Automated Subsurface Sample Acquisition
Technologies for Lunar Exploration

October 4, 2007

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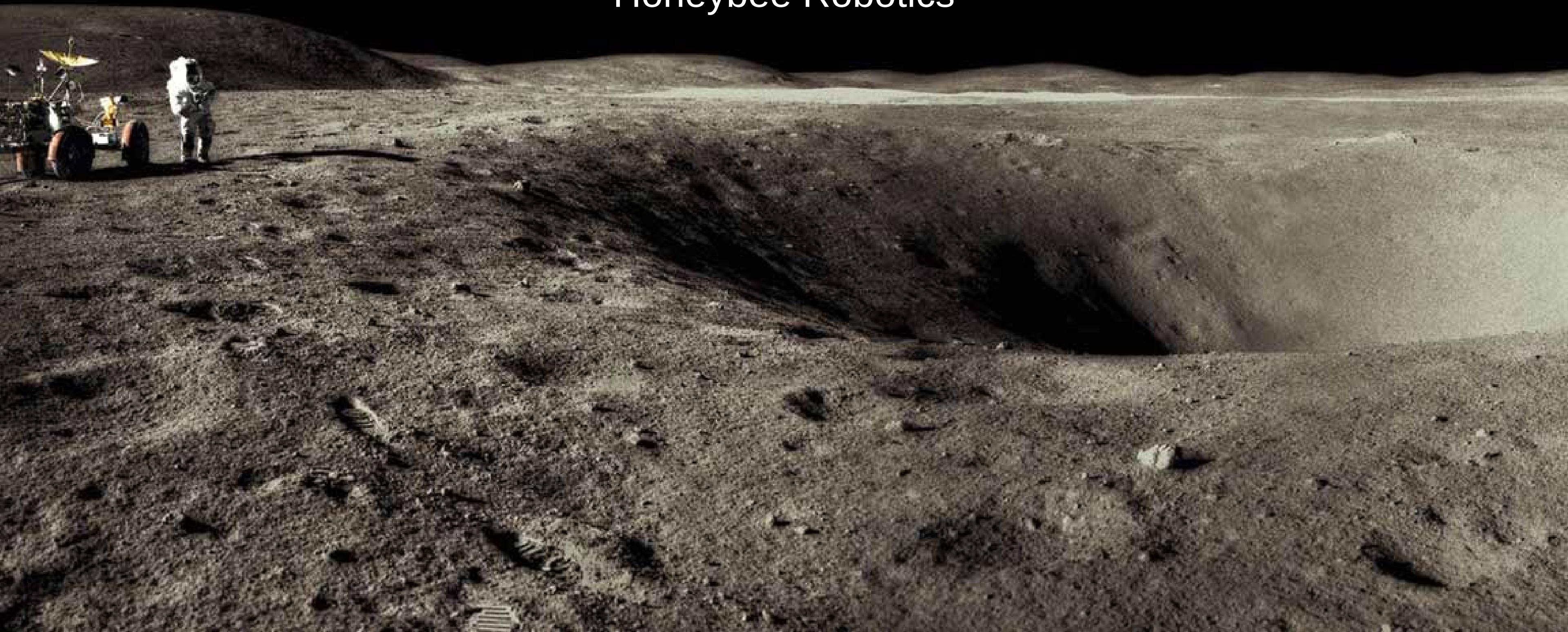
Honeybee Robotics



Agenda

- *Objectives*
  - *Overview of drill-based strategies for Subsurface Sample Acquisition*
  - *Summary of recent & ongoing development work in this area*
  - *Key challenges ahead*

- Discussion Outline
  - About Honeybee
  - Where We Are
  - Functional Components of Drill-Based Automated Sampling
  - Design Drivers: Sample & Target Characteristics, Others
  - Some of our recent experiences (SATM, DAME, MARTE, CRUX)
  - Lessons Learned & Challenges
  - Concluding Remarks
  - Questions

About Honeybee

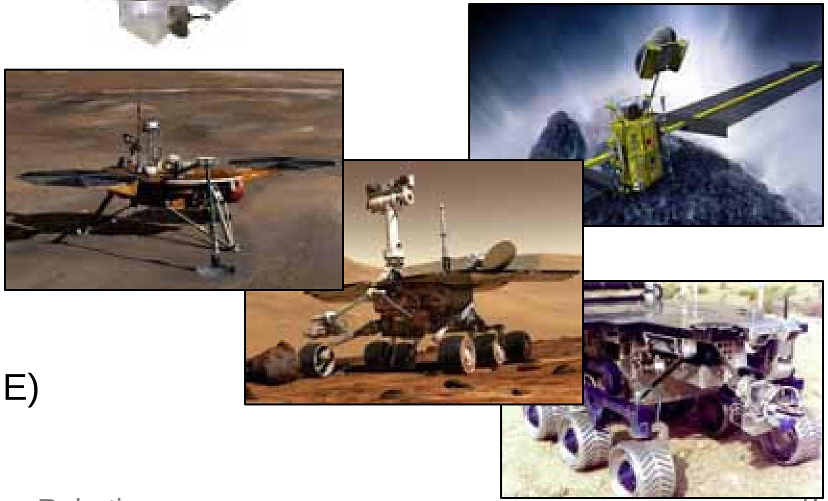
- **Honeybee Robotics** Spacecraft Mechanisms Corp.
  - Est. 1983
  - HQ in New York (midtown Manhattan)
  - Small office in Houston (NASA Pkwy)
  - Currently 37 employees (27 engineers)
    - Engineering Staff: 80% ME, 20% EE-CE-CS
  - ISO-9001 & AS9100 Certified

- Historical Progression:
  - Systems Integrator of industrial robotic work cells
  - Custom end-of-arm tooling & industrial systems
  - First NASA work in late 1980's
    - FTS end-effectors
    - On-orbit structural assembly
    - GSFC Mole (burrowing powder sampling tool)

GSFC Tethered Mole

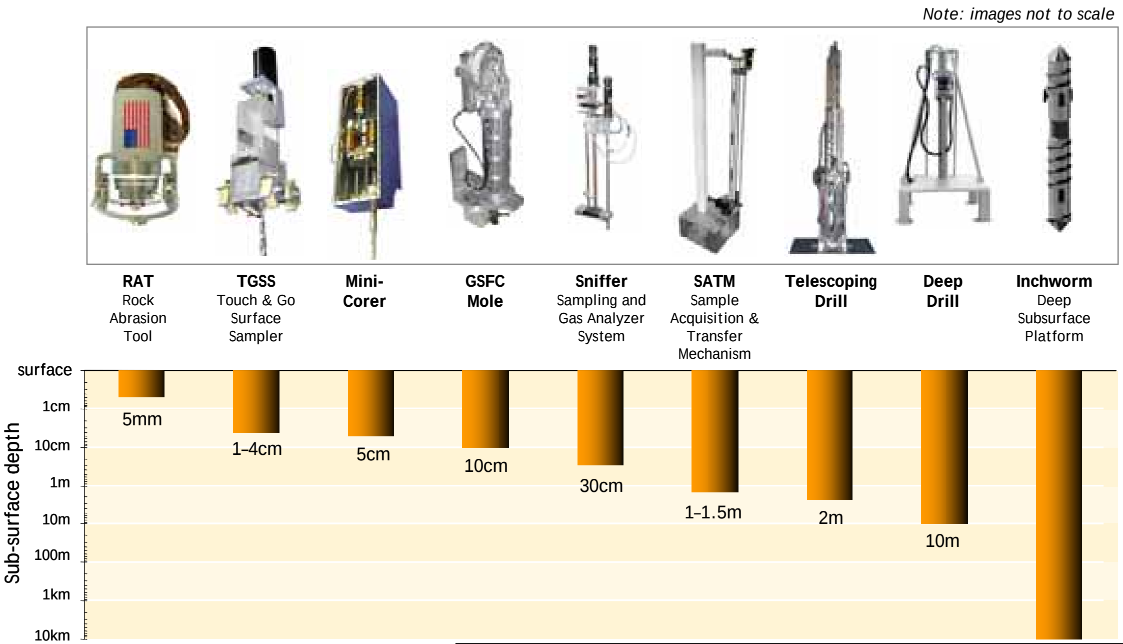
FTS WAM/WAF

- Subsurface Access & Sampling:
  - Phoenix Icy Soil Acquisition Device
  - MER Rock Abrasion Tools
  - ST4/Champollion SATM (1-m comet sampler)
  - Athena Mini-Corer (5-cm rock coring drill)
  - 10-meter class drills (Mars Deep Drill, MARTE, DAME)
  - Etc.



Where We Are

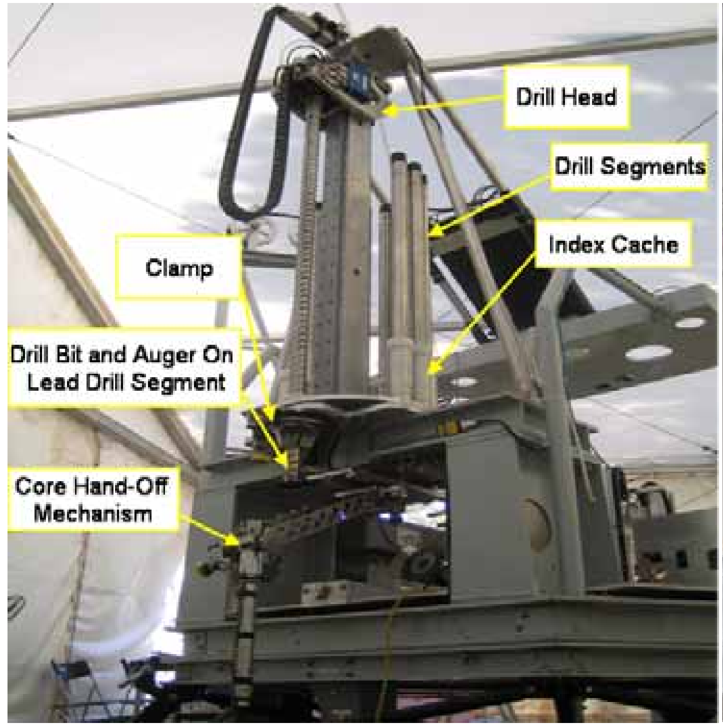
- Many organizations working the SA area: Honeybee, JPL, Swales, Alliance, UTD, JSC/NORCAT, JSC/BH, etc.
- Numerous <u>point designs</u>
  - Different sample types for different purposes from various targets (some more representative than others)
- Very difficult to assess TRL and compare performance
  - Not always apples-to-apples (different objectives)
  - Prototype meant to demonstrate specific subset of overall functionality
  - Original sample or target requirements have become obsolete (or irrelevant)

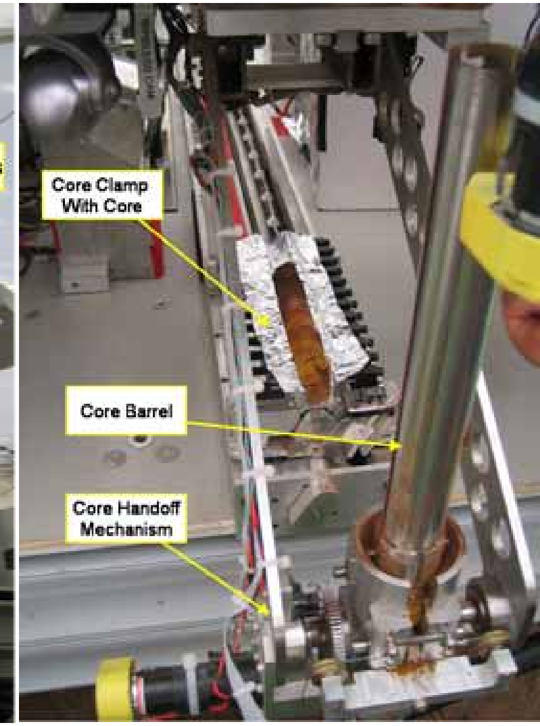


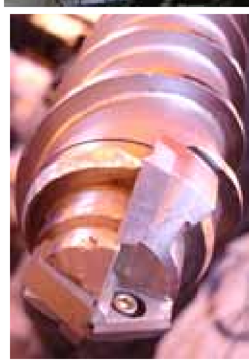
This talk focuses on 1m+ systems

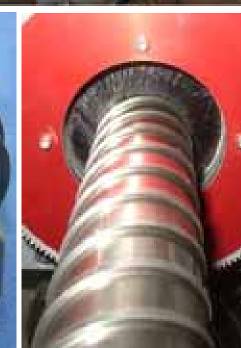
Functional Components of Drill-Based Automated Sample Acquisition Systems

- Access (Drilling)
  - Stabilization & Load Isolation
  - Defeat Formation
  - Transport Cuttings
- Sampler
  - Obtain
  - Retain & Extract
  - Transfer
- Sample Storage (Cache)
  - Accept
  - Contain
- Maintenance
  - Manage Dust/Debris
  - Contamination Control
  - Bit Exchange
  - String Extension
- Fault Detection, Prevention & Handling
  - Intelligent Control (software)
    - Avoidance & Recovery
  - Hardware Recovery
    - Example: Bit release





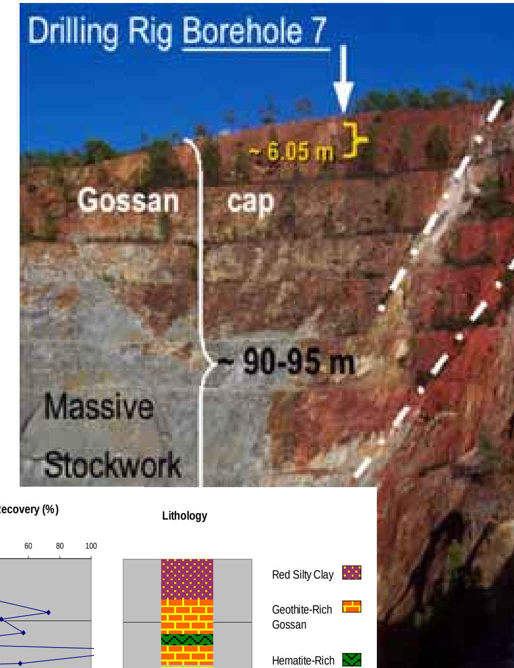


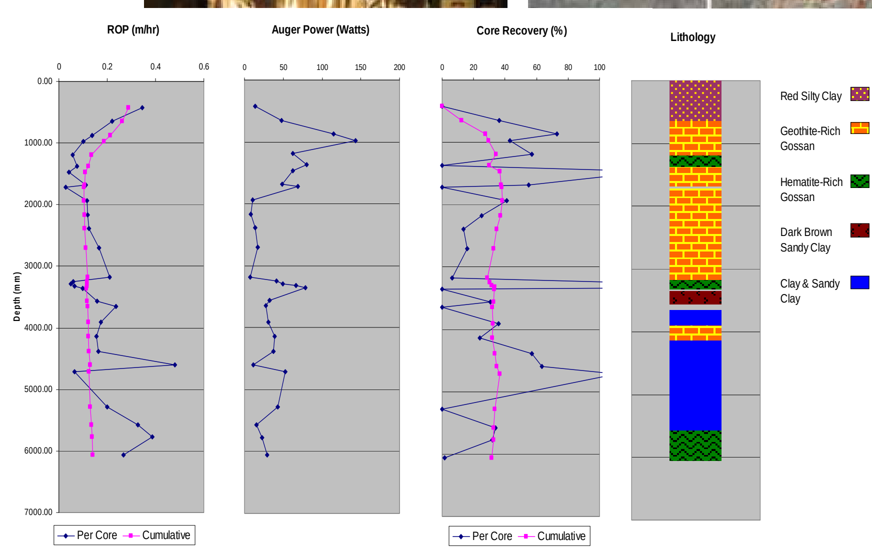


There's a lot going on! Systems must generally consider all of these functions

Design Drivers: Sampling & Target Characteristics

- Sample specifications:
  - Objective & Key Characteristics to Preserve
    - Petrology/mineralogy/chemistry
    - Water & other trapped volatiles
    - Trace organics
  - Cores vs. Cuttings
  - Depth & Knowledge of Sample Location
  - Quantity
  - Thermal limits
- Target specifications:
  - Scale of heterogeneity
  - Strength/consolidation
  - Hardness/abrasiveness
  - Porosity
  - Etc.





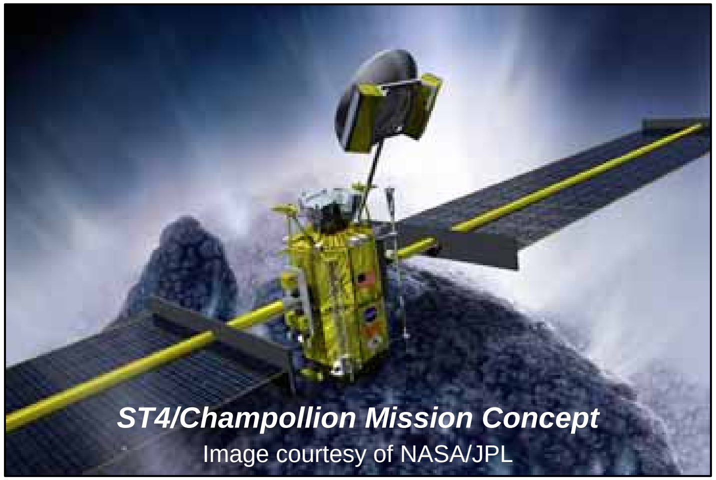
System design obviously <u>starts</u> with Sample & Target characteristics

Other Design Drivers

- Other instruments that might need access to borehole
- Interface with surface instruments or sample cache
- Platform related constraints (e.g., tilt, positioning, reaction capability)
- Reliability & Environment: thermal, torque margin, seals, etc.

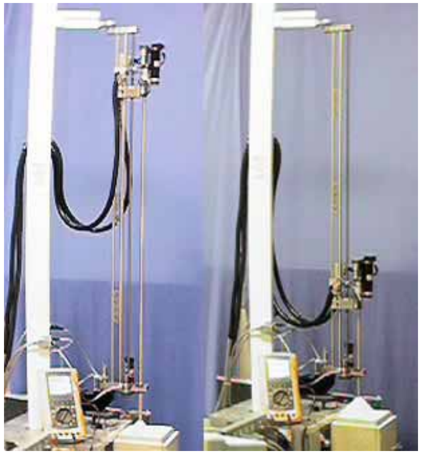
ST4 / Champollion Sample Acquisition & Transfer Mechanism (SATM)

- TRL 4
- Mass < 10 kg
- 1.2-meter drilling stroke; 13-mm drill string diameter
- Power consumption: 25 W-hr (40 MPa material)
- Drill Rate: 1 cm/min (40 MPa material)
- Acquires locally mixed powder sample (up to 0.1 cc)
- Surface instruments:
  - GCMS Oven (0.1 cc of sample)
  - Microscope (sapphire window)



ST4/Champollion Mission Concept

Image courtesy of NASA/JPL

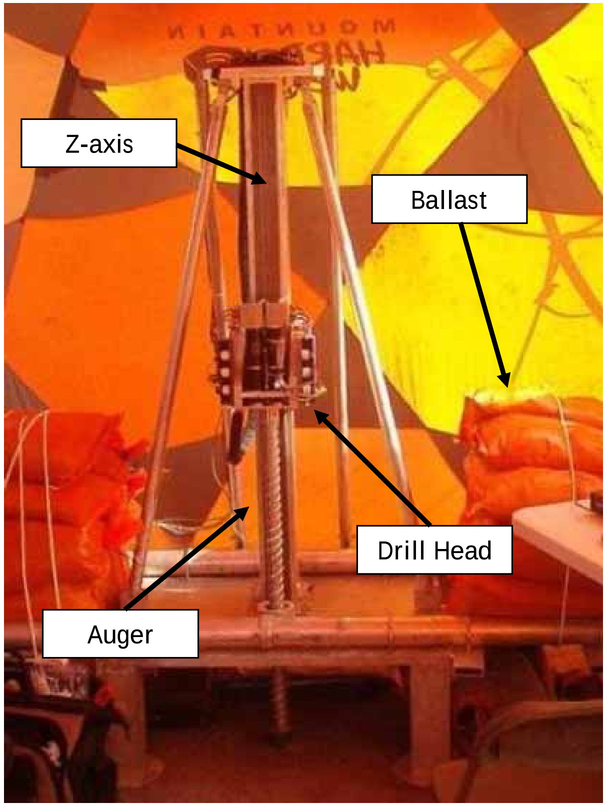


SATM Prototype Drilling into Chalk Sample

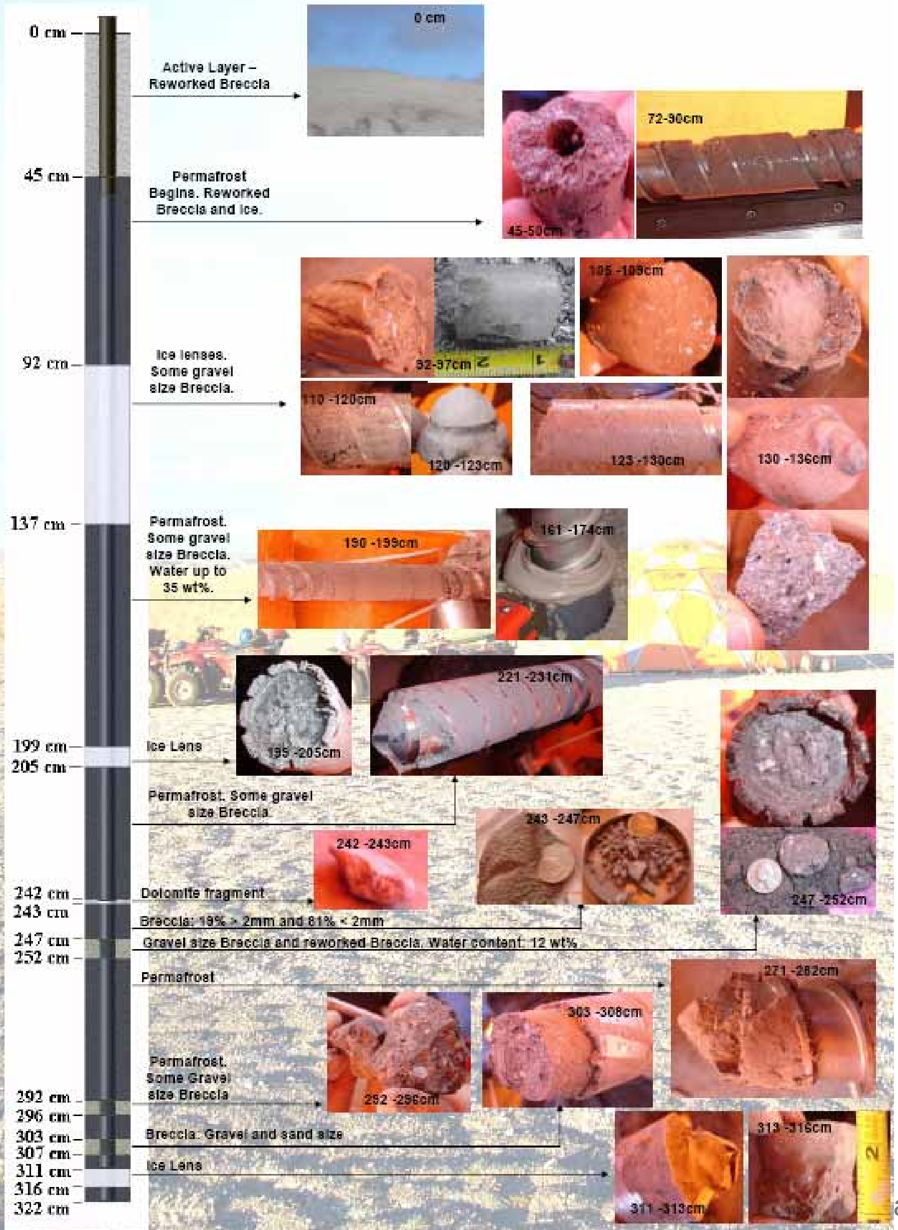
Cryogenic testing

Drilling Automation for Mars Exploration (DAME)

- 2004 to present
  - PI: Dr. Brian Glass, NASA Ames
  - HBR provided drill
- Project Objective:
  - Intelligent software control of Drill
- Progress:
  - Year 1: Characterized Faults
  - Year 2: Diagnosed Faults (observer)
  - Year 3: Demonstrated Fault Avoidance & Recovery
  - Year 4: More Development of Diagnostic & Executive
- Drill Design – Notable Experience:
  - Exposure to complex target formation
    - Drilling challenges: conglomerates, ice layers, permafrost
    - Informed models used in Lab testing
  - Mechanisms & Down-hole instrumentation
    - Rugged, dust/water resistance
  - Low-Level control limitations
    - Algorithm flexibility
  - 3.2 meters (HMP Devon Island record?)

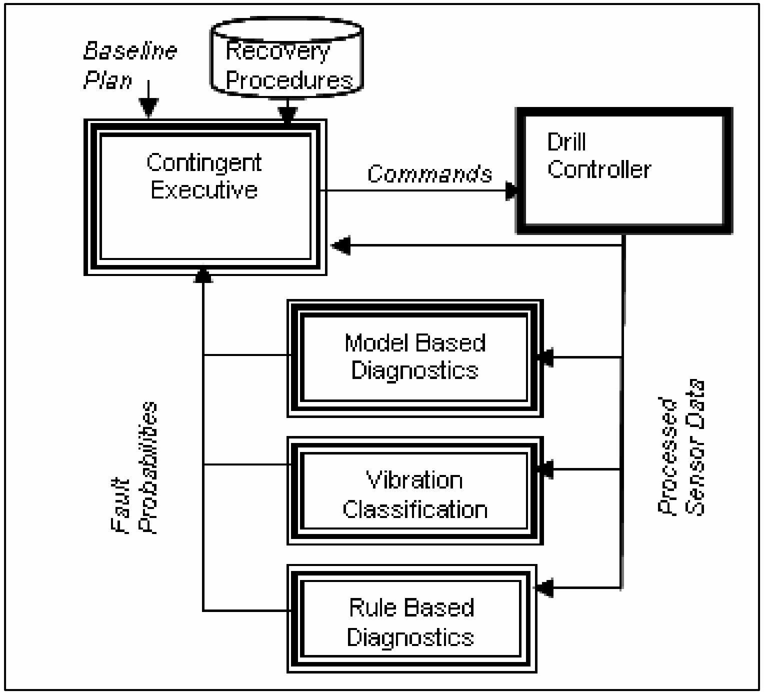


More DAME…



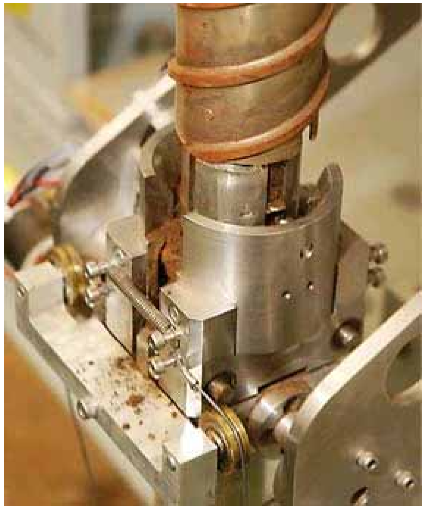
Drill Faults

- Auger Binding or Choking
- Bit Jamming or Inclusion
- Hard Material
- Auger Corkscrewing



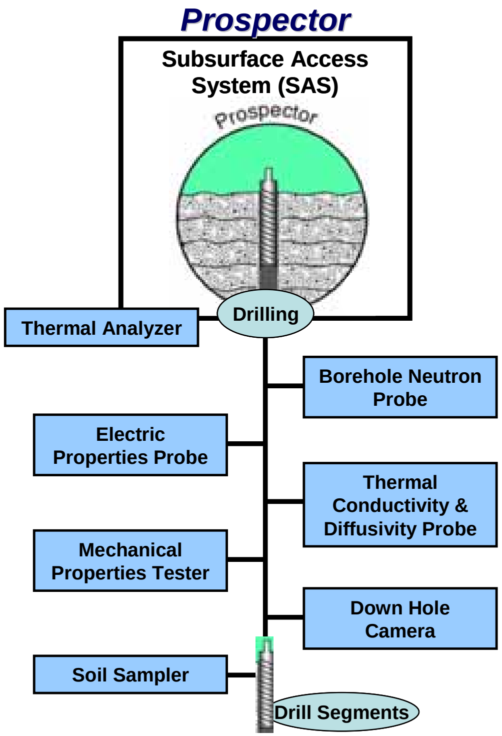
Mars Astrobiology Research & Tech. Experiment (MARTE)

- 2004 to 2005 (HBR involvement)
  - PI: Dr. Carol Stoker, NASA Ames
  - HBR provided drill
- Project Objective:
  - Astrobiology drilling mission simulation
- Progress:
  - Year 1: Drill Design (25-mm diameter core)
  - Year 2: Field Tests in Santa Cruz, Rio Tinto (ESP)
- Drill Design – Notable Experience:
  - More exposure to complex target (formation)
    - Drilling challenges: unconsolidated, very mixed, silty clays, gossan
      - Main Problem: **Chip Transport** near cutting interface was problematic
    - Poor & Unpredictable Core Recovery (~30%)
      - Although similar to terrestrial drill ground truth core
    - Stressed the importance of higher fidelity lab testing
  - Mechanism Problems
    - Dust clogged mechanisms
      - Down-hole sample capture mechanism
      - Core barrel transfer mechanisms
    - Core extrusion – Split Tube helped
    - Self-Cleaning capability cannot be after thought
  - Positive Notes
    - Achieved over 6 meters
    - Demonstrated:
      - Automated Drill String Assembly (good reliability)
      - Core Acquisition, Retrieval & Transfer (poor reliability)
    - Compressed air – a very small amount makes a huge difference



Construction & Resource Utilization Explorer (CRUX)

- 2005
  - PI: Dr. Jerry Johnson, ERDC-CRREL
  - HBR was to provide SAS Drill & Sampler
- Project Objective:
  - Develop payload for Lunar construction & resource reconnaissance
- Phase 1 Progress
  - Cancelled after 5 months
  - Early R&D, proved drilling approach, trade studies
  - 2m demo unit partially completed
- Drill Design – Notable Experience:
  - Focused mainly on access (drilling)
  - Lab testing in compacted frozen Lunar simulant (JSC-1, FJS-1)
  - Rotary Percussive & Rotary approaches tested
  - Various auger & bit designs tested



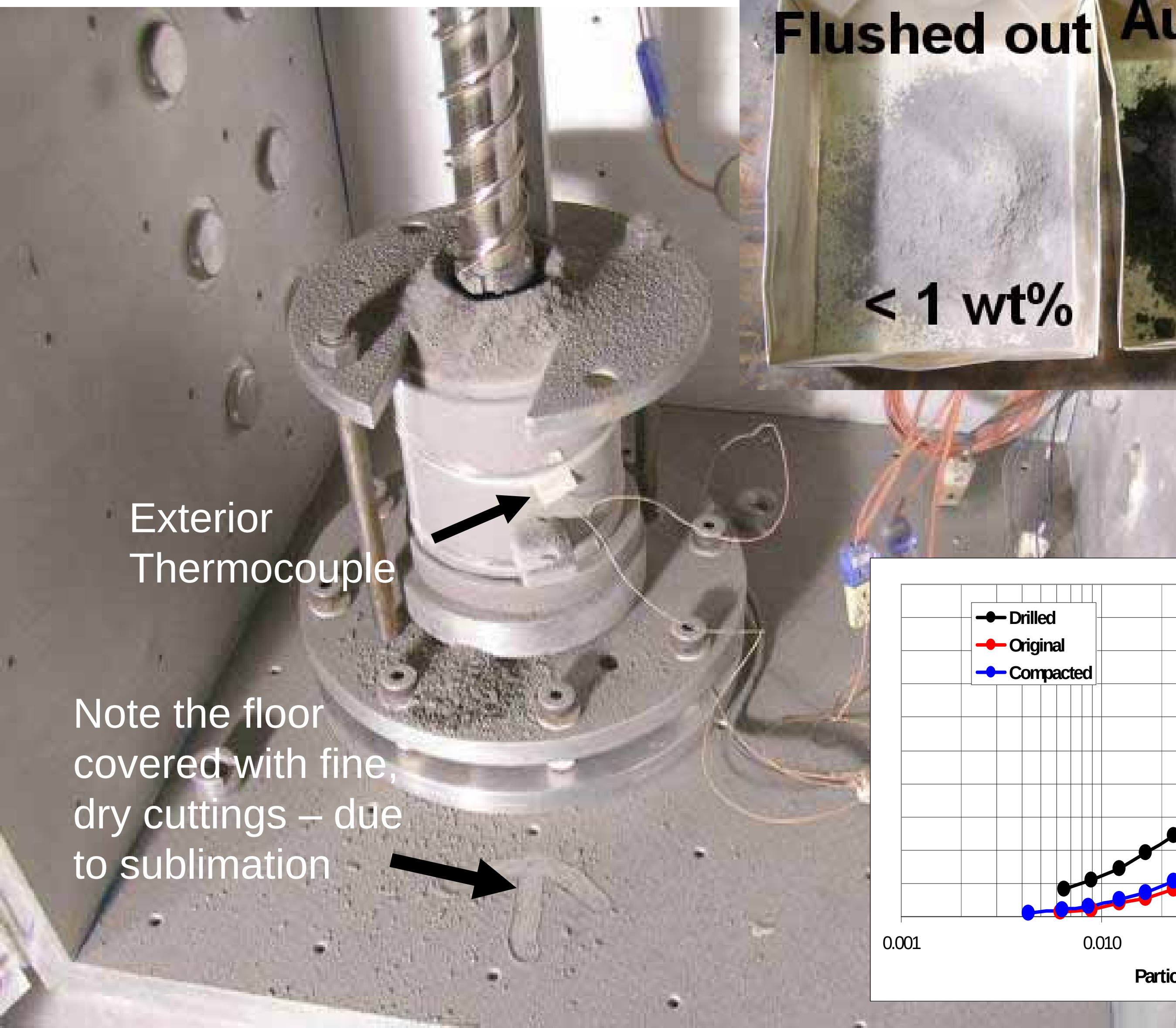
- Form 2m+ borehole in low temp, water ice bearing, compacted regolith from low weight platform
- Acquire samples at depth, handing off to TA/TEGA, retaining volatiles
- Accommodate downhole sensing for 5 instruments

More CRUX…

Very steep rim of cuttings!

The core was as hard as a rock and very difficult to break off.

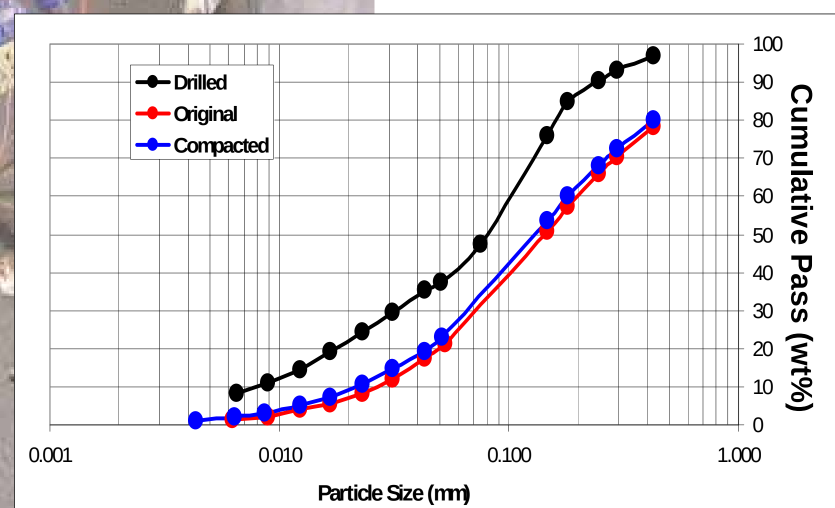
More CRUX…



Dry core was very fragile

Exterior Thermocouple

Note the floor covered with fine, dry cuttings – due to sublimation



Lessons Learned & Challenges pertaining to a Lunar regolith sampler

- Major Challenge – Control of unconsolidated particles & dust remains the major challenge
  - Subsurface Access: Effective Cuttings Removal
  - Sample Acquisition: Handling Widespread Tendencies of Material
  - Mechanism Reliability: Keeping Particulate Build-Up to a Tolerable Level
  - For these reasons:
    - Downhole mechanisms (and those internal to casing) should all but be eliminated if they can't be designed to tolerate a large amount of compacted dust
      - Passive means of retaining the sample (e.g., soil cohesion) should be adopted if possible
    - Extruding or manipulating samples (consolidated or otherwise) should be vibration assisted to avoid jamming/clogging
    - Use of pneumatics should seriously be considered

- Bit Design – Cutting capability is not the tallest pole however it could be if operating time and power are constrained.
  - ALSD: 500 W, 5 Joules/blow, 50-80N, WC bit driven in RP fashion
  - Bit may need to be scaled to require less power
  - Also, bit design as it relates to cuttings removal is critical (see above)

Lessons Learned & Challenges pertaining to a Lunar regolith sampler

- Target Models & Effects of Water Content
  - Testing in realistic, complex target models to required depth must be emphasized from the beginning of development
    - Requires concurrence by lots of folks
    - Early establishment of preliminary models (and preparation procedures) is necessary, understanding that models may change with continued research
  - Field testing is good in order to discover new challenges, however most sites will have too much moisture
    - Exorbitant amounts of water (by the lunar standards) can cause many artificial problems
  - Testing in ice-bearing materials at vacuum & temperature
    - "Clumping" has been observed in high-water content (20-30 wt%) soil mixtures even at ambient & bulk temperatures well below 0°C.
    - Sublimation of water (even small amounts) will alter cuttings transport behavior (enhances) – It is important to test both "dry" & "wet" cases.

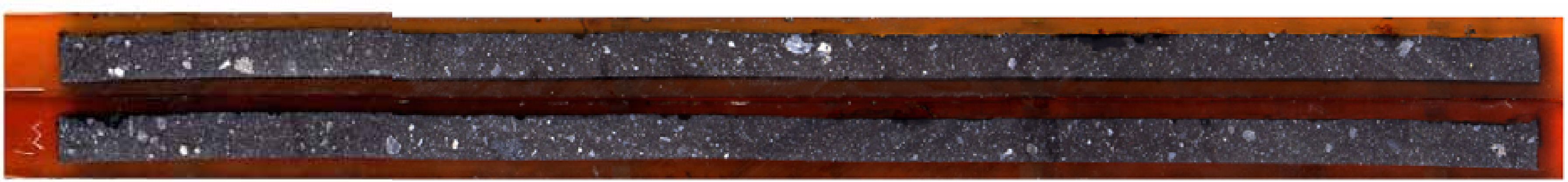


Image of epoxy encapsulated core 76001 - sawn lengthwise, twice - scanned at low resolution (100dpi) - and compressed. Total length is ~30 cm. Summary of Apollo Drive Tubes, C. Meyer, Lunar Sample Compendium

Concluding Remarks

- Drill-based systems can be a viable option for obtaining relatively unaltered lunar regolith samples from 2 meters.
  - Rapid access to subsurface… enables broad site characterization

- However… the perceived risk and cost needs to come down
  - Some have a negative perception of drills (not completely unjustified)

- To reduce cost and increase reliability, we need to:
  - Consider simpler systems… we may need to sacrifice some capability
    - e.g., cuttings instead of cores
  - Consider relaxing other requirements that have operational an work-around
    - e.g., sample recovery rate, cross contamination
  - Test correctly from the beginning
    - Develop standard tests (realistic environment, controlled) so that we can really track TRL
  - Continue to develop technologies that enhance reliability, such as:
    - Business end (bits, cuttings transport, sample chamber/manipulator, debris mgt.)
    - Intelligent control
    - Pneumatics

- In 2008, through PIDDP, HBR will begin construction of a “dirty” chamber (near-cryo, low vac) and we also plan to complete the CRUX demo test bed
  - 2-m drilling tests

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