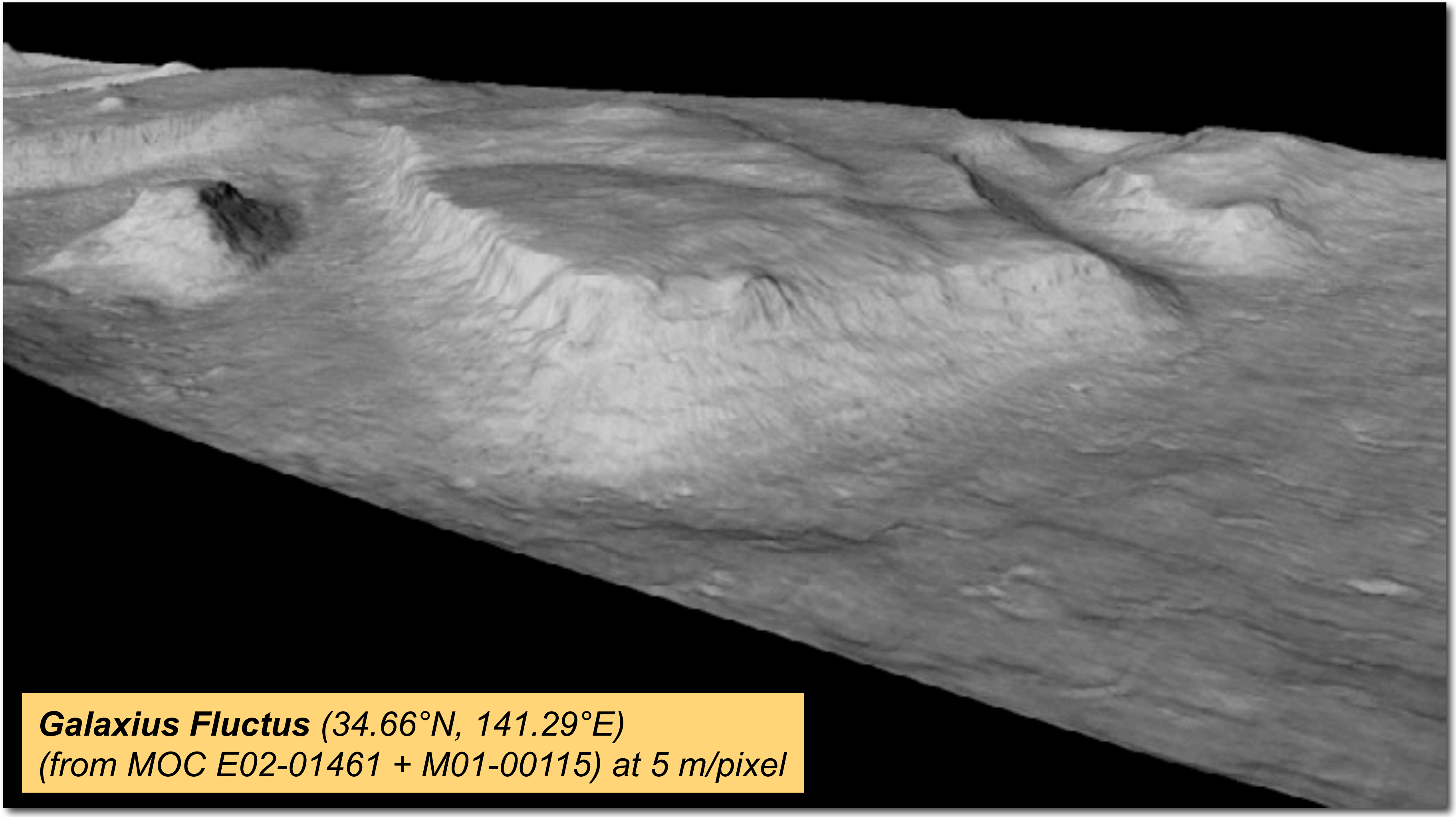
- Collaboration with CTX Team
- Provided rapid turn-around stereo modeling

Mars Express HRSC

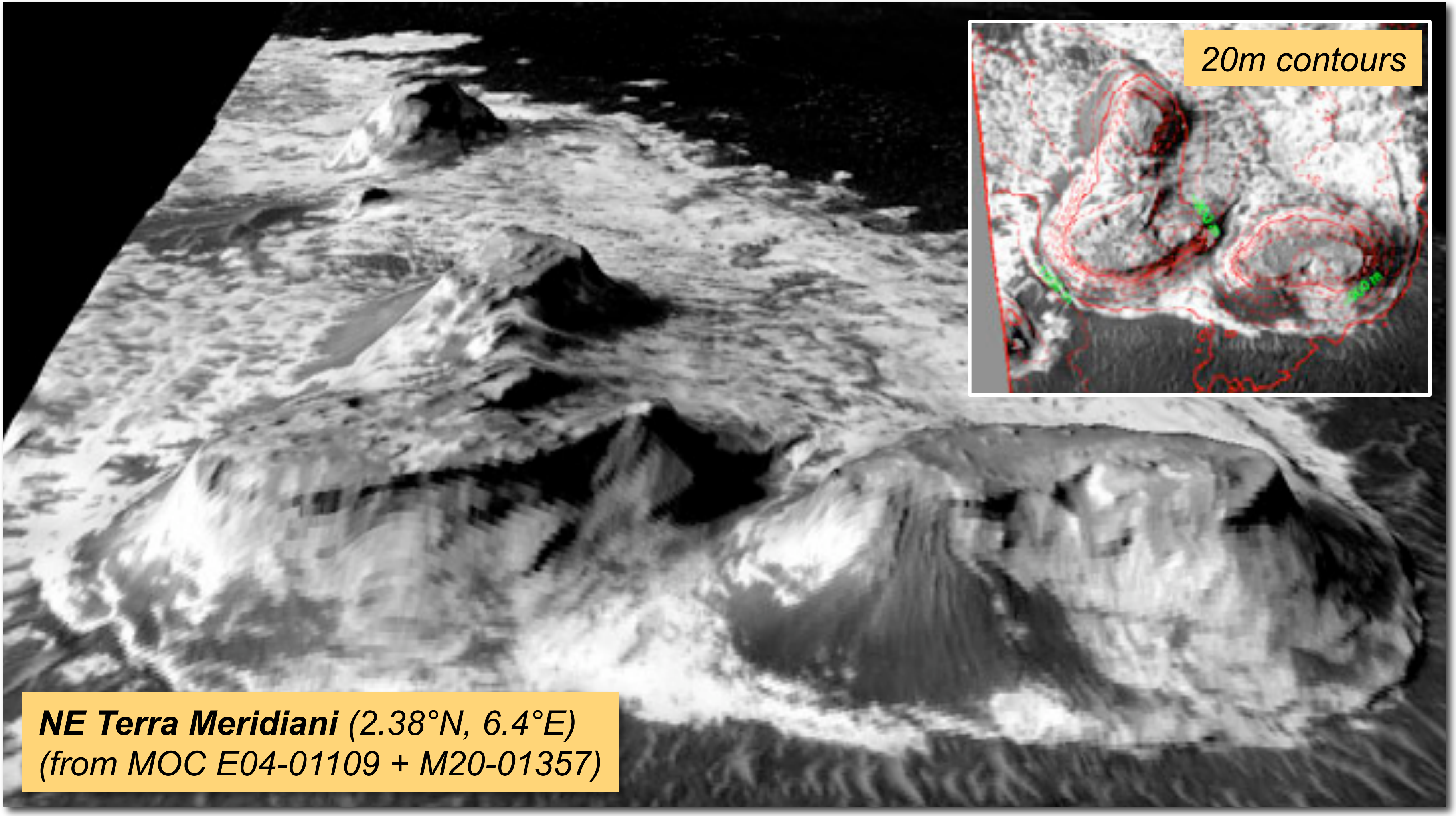
- Collaboration with USGS, DLR
- Formal comparison of Digital Elevation Model (DEM) products
- Four controlled data sets

Mars Terrain Models

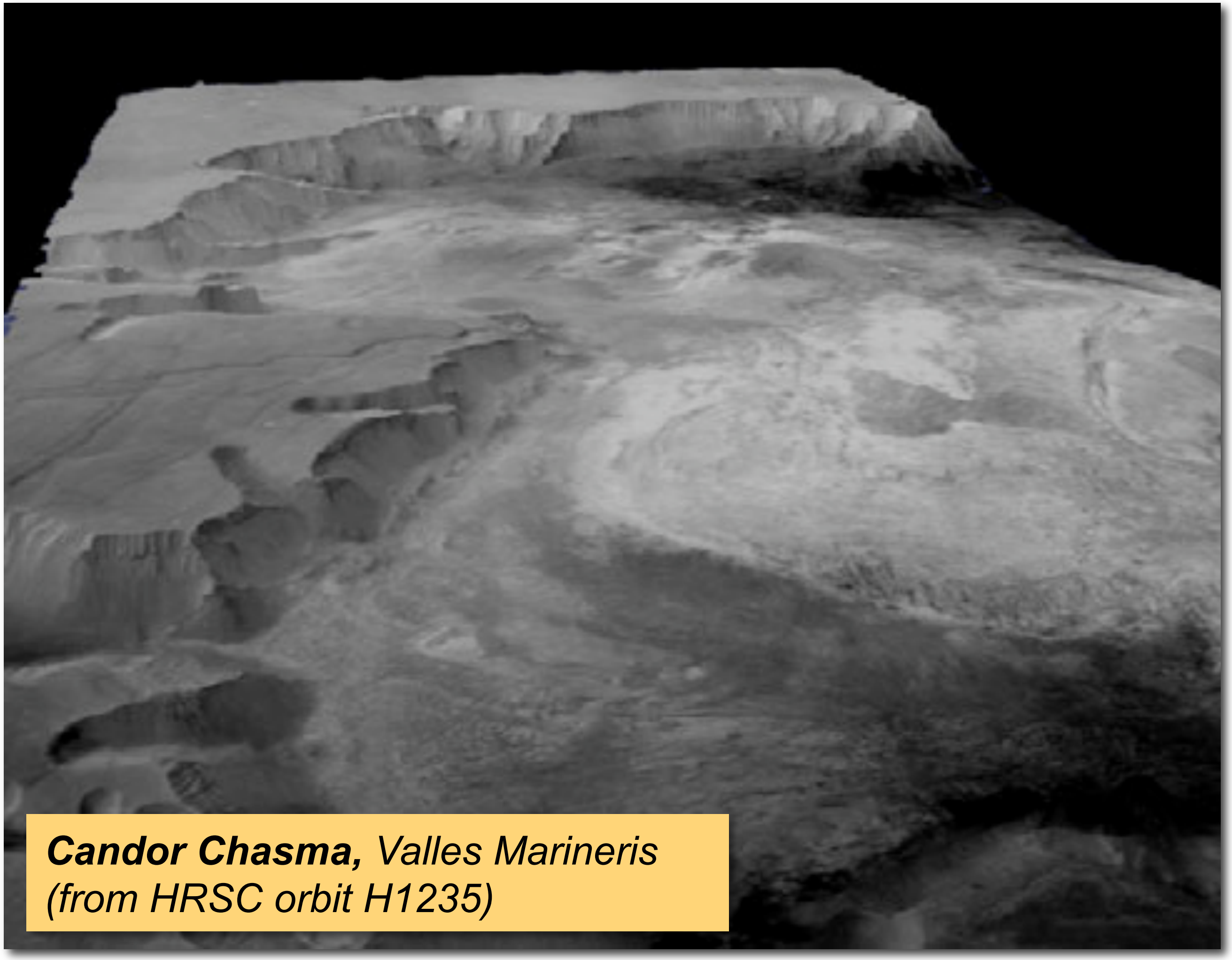


Galaxius Fluctus *(34.66°N, 141.29°E)*
(from MOC E02-01461 + M01-00115) at 5 m/pixel

Mars Terrain Models

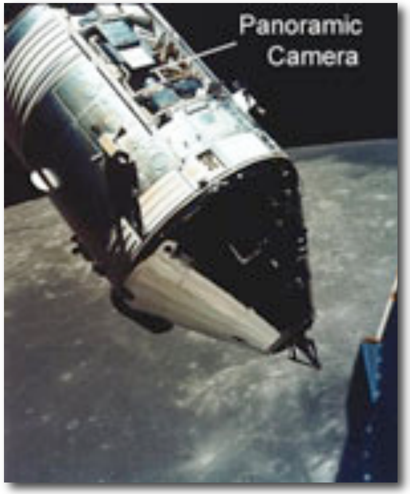


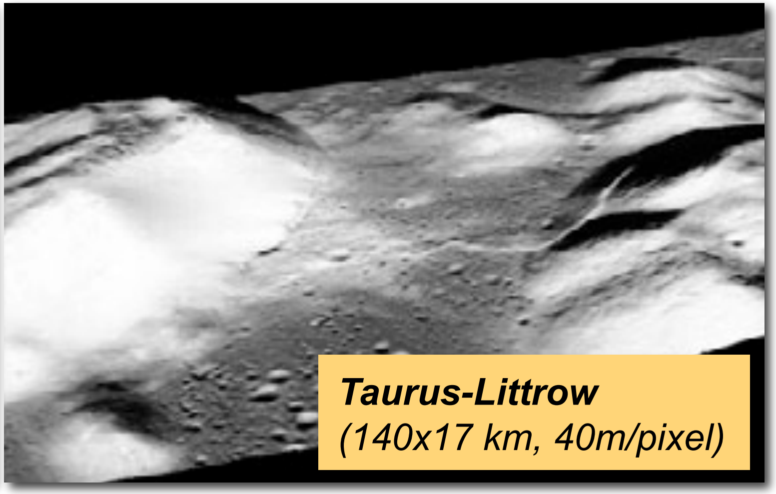
Mars Terrain Models



***Candor Chasma,** Valles Marineris*
(from HRSC orbit H1235)

Lunar Terrain Models





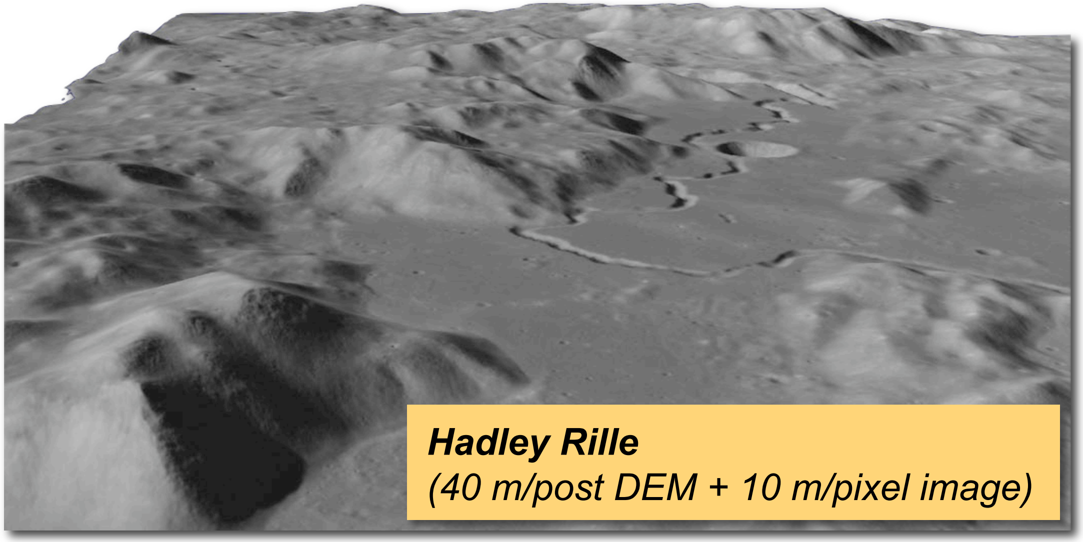
Taurus-Littrow
(140x17 km, 40m/pixel)

Apollo Panoramic Camera

- 3D terrain model of Taurus-Littrow valley (Apollo 17)
- Featured at the Hayden Planetarium (American Museum of Nat. History)

Apollo Metric Camera

- Systematic creation of image maps & DEMs
- Refinement of the Lunar geodetic control network (with USGS)
- NASA Lunar Mapping & Modeling Project



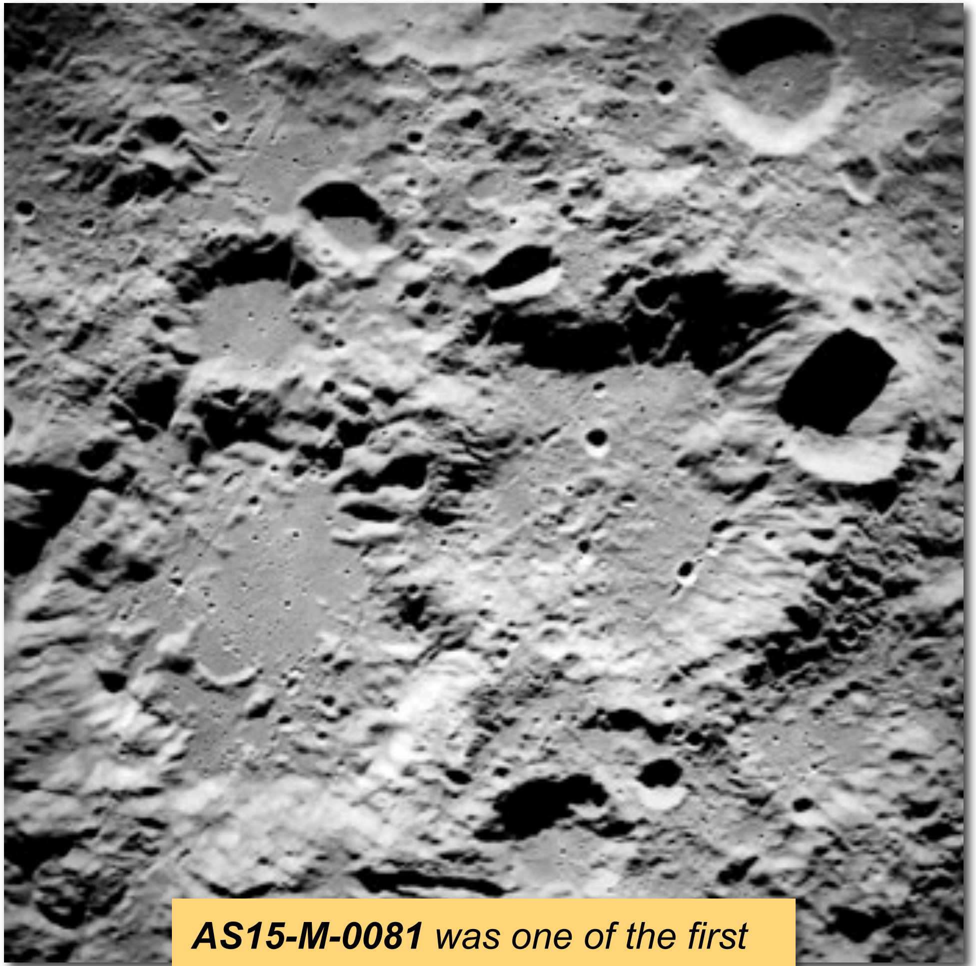
Hadley Rille
(40 m/post DEM + 10 m/pixel image)

Lunar Terrain Models

Apollo Image Archive project

- **apollo.sese.asu.edu** (Mark Robinson, ASU)
- Photogrammetric scans of original Apollo films (200 pixel/mm, 14-bit)

Apollo Mapping Camera

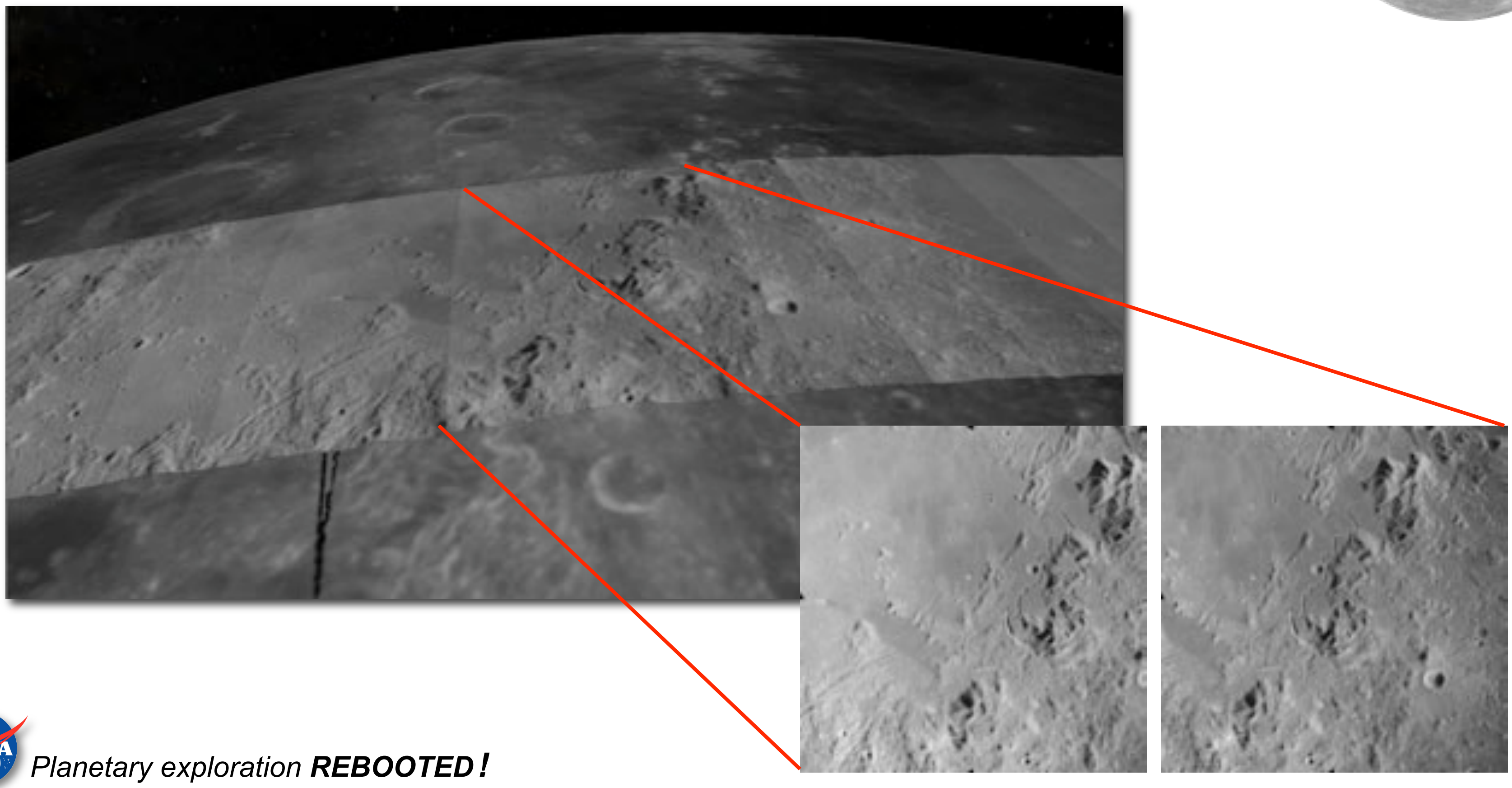


AS15-M-0081 *was one of the first images to be scanned …*

Lunar Terrain Models

Large-scale mapping

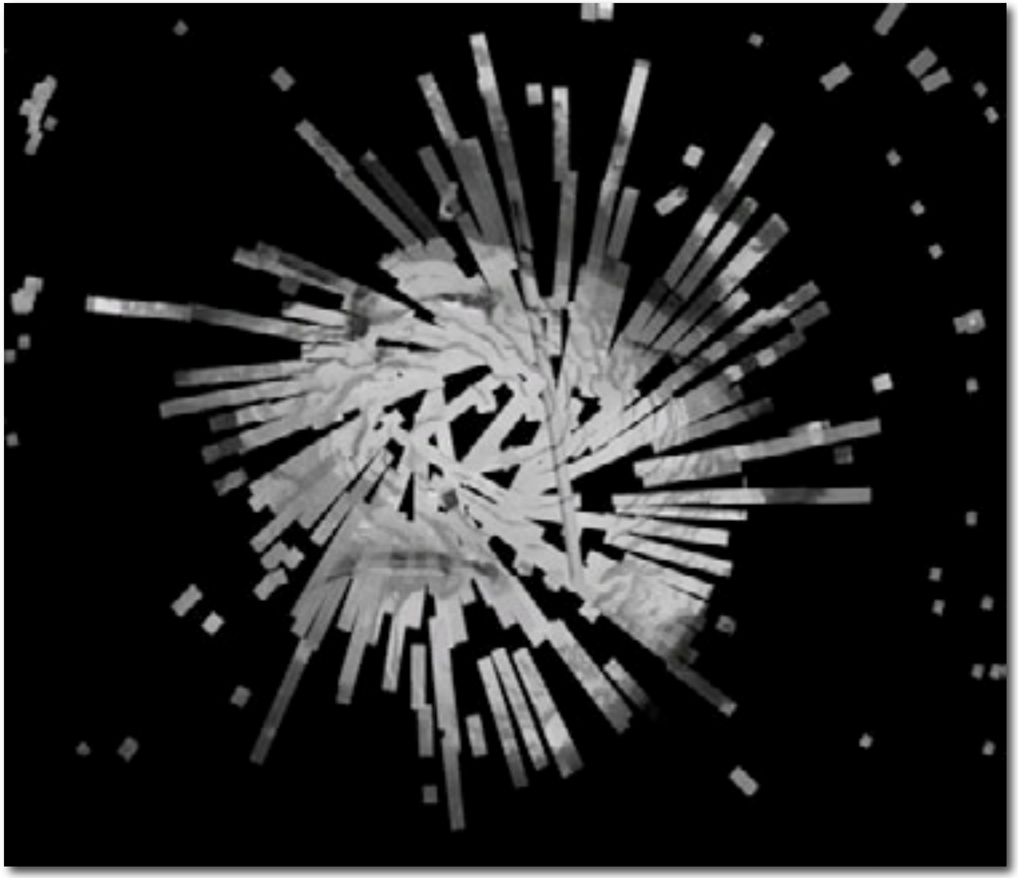
- Systematic reconstruction of the "Apollo Zone"
- Stereo vision & mosaicking of Apollo Metric Camera scans
- 8,000 stereo pairs from Apollo 15-17



Prior Work in Mosaicking

CTX polar mosaic (2007)

- 40.3 gigapixel mosaic (610 thousand tiles)
- 305-GB of source imagery
- 5 CPU-days of processing
- Collaboration with Malin Space Science Systems



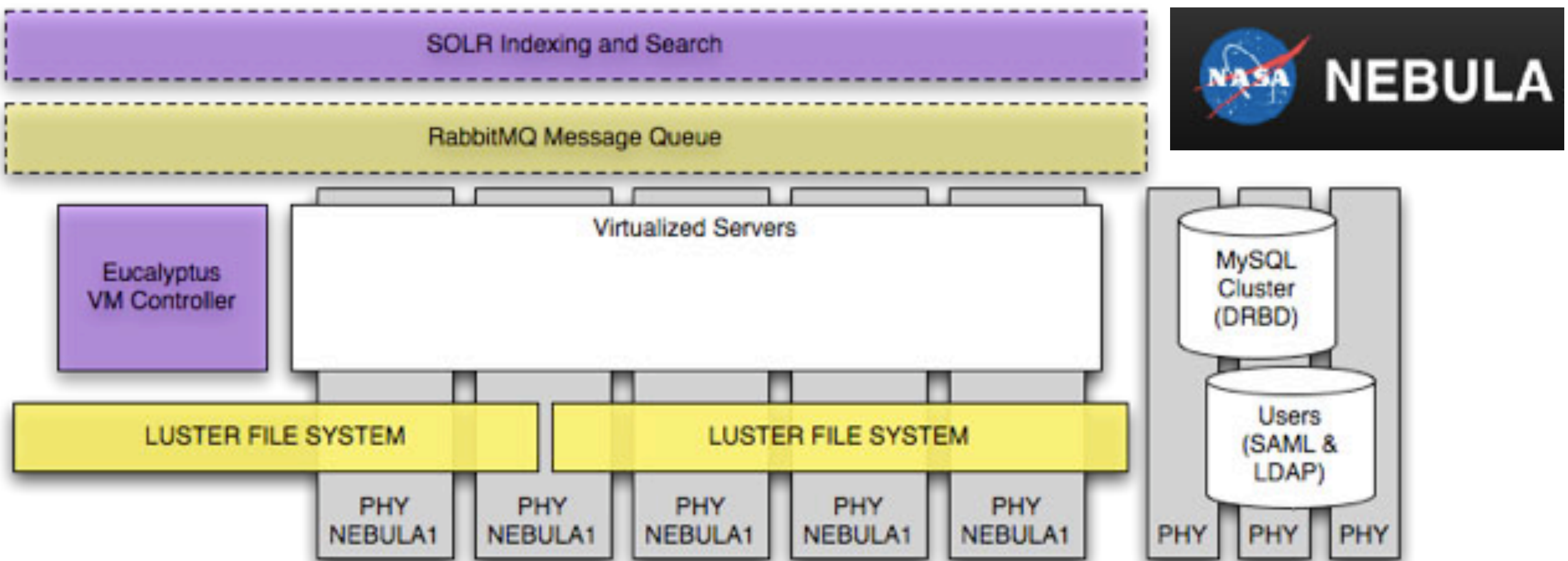
Old mosaic engine

- Single-threaded
- One-shot (if it crashed, had to start over…)
- Could not incrementally add imagery to a mosaic

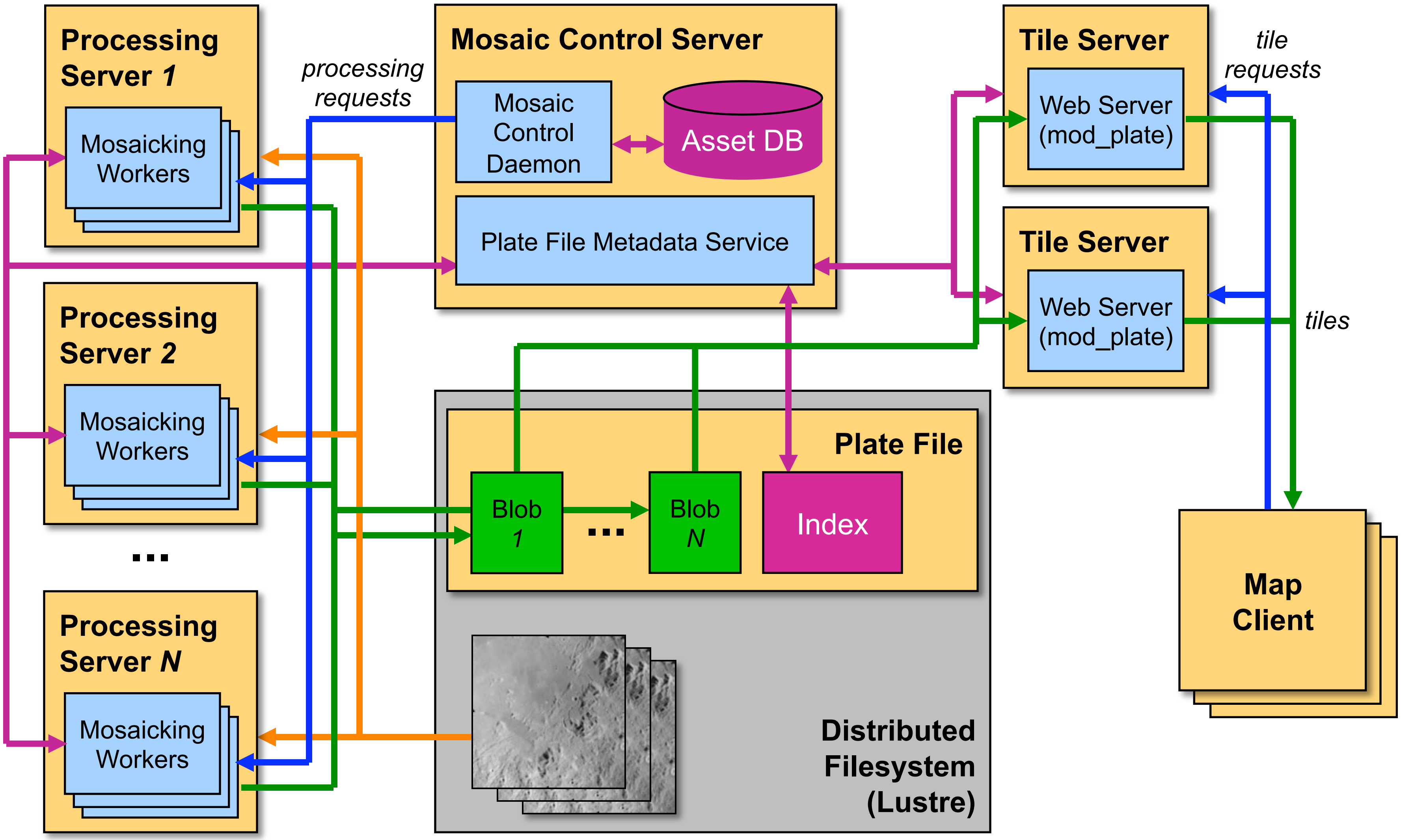
Improved Mosaic Engine

Key features

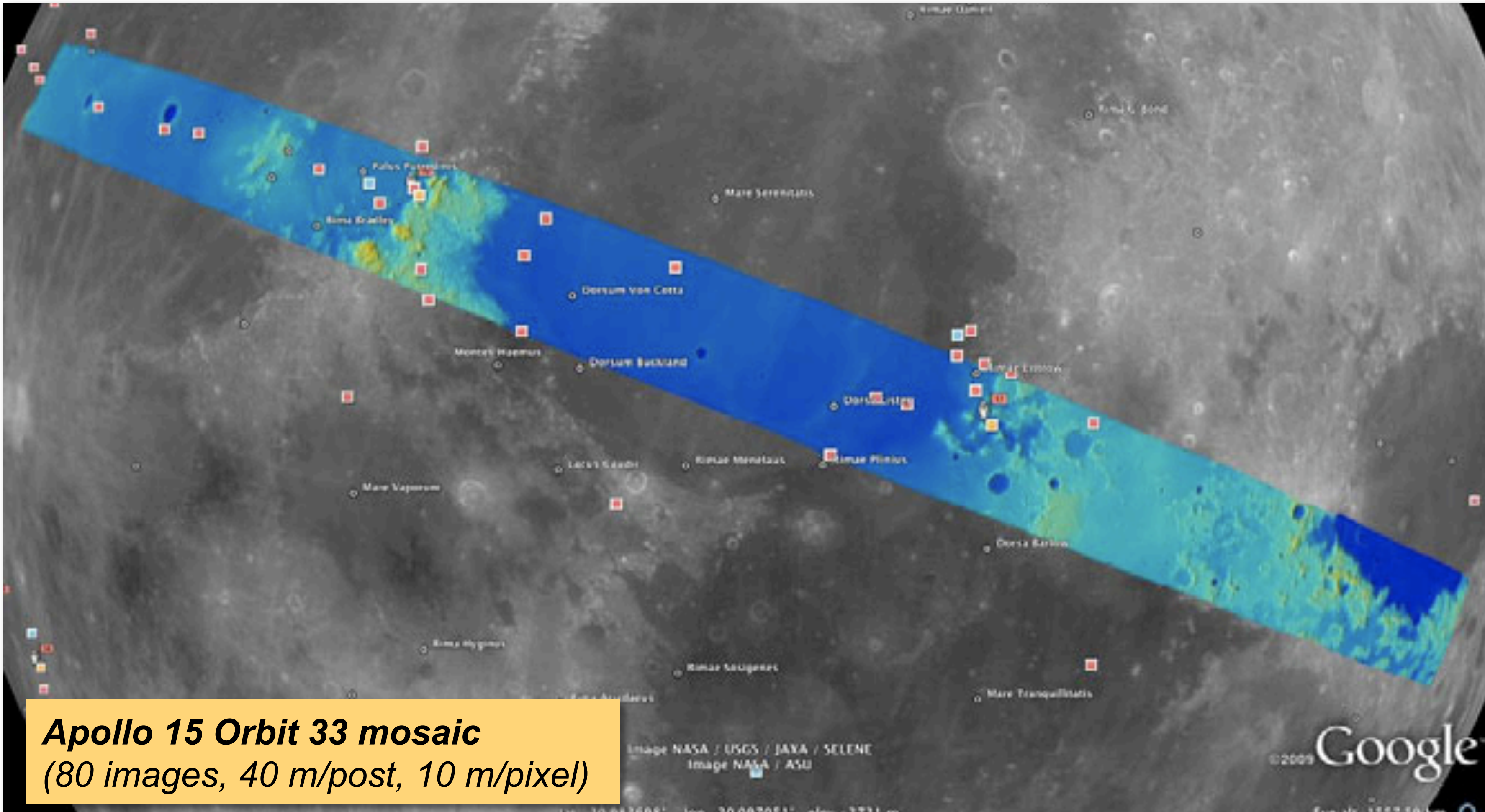
- High-performance, distributed processing (NASA Nebula cloud computer)
- Supports incremental updates & roll-back on mosaicking failures
- Aggregation of image tiles into indexed "plate files" (highly scaleable and efficient)



Improved Mosaic Engine



Apollo 15 Orbit 33



Apollo 15 Orbit 33 mosaic
(80 images, 40 m/post, 10 m/pixel)

M. Broxton, A. Nefian, et al. (2009)
"3D Lunar terrain reconstruction from Apollo Images"
Int'l Symposium on Visual Computing

Coming Soon …

Complete HiRISE Mosaic

- Mars Reconaissance Orbiter HiRISE imager
- Each image: 20,000 x 50,000 pixels

Mosaic stats

Tile Dimensions	256 x 256 pixels
Root Tiles / Image	15,000
Tile Space	25 KB
Tiles Total	229 million
Total Mosaic Size	5.7 TB

Part 3: Participatory Exploration

Purpose

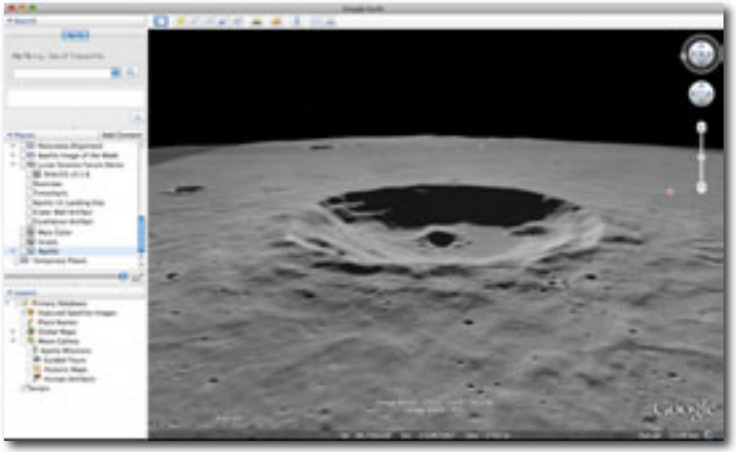
- Enable everyone to actively participate in NASA missions
- Explore space in **bold**, new ways
- Engage & educate students

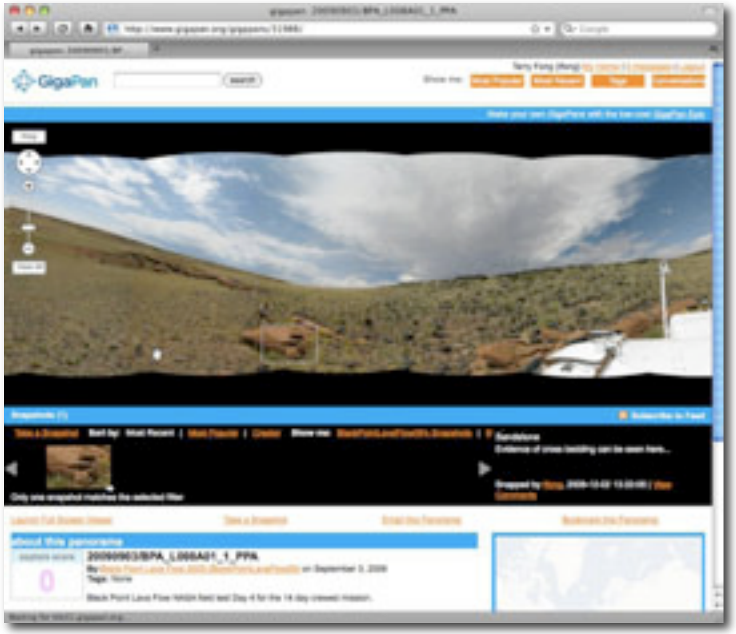
NASA data for everyone

- Easy access to planetary data
- Reach millions of users (very low barrier to entry)
- Neo-geography browsers (Google Earth, WorldWideTelescope)

Citizen science

- Volunteers help perform science
- Informal & formal education
- Social networking





NASA Data for Everyone

Our goals

- Make NASA's geospatial data universally and easily accessible
- Enable millions of people to find and use NASA data
- Improve planetary science & exploration missions

How do we do this?

- Process raw data into maps (mosaics, terrain models, etc)
- Support geo-browsers & GIS platforms through open standards
- Provide incremental updates, so that data can be shared in near real-time

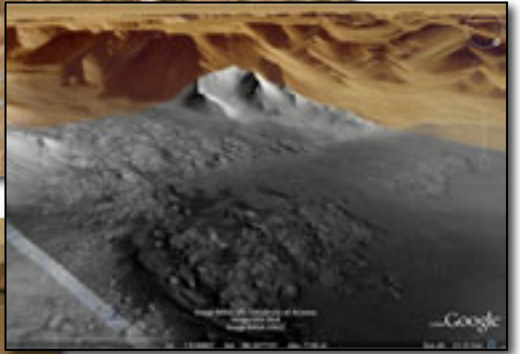
Mars in Google Earth

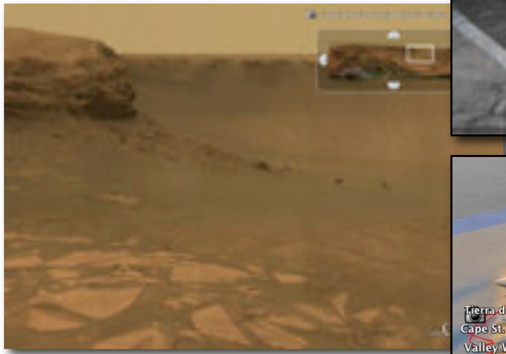
a.k.a. “Google Mars 3D”

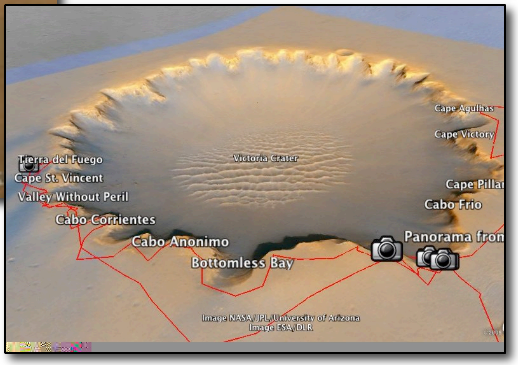
- Launched Feb. 2, 2009
- Co-developed with Google
- Built in to Google Earth v5

Content

- Global maps: topography, infrared, historical, etc.
- Imager footprints & overlays: HiRISE, CTX, MOC, etc.
- MER tracks & panoramas
- Tours (Bill Nye & Ira Flatow)
- Live from Mars: THEMIS images within hours
- And much more …







R. Beyer, M. Broxton, et al. (2009)
”Visualizing Mars data and imagery with Google Earth”
American Geophysical Union

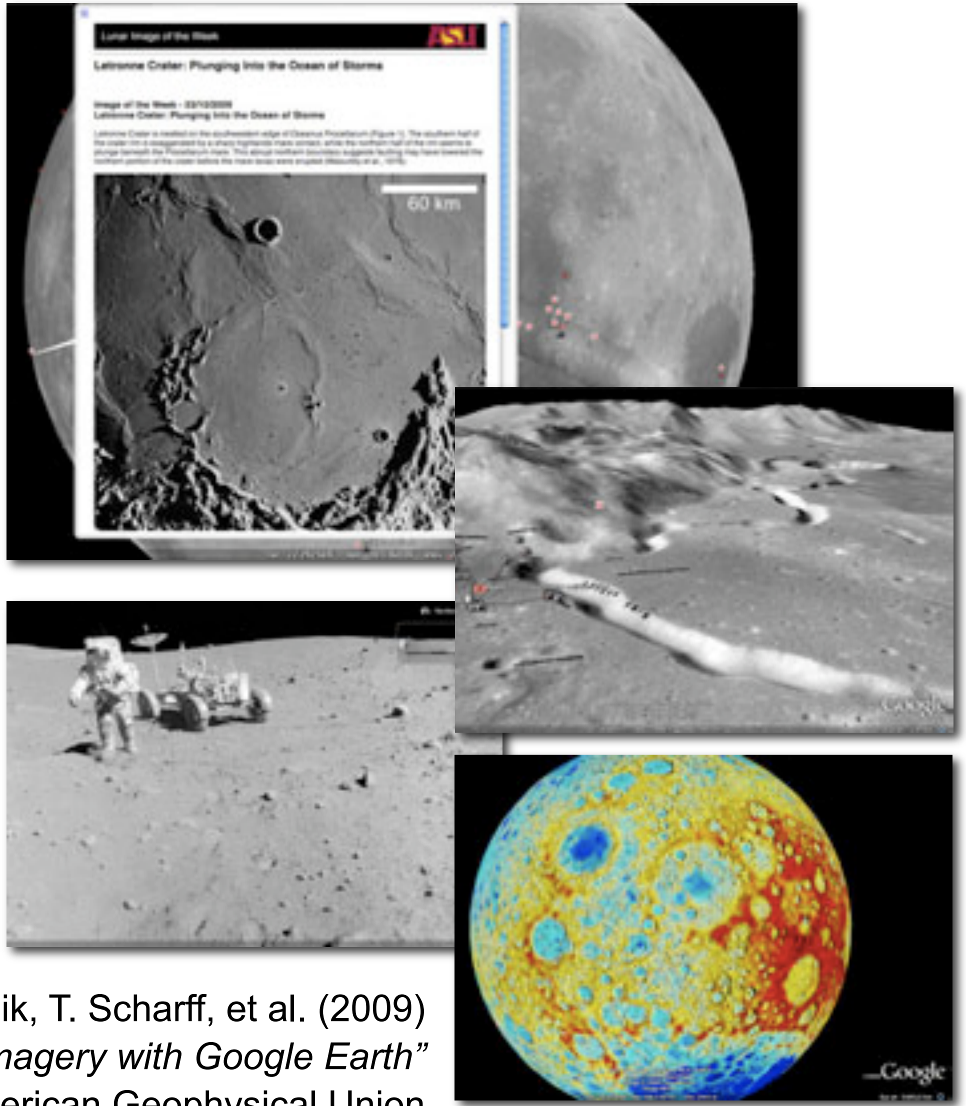
Moon in Google Earth

a.k.a. "Google Moon"

- Launched July 20, 2009
- Co-developed with Google
- Built in to Google Earth v5

Content

- Global maps: topography, geologic, historical, etc.
- Spacecraft imagery: Apollo, Clementine, Lunar Orbiter
- 3D models of spacecraft, landers, and crew rovers.
- Tours (Andy Chaikin, Buzz Aldrin & Jack Schmidt)
- And much more …

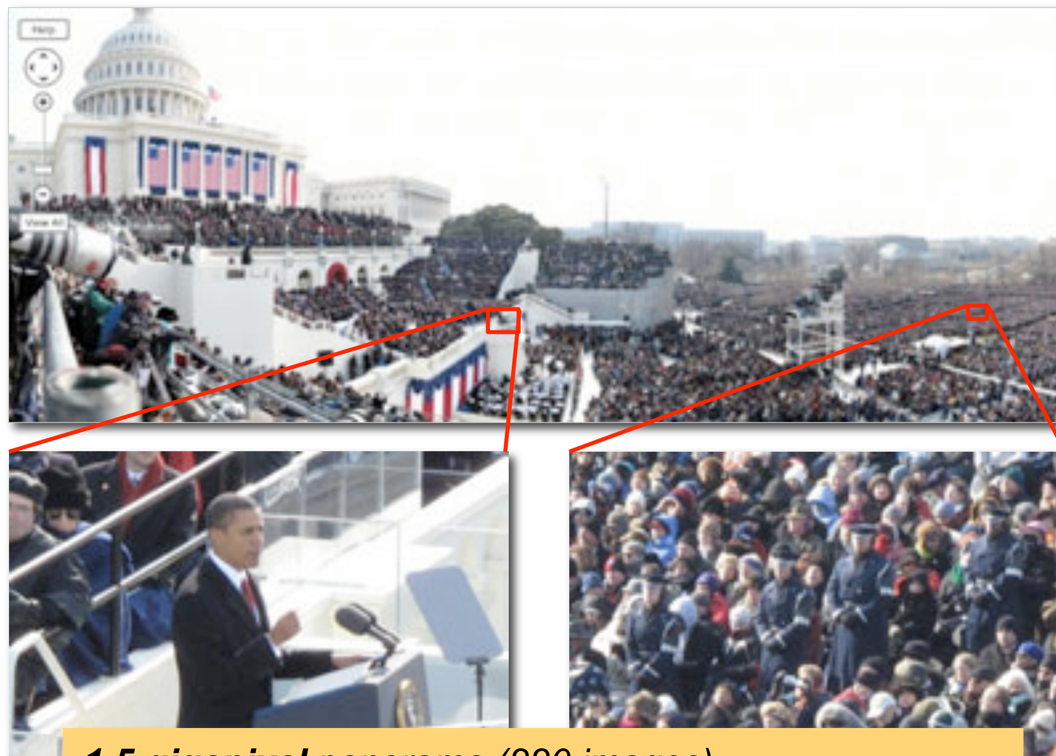


M. Weiss-Malik, T. Scharff, et al. (2009)
"Visualizing Moon data and imagery with Google Earth"
American Geophysical Union

GigaPan

Explorable images to engage, inform, and inspire

- Interactive, gigapixel panoramas (gigapan.org)
- Robotic pan/tilt head + stitching software + collaboration web site
- Co-developed with CMU

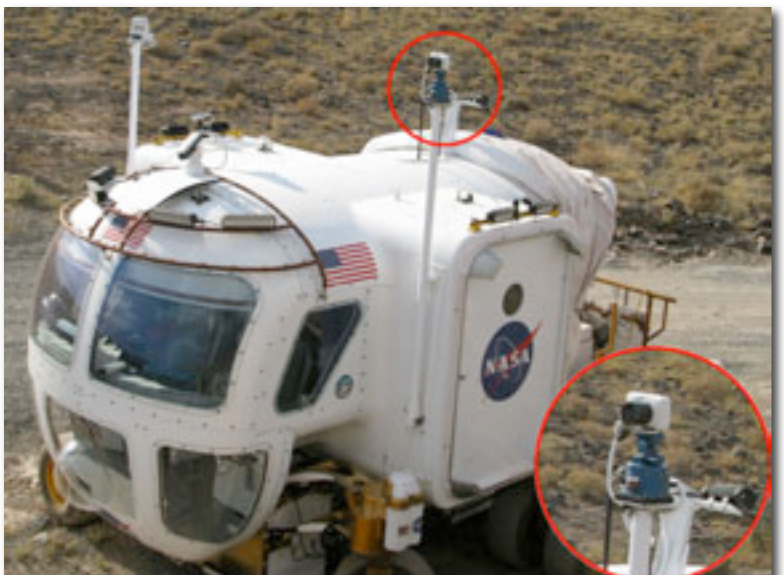


1.5 gigapixel *panorama (220 images)*
Viewed more than ***10 million times*** *since Jan 2009*

GigaPan on the Lunar Electric Rover

Desert RATS 2009

- GigaPan “Voyage” (rugged pan-tilt + embedded processing/server)
- Remotely operated by science backroom (ground control)
- Context & high-resolution imaging for field geology



Traverse N1, Station 1 (Aug 29, 2009)
290x40 deg panorama (112 images)

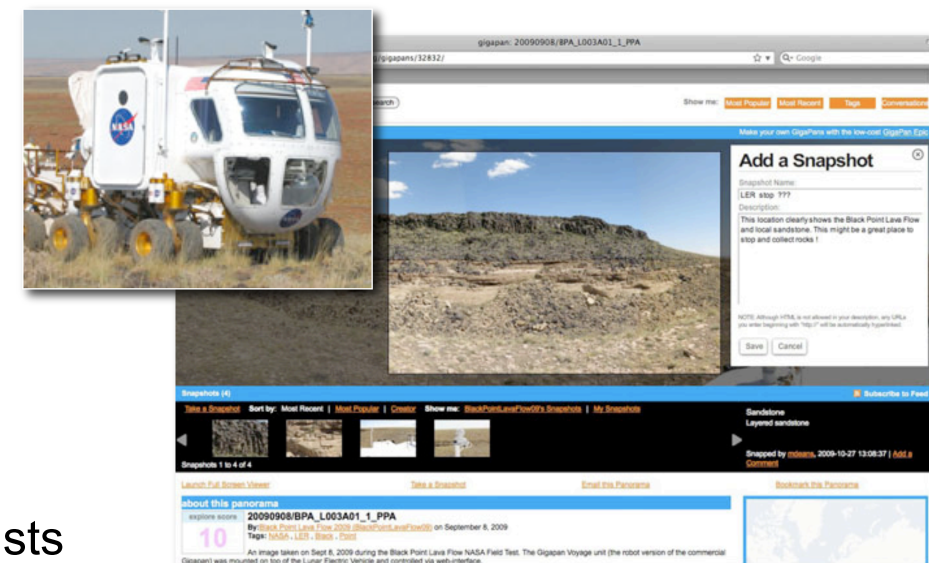
Participatory Exploration for D-RATS 2010

Objectives

- Citizen science using GigaPan
- Involve public & students

Pre-test (Dec 2009 – May 2010)

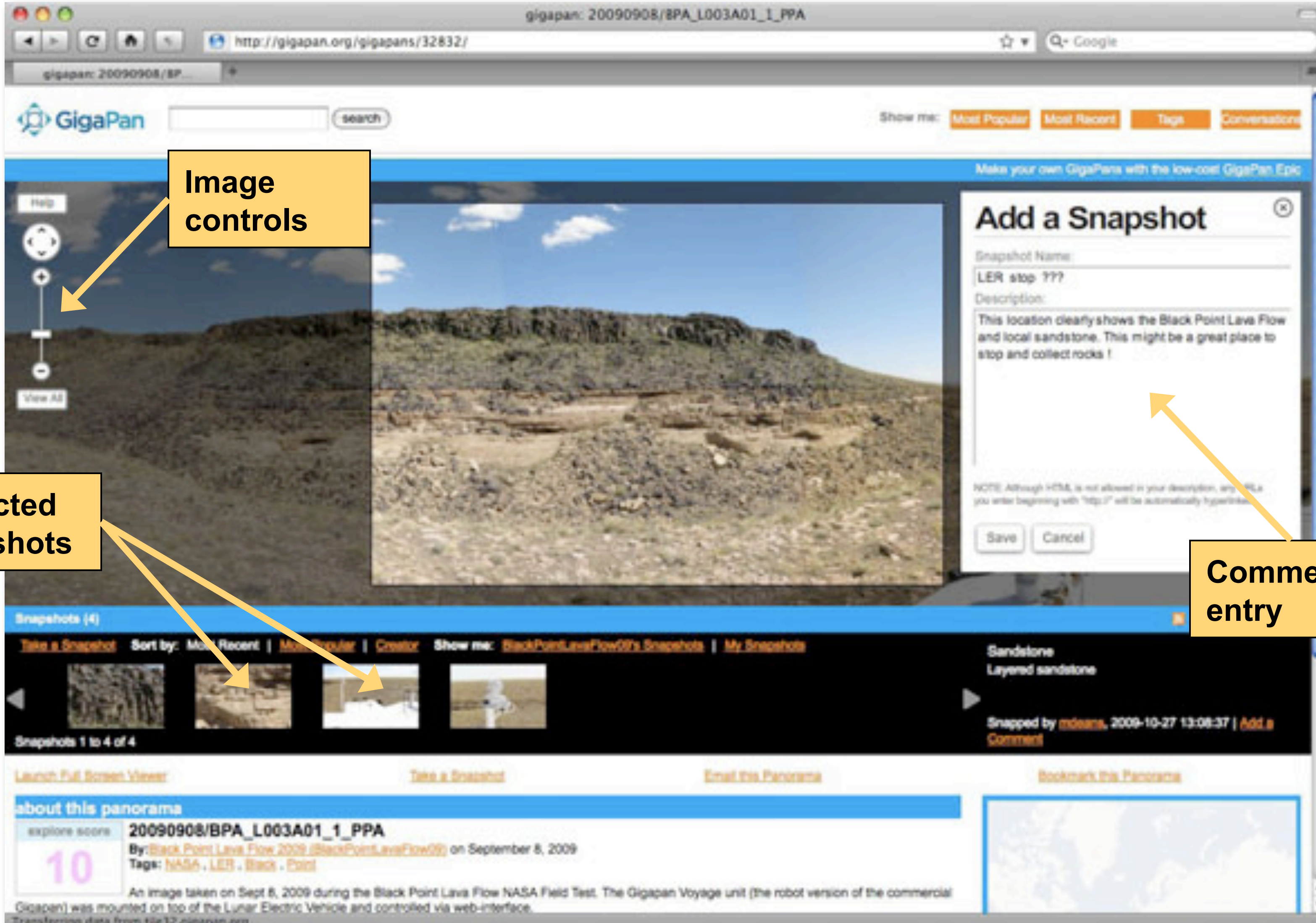
- Manually take GigaPans on preliminary LER traverse plan
- Public explores panoramas, takes snapshots & adds comments
- On-line discussion w/ scientists (places to stop, tasks, etc.)
- Public input for final plan



Field-test (Aug – Sept 2010)

- Take GigaPan panoramas from LER & publish via gigapan.org
- Public explores panoramas & discusses discoveries w/ scientists

Citizen Science



Citizen Science

Formal education (pre-test)

- Higher education (college students)
- Structured classroom activities (e.g., geomorphology)
- Collaboration: Kip Hodges (ASU)

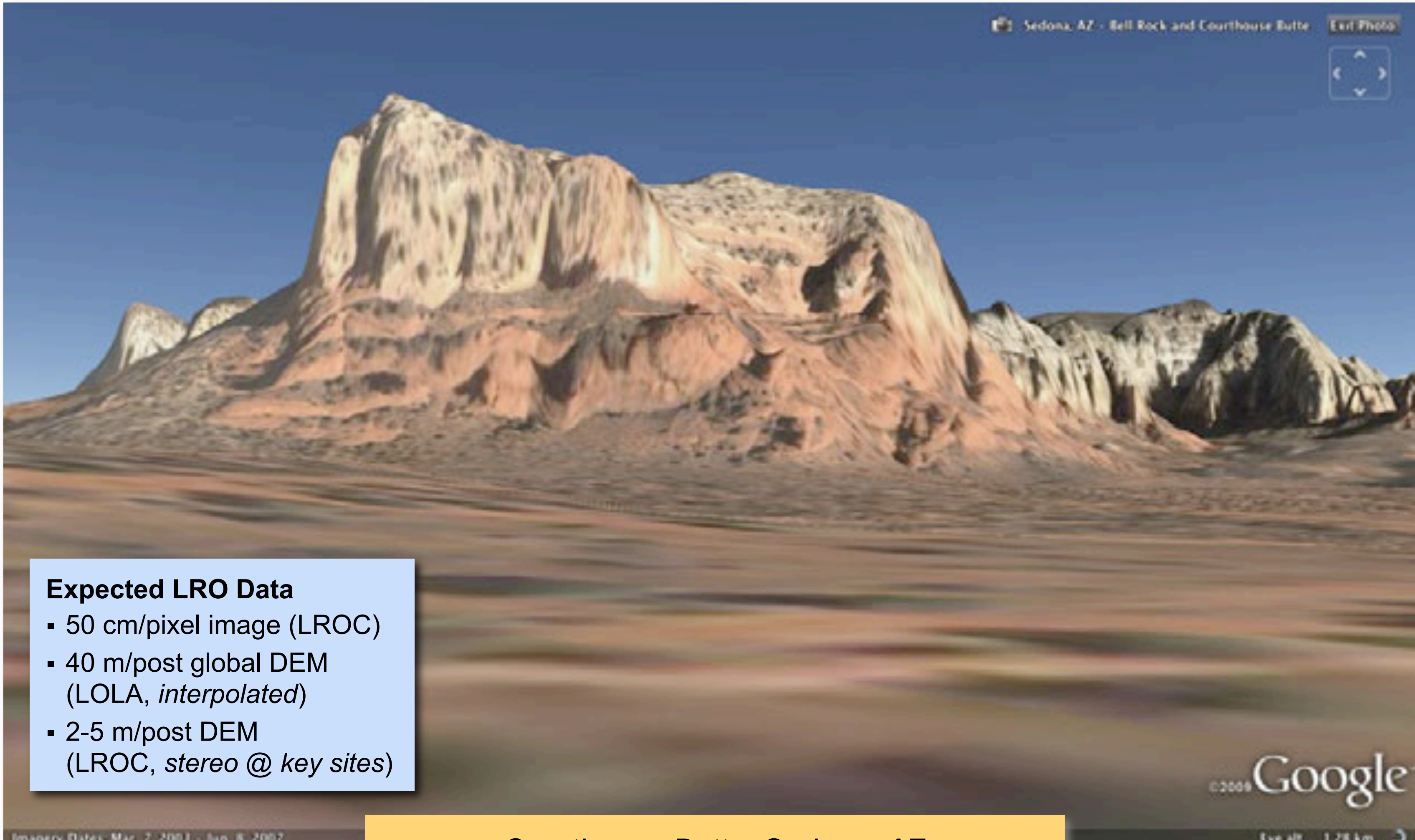
Informal education (field-test)

- K-12 students
- Museum summer programs (e.g., San Francisco Exploratorium)
- Collaboration: Illah Nourbakhsh (CMU)

"Web 2.0" engagement

- General public
- "Viral" involvement via social networking & modern web platforms
- Collaboration: Google & Facebook

GigaPan in Google Earth

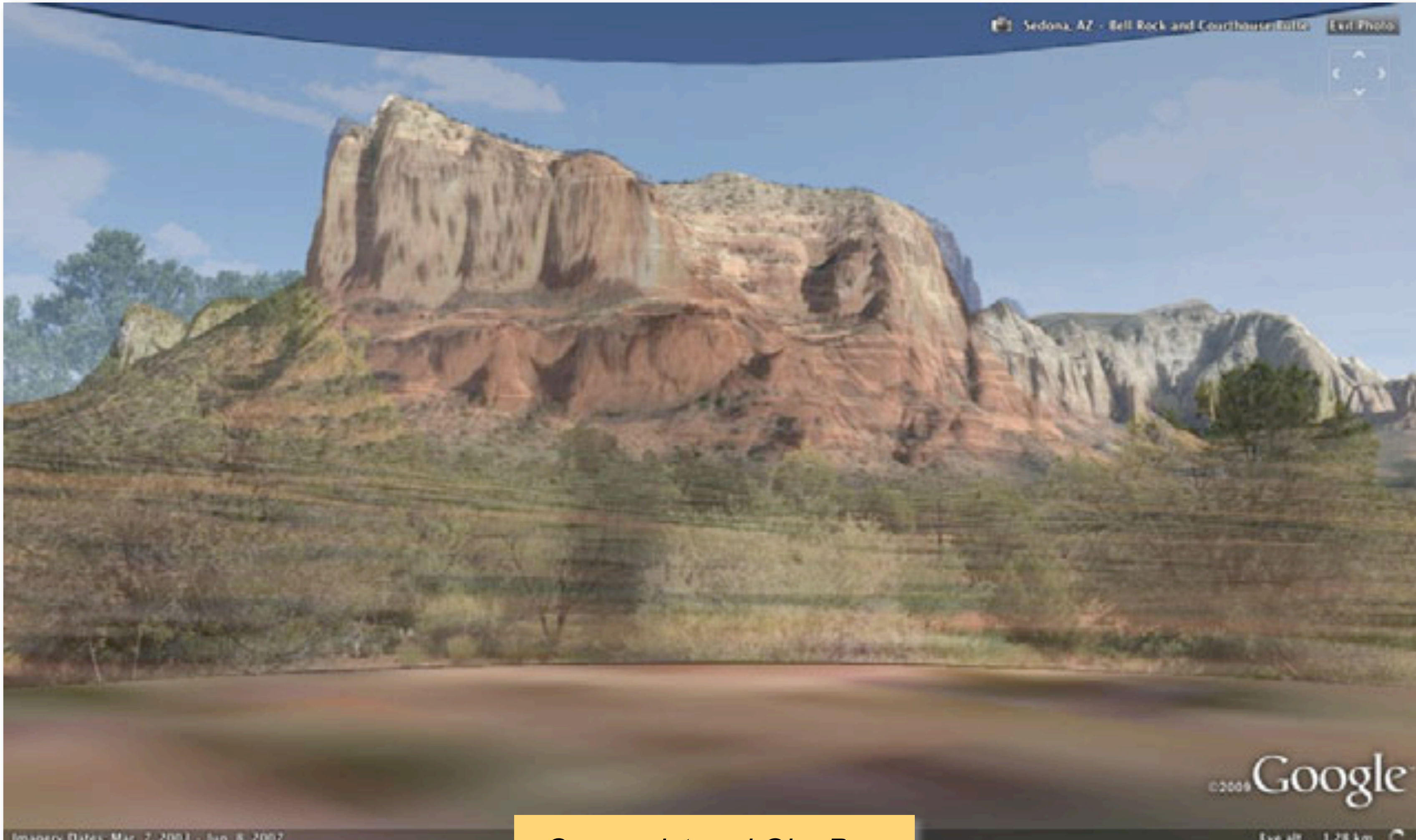


Expected LRO Data

- 50 cm/pixel image (LROC)
- 40 m/post global DEM (LOLA, *interpolated*)
- 2-5 m/post DEM (LROC, *stereo @ key sites*)

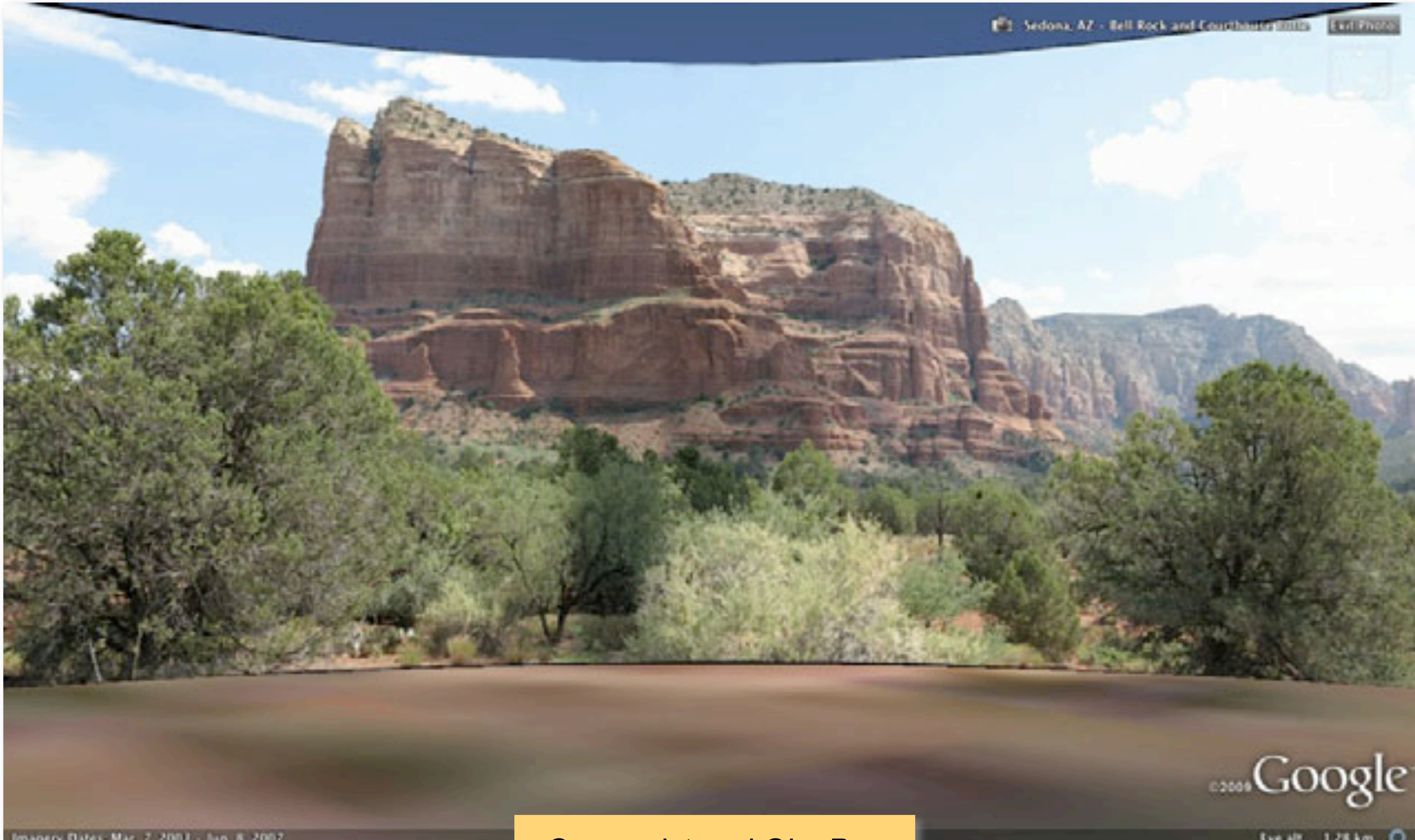
Courthouse Butte, Sedona, AZ
(60 cm/pixel satellite image on 10 m/post DEM)

GigaPan in Google Earth



Geo-registered GigaPan
(50% transparency)

GigaPan in Google Earth



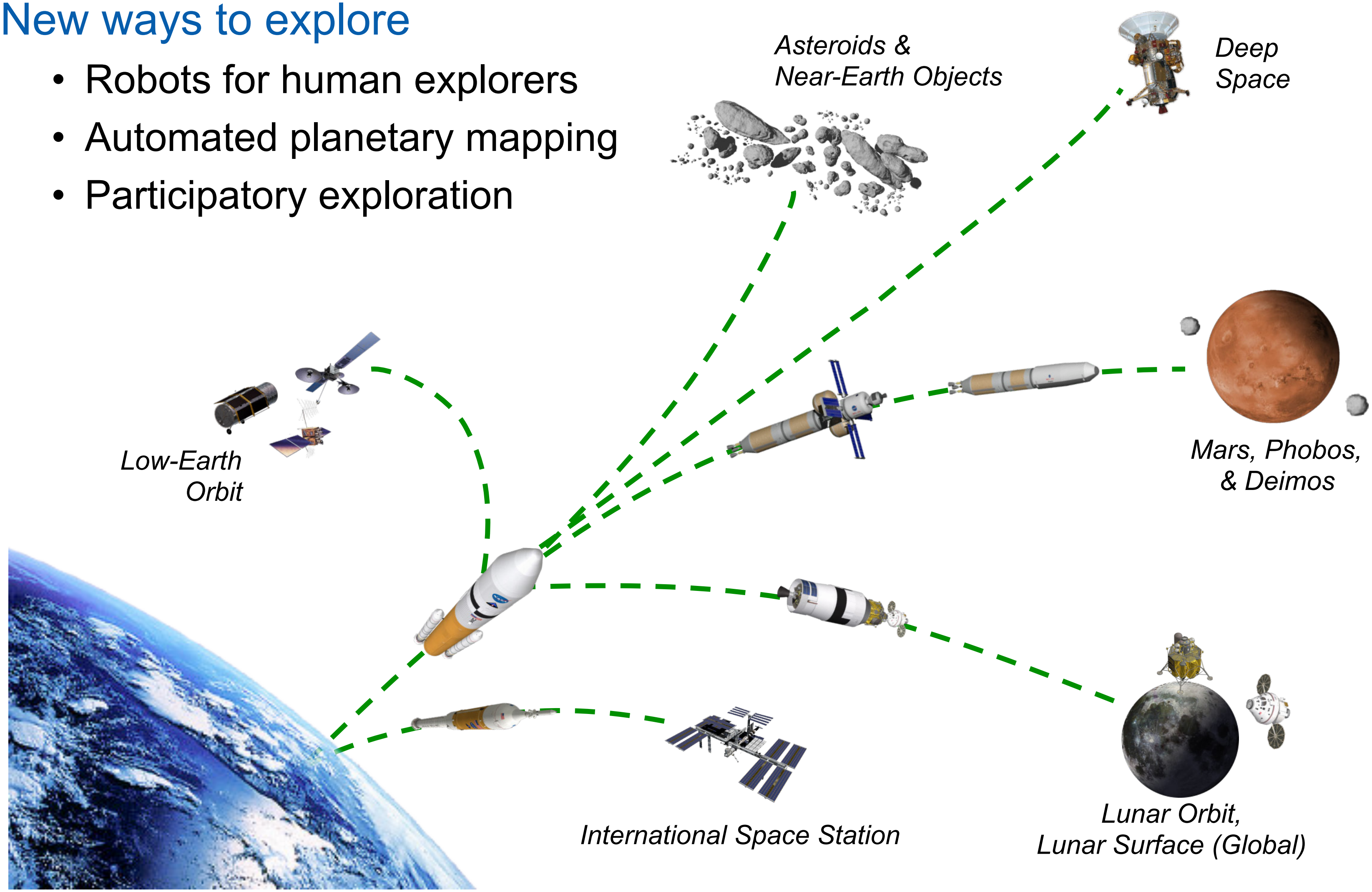
Geo-registered GigaPan (no transparency)

GigaPan in Google Earth

Conclusion

New ways to explore

- Robots for human explorers
- Automated planetary mapping
- Participatory exploration



NASA Summer 2010 Internships

Undergraduate Student Research Project (USRP)

- Sophomores, Juniors, & Seniors
- Deadline: January 22, 2010
- **http://www.epo.usra.edu/usrp**

Motivating Undergraduates in Science and Technology (MUST)

- Sophomores, Juniors, & Seniors
- Deadline: February 1, 2010
- **http://scholarships.hispanicfund.org/applications**

Intelligent Robotics Group

- Graduate students
- Deadline: February 28, 2010
- **e-mail: terry.fong@nasa.gov**

Questions?

Intelligent Robotics Group
Intelligent Systems Division
NASA Ames Research Center

irg.arc.nasa.gov