Planetary Exploration *REINVENTED*

New ways of exploring the Moon, Mars, & beyond

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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
- ATHLETE, K10, Chariot
- Mars Rovers
Exploration destinations
(one-way travel times)

Earth

International Space Station (2 days)

Moon (3-7 days)

Lagrange Points and other stable lunar orbits (8-10 days)

Mars (6-9 months)

Near-Earth Asteroid (3-12 months)

Future missions will be longer, more complex, & require new technology

Robotics and Mobility
Deep Space Habitation
Advanced Spacesuits
Advanced Space Comm
Advanced Propulsion
Resource Utilization
Human-Robot Systems
New Ways of Exploring

Part 1: Robots for human exploration
• Complement & supplement humans
• Off-load “unproductive” tasks
• Before, supporting, & after humans

Part 2: Neo-geography
• Automated planetary mapping
• Easy access to planetary data
• “Desktop exploration”

Part 3: Exploration GDS
• Reusable software tools for distributed science operations
• Web-based & open standards
• Plan, monitor, explore
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Part 1: Robots for Human Exploration

Robots before crew
• Scouting, prospecting, etc.
• Site prep., equipment deploy, etc.

Robots supporting crew
• Inspection, mobile camera, etc.
• Heavy transport & mobility

Robots after crew
• Follow-up & “caretaking” work
• Close-out tasks, maintenance, etc.

Human-robot teaming
• Coordination
• Cooperation
• Collaboration
Robotic Recon Experiment

Objectives

• Test **robotic recon** ahead of crew
• Test **coordinated human-robot** field exploration
• Fold lessons learned into lunar **surface science ops concepts**

Results

• Captured **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

Why Is Recon Useful?

Shorty Crater (Station 4)

Landing Site

Shorty Crater (Station 4)
Field Experiment (2009)

Pre-Recon
- Mar 1 – June 1
  - Satellite images
  - Geologic map

Robot Mission
- June 14 – 26
  - K10 at BPLF
  - Ground control at NASA Ames

Pre-Crew
- July 1 – Aug 15
  - Recon images
  - Terrain models

Crew Mission
- Aug 29 – Sep 3
  - SEV at Black Point
  - Science backroom at Black Point
Black Point Lava Flow

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

100% scale

GigaPan panorama close-up

Terrain image (55 microns / pixel)
Surface Data

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

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Crew Mission

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
Robotic Recon Results

“West” region

- **Pre-recon** plan was designed to be Apollo-like
  - Rapid area coverage (visit 5 geologic units)
  - Single visit

- **Post-recon** plan is significantly different
  - More flexible & adaptable
  - Recon data supports real-time replanning

- Impact of recon
  - Reduced science uncertainty
  - Improved target prioritization


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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

Why is Follow-up Useful?

Landing Site

Shorty Crater
Lunar Analog Site: 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
(75° 22’ N, 89° 41’ W)
Haughton Crater

- Polar impact structures: mixed impact rocks & ejecta blocks
- Subsurface water ice
- Remote, isolated, difficult to access

Shackleton Crater
2005 Arecibo radar image

Haughton Crater radar image

19 km
20 km
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

- Stratified sediments
- Contact between carbonates
- View East into crater
- Gray carbonate breccia
Geophysical Survey

subsurface ice wedges
Robotic Follow-up Plan
Robotic Follow-up Results

Geologic Mapping
• Verified & amended the geologic map in multiple locations
• In some places, robot data was ambiguous, or lacked sufficient detail to re-interpret the map

Geophysical Survey
• Enabled study (correlation of surface & subsurface features) of “polygons”
• Determined average depth of buried ice layer

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Part 2: Neo-Geography

Overview

• Revolution in mapping
• Revolution in geographic tools
• LOTS of planetary data …

Modern planetary mapping

• Satellite imaging (Moon, Mars, etc.)
• Automated map processing
• Live mission data

Desktop exploration

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

"Urgent Processing and Geodetic Control of Lunar Data"
Workshop on Science Associated with the Lunar Exploration Architecture
Really Big Images

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

Digital imagery
- Cameras keep getting better
- Higher resolution & dynamic range
- High-res digital scans of old film

Apollo Metric Camera
- 16,000 x 16,000

HiRISE
- 20,000 x 40,000

HRSC
- 5184 x 16000

CTX
- 5064 x 16000

MER Pancam
- 1024 x 1024

MSL Mastcam
- 1200 x 1200

MOC-NA
- 2048 x 4800

LROC
- 10000 x 50000
Map Processing Pipeline

Data Sources
- PDS
- LMMP Portal
- International
- Historical
- Earth Satellites

ARC
- Metadata DB
- Web Services
- Ingestion
- Mosaicking
- Tiling
- Stereo Generation
- DEM Production
- Local Image Storage
- Bundle Adjustment

HTTP Clients
- WWT
- Uniview
- ArcGIS
- WorldWind
- WMS

GE Client
App Engine
Google Storage

Pleiades

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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
Lunar Terrain Models

Apollo Panoramic Camera

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

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

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)
Apollo Zone Digital Elevation Map (DEM)

Mosaic of 4,000 images
- Apollo Metric Camera
- 73,728 x 368,640 pixels

Equatorial Lunar Surface (38S-34N lat)
- 1,024 pixel / deg
- Vert. acc 40.9m (LOLA)
- Vert. stdv 37.8m
- Horiz. acc 91.3m (LOLA)

Controlled to LOLA through LRO-WAC

40,000 CPU hours
(4 days on Pleiades supercomputer)
Apollo Zone Digital Image Mosaic (DIM)

Reconstructed albedo using lunar Lambertian reflectance model
Explore Mars in 3D

- Released Feb. 2, 2009
- Co-developed with Google
- NASA Ames created content & processing scripts

Content

- Global maps: topography, infrared, historical, etc.
- Imager footprints & overlays (HiRISE, CTX, MOC, …)
- Mars rover tracks & color panoramas
- Tours (Bill Nye & Ira Flatow)
- Live from Mars: THEMIS
- And much more …
Explore the Moon in 3D

- Released July 20, 2009
- Co-developed with Google
- NASA Ames created content & processing scripts

Content

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

Explore Mars in 3D
- Released July 12, 2010
- Co-developed with Microsoft Research
- http://worldwidetelescope.org

Content
- Largest digital image mosaic of Mars ever created
- Historical maps
- Guided tours (Carol Stoker and Jim Garvin)

MOC vs. HiRISE

<table>
<thead>
<tr>
<th>INPUT</th>
<th>MOC</th>
<th>HiRISE</th>
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</thead>
<tbody>
<tr>
<td>Total # of images</td>
<td>74,359</td>
<td>13,342</td>
</tr>
<tr>
<td>Pixels / Image</td>
<td>16 Megapixels</td>
<td>1.25 Gigapixels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTPUT</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Image Tiles</td>
<td>~38 Million</td>
<td>~526 Million</td>
</tr>
<tr>
<td>Total Mosaic Size</td>
<td>843 Gigabytes</td>
<td>12 Terabytes</td>
</tr>
</tbody>
</table>
**Ames Stereo Pipeline (ASP) for Earth**

**ASP for Earth (open-source)**
- High-quality stereo correlation for large satellite images
- Camera models for NASA satellites, DigitalGlobe satellites, RPC imagers, etc.
- Linux/OS-X command-line tools (desktop to super computers)

**Performance**
- Approx. 5 min CPU time / km² (NASA Pleiades supercomputer with 3 GHz Xeon processors)
- 5 hours for DigitalGlobe stereo imagery subsampled to 1 m/px
- 60% success rate without any human intervention

*Colorized DEM of Basalt Hills Quarry (CA) derived from Digital Globe WorldView*
SRTM vs. Ames Stereo Pipeline

Shuttle Radar Topography Mission (30 m/pixel)

Ames Stereo Pipeline (DG WorldView, 1.5 m/pixel)

1.15 km
South American Glacier

Hill shaded digital elevation map

Credit: M. Willis
Jakobshavn Glacier

WorldView DEM Mosaic (7/9/10-7/11/10)

Credit: D. Shean (Univ. of Wash)

3-5 m/pixel
2,500 km²
(6 input images)
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Science Mission Support

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## Exploration Use Cases

<table>
<thead>
<tr>
<th>Year</th>
<th>K10</th>
<th>D-RATS</th>
<th>PLRP</th>
<th>NEEMO</th>
<th>ISRU</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
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<tr>
<td>2008</td>
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<td>2009</td>
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<td>2010</td>
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<tr>
<td>2011</td>
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<tr>
<td>2012</td>
<td></td>
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<tr>
<td>2013</td>
<td></td>
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</tr>
</tbody>
</table>
xGDS is …

- Map content management
- Planning tool
- Real-time plots, maps, notes
- Post-processing data archive
- Browse and search tools

Users

- Field scientists
- Planetary scientists
- Mission planners
- Flight controllers
- Local & distributed teams
Architecture

Data Interfaces

- Path Planner
- Crew tracking
- Vehicle tracking
- Robot tracking
- Payload data

Data store

MySQL

Django

Map server
- Web planner
- Console log

Data maps

Data search

Plots
- Raster maps

xGDS

apache

User Interfaces

Google Earth
- Web Browser
Map Server
Web Planner

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Tracking

- **Data Products**
- **Vehicle**
- **Tracks**

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Plots

- Neutron Spectrometer Sn/Cd Ratio
- Neutron Spectrometer Sn counts/s
- Neutron Spectrometer Cd counts/s
- Drill Thrust (N)
- Drillhead Position (cm)
- NIR Water 1
- NIR Water 2
- NIR Bound OH
- NIR Grass
- Latitude
- Longitude

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Raster Maps
**Console Log**

![Console Log Image]

**Cross-referenced images**

**Real time notes**

<table>
<thead>
<tr>
<th>Simulation ID</th>
<th>Console Position</th>
<th>Test Condition</th>
<th>Timestamp (HH:MM:SS)</th>
<th>Log Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-RATS 2011</td>
<td>EV2CT</td>
<td>Condition 7</td>
<td>2011-09-09 21:38:45</td>
<td>Last three samples wrap up: Sampled lower mudstone, interbedded mudstone/tilstone, and then interbed sandstone above mud/tilstone. Sample 0513, lower unit, lower unit, sandstone with shale, adjacent to piece with ripple bedding forms present in cross section. Large problems with this EVA due to communications and lots of data problems. Cameras were patchy at best, never got control of camera 1, never got GPS down, etc. Pretty hard to evaluate condition.</td>
</tr>
<tr>
<td>D-RATS 2011</td>
<td>EV2CT</td>
<td>Condition 7</td>
<td>2011-09-09 21:37:17</td>
<td>Sample 0512, lower unit, sandstone with shale, adjacent to piece with ripple bedding forms present in cross section. Large problems with this EVA due to communications and lots of data problems. Cameras were patchy at best, never got control of camera 1, never got GPS down, etc. Pretty hard to evaluate condition.</td>
</tr>
<tr>
<td>D-RATS 2011</td>
<td>IM</td>
<td>Condition 7</td>
<td>2011-09-09 21:05:31</td>
<td>Huge problems with this EVA due to communications and lots of data problems. Cameras were patchy at best, never got control of camera 1, never got GPS down, etc. Pretty hard to evaluate condition.</td>
</tr>
<tr>
<td>D-RATS 2011</td>
<td>EV1CT</td>
<td>Condition 4</td>
<td>2011-09-09 21:02:00</td>
<td>EV4: Sample 0103 (red sandstone?) context: SEVA-20110909-205446-C18 Crossing basin field, did not find anything in place. Some low features on basin with some discoloring.</td>
</tr>
<tr>
<td>D-RATS 2011</td>
<td>EV1CT</td>
<td>Condition 4</td>
<td>2011-09-09 21:00:00</td>
<td>EV4: Sample 0530-Platy red material - two fragments from larger material that is naturally fractured (no hammer necessary - float). Weathered surface reddish-brownish color, texture like a basketball. Small submm blackish grains (biologic or phenocrysts or inherent) and whitish grains. Other subsides is more homogenous, redish brown undulating surface; side surface demonstrates vertical stratigraphy with darker band in middle, lighter on sides; some phenocrysts, sub-mm crystals, glint in sun (second half from soicon). Sample: SEVA-20110609-205751-C17 Context: SEVA-20110909-205434-C17</td>
</tr>
<tr>
<td>D-RATS 2011</td>
<td>Ops</td>
<td>Condition 7</td>
<td>2011-09-09 20:59:48</td>
<td>Comm with EV1 was out for most of the EVA. Could only hear her on Big Loop. Sent an EVAS text to let her know.</td>
</tr>
</tbody>
</table>
Pavillion Lake Research Project

Science objectives
- Map lake geology & biology
- Study microbialite formation

Challenges
- Distributed science team
  - Submersible pilot / scientist
  - Remote science team
- Real-time (re)planning
- Long-term data analysis

Planning needs
- Maps of the lake and surrounding area
- Data from past & precursor missions
- Where can we go & not go?
- Where do we need to start & end each flight?
- Coordination and collaboration
Web-based Planner
Monitoring

Vehicle

Notes

Tracks

Flight plan
Replanning

Pilot: “...this would be a good place to come this afternoon for sampling...”
Data Browsing
Viewing Data
<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Event</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-07-10</td>
<td>12:38:49</td>
<td>microbialites</td>
<td>A lot of scattered small microbialites. This is a place to check if mbs are growing on rocks. Depth is 32 feet.</td>
</tr>
<tr>
<td>2009-07-10</td>
<td>12:41:14</td>
<td>trees</td>
<td>A lot of fallen trees in the area. Some have microbialite cover. Some might be large microbialites.</td>
</tr>
<tr>
<td>2009-07-10</td>
<td>12:44:34</td>
<td>trees</td>
<td>Lots of trees with microbialites.</td>
</tr>
<tr>
<td>2009-07-10</td>
<td>12:46:39</td>
<td>note</td>
<td>This is a good spot to look for a spring</td>
</tr>
<tr>
<td>2009-07-10</td>
<td>12:47:44</td>
<td>trees</td>
<td>Log with a large microbialite growing on it. 17 feet.</td>
</tr>
<tr>
<td>2009-07-10</td>
<td>12:50:29</td>
<td>trees</td>
<td></td>
</tr>
</tbody>
</table>

**Video Links:**
- 20090710A-12443615
  - Still
  - Video
  - Half Res Video
- 20090710A-12503004
  - Still
  - Video
  - Half Res Video
Development Lessons Learned

Open standards: HTML & KML

- Easy to create, distribute, and visualize content
  → Focus on data, not on software
- Google Earth, Firefox/Chrome/Safari
  → Reduces development and training time
- Facilitates integration with standards-compliant 3rd party tools

Modular implementation using open source

- Apache, MySQL, Django & Python, jQuery & JavaScript
- Focus on writing the “glue” between mature modules
- Quickly prototype new solutions/features

http://xgds.org

- Cloud hosting soon (Google AppEngine or Amazon EC2)
- Open-source release (Apache 2) this fall
Conclusion

New ways to explore

- Robots for human explorers
- Neo-geography
- Exploration ground data system