The Road to Realizing In-space Manufacturing

Characterize→ Certify→ Institutionalize→ Design for AM

Presented to Barnard-Seyfert Astronomical Society of Nashville

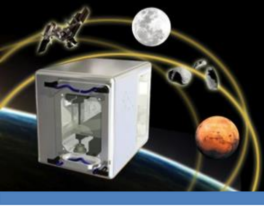
June 18, 2014

Mallory M. Johnston
In-Space Manufacturing
Science and Technology Office
NASA Marshall Space Flight Center

Marshall Space Flight Center’s technical capabilities and engineering expertise are essential to the nation’s space exploration goal of sending humans beyond Earth and into deep space.

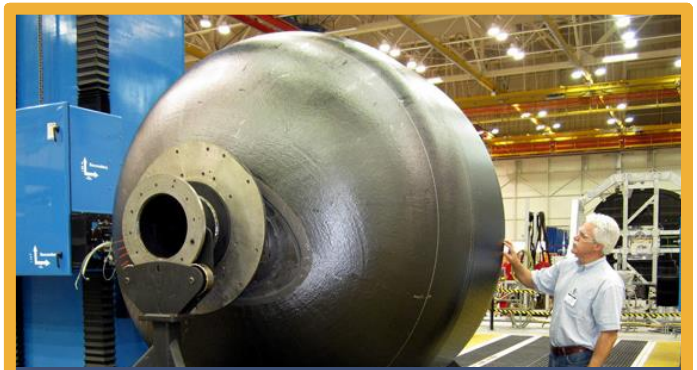
- Our core capability is in space transportation and propulsion systems with unique expertise in large-scale complex space systems development.

- We advance space technologies, spark economic development, expand our knowledge, and inspire a new generation of explorers.



The National Aeronautics and Space Administration

Human Exploration and Operations



Space Technology

Science

Aeronautics Research

Marshall supports three of the NASA Mission Areas.

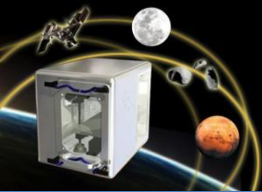
Marshall Mission Areas

Understanding Our World and Beyond

Living and Working in Space

Traveling To and Through Space

America's Human Spaceflight Architecture



Traveling To and Through Space

Space Launch System (SLS)

America's next human-rated heavy-lift rocket – safe, affordable, and sustainable for beyond Earth orbit exploration

Commercial Spaceflight

Partnering for success –
sharing facilities and expertise

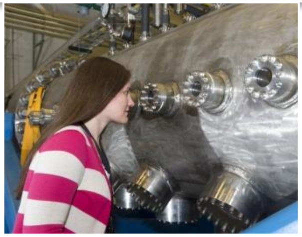
Research for the Future

New fuels, new manufacturing and test methods, and advanced concepts

Launching SLS in 2017

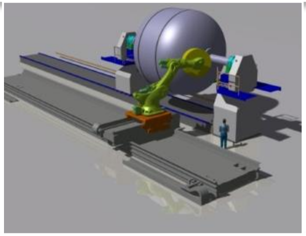
Testing J2-X Upper Stage Engine

Supporting Commercial Spaceflight



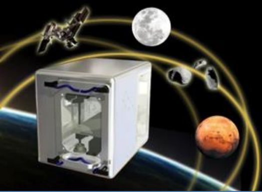
Affordable Testing for Nuclear Fuel Prototypes

Collaborative Engineering Design



In-space Cryogenic Fuel Storage Concept

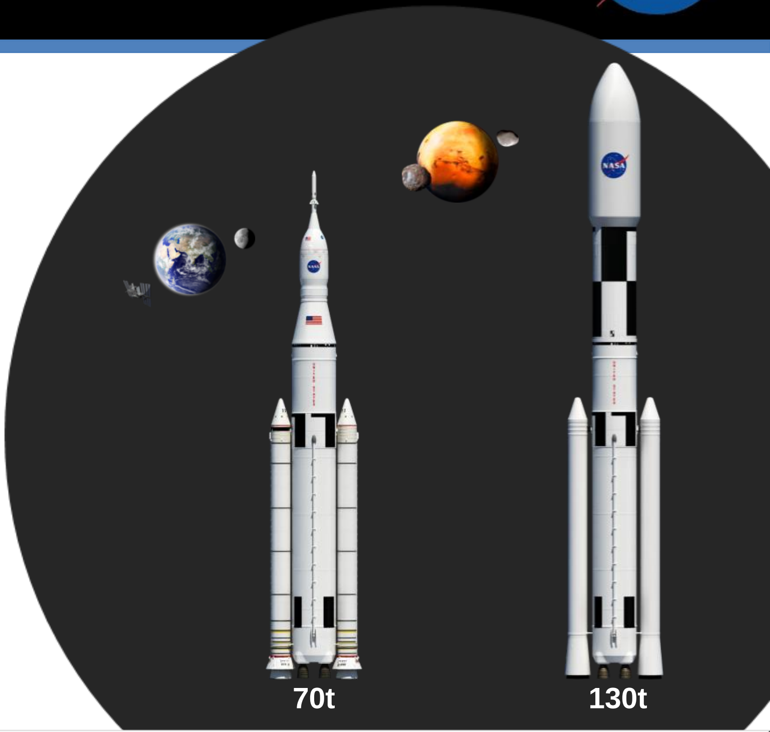
Marshall is leading our nation's propulsion capabilities.



Traveling To and Through Space

SLS – America's Heavy-lift Rocket

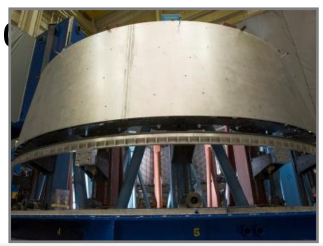
- Provides initial lift capacity of 70 metric tons (t), evolving to 130 t
- Carries the Orion Multi-Purpose Crew Vehicle (MPCV) and significant science payloads
- Supports national and international missions beyond Earth's orbit, such as near-Earth asteroids and Mars



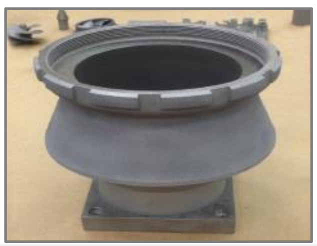
Solid Rocket Booster Test

Friction Stir Welding for Core Stage

Shell Buckling Structural Test



MPCV Stage Adapter Assembly



Selective Laser Melting Engine Parts

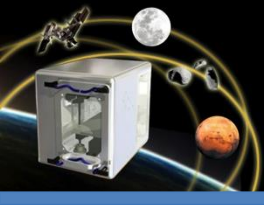
RS-25 Core Stage Engines in Inventory

SLS is essential to the nation's space exploration goals.

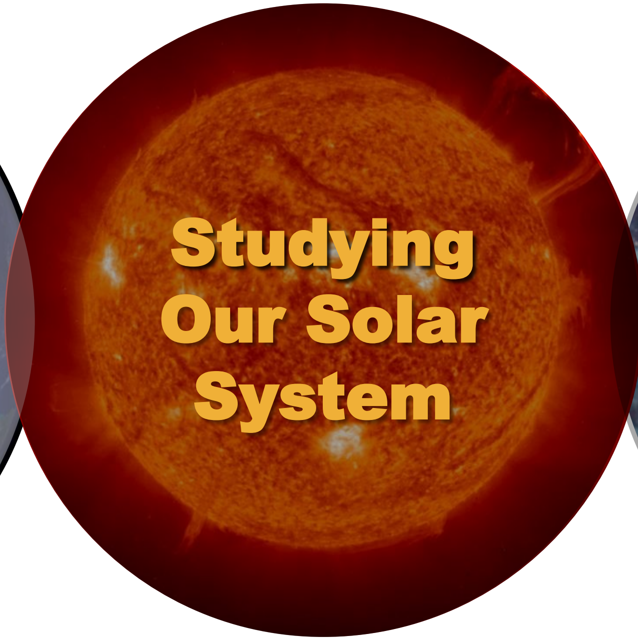
Traveling To and Through Space

SLS – On track for first flight in 2017

- Focusing on key tenets of safety, affordability, and sustainability
- Meeting commitments on or ahead of schedule
- Engaging the U.S. aerospace industry: prime contractors on board, with work being done across the country
- Spurring innovation through advanced development contracts
- Manufacturing Orion spacecraft adapter hardware for 2014 flight test
- Delivering a national infrastructure asset for missions to asteroids and Mars

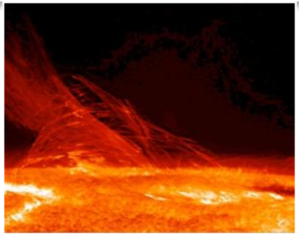


Understanding Our World and Beyond




Weather & Climate Monitoring


SERVIR


SUMI Solar Capture


Discovery & New Frontiers

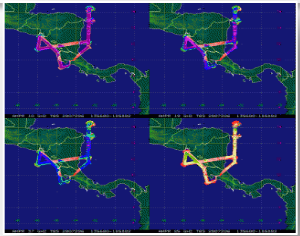

Chandra


James Webb Space Telescope

Marshall is expanding knowledge of our world and beyond.

Observing Earth

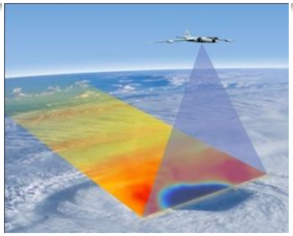
- Understanding global climate system patterns
- Improving weather forecasts and storm warning times
- Predicting the intensity and dynamics of storms
- Providing and analyzing data for urban planning and natural resource and environmental management



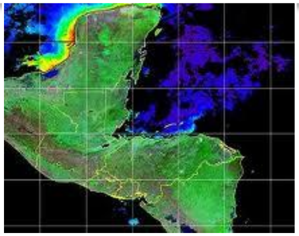
AMPR

Weather & Climate Monitoring

PEOPLE - ACE



Hurricane Imaging Radiometer



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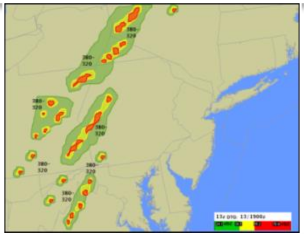
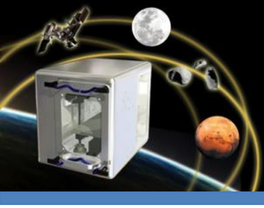
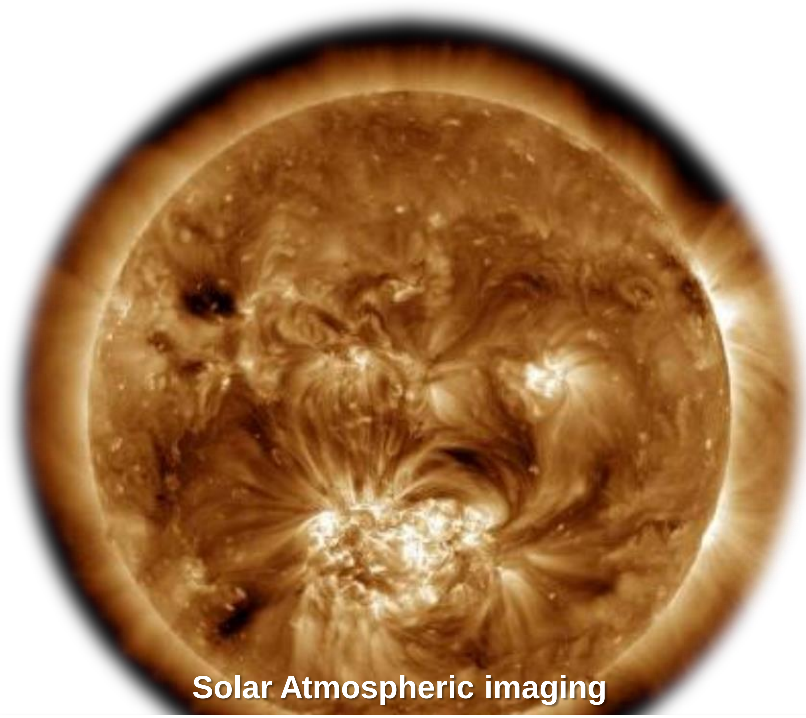


SPoRT

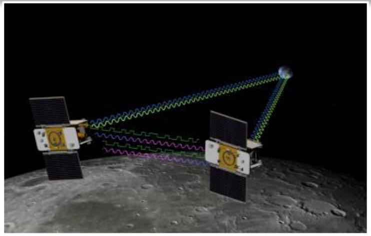


Studying Our Solar System

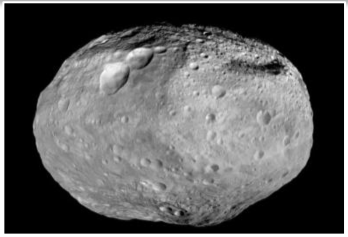


Solar Atmospheric imaging

- Managing missions through our solar system to learn more about asteroids, planets, and their moons
- Developing robotic landers that can safely land on precise locations without human control
- Learning how the sun and space weather affect life on Earth
- Mapping the moon and measuring its gravitational field



GRAIL, twin spacecraft mapping the moon



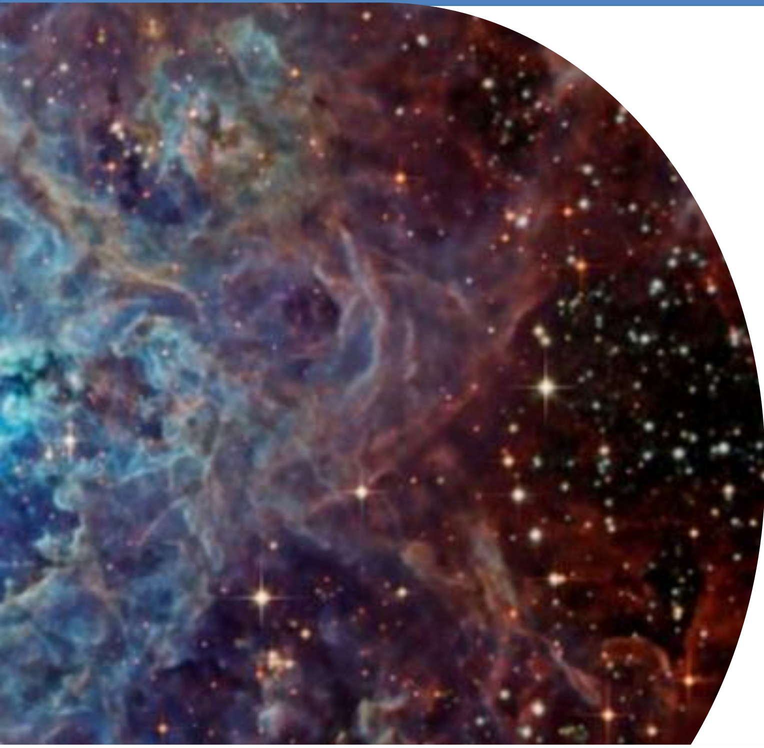
Asteroid Vesta from Dawn spacecraft

Robotic Lander autonomous landing test

Preparing SUMI for flight

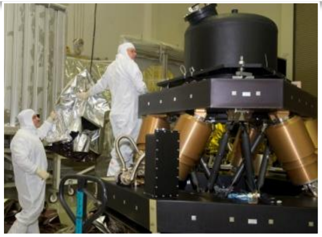
Solar Wind, Electrons, Alphas, and Protons (SWEAP)

Exploring the Universe Beyond



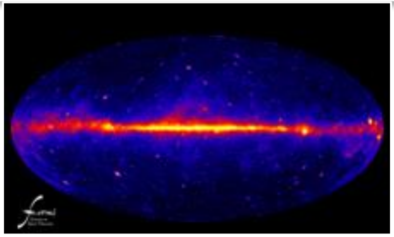
- Analyzing complex data from various space observation instruments
- Developing and testing optical systems for advanced deep-space telescopes applications
- Capturing visible and infrared light, gamma rays, and X-rays

JWST mirror testing



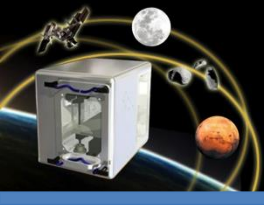
JWST instrument testing

Cats Eye Nebula from Chandra X-ray Observatory



Fermi Gamma-ray Space Telescope map of the Gamma-ray sky

Omega Nebula from Hubble



Living and Working in Space

Supporting Life in Space

Supporting Scientific Research on the International Space Station

Lab Training Complex

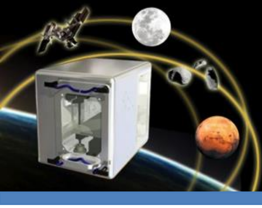
Payload Operations Center

ECLSS testing at Marshall

Microgravity Science Glovebox

ISS U.S. Destiny Lab

From large space structures to life support systems and operations, Marshall supports crews in space.



Living and Working in Space

Supporting Life in Space

- International Space Station
  - Continual human presence since 2000
  - Completed in 2010
- Major U.S. nodes and modules
- Cleaning air and recycling water
- Environmental effects on people and materials

ISS Test Facility at Marshall

Node 3 Tranquility

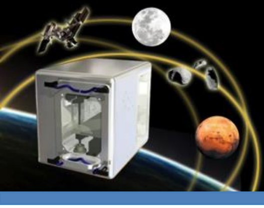
Delivery of the ISS Cupola

Atmosphere Resource Recovery and Environmental Monitoring

Multi-purpose Logistics Module, Leonardo

Environmental Control & Life Support System (ECLSS)

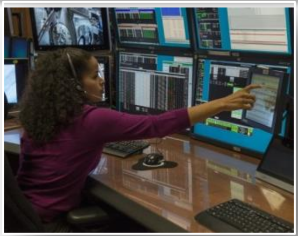
Marshall develops systems for living and working on the ISS.



Living and Working in Space

Supporting Scientific Research in Space

- Manage science operations around the clock
- Window Observational Research Facility
- Materials Science Research Rack
- Microgravity Science Glovebox



Payload Operations Center at Marshall

WORF – Window Observational Research Facility

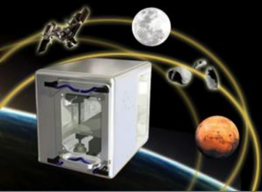
EXPRESS Racks for Destiny Module

Materials Science Research Racks

Microgravity Science Glovebox

Destiny Laboratory

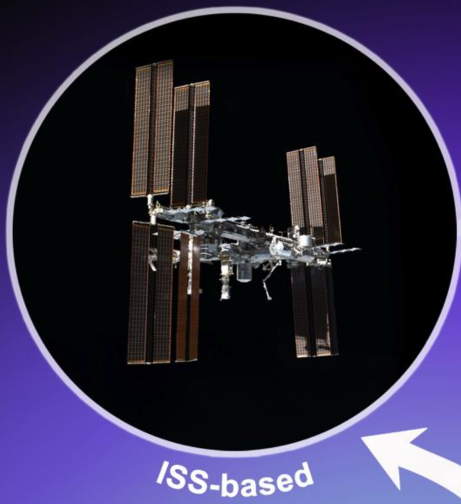
Marshall is the command post for science on the ISS.



NASA Advanced Manufacturing Technology

ISS Platform

- In-space Fab & Repair Plastics Demonstration via 3D Printing in Zero-G
- Qualification/Inspection of On-orbit Parts using Optical Scanner
- Printable SmallSat Technologies
- On-orbit Plastic Feedstock Recycling Demonstration
- In-space Metals Manufacturing Process Demonstration



Planetary Surfaces Platform

In-situ Feedstock Test Beds and Reduced Gravity Flights Which Directly Support Technology Advancements for Asteroid Manufacturing as well as Future Deep Space Missions.

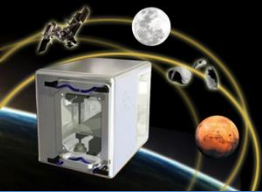
- Additive Construction
- Regolith Materials Development & Test
  Synthetic Biology: Engineer and Characterize Bio-Feedstock Materials & Processes

Earth-based Platform

- Certification & Inspection of Parts Produced In-space
- In-space Metals Fabrication Independent Assessment & NASA Systems Trade Study

Earth-based Platform (cont.)

- Printable Electronics & Spacecraft
- Self-Replicating/Repairing Machines
- In-situ Feedstock Development & Test: See Asteroid Platform



In-space Manufacturing Technology Development Vision

Earth-based

International Space Station

3D Print Tech Demo

Metal Printing

Printable Electronics

Add Mfctr. Facility

Optical Scanner

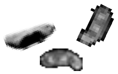
SmallSats

Recycler

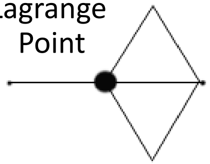
Self-repair/ replicate

Exploration

Asteroids



Lagrange Point



Lunar

Mars

Pre-2012	2014	2015 2016 2017 2018	2020-25	2025	2030 - 40

Pre-2012

Ground & Parabolic centric:
- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

2014

- **In-space:3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **AF/NASA Space-based Additive NRC Study**
- **Synthetic Biology**
- **ISRU Phase II SBIRs**
- **Ionic Liquids**
- **Printable Electronics**

2015–2018

- 3D Print Utilization Catalogue
- In-space Verification: Optical Scanner
- Additive Manufacturing Facility (AMF)
- In-space Recycler Demo: recycle printed plastic part back into feedstock
- Metal Demo Options
- In-space Material Database

ISS: *Utilization/Facility Focus*
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- SmallSat Build & Deploy
- Synthetic Biology Demo

2020-25

Lunar, Lagrange FabLabs
- Initial Robotic/Remote Missions
- Provision some feedstock
- Evolve to utilizing in situ materials (natural resources, synthetic biology)
- Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”
- Autonomous final milling to specification

2025

Planetary Surfaces Points Fab
- Transport vehicle and sites would need Fab capability
- Additive Construction

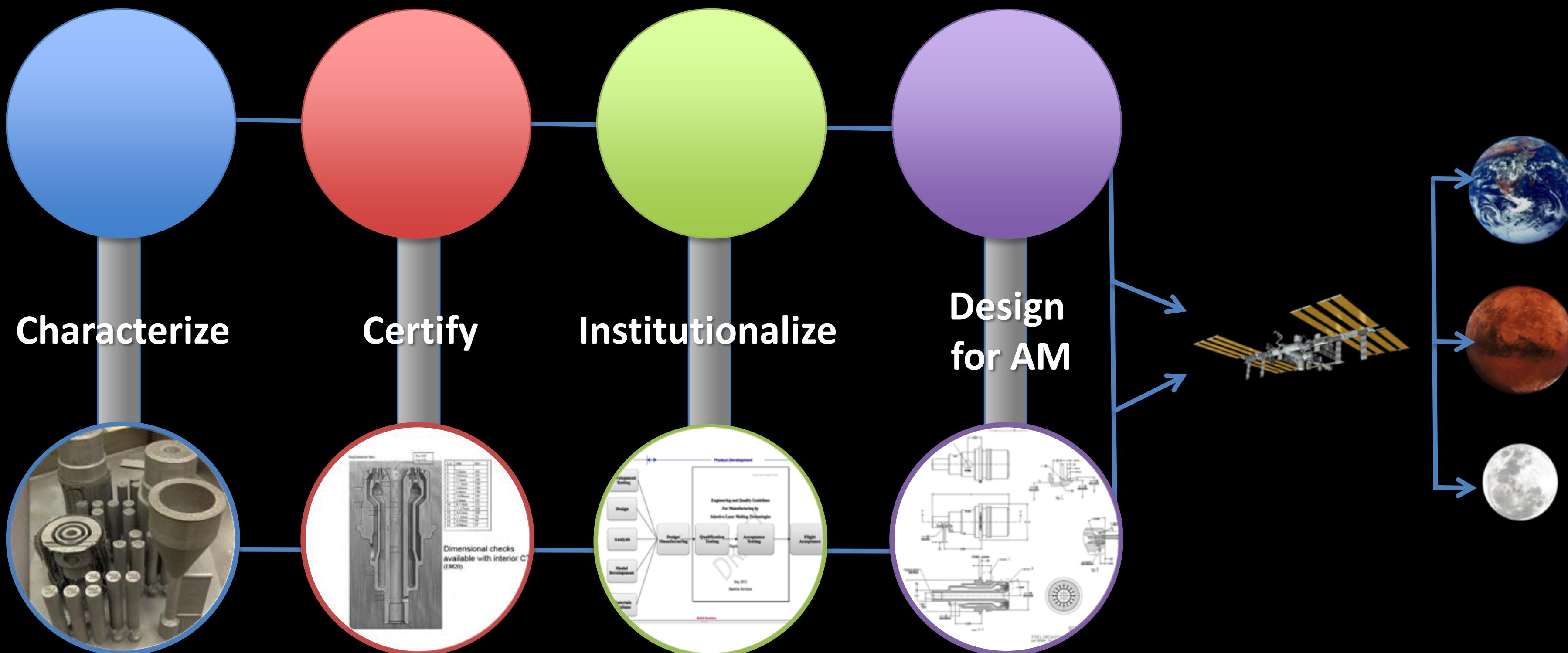
2030 - 40

Mars Multi-Material Fab Lab
- Utilize in situ resources for feedstock
- Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
- Product: Fab Lab providing self-sustainment at remote destination

ISS Technology Demonstrations are Key in ‘Bridging’ Technology Development to Full Implementation of this Critical Exploration Technology.

The Road to In Space Manufacturing

In-Space Additive Manufacturing



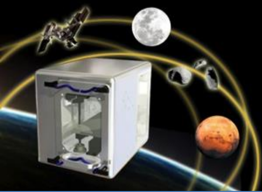
SLM manufactured injector, mechanical property and microstructure test articles

CT Scan Nondestructive Inspection and Dimensional Verification

Process Standards documentation for qualification/ certification process

Design for Additive Manufacturing Process

Parallel paths toward Certification of Space System Designs

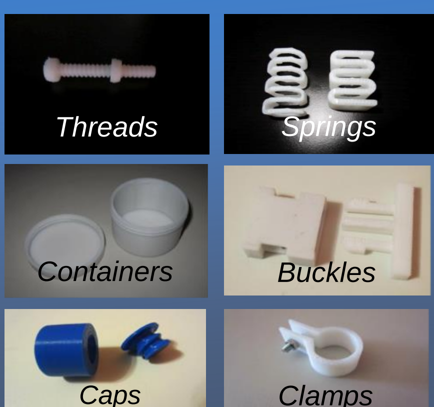


3D Print Tech Demo on ISS

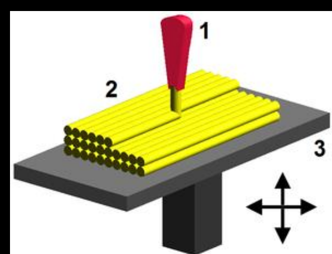
Microgravity Research

3D Print Ground Testing

Potential Mission Accessories



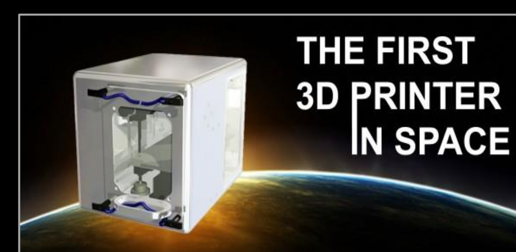
The 3D Print project will deliver the first 3D printer on the ISS and will investigate the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.



Melt deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

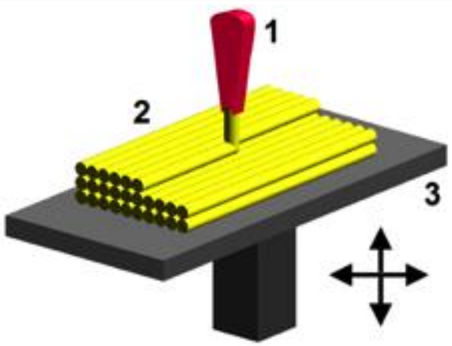
3D Print Specifications	
Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Est. Accuracy	95 %
Resolution	.35 mm
Maximum Power	176W (draw from MSG)
Software	MIS SliceR
Traverse	Linear Guide Rail
Feedstock	ABS Plastic

3D Print in Micro-G Science Glovebox (MSG)

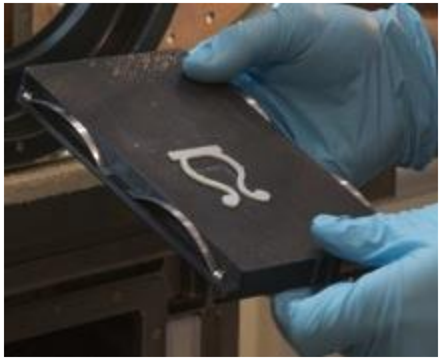


What is 3D Printing?

Additive Manufacturing (AM) or 3D Printing (3DP) is the method of building parts layer-by-layer. Melt deposition fabrication builds the object out of plastic deposited by a wire-feed via the extruder head. The parts are 'printed' from 3D CAD drawings loaded on the printer or uplinked from Earth.



Melt deposition modeling:
1 - nozzle ejecting molten plastic
2 - deposited material (modeled part)
3 - controlled movable table

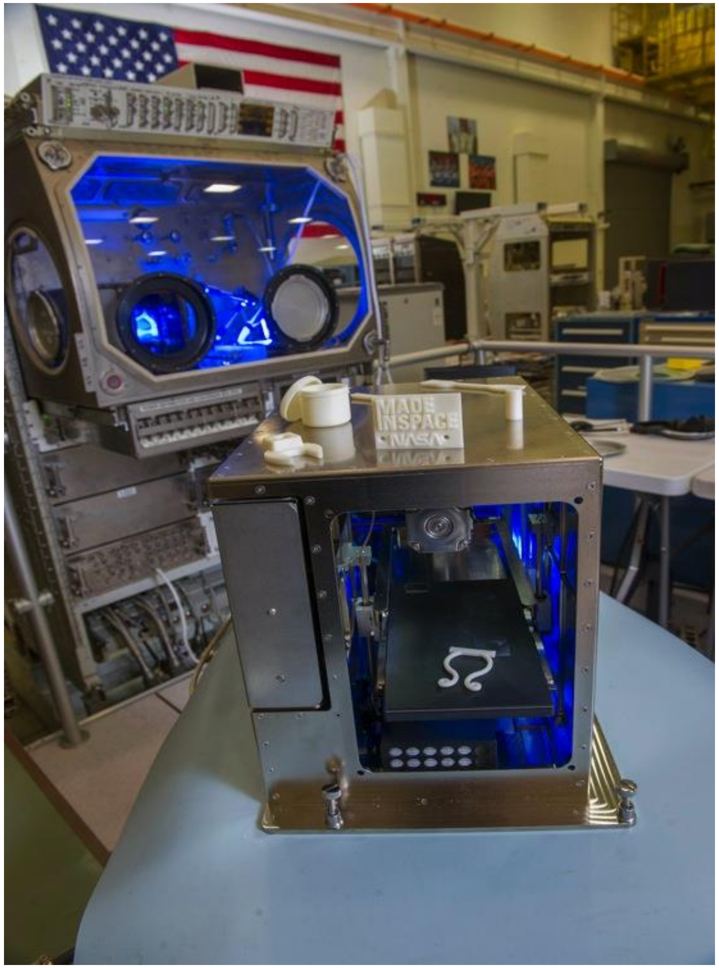


Small Part on Print Tray

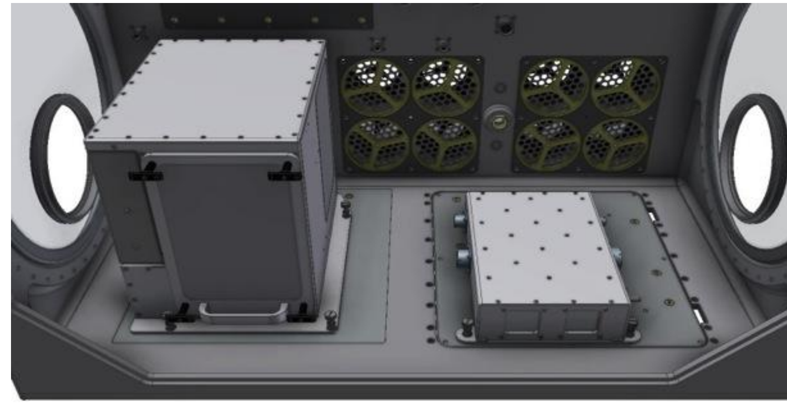
- **Benefits**
  - Low energy, low mass
  - Relatively low melting temperature
  - Toxicity level 0
  - Adaptable (could be used in the future to print parts approximately 6cm x 12 cm x 6 cm uplinked from Earth)
  - Risk mitigation for a future AM facility

3D Printing in Zero-G You Tube Video

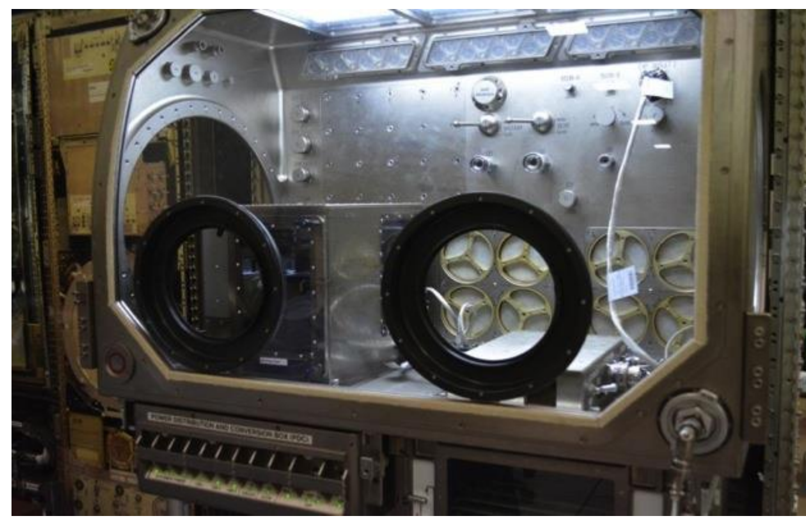
3D Print Images



3D Print Flight Unit with the MSG Engineering Unit in the background



CAD model of the 3D Print printer and electronics box in the MSG

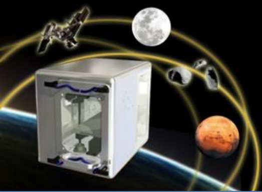


3D Print Flight Unit within the MSG Engineering Unit a MSFC

3D Print Roles and Responsibilities

- Made in Space, Inc. responsibilities
  - The design, build, and craftsmanship of the hardware and software as is defined by the SBIR Phase III effort.
  - Assure that the design satisfies all requirements, both functional, safety and interface
- MSFC NASA roles and responsibilities
  - The MSFC Additive Manufacturing (AM) branch, EM42, serves as the NASA PI for functional objectives
  - To provide insight to ensure that the hardware meets minimum flight requirements and passes flight qualification testing
    - With the understanding that this is a Technology Demonstration and the project accepts the risk associated with that.
    - These minimum flight requirements, whether in the ICD or via the safety process, primarily fall under the safety and/or 'do no harm' to interfaces categories.
  - To perform integrated development testing and final V&V testing of the delivered flight hardware
  - To integrate the delivered MIS printer into the ISS MSG

This has been an ideal collaboration which illustrates how leveraging the mutual strengths of the government and small business can lead to remarkable capabilities that would not otherwise be possible, particularly with such ambitious schedules and budgets.



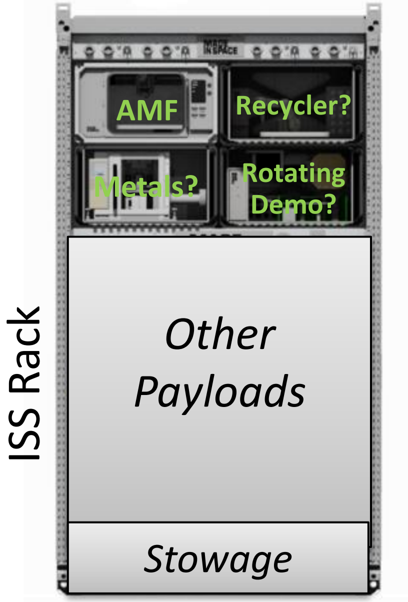
Additive Manufacturing Facility on ISS: The Bridge to Essential Exploration Technologies

3D Printing in Zero-G ISS Tech Demo

3D Print is the foundation for In-Space Manufacturing

- Step 1: Demonstration of Printer and Process in micro-g
- Step 2: Demonstration of functionality/ utilization of printed parts

Additive Manufacturing Facility

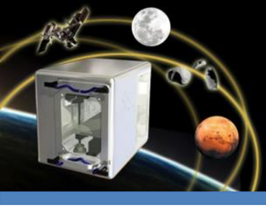


- AMF incorporates design, process, and operational lessons learned from 3D Print Tech Demo
- AMF provides commercialization, exploration, and ISS Logistics/Tools functionality
- Potential for additional Tech Demos and/or facilities such as a Recycler, Metal Printer, Printable Electronics, etc. for increasing In-space Manufacturing capability

Critical Enabler for Exploration Missions

- In-space Manufacturing Tech Development & Demonstration on ISS is a critical enabler for the future of space exploration
- Enables a sustainable/ Earth independent capability
- Will be a testbed for:
  - **human exploration** (to use in space mfg. as a tool),
  - **building large structures** (design w/out launch environments & restrictions),
  - **building spacecraft in space** (for on-demand missions),
  - **building in situ** (for exploring/building on the moon, Mars, asteroids and beyond)

The 3D Printing in Zero-G Demonstration serves as a design, process, and operational risk mitigation for the commercial Additive Manufacturing Facility



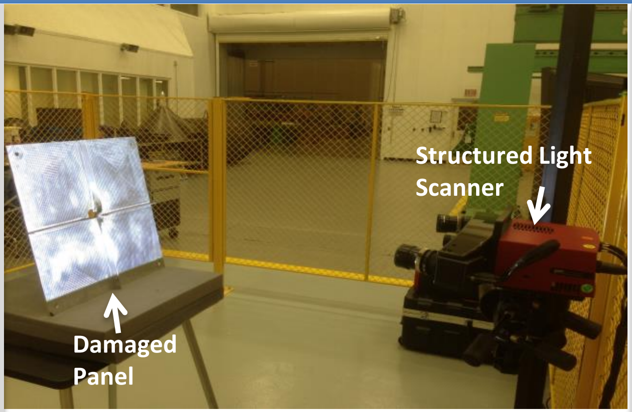
Additive Manufacturing Facility (AMF) Development

- **AMF will incorporate key design, process, and operational lessons learned from the 3D Print Tech Demonstration in order to provide a permanent, commercial 3D Printer on ISS for both external and NASA customers. Updates will include, but are not limited to:**
  - New material capabilities (for more usable, robust parts)
  - Larger Build Platform resulting in wider range of print options
  - State of the art electronics and s/w upgrade (for increased automation, more finite resolution, and faster prints)
  - New build platform addition (for stronger parts and more automation)
  - Additional lessons expected to come out of the tech demo when on the ISS later in 2014
- **AMF Enables**
  - Commercialization – MIS has marketing plan and multiple external commercial customers identified
  - ISS Utilization – Discussions underway with Crew Tools, Logistics & Maintenance, and Payload Teams to identify potential parts for On-orbit Utilization Catalogue
  - Exploration Test-bed – Collaborate with other NASA AES projects, such as Heat Compactor and Advanced ECLSS to lay the groundwork for Additive Manufacturing in-space systems using ISS as a test-bed.

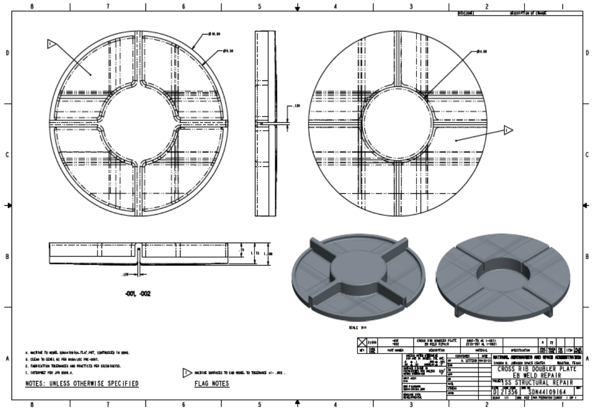
AMF Example Printed Parts

Structured Light Scanning

Close-up of simulated MMOD Damage to External ISS Panel

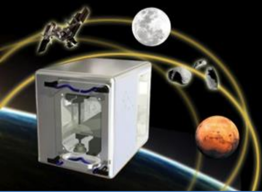


Scanning the Damaged Panel



CAD for custom doubler 'patch' for damaged area

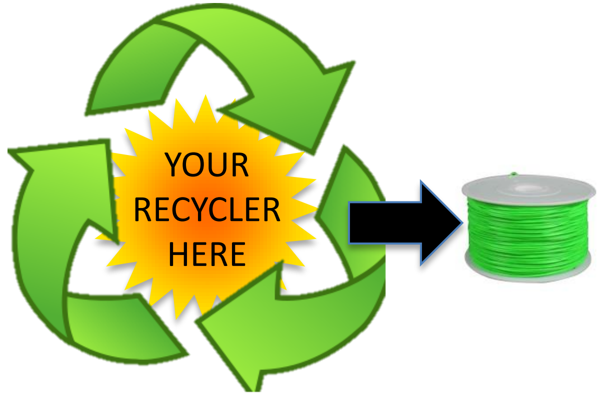
- A verification and certification process for parts additively manufactured on-orbit is needed.
- First step in establishing such a process:
  - Flight certify a CoTS Structured Light Scanner, an optical measuring technique frequently used for the characterization of the surface geometry of parts
  - Demonstrate scanning and geometric verification/validation on ISS for 3D Printer Technology Demonstration parts
  - Compare parts printed in space to CAD nominal and ground-based parts using quantifiable data on the accuracy of the build process and parameters
  - Verify that parts printed in space meet design specification
- Additional uses:
  - Create duplicate parts - scan original parts, create build instructions, print
  - 'Reverse Engineering' and repair of broken parts on ISS
  - Physiological measurements for crew health/human research projects
  - Any payload or experiment requiring data on geometrical changes (coatings, micro-meteoroid impacts to external experiments or components).
  - Convert packaging and waste to feedstock



Recycler

Build	Recycle	Sustainable Reuse

Original Part Printed



Recycle printed part back into Feedstock Filament

Use Recycled Filament to Print new parts

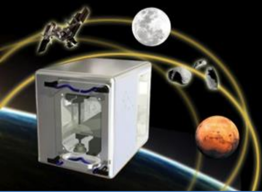
- Recycling and reclaiming the feedstock is required to develop a self-sustaining, closed-loop in-space manufacturing capability
  - Less mass to launch
  - Increase "on demand" capability in space
- 2014 Phase I SBIR call entitled, "Recycling/Reclamation of 3-D Printer Plastic for Reuse" closed on 1/29/14.
- Potential transition from SBIR to ISS Technology Demonstration in conjunction with 3D Printer activities

What Could Be:

- Expand recycle/reclamation capability to include other build materials, e.g. metals
- Convert packaging (packaging material selection compatibility with manufacturing technology) and potentially trash to build materials

Design for AM

- **To achieve maximum benefit and integration to the fullest extent. Additive Manufacturing (AM) must be incorporated at the Design Level - Design for AM, On-Orbit Repair and Replacement.**

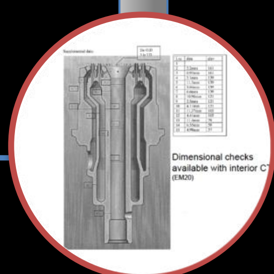


The Road Ahead

In-Space Additive Manufacturing

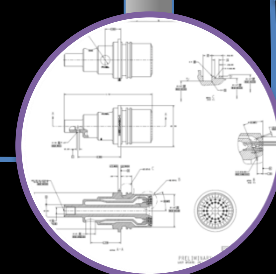
Characterize — **Certify** — **Institutionalize** — **Design for AM**

SLM manufactured injector, mechanical property and microstructure test articles

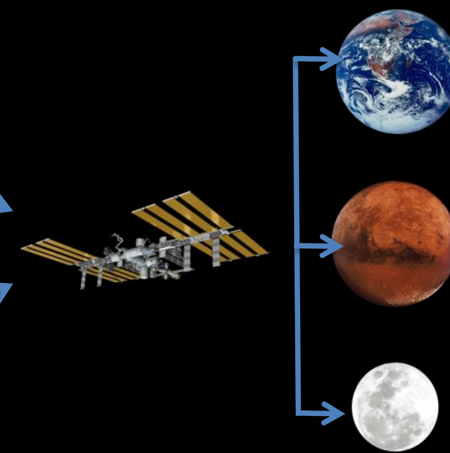


CT Scan Nondestructive Inspection and Dimensional Verification

Process Standards documentation for qualification/certification process

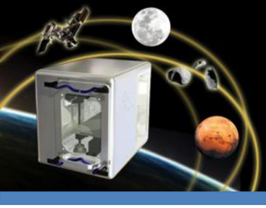


Design for Additive Manufacturing Process



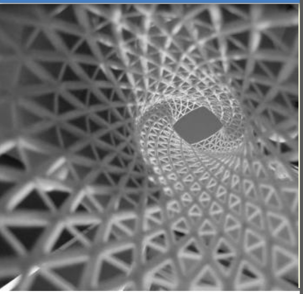
Ground-Based Additive Manufacturing of Propulsion Components

Parallel paths toward Certification of Space System Designs



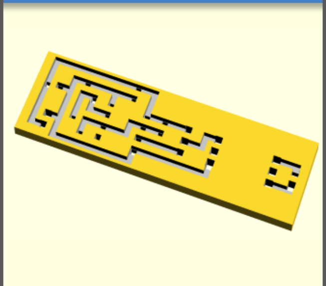
What Could Be

NON-METALS



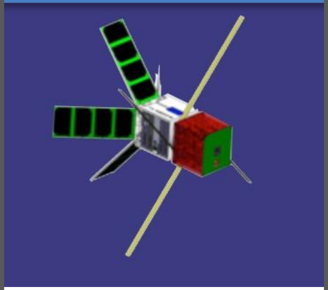
Additive manufacturing using nonmetallics is the simplest solution to many on-orbit needs. An expanding suite of feedstock materials coupled with manufacturing in vacuum creates new architecture and design possibilities.

PRINTED ELECTRONICS



Leverage ground-based developments to enable in-space manufacturing of functional electronic components, sensors, and circuits. Image: *Courtesy of Dr. Jessica Koehne (NASA/ARC)*

PRINT-A-SAT



The combination of 3D Print coupled with Printable Electronics enables on-orbit capability to produce “on demand” satellites.

METALS

Additively manufacturing metallic parts in space is a desirable capability for large structures, high strength requirement components (greater than nonmetallics or composites can offer), and repairs. NASA is evaluating various technologies for such applications. Image: *Manufacturing Establishment website*

REPAIRS

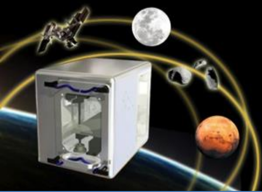
Astronauts will perform repairs on tools, components, and structures in space using structured light scanning to create digital model of damage and AM technologies such as 3D Print and metallic manufacturing technologies (e.g. E-beam welding, ultrasonic welding, EBF3) to perform the repair. Image: *NASA*

CONTOUR CRAFTING

Contour Crafting Simulation Plan for Lunar Settlement Infrastructure Build-Up B. Khoshnevis, USC

Illustration of a lunar habitat, constructed using the Moon's soil and a 3D printer. Credit: Foster+Partners

Characterize→ Certify→ Institutionalize→ Design for AM

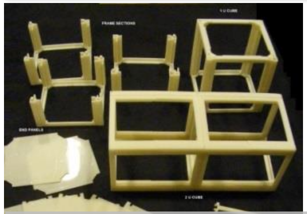
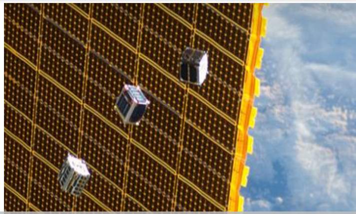


Non-Metals

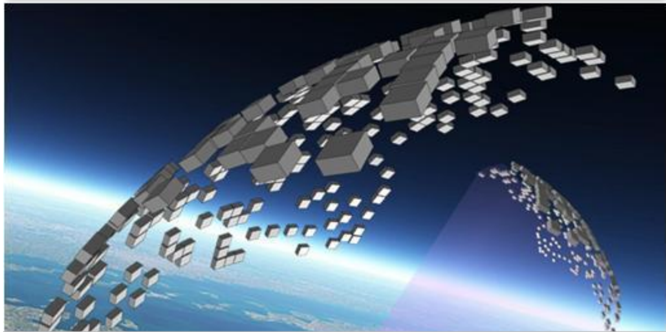
- **ABS plastic will be used for initial Additive Manufactured demonstration articles on ISS**
- **Other nonmetallic materials, currently being utilized/developed for ground-based printers are candidates for ISS evaluation/applications**
  - Ultem 9085 high strength thermoplastic
  - Carbon fiber reinforced WINDFORM XT
  - Other polymer matrix composites, e.g. UTEP developments
- **Conductive Polymers**
  - Build circuits into structure
  - Build sensors, antennas, customized heat exchangers
- **Cubesat structures**
- **Go external**
  - ISS Technology Demonstration for automated external additive manufacturing
  - Free-flying platforms for autonomous manufacturing of on-demand cubesats


Above: Tools • Below: Spares/Standard Hardware

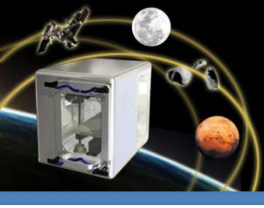


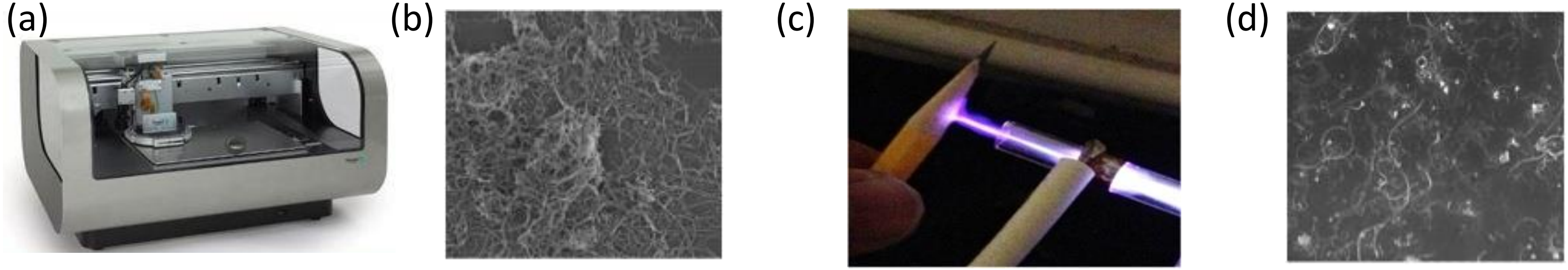
Left: Printed Cubesat structural elements
Right: Cubesats deployed from ISS



Cubesat swarm from Autonomous Manufacturing Platform



Printable Electronics

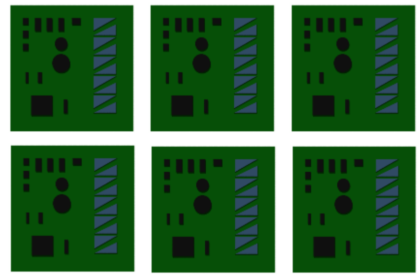


Inkjet Printing: (a) Dimatix piezoelectric inkjet printer (b) CNT ink spot by drop casting showing CNT aggregation (c) Single jet plasma system (d) spot of CNT ink by plasma jet showing even, conformal deposition and no aggregation

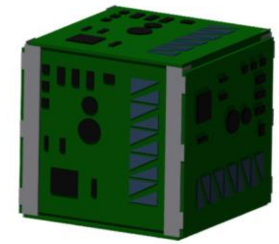
- **Develop in-space manufacturing capabilities to produce functional electronic and photonic components on demand.**
- **Printable inexpensive functional electrical devices is a rapidly evolving field**
  - substrates include plastic, glass, silicon wafer, transparent or stretchable polymer, and cellulose paper, textiles
  - Various inks with surfactants for stability are emerging (carbon nanotubes, silver, gold, titanium dioxide, silicon dioxide)
- **Take the first step towards printing electronics on-demand in space – building block approach**
  - Select, develop and characterize inks for electronics printing
  - Development and fabrication of electronic printer
  - Demonstrate circuit blocks
- **Fly a Technology Demonstration on ISS to build some functional electronic/ photonic circuits, sensors, electrodes, displays, etc.**
- Mature on-orbit capability to print-on-demand. Parts are printed from computer aided design (CAD) models which can be pre-loaded or uplinked from Earth

Print A Sat Project

Print ChipSat Structure On ISS using 3D Print



Launch Six Unique ChipSats Printed on the Ground by ARC & JPL



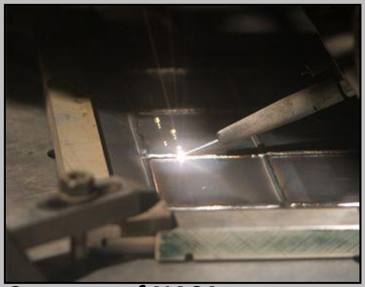
First 100% Printed Cubesat to be Printed in space using printable electronics

- **Develop the capability to additively manufacture a Cubesat in space which incorporates proof-of-concept for printable electronics**
- **Interest across NASA, DoD, DARPA, Commercial, and Academia**
- **First step:**
  - Print Cubesat's structural supports using 3D Print ISS Tech Demo On-orbit
  - Print ChipSats on ground and launch to ISS
  - Deploy from ISS to demonstrate Printable Spacecraft proof-of-concept
- **Next steps**
  - Develop capability to print electronics on ISS
  - Enable "science on demand" or "observations on demand"
  - Establish pathfinder for commercial model of in-space Cubesat production on ISS

Metals

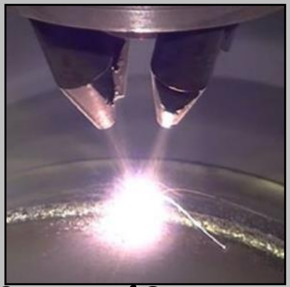
- **NASA/MSFC contracted with Wohlers Associates to perform independent assessment of mainstream and novel metals AM technologies for in space applications**
  - Ten (10) Selection Criteria identified including: microgravity; working in a vacuum; post-processing requirements; material form, use, recyclability, and disposal.
  - Nine (9) AM technologies for evaluation identified
    - Crowd sourcing with social media
    - Interviews with AM experts
    - Discussions with Aerospace leaders such as Made In Space, Langley Research Center; and ESA
  - Approach to evaluation identified
- **Final Report due June 30, 2014**
- **NASA Space Technology Mission Directorate tasked LaRC to conduct systems analyses of Metals AM technologies to support 2015 selection for ISS tech demonstration**

Electron beam freeform fabrication



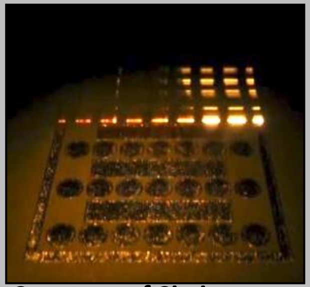
Courtesy of NASA

Laser-engineered net shaping



Courtesy of Optomec

Electron beam melting



Courtesy of Sirris

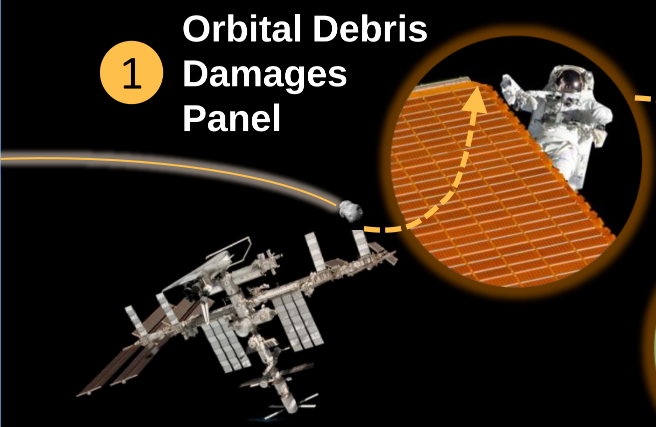
Microgravity Casting Process

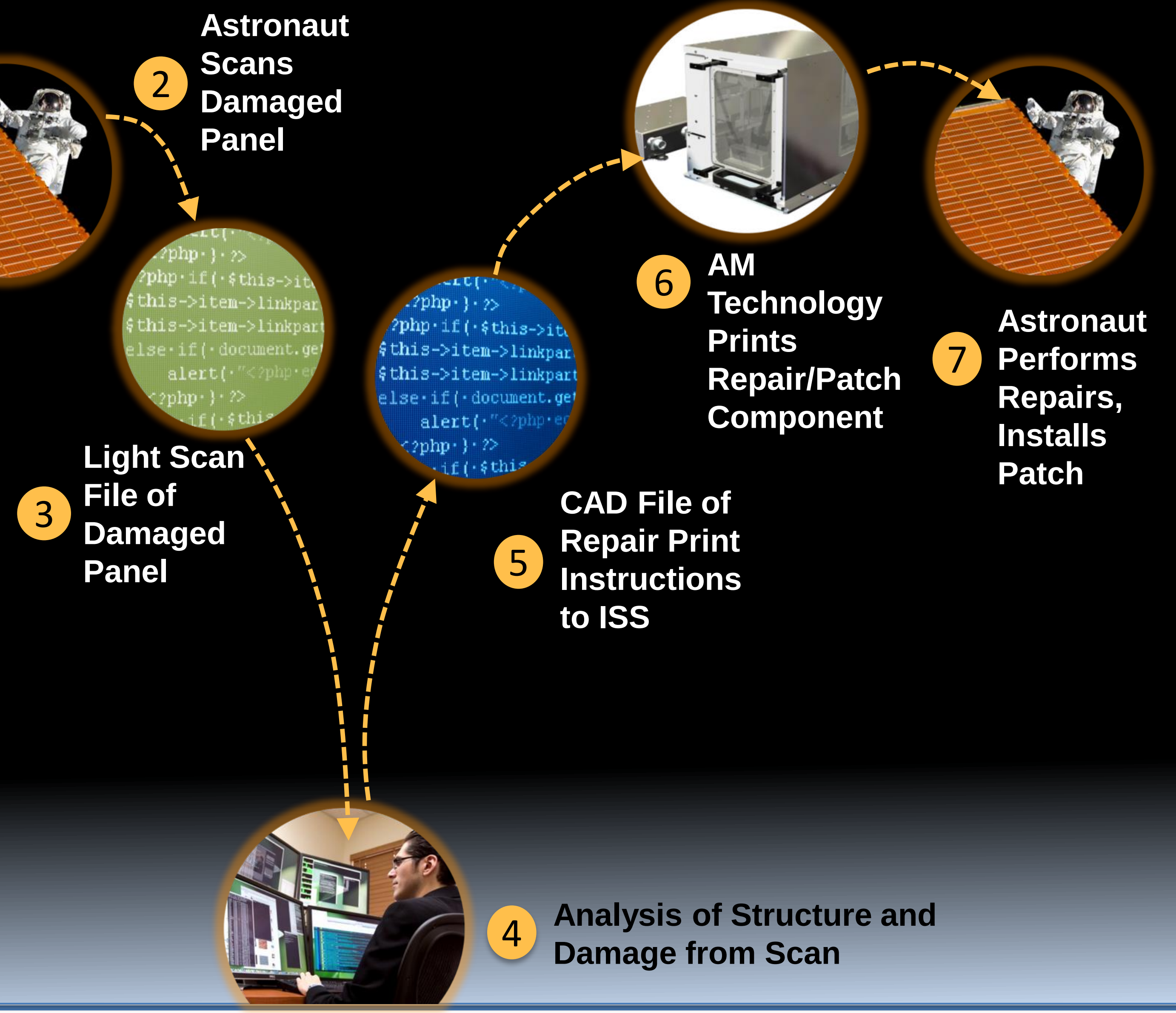
Courtesy of Made In Space

Status Courtesy of

WOHLERS ASSOCIATES

Repairs





- One example of many envisioned repair possibilities
- Structured light scanning will be an essential element for most, if not all, repairs.
- AM technologies can be used directly to repair parts (e.g., LENS, EBF3, Ultrasonic Welding, 3D Print, etc.), print a patch, or create a new replacement component.

Contour Crafting

- **A new technology (developed at the University of Southern California) for robotic and autonomous construction; allows for versatile design options & construction materials**
- **Current capabilities (at USC and MSFC) are for small structures only**
- **Current R&T efforts to improve TRL and space and terrestrial applicability (NIAC)**
- **Large-scale demonstration of the new technology will be proposed in conjunction with US Army's Corps of Engineers in FY15**
- **Space applications focusing on remote lunar base construction, MMOD and radiation protection solutions**
- **Terrestrial applications for forward operating bases construction capability for military; for rapid, disaster relief efforts (FEMA); and low cost housing for developing countries**


Lunar base construction


CC nozzle with corrugated wall


MSFC Demonstration

Summary

- **In-space Manufacturing offers:**
  - Dramatic paradigm shift in the development and creation of space architectures
  - Mission safety risk reduction for low Earth orbit and deep space exploration
  - New paradigms for maintenance, repair, and logistics.
- **TRL advancement to application-based capabilities evolve rapidly due to leveraging of significant ground-based technology developments, process characterization, and material properties databases**
- **NASA-unique Investments are required primarily in applying the technologies to microgravity environment.**
- We must do the foundational work. It's not always sexy, but it is fundamental.
  - Characterize
  - Certify
  - Institutionalize
  - Design for AM
- **What Could Be – is limited only by the imagination (and funding)**

"What will we build? We will build EVERYTHING"

– Astronaut Don Pettit

For more information please contact:

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Characterize

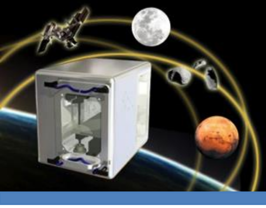
- **Materials – constituents, feedstock, components (microstructure, surface finish, etc.)**
- **Properties – full/tailored suite of physical, mechanical, thermal properties as would be required for any space qualified component**
- **Process**
  - Ground-based
  - Microgravity-based
- **Inspection processes as applied to additively manufactured parts**
- **Reuse/Recycling**
  - Contamination
  - Properties vs. Original/Virgin Feedstock
  - Qualify Verification against Feedstock Specifications

Characterization element benefits significantly from ground-based Additive Manufacturing development

Certify

- **Technical capability to print parts on-orbit must go hand-in-hand with qualification/certification process to ultimately enable production of usable parts, structures, and systems in space.**
- **Typical certification process involves one or a combination of:**
  - Test
  - Analysis
  - Similarity
- **Certify the Process - Generate process repeatability & reliability data at statistically significant levels**
  - Geometric verification/validation of parts
  - Material properties
  - Process monitoring for real time “certification” of build
  - Database of every part needed for configuration management
- **Certify the part**
  - Inspect Components
  - Test on ground and/or on orbit?
- **Certify by process similarity – how to validate process/print was performed as designed (visual monitoring, other sensors)**

Test what you fly. Fly what you test.



Institutionalize

- **Mature from lab curiosity to in-line capability**
  - Culture – awareness and acceptance of additive manufacturing technologies
  - Building block approach for development of more complex systems
  - Standardize
    - Feedstock, materials, processes, inspections, acceptance procedures
    - Configuration control
    - Life cycle management
  - Demonstrate reliability – trust the process and the part
  - Innovation – expand the application space
  - Involve astronauts, crew systems, space systems developers
    - First line implementers
- **Create standard parts catalog for ISS**
- **Go external**
  - Large and more complex systems and structures will require capabilities that operate autonomously in space
  - Development efforts can build on foundation established by Earth-based and ISS-based (pressurized volume) capabilities and characterization efforts

Design for AM

- **To achieve maximum benefit and integration to the fullest extent. Additive Manufacturing (AM) must be incorporated at the Design Level - Design for AM, On-Orbit Repair and Replacement.**