# Scavenging Flight Hardware as a Transitional Form of Non-Volatile Resource Utilization.

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# Introduction

***Supportability*** ***refers to the maintenance, logistics and operations needed to sustain a long term human-robotic operation.***

**Supportability issues drive the retirement of exiting capabilities**

- Space Shuttle after 2010 and Space Station after 2015
- A supportable infrastructure is key to building a long term capability.

**Lunar Supportability Technology Roadmap describes a *Resource Independence Strategy***

- Breaking the dependence on logistics early provides greatest benefit.
- Currently ISRU (particularly non-volatile) appears late in the program.

**Supportability Technologies**

- Supportability as Embedded capabilities
- Supportability as external Process technology
- Establishes relationship of Repair, Scavenging, In-Situ Fabrication

**Scavenging Flight Hardware provides a transition to ISRU**

- Treats portions of flight vehicle as payload
- Leads to "Bootstrap" of Non Volatile ISRU

# Lunar Supportability Needs

## Lunar Outpost compared to Space Station Logistics:

- Lunar payload only ~20% of ISS payload (simple cargo mission)
- Lower flight frequency
- No return option for hardware servicing

## Greater Risk of Damage

- More EVAs long travel distances over rugged terrain
- Environmental Degradation: High Vacuum, Thermal, Intense Radiation
- Hardware Surface Damage left untreated results in:
  - Mechanical Shaft & Bearing Failures
  - Leakage of Hatchways and EVA Suits
  - Degradation of Optics and Instruments
  - Malfunction of Fluid Connectors, Electrical Connectors, and Cables

## Operational Constraints

- Limited Crew Skills in Diagnostic, Repair, Fabrication
- Limited Equipment Availability
- Sparse power and communications infrastructure

# Resource Independence Strategy

## Lunar Outpost Supportability Plan: *(ref J. Green)*

- Migrate from 100% <u>Logistics Dependence</u> toward <u>Logistics Independence</u>
- Select technologies to minimize the dependence on (imported) Earth resources
- Minimize the cost of supporting long term operations
- Maximize use of available resources (scavenge, recycle, ISRU)
- Demonstrate resource independence that is essential to Mars missions

## Path to Logistics Independence starts with In-Situ Maintenance

- <u>In Situ Component Level Replacement</u> saves 82% Mass & 95% Cost (electrical).
- Requires In Situ Diagnostic, and Test capabilities
- In Situ Repair of Structural Damage
- In Situ Repair of Cumulative Surface Damage (Wear and Tear)
- Need <u>Repairable Hardware Designs and Materials</u>
- <u>Repairable</u> also implies <u>Scavengable and Reusable</u>
- <u>Must address operational limitations</u>
  - Minimize equipment required
  - Minimize Crew Skill required

# Flight Hardware an In-Situ Resource

## Scavenging Flight Hardware *improves payload performance*

- Cargo Landers have complete systems available in good (slightly used) condition
- Exploit landers as a source of scavengable (or salvageable) hardware
- Flight vehicle is regarded as payload (Cargo Lander)
- Alternative to logistics payload as source of spares
- Scavenged and reused hardware can build infrastructure including ISRU
- Maintenance and Scavenging involve the same Operations

## Scavenged Materials

- Surplus Hardware can be scavenged for it material content
- Alternative to logistics source for supportability process materials
- Provides a “low hanging fruit” alternative to non-volatile ISRU

## In-situ Repair and Scavenging drives new requirements

- Requires New In Situ Process Technologies
- Requires New Embedded Technology design requirements
  - Hardware: Common, interchangeable, reconfigurable, accessible, self diagnostics and self prognostics
  - Materials: Common, recyclable, reusable by in-situ processes

# Supportability Technology Development Strategy

**Logistics Environment:**
- Sparse Logistics
- Low Equipment Capacity
- Low Crew Availability
- Limited Skill Set
- Open Loop (no return)

**Operating Environment:**
- Frequent EVAs
- Wear & Tear
- Accidental Damage
- Environment Degradation

**Needed Capabilities:**
- Embedded Diagnostics
- External Diagnostics
- Preserving HW Integrity
- Root Cause Analysis
- Tool Calibration
- HW Commonality
- Scavengable Flight Hardware
- Scavengable Materials

**Goal: Logistics Independence**

**Supportability Technology Strategy**

**Lunar Supportability Technologies**

# Supportability Technologies

## Lunar Supportability Technologies

- **Embedded Technologies**
  - **Diagnostics, Test & Verification**
    - Embedded Diagnostics Prognostics
    - Signal Diagnostics
    - Diagnostic Operations
  - **Maintenance & Repair**
    - Component Reparability
    - Plug-N-Play Avionics
  - **Scavenging & Recycling**
    - Scavenge-ability
- **Process Technologies**
  - **Diagnostics, Test & Verification**
    - Electronic Diagnostics &Test
    - Non Contact Measurement
    - Diagnostics Operations
  - **Maintenance & Repair**
    - Electronics Repair
    - Surface Repair
    - Structural Repair
  - **Scavenging & Recycling**
    - Hardware Scavenging & Reuse
    - In-Situ Fabrication
    - Recycling Processes

# Supportability Technologies

**Lunar Supportability Technologies**

## Embedded Technologies

**Embedded Technology Criteria:**

- Access without Violation of Integrity
- Embedded Prognostics and Diagnostics
- Common Components and Interfaces
- Flexible-Reconfigurable Hardware
- Scavengable Components & Materials
- De-ratable Hardware Design

## Process Technologies

**Process Technology Criteria:**

- Process Environment Compatibility
- Dependencies (measures complexity)
- Resource Effectiveness
  - Minimizing imported resources
  - Maximizing in-situ resources
- Utility (multiple applications)

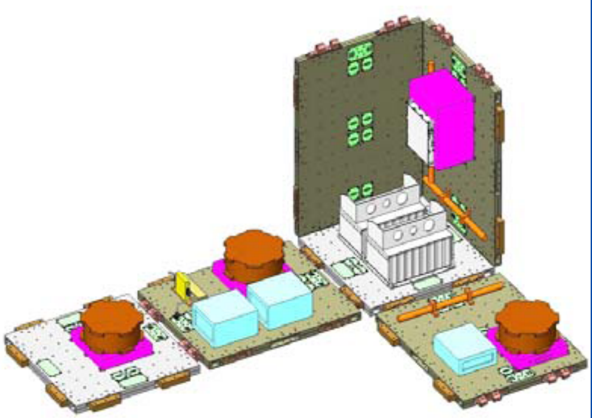
# Scavenging Flight Hardware

## Primary Scavenging Application: Build an inventory of spares

- Lunar Replacement Unit (LRU) easily acquired, checked-out and used.
- Sub-assemblies Replacement Units (SRU) are Intermediate Level
- Single Components. (Avionics is usually disabled by a few components)

## Secondary Scavenging Application: Repurpose Flight Hardware

- Expand Infrastructure: Power, Communications, Robotics
- Supportability: Maintenance tools and facilities
- ISRU: Resource Acquisition and Processing Equipment.
- *EXAMPLE*: A scavenged flight computer serves as controller for maintenance or fabrication equipment or ISRU processes.



***Air Force Plug n Play Satellite*** technology developed by the Air Force Research Lab is intended to quickly integrate and launch satellites in 6 days. PnP architecture attacks the integration complexity and accessibility issues that impede rapid deployment .

- Accommodates a wide array of instruments and avionics combinations.
- Highly accessible enclosure assemblies with hinged unfold-able structure
- Uses a self organizing data network system for rapid integration
- Distributes power with the network. (like USB)
- Permits rapid access for last minute changes with minimum turn around.
- *Plug N Play Avionics features are Enabling for Electronics Scavenging.*

# Scavenging Materials

**Hardware may be scavenged for its material content and recycled for repairs or to create new hardware by in-situ fabrication**

- Fabrication with recycled material would produce only simple components.
- Simple components can be combined with small amounts of high value technology to create new equipment.
    - Bearings,
    - Electronics,
    - Optics,
    - Sensors,
    - Valves
- Concept harkens back to the *"vitamin technology"* a concept introduced *by Freitas in 1980*
- Up mass is minimized
- In situ resources is maximized

# Fabrication with Scavenged Materials

**Most conventional fabrication processes are not viable:**

- Incompatible with space environment,
- Massive payload costs
- Complex Dependencies, Complex Feedstock Pre and Post process operations
- Imported Process Resources (gases, lubricants, fluxes)
- Poor Resource Utilization (waste product)
- Poor Utility

**Free Form Fabrication processes that exploit the envionment are more viable**

- **Electron Beam based FFF is a particularly attractive for space applications**
- *Space Compatible*: Vacuum, low G
- *Simple Dependencies*: Uses only Electric Power and Feedstock
- *Resource Effective*: Little or no waste
- *Utility*: Flexible, Uses wide variety of materials

**E-Beam Fabrication (EBF3) (ref K. Taminger LaRC)**

**E-Beam Melting (EBM) (ref Arcam AB)**

# Fabrication Technology

## Current FFF Fabrication Limitations:

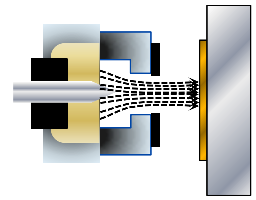
- Products are rough casting-like requiring a post process machining to finish
- Finishing machining defeats the advantages of FFF

## Advancing FFF

- Improve fundamental material feedstock processing and delivery with Electrostatic & Electromagnetic and Acoustic Methods
  - Solid (Powder)
  - Liquid (Droplets)
  - Vapor & Ion Deposition
- Near Term: *Pre-Encapsulated Hardware* into In situ fabrication processes. *(“Vitamin technology)*”
- Long Term: *Develop Progressive Refinement* technologies provide precise finished products.

**Advances in Industry:** FFF in metals has been rapidly maturing and some have quality the same or better that conventional processes. Certain FFF Titanium Turbine Components are currently being qualified for Aerospace Applications
*(Ref, Aerospace Manufacturing and Design)*

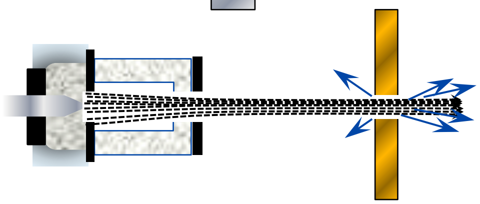
# Fabrication & Feedstock Processing Technologies



Electrostatically Directed Powders

## Powder Technologies:

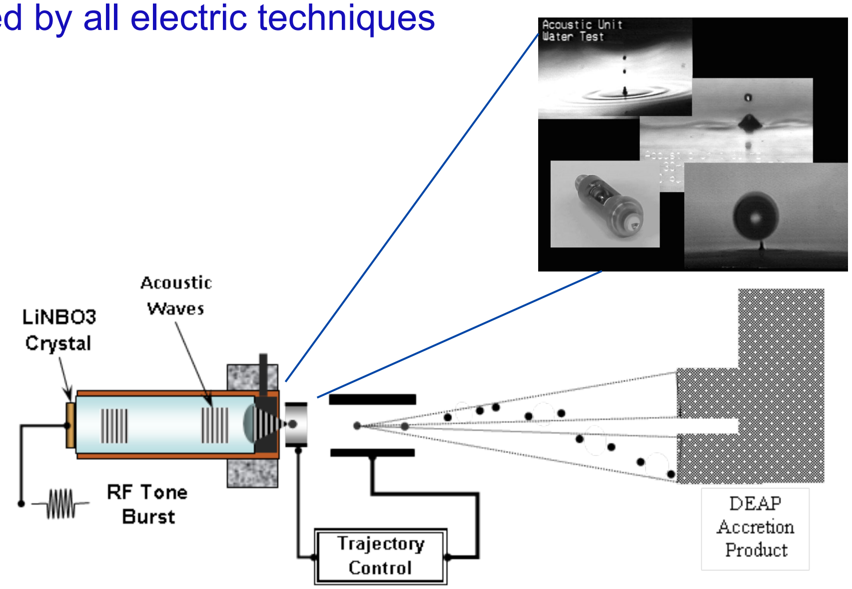
- Suited for high temperature materials
- Exploit naturally occurring media
- Manipulated by all electric techniques

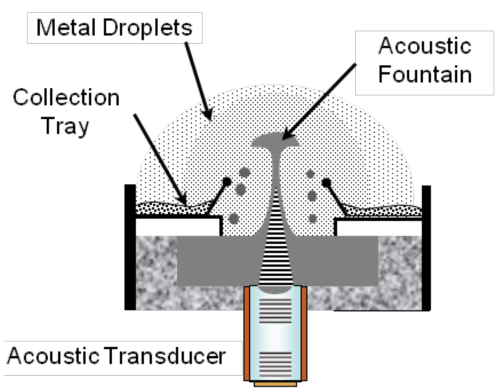


Electrostatically Driven High Velocity Particle Jet

## Droplet Accretion:

- Suited for low volatile metals
- Precise Acoustic Ejection
- Electrostatic Electromagnetic Manipulation

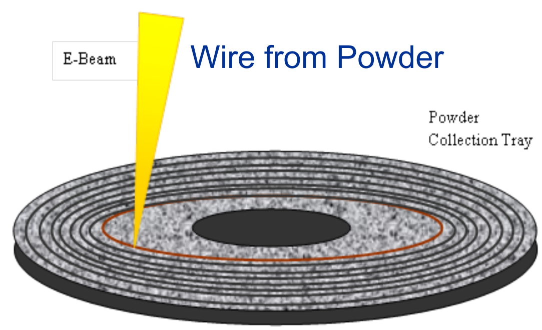



## Metal Feedstock Generation:

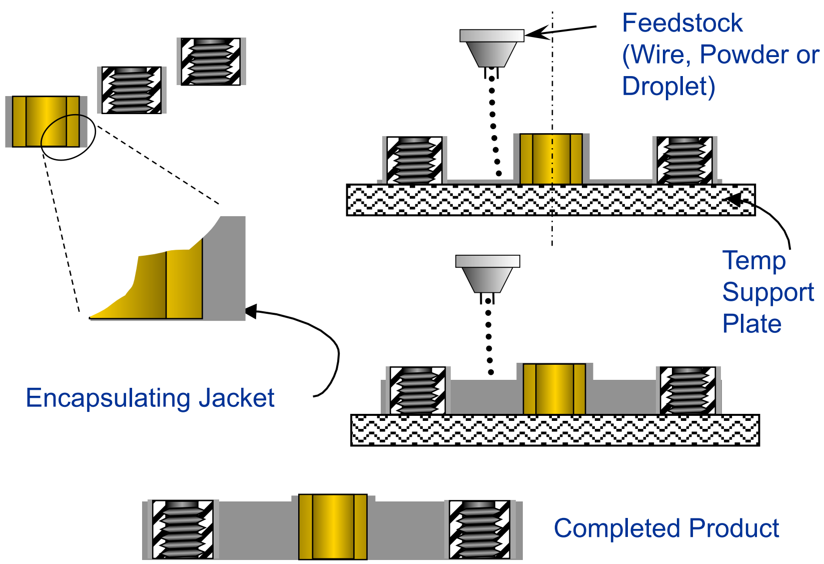
Molten Metal converted to a versatile powder feedstock.

- Acoustic Fountain Technique
- Scavenged or ISRU metals
- Converted into intermediate feedstock by FFF technique.



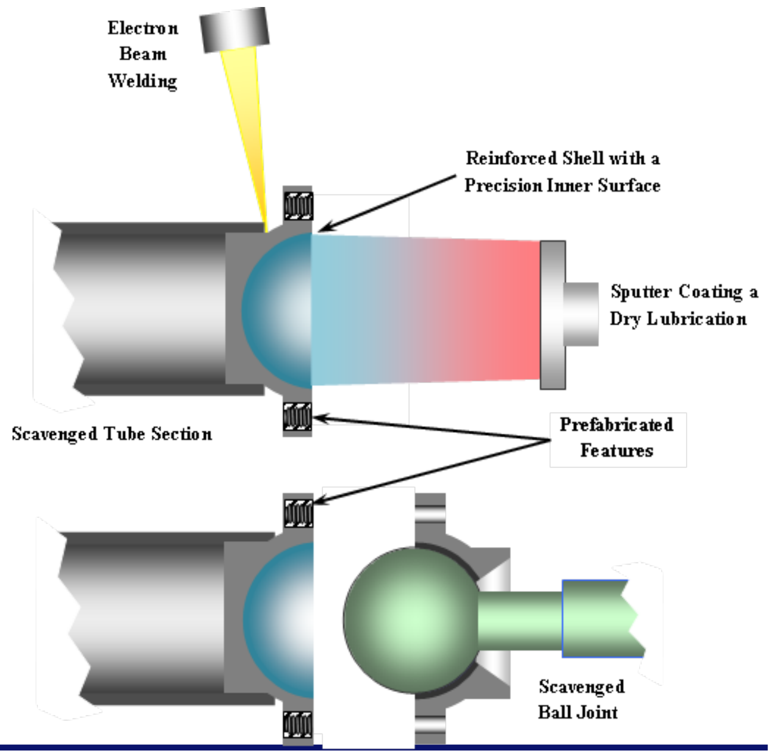

Wire from Powder

# Pre-Encapsulated Technology




**Pre-encapsulated Features:** Pre-encapsulated precision components or mechanisms can be integrate into FFF products.

- Imported or Scavenged Features
- Similar to "weld on" features.




**In-Situ Fabricated Assemblies** may be composed of a mix of hardware and materials from various sources

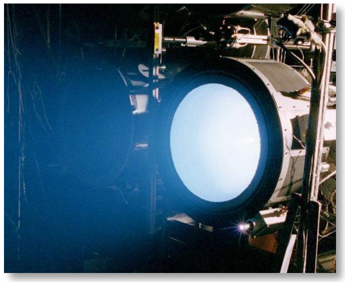
- Imported Pre-Encapsulated hardware
- Scavenged Hardware
- FFF Fabricated Components

# Advancing Surface Repair and Finishing

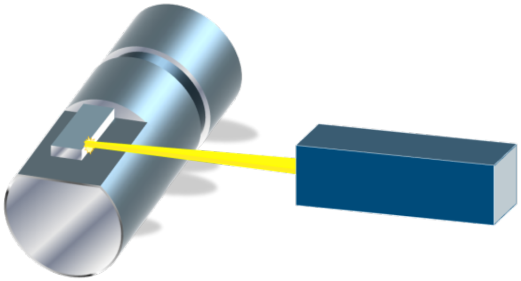
## Focused Ion Beam Technologies for Surface Repair and Finishing

**FIB** technology provides molecular scale manipulation of materials using focusable, steerable beams. FIB eliminates masking materials and steps .

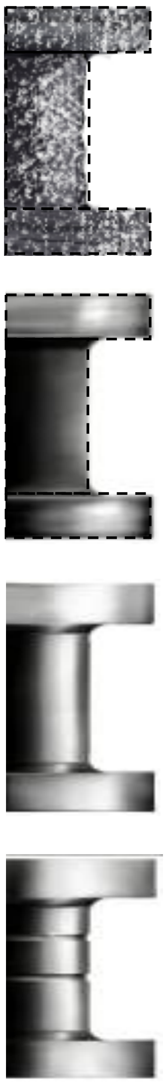
- Subtractive Processes
  - Ion Etching: Etches materials, Removes Contamination, Etch Features
  - Ion Milling: Cut deep features, form cutting edges, smooth surfaces
- Additive Processes
  - Ion Deposition (Sputtering) (metal, ceramic, polymers)
    - Fill Voids and Scratches
    - Apply Coatings (optical, conductive, insulating, lubrication)
  - Ion Implantation: Enhance material properties
    - Electrical
    - Harden Metals



- Uses electrostatic/electromagnetic fields for beam manipulation
- High Vacuum and Low Gravity compatible
- Compatible with Electron Beam technology
- Shares a heritage with Ion Propulsion



# "Progressive Refinement" Free Form Fabrication



***<u>Progressive Refinement FFF</u>*** combines *<u>Additive and Subtractive</u>* processes with closed loop controls and variable process scaling to fabricate a finished product. <u>Represents a convergence of Supportability technologies</u>.

- Non Contact Measurement Technologies to monitor the process (closed loop)
- Additive + Subtractive processes alternate to correct errors.
- *<u>Progressively Refinement</u>* rescales processes as product approaches the final dimensions.

  \+ **Millimeter-Scale Additive:** Weld Wire or Powder Deposition,

  \- **Millimeter-Scale Subtractive:** Electron Beam Ablation and Glazing

  \+ **Micrometer-Scale Additive:** Droplet or Colloidal Deposition

  \- **Micrometer-Scale Subtractive:** Electron Beam Ablation or Ion Etching

  \+ **Molecular-Scale Additive**: Vapor or Ion (sputtering) Deposition,

  \- **Molecular-Scale Subtractive:** Ion Etching, Focused Ion Beam Milling

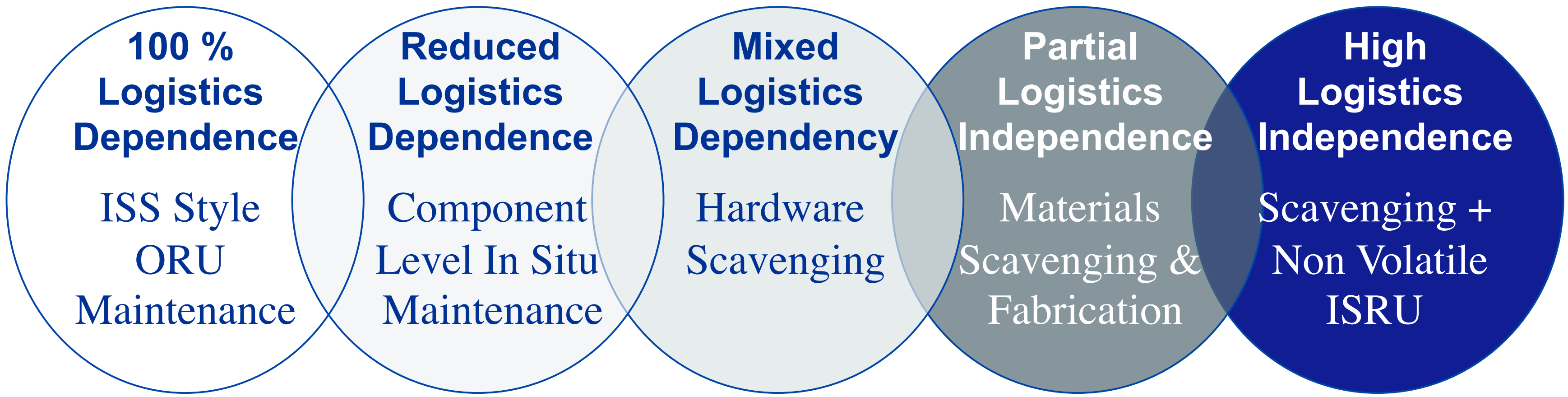
- <u>Ion Implantation and Deposition</u>: Applies molecular scale final finish coating and adjusts surface properties
  - Mechanical Hardness
  - Electrical and Thermal Conductivity
  - Corrosion Resistance

# Summary

## Supportability Strategy calls for *Logistics Independence*.

- In-situ Diagnostics, Repair and Scavenging technology are closely interrelated
- Scavenging exploits available cargo lander flight hardware as “payload”
- Complex “Vitamin” technology is imported from Earth as payload or flight hardware
- Scavenging Materials serves as a near term alternative to non volatile ISRU
- Flight Hardware designers must *embedded* repairable and scavengable features
    - Accessible , Self Diagnostics, In Situ Repairable Materials
- Electric Material Manipulation techniques are essential to advancing In situ repair and fabrication [Electrostatic, Electromagnetic, Acoustic]
- Electron Beam and Ion Beam and Acoustic techniques are all electric, vacuum compatible technologies suited for in-situ repair and fabrication
- Progressive Refinement is a hybrid approach to FFF and may change how we make metal components in low volume high value production.

# Conclusion




**Adopting *Logistics Independence* is an approach that can improve program Supportability and Affordability**.

- In Situ Component Level Maintenance begins reducing costs early
- Success depends on *Embedding Supportability* into Flight Hardware
- Hardware and Material scavenging eases the transition to ISRU
- Supportability processes can be used to "Bootstrap" the ISRU infrastructure.
- The Supportability path to ISRU begins at the Space Station

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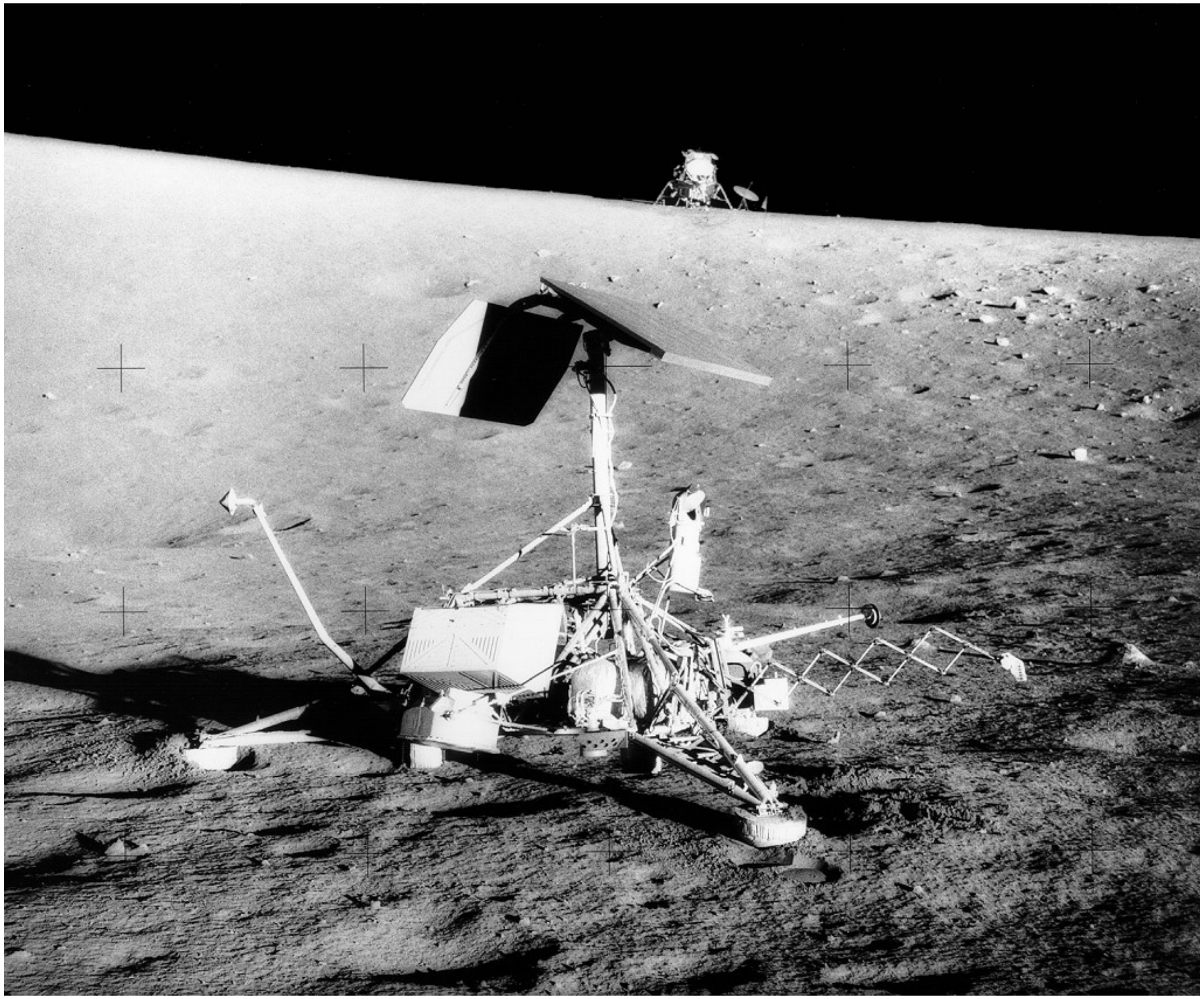
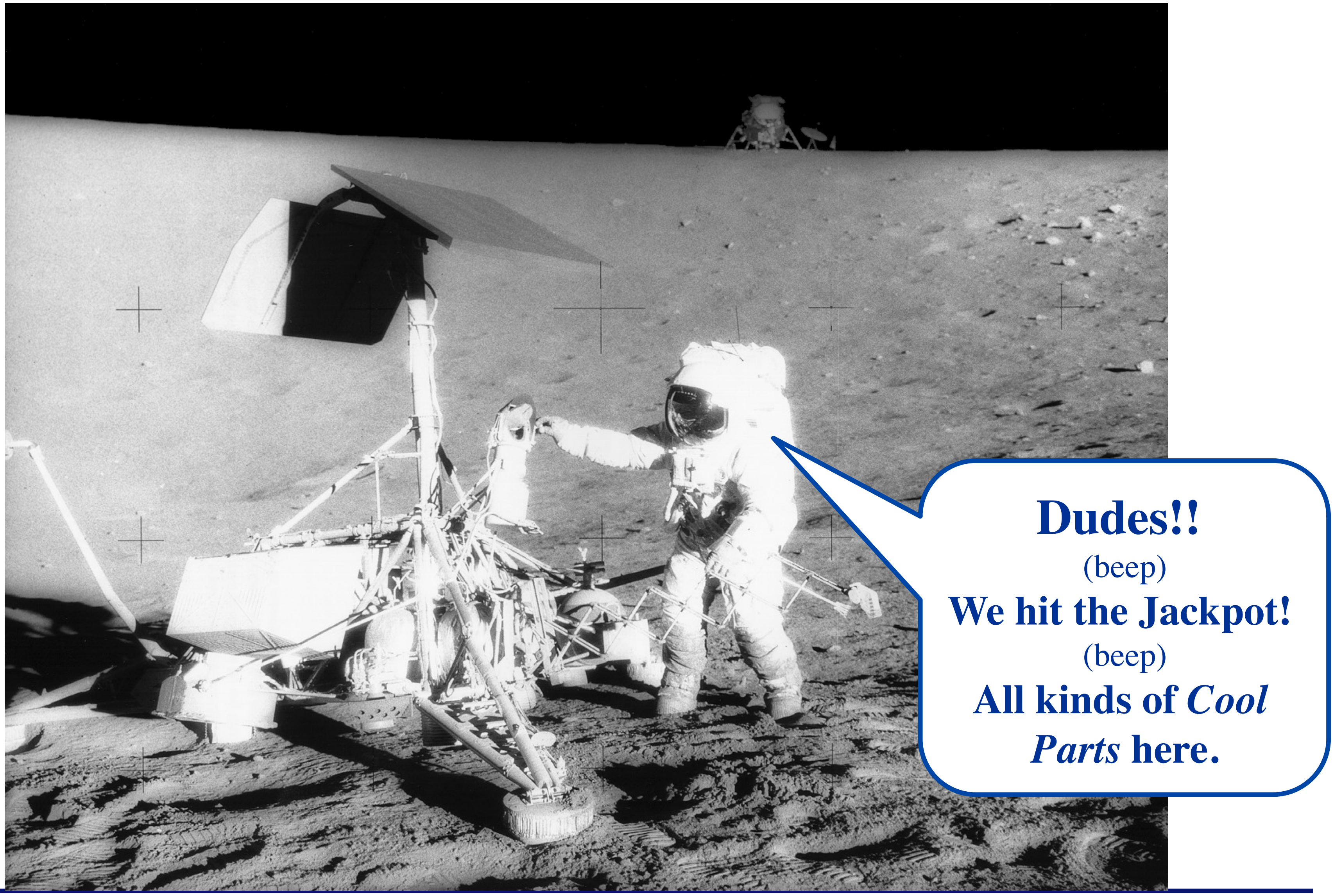
# Scavenging



Apollo 12 meets Surveyor

# Scavenging


Dudes!!
(beep)
We hit the Jackpot!
(beep)
All kinds of *Cool Parts* here.