The Cubesat Revolution:

Lessons Learned, Applied, and Advanced from the Apollo Decade

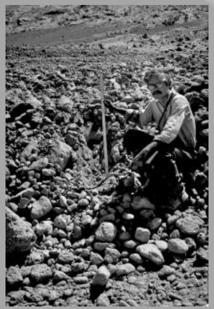
Dr Pamela Clark, Space Science Center, Morehead State University

Utilizing material from my soon to be published book

Extreme Science:

Apollo Surface Activities as Baseline and Breakthrough for Exploring Extreme Environments

Utilizing sources from NASA Oral History Project including Farouk El Baz, Lee Silver, Jim Head, Harrison Schmitt



Background Image Credit: NASA of Capstone

The cubesats are indeed a disruptive technology, but the cubesat paradigm also advances concepts developed in the early days of space exploration that made NASA’s Apollo program so successful.

This fact is especially important when considering Return on Investment for deep space cubesats.

The Apollo program was a daring and risky experiment initiated early in a decade that began with a high project failure rate and ended with the most extraordinary technological achievement of all time, the human exploration of another body in the solar system.

Cubesats generally, but especially in deep space, are a high-risk venture where early high failure rates are a crucial part of lessons to be learned for success.

During NASA’s first decade, much of the focus was on the development technologies required for operating on a relatively short-term basis in deep space:

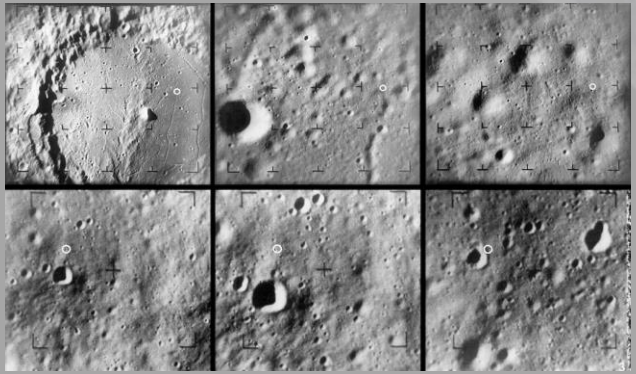
- Achieving orbit
- Reentry and landing
- Orbital and then deep space communication
- Orbital and then deep space navigation, and tracking
- Rendezvousing with another body in orbit and in space
- Rendezvousing, orbiting and landing on another body
- Remote sensing via unmanned spacecraft
- Maintaining a life support system
- Human mobility and geological surveying of another body
- Sample return from another body

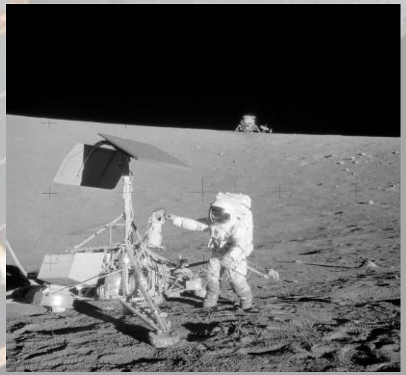
During the Apollo decade, ‘precursors’, ground-breaking technological steps by themselves, were essential, providing the reconnaissance data critical for planning, simulating, and executing Apollo field activities.

- The earliest, Ranger (1961-1965), a hard lander, implemented by NASA JPL, established the basic capabilities for navigation, tracking, and communication from the Earth to the Moon.

- Lunar Orbiter [1966-1967], implemented by NASA Langley, the first American lunar orbiter, confirmed the capability for orbital insertion and provided pictures of the potential landing sites at nominal resolution of 1 meter.

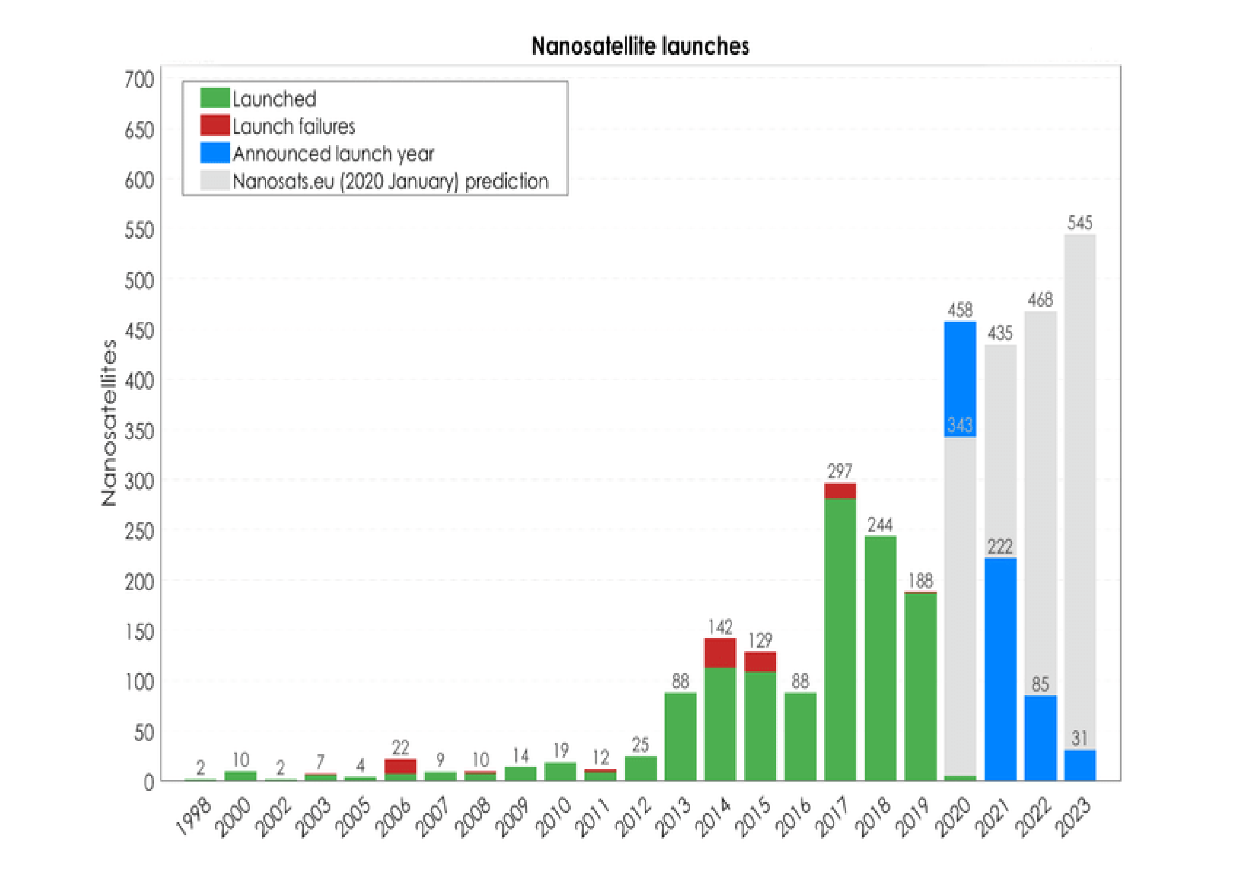
- Lunar Surveyor [1966-1968], implemented by NASA JPL, the first ‘controlled descent’ lunar lander, established that the regolith could support a lander and its crew, and provided the first pictures and compositional data of the lunar surface in situ. Aerial reconnaissance data with comparable resolution were obtained for selected terrestrial sites where simulation and astronaut training would be performed.





Just as in the Apollo decade, with early lunar orbiter and lander precursors to human landing, early cubesats can be considered 'precursors' to widespread multi-platform missions.

An essential goal for the cubesat paradigm has been the development and testing of current state of the art technological capabilities, building on the microminiaturization trends that started during the Apollo program, that will again revolutionize access to space.



Progress over almost twenty years

- Prior to 2015: 1-3 U and Prototype subsystem
- 2015-2018: 3-6 U and improved 'control' systems
- 2018 to current: 6U and broader user (e.e.g, science) focus

Temptation: more 'management'

Year	Name	Goal
2003	Quake Sat Stamford	Space-based detection ELF signals as Equake precorsurs
2005	UWE U Wurzberg	Test internet communication and solar cells in space
2006	GeneSat Santa Clara U	Life Support, Study activity of bacteria
2008	AAUSat2 Aalborg U	ADCS, Gamma-ray detector
2008	CanX2 U Toronto	Demo Formation Flying
2013	AAUSat3 Aalborg U	AIS system for ship tracking in arctic
2013	PhoneSat 1, 2	Consumer Grade Smartphone Communication
2013	Firefly Taylor U	Gamma-ray detection signature from thunderstorms
2014	QB5OP1, 2 Von Karman Inst	Thermosphere research (ion and neutral Mass Spectrometers)
2017	Asteria JPL	Demo fine pointing control for exoplanet search
2017	CXBN2 Morehead State U	Cosmic X-ray Background Mapping to determine source
2018	Irvine02, Irvine cubesat STEM program	Test propulsion system and LED communications
2018	MarCO JPL	Dual band communication at Mars
2018	CubeSail 1, 2 U of Illinois	Solar Sail Propulsion in LEO
2018	SPOC U of Georgia	Ocean Color Spectroscopy
2018	RainCube JPL	Precipitation Monitoring Radar
2022	LunaHMap Arizona State	Deep space propulsion system, Neutron spectrometer, Orbiter, Water

During the Apollo decade, the scientists, engineers, technicians, not to mention astronauts, who made success possible were not micromanaged. They were self-starters:

- who were motivated by the strategic and cultural importance of their work as well as the extreme technical challenges,
- who had ability to work with problem-solving teams to create, propose and test until solutions found.

That approach should be familiar and welcome to those working in cubesat teams in terms of ’ideal’ approach

- Lean, flat, and with multi-functional members, who can and like to fix problems on the fly
- Experienced system/project manager, minimal turnover in leadership
- Systems-mindedness, communication pervasive
- Flexibility for evolving requirements and solving problems close to the source as the occur.
- Identify, assess impact of, communicate, and prioritize dealing with risks early
- As form broader ‘user’ communities, requirements documentation and management process crucial for flowdown and traceback, but should be done systematically (not case by case) with workable ‘good enough’ institutional model and focus on content (interfaces, performance) rather than format (tools)
- Utilize existing commercial infrastructure, and generic off the shelf’ to support development of state of art ‘payload’.
- Careful to prevent 'scope creep’
- Share and Support the development of compact reusable fabrication, calibration and testing facilities to lower costs.

In the early days of NASA, just as in the cubesat era, understanding of what constitutes adequate information capture, and documentation, was evolving.

Extreme programmatic and environmental constraints resulted in flexible experimenting with and training in the use of minimal resource approaches.

Portable Life Support… Open Rover and Apollo Space Suit, NOT a large, energy hungry pressurized rover. Design for ‘field work’ including gloves, cuffs. Field work without a field notebook and pencil?? Oral/audio documentation technique repeatedly simulated.

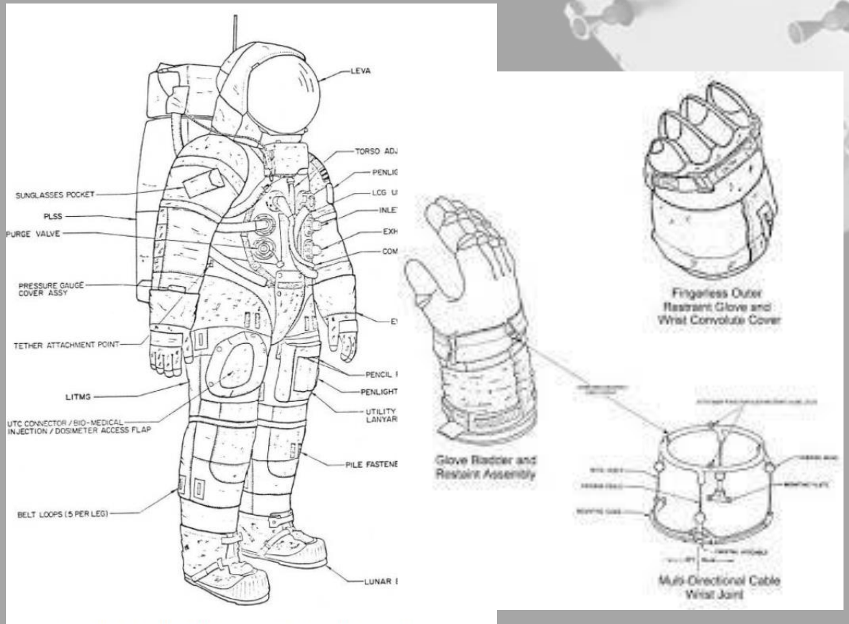


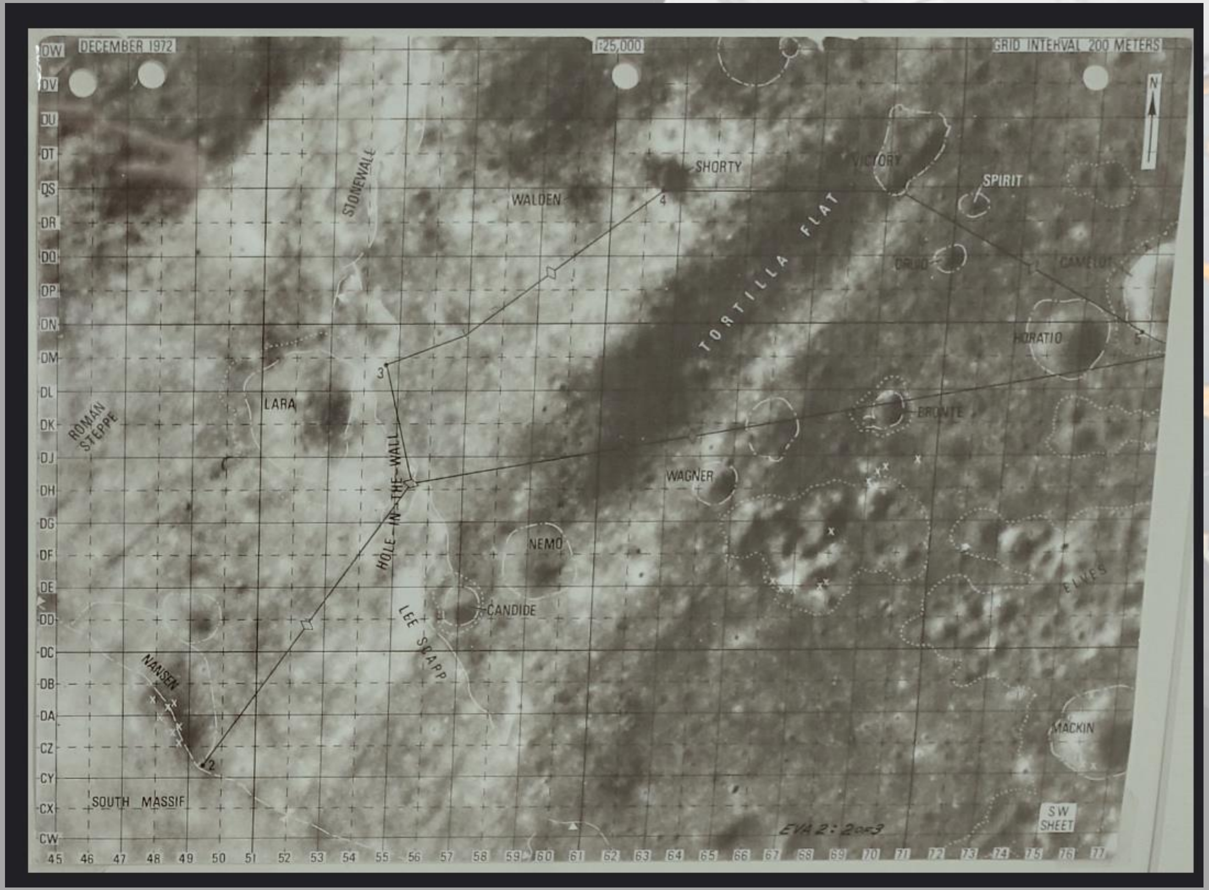
Fig. 2.43 Features With EVA Accessories (Apollo 11-13 Version Shown)

Type 1. Object Named	Type of Object (e.g., boulder) and general composition (e.g., anorthositic) provisional description		
Type 4	contacts with other objects (e.g., conformable, intrusive, parallel, slumped, volcanic)		
Type 2. Properties	Class A. Optical Properties	examples include color, luster, albedo, texture	
	Class B Mechanical Properties	examples hardness, strength, coherence, resistance, geomorphic exposure	
	Class C Geometrical Properties	1) size-shape	e.g., thickness, angularity, dimension, extent, tabularity
		2) orientation	e.g., attitude, direction, trend, position, location
	Class D Structural Properties	1) internal structures	e.g., fabric, cleavage, layering, texture
		2) external structures	e.g., folds, faults, fractures, joints
Type 3	Final summation (object name confirmed specific name and composition)		

Fig. 2 Types of information to be used in order in systematic description of system

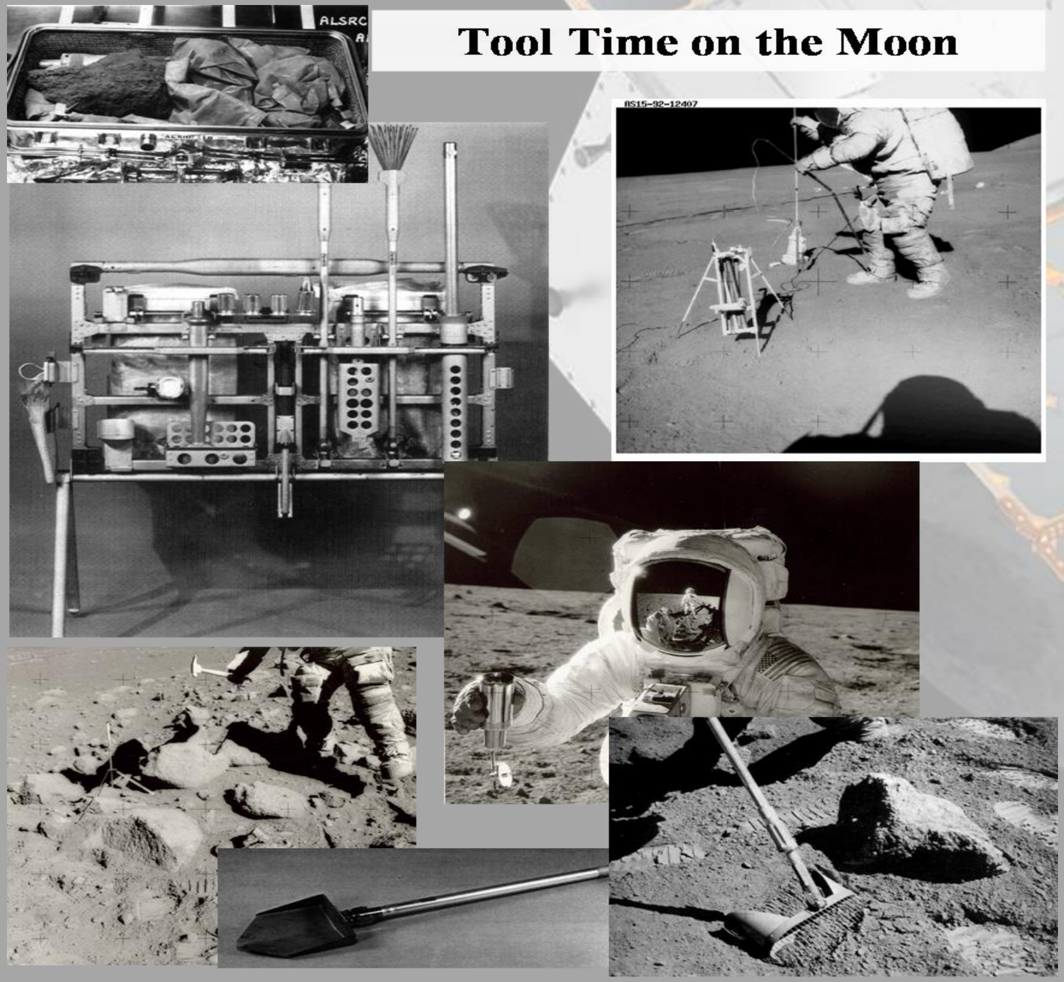
In the early days of NASA, just as in the cubesat era, understanding of what constitutes adequate information capture, and documentation, was evolving.

Maps aerial (orbital) photography annotated with topography contours, traverse routes and landmarks as opposed to highly detailed geological unit maps for ease of use.



In the early days of NASA, just as in the cubesat era, understanding of what constitutes adequate information capture, and documentation, was evolving.

Tools designed for efficiency literally using time motion studies, and field work evolved to standard ‘choreography’ for documentation and sampling.



Activity	Pre-Activity	During Activity	Post-Activity
Site Characterization 5 min/event, 2 crew	Panoramic viewing (audio and photo) to locate sampling sites, outcrops		
Surface Sampling, Soil 2-3 min/sample, 1 crew	orient, document (audio and photo)	collect using shovel or scoop w/ or w/out long handle	document (audio and photo), encapsulation procedure in bags
Surface Sampling, Fragments 2-3 min/sample, 1 crew	orient, document (audio and photo)	collect using rake	document (audio and photo), containment procedure in bags
Surface Sampling, Rock 2-3 min/sample collected, 1 crew	orient, document (audio and photo)	collect using glove, tongs, rock hammer and chisel	document (audio and photo), containment procedure in box
Subsurface sampling (20 cm) shallow core 4 min/sample, 1 crew	orient, document (audio and photo)	collect using core tube or shovel/trench tool	document (audio and photo), special containment procedure for shallow tubes
Subsurface sampling (2 m) regolith drill 25 min/2m, 1 crew plus last 5min, 2 crew)	Orient, document (audio and photo)	Power Drill	document (audio and photo), special containment procedure for cores
Crustal structure gravimeter, 5 min/reading, 1 crew	orient, document (audio and photo) location of measurement	take gravimeter measurements for station	Stow for next station
Crustal structure, active seismic 20 min plus 3 min/ explosive device, 1 crew	orient, document (audio and photo) site for central station and geophones	Deploy central station and geophones near lander on foot.	Deploy explosive devices at selected locations with underlying structure of interest
Crustal structure, magnetometer 1 crew, 30 seconds	orient, document (audio and photo) location of measurement	take magnetometer measurements for station	Stow for next station
Instrument package 2 crew 3 hours	orient, document (audio and photo) site for central station	Set up central station and individual experiments, connect to central station	test and turn on (removing dust covers) when departed

In addition to essential advances in space communication, transportation, and navigation, the Apollo decade initiated advances in microsensors and processors, cooling technology, materials for extreme environments, accurate timekeeping… a smattering at https://www.nasa.gov/sites/default/files/80660main_ApolloFS.pdf

NASA Facts

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center

FS-2004-07-002-JSC
July 2004

Benefits from Apollo: *Giant Leaps in Technology*

The Moon, a luminous object in the night sky that once inspired limitless speculation, afforded the inspiration for scientific discoveries in space and on Earth – thanks to the Apollo Program.

The world was captivated on July 20, 1969, when hundreds of millions watched through the lens of a compact camera built specifically for space as man planted his first step onto the lunar surface. Astronauts recorded details of the momentous occasion with special pens that allowed ink to flow freely in low gravity. Other technologies like breathing apparatuses, fabric structures, communications and protective coatings that made man's step on the Moon possible soon led to giant leaps in technology on Earth.

NASA's Office of Technology Transfer and Commercialization licenses space-age technologies and connects with the private sector through business-to-business partnerships for the creation of products that improve lives here on Earth. Below are a few of the many viable commercial products America enjoys today with roots that reach as far as the Moon.

Playing with the Pros

Sports and recreation manufacturers looked to NASA upon landing on the Moon in pursuit of improving their game.

Walk, jog or run like an astronaut

"Moon Boot" material has revolutionized athletic footwear, improving shock absorption and providing superior stability and motion control. Al Gross, a NASA Apollo Program engineer, used his space expertise to improve athletic shoes. He substituted DuPont's Hytrel plastic for foam materials in the shoe's mid-sole to eliminate cushioning loss caused by body weight. An external pressurized shell and stress-free "blow molding" process adapted from NASA spacesuit technology was also used. The resulting compression chamber mid-sole allowed the popular shoemaker, AVIA Inc., to reconfigure designs for specific sports and provide a "first step" toward a durable, foamless, non-fatiguing mid-sole. *Spinoff 1991*

To the Moon, through the roof

Houston's Reliant Stadium features the first retractable roof of its kind, made possible by NASA technology. NASA's spacesuit fabric has fostered many new innovations, including a permanent structure fabric developed for the Apollo Program and produced by New York-based Birdair, Inc. Pound for pound, the material is stronger than steel and weighs less than five ounces per square foot. Its translucency value, which ranges from four to 18 percent, reduces lighting needs and helps maintain the natural grass playing field. Its reflectivity lowers cooling costs, and the Teflon coating reduces maintenance costs by increasing the fabric's resistance to moisture, temperature extremes and deterioration. These factors combine to lower initial costs and speed construction.

There are two applications for Birdair's fabric; tension structures that are supported by a network of cables and pylons (used in the Reliant Stadium), or temporary air-supported structures that consist of an outer membrane and an inner liner. On average, the use of fabric covering, which can last up to 20 years, can help reduce building costs by as much as 30 percent. *Spinoff 1978 and 1990*

Rearranging furniture in a stadium

Together, NASA and General Motors developed a way to move heavy loads more easily by lifting them onto a thin air cushion. Rolair Systems, Inc. was formed by former General Motors' engineers and has found commercial uses for the innovation. Hawaii's Aloha Stadium uses this technology to re-arrange the stadium seating by moving an entire 7,000-seat section on a cushion of air. A single operator can reposition this huge section in just half an hour. *Spinoff 1978*

Safeguarding You and the Environment

Technologies guarding astronauts on the Moon now protect you and the environment on Earth.

Astronaut flight suits fighting fires on Earth

Fire hazards are much greater in atmospheres containing a high percentage of oxygen under pressure. After the 1967 Apollo fire, NASA needed to find new ways to protect astronauts and their vessels. The Monsanto Company developed a chemically treated fabric called Durette that does not burn.

A National Bureau of Standards/NASA project resulted in a lightweight breathing system including facemask, frame, harness and air bottle marketed by Scott Aviation. Aluminum composite material was used to reduce the weight of the overall apparatus, and the frame and harness were designed to be much easier to put on and take off. Today nearly every major manufacturer of breathing apparatus incorporates NASA technology in some form, helping to reduce the incidence of inhalation-related injuries. *Spinoff 1982*

Safety in security systems

Technology developed by NASA led to an intruder detector that helps prevent burglaries. Before prowlers can break in, vibration-sensing detectors pick up movements of anyone within range and relay warnings to portable radio receivers that alert guards or residents. Encased in a stainless steel tube, the detectors are implanted in the ground outside the facility being protected - home, bank, industrial complex or other facility. *Spinoff 1978*

Solar Panels: more power, less pollution

Innovations developed with technology from NASA's Apollo lunar module program has created a renewable energy resource used on Earth and in space. Solar panels collect electricity by absorbing light when it strikes the surface and transfers it to a semiconductor. These solar panels are used on calculators, street lights, houses and on the International Space Station. The solar array surface area currently on orbit is 9,600 square feet, nearly half (40%) the size of a football field (24,480 square feet). The skyscraper-sized solar arrays harness energy from the sun to power the Space Station. *Spinoff 1981*

Chlorine-free pools

NASA's silver ion technology has been used to create an automatic pool purifier. Caribbean Clear Inc. system offers an alternative to chemicals, such as chlorine and bromine.

Purifiers use silver ions, as used in Apollo Purification Systems, to kill bacteria, copper ions and algae. They produce spa or pool water that exceeds EPA Standards for drinking water. *Spinoff 1994*

Apollo innovation shakes up seismology

Through a contract with NASA, Wyle-3S built an enormously forceful shock and vibration system to simulate liftoff stresses on the launch pad. In addition to earthquake testing, the company has adapted its shaking technology to evaluate railway cars, rail- or road-transported cargo, truck refrigeration units and highway pavements without destroying or harming its surroundings. *Spinoff 1979*

Medical Marvels from the Moon

Apollo-based technologies launched major medical breakthroughs on Earth.

Shocking heart monitors

NASA's Apollo technology was used by Medrad to develop the AID implantable automatic pulse generator, which monitors the heart continuously, recognizes the onset of a heart attack and delivers a corrective electrical shock. The pulse generator is, in effect, a miniaturized version of the defibrillator used by emergency squads and hospitals to restore rhythmic heartbeat after fibrillation. Once implanted, it needs no specially trained personnel or additional equipment and consists of a microcomputer, a power source and two electrodes that sense heart activity. *Spinoff 1980*

Apollo sets the pace

St. Jude Medical's Cardiac Rhythm Management Division used Apollo technology to develop a programmable pacemaker system. A physician can communicate with a patient's pacemaker by means of wireless telemetry signals transmitted through the communicating head held over the patient's chest. Where earlier pacemakers delivered a fixed type of stimulus once implanted, this system enables "fine tuning" of the device to best suit the patient's changing needs. *Spinoff 1980*

Easier treatments for dialysis patients

Technology originally developed under NASA contract by Marquardt Corporation, a chemical process was developed to remove toxic waste from used dialysis fluid. This discovery led to the development of a kidney dialysis machine using "sorbent" dialysis, a method of removing urea from human blood by treating a dialysate solution. The process saves electricity and gives the patient greater freedom of movement during treatment. *Spinoff 1992*

Cool ideas from Apollo

NASA's Cool Suit technology — originally designed to keep astronauts cool during launch using a water circulation system — is now used by hazardous materials workers, armored vehicle crews, firefighters and NASCAR drivers. Multiple sclerosis patients and children born without sweat glands and a disorder that causes extreme sun sensitivity wear built-in water circulation vests that provide them cool comfort. A surgical personal cooling system has also been developed for medical personnel working in hot operating room environments. And, horse saddle pads made with this technology can lower the horse's temperature by 4 to 6 degrees. Another innovation includes a liquid-cooled bra that aids in the detection of cancer using infrared thermography. By increasing the temperature difference between normal and cancerous tissue through cooling, differentiation becomes more apparent on thermograph. *Spinoff 1979, 1982 and 1989*

Precise prescription doses

Under one of the earliest contracts awarded during the Apollo lunar landing program, Parker Hannifin Corporation developed and produced equipment for controlling the flow of propellants into the mammoth engines of the Saturn Moonbooster. Today, Parker is supplying the huge valves that control propellant flow from the Space Shuttle's external fuel tank to the engines of the Shuttle Orbiter as well as the "peanut valve," named for its small size. In 1977, NASA and Parker created the Programmable Implantable Medication System (PIMS) for continuous, computer-directed delivery of precisely metered medication — insulin, for example — within a patient's body. *Spinoff 1988*

At Home with Apollo

Many everyday home and consumer products today trace their roots to technologies born during Apollo missions.

No cords attached

Utilizing NASA's cordless innovations, Black & Decker created cordless, lightweight battery-powered precision instruments designed to give surgeons optimum freedom and versatility in the operating room. It also led to today's electric screwdrivers, drills and other portable and chargeable devices. Cordless power tools are also used to help build the International Space Station on orbit. *Spinoff 1981*

Clocks with rocks

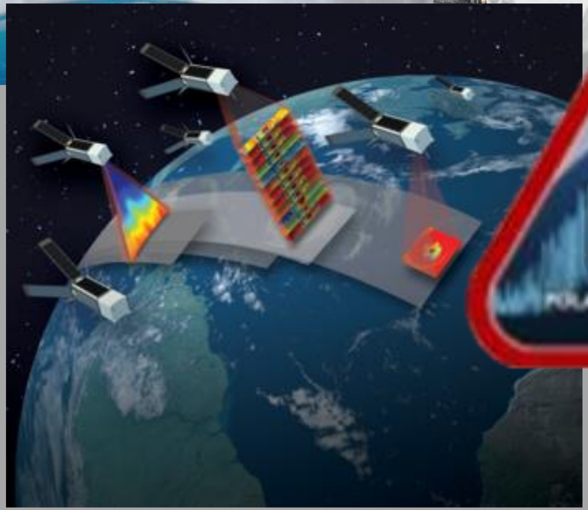
To keep missions on time, General Time Corp. developed electrically stimulated quartz crystals. Quartz provides a stable time base, giving clocks an accuracy of one minute a year. By vibrating up to 4,194,304 times a second, these clocks keep millions of people on time around the globe. *Spinoff 1976*

Busting the dust

Apollo astronauts needed a portable self-contained drill capable of extracting core samples from 10 feet below the lunar surface. Black & Decker used a specially developed computer program to optimize the drill's motor and minimize power consumption. Refinement of the technology eventually led to the cordless vacuum cleaner called the Dustbuster. It has no hose, no cord, is 14 inches long, and also comes with a storage bracket that also serves as a recharger. *Spinoff 1981*

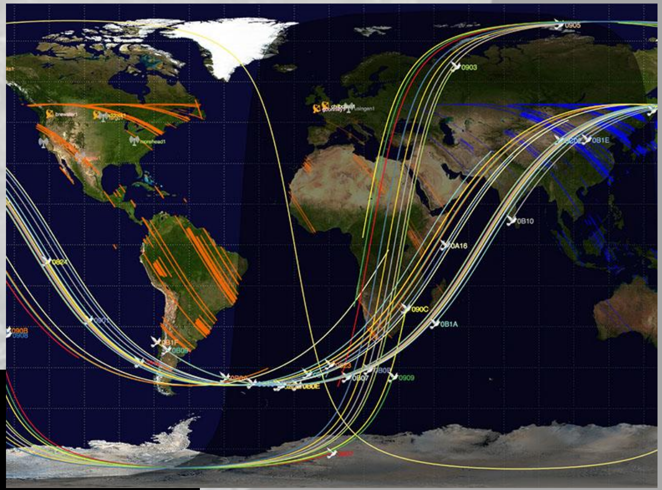
Beyond Apollo: Cubesats are ideally suited to advance exploration with capabilities initiated but not available in the Apollo decade: Distributed micro- and nano-sensors and electronics on distributed platforms.

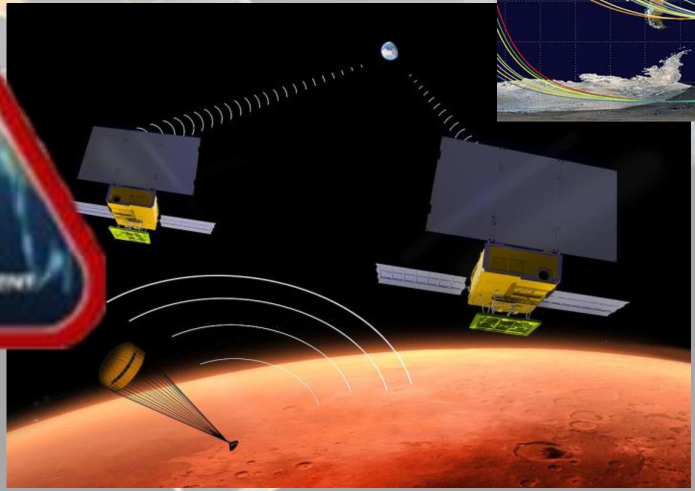
Examples: Colorado State TEMPEST (Temporal Experiment for Storms and Tropical Systems), MIT TROPICS (Time Resolved Observations of Precipitation Structure and storm Intensity with a Constellation of Smallsats), JPL PreFire (Polar Radiant Energy in the Far Infrared Experiment), JPL MarCO (Mars Cube One), Planet Lab ~200 Doves/Superdoves (Ongoing Global Earth Imaging) Image Credits: from developers



PREFIRE

POLAR RADIANT ENERGY IN THE FAR INFRARED EXPERIMENT





The engineers, scientists, and technicians of Apollo era, revolutionary itself,

- **generated the problem-solving approach as the working model and**
- **developed the technology as the essential foundation**

for the current cubesat paradigm.

The Cubesat Revoution has Apollo Roots

Questions?

Contact: p.clark@moreheadstate.edu

LunarCubes Workshop on Friday!