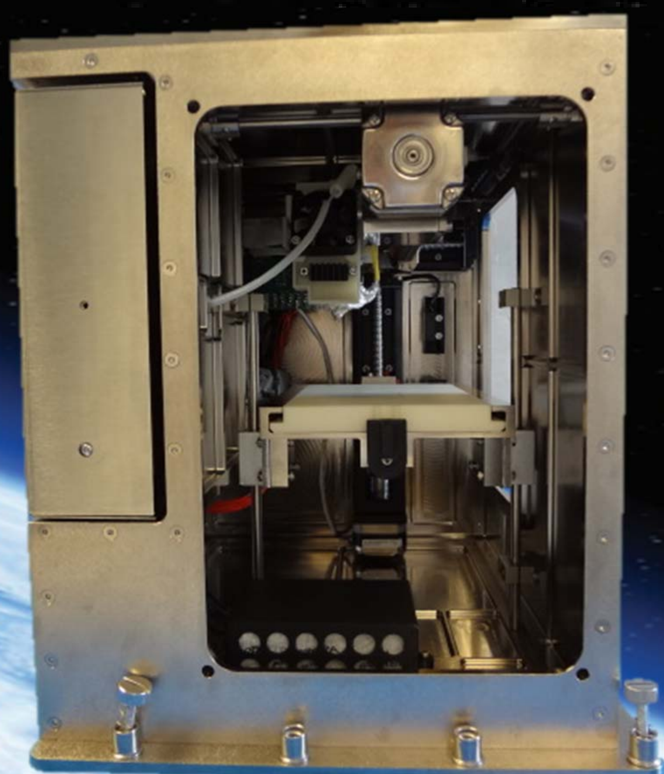

3D Printing in Zero-G ISS Technology Demonstration

June 18, 2014

NASA Advanced Manufacturing Technology

Marshall Space Flight Center

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

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NASA In-space Manufacturing Technology Development Vision

3D Print Tech Demo

Metal Printing

Optical Scanner

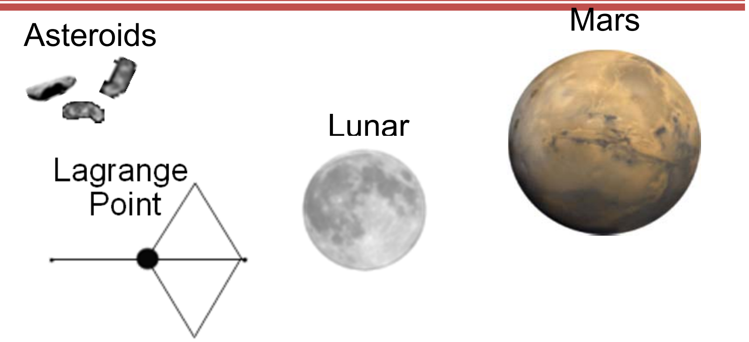
Printable Electronics

SmallSats

Recycler

Add Mfctr. Facility

Self-repair/ replicate



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

- **POC 3D Print: First Plastic Printer on ISS Tech Demo**
- **NIAC Contour Crafting**
- **NIAC Printable Spacecraft**
- **Small Sat in a Day**
- **NRC Study**
- **Center In-house work in additive, synbio, ISRU, robotics**

2015 2016 2017 2018

- Next Generation 3DPrint
- SmallSat in a Day ISS Demo
- Recycler Demo: recycle plastic

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

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. We believe this design is the right one for taking the very first step toward manufacturing in space!

All dates and plans beyond 2014 are notional and do not imply planned investments

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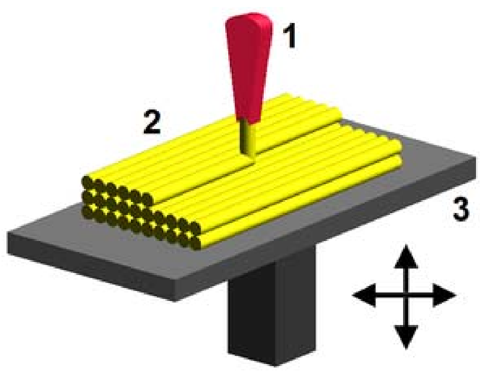
How 3D Print Works

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

- 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

Cases for Additive Manufacturing on the ISS

- Known/Predicted Repair: limit need for 'stockpiling' of parts
- Known Production & Assembly: Structural and geometrical constraints caused by launch loads and vehicle stowage requirements may be by-passed in order to build components in space and taking advantage of the absence of gravity.
- Unknown Repair & Replacement: The ability to create makeshift replacement tools while waiting for resupply could prevent flight experiments from losing critical run-time as well as possibly serving as a life saver in critical human systems equipment.
- New Experimentation Advantages: Given the opportunity to build freeform shapes in space, researchers on the ground and on-board alike will undoubtedly discover new and interesting ways to use the technology. One such opportunity is to include educational aspects where students can design and build parts in space. The applications opportunities become virtually boundless.

3D Printing In Zero-G Technology Demonstration Overview

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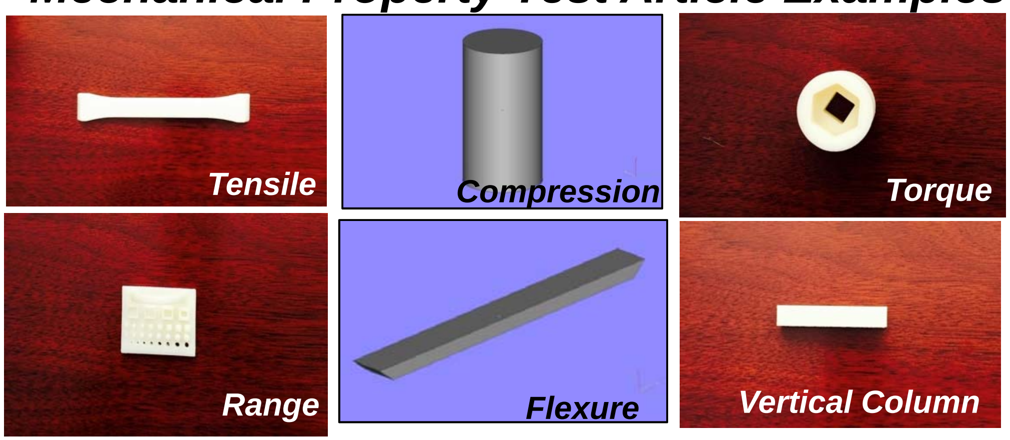
- **The 3D Print project will deliver the first 3D printer on the ISS to investigate the effects of consistent microgravity on melt deposition additive manufacturing and print parts in space**.
    - Builds 3D objects, layer-by-layer, with Acrylonitrile Butadiene Styrene (ABS) plastic (same material as Legos)
    - With reloadable feedstock, replacement extruder heads and electronics boxes, potential for hundreds of hours of use
- **3D Print Primary Objectives**
    - Successfully perform extrusion-based AM on-orbit by printing multiple parts from polymer material with print quality comparable to Earth-based parts
    - Demonstrate nominal extrusion and traversing
    - Perform 'on-demand' print capability via CAD file uplink for requested parts as they are defined
    - Mitigate Functional & Design Risks for Future Facilities

Mechanical Property Test Article Examples

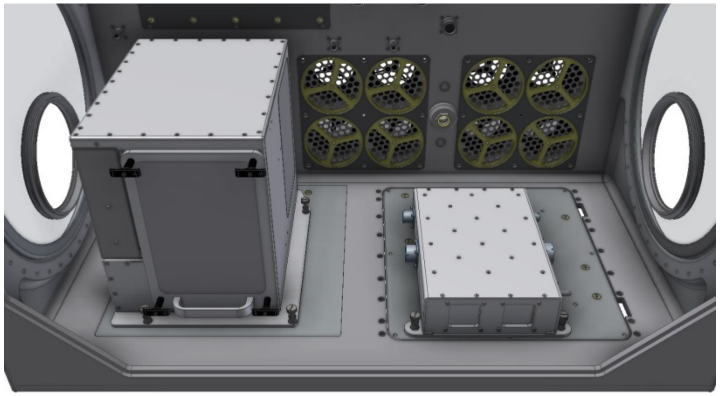


Dimensions	**33 cm x 30 cm x 36 cm**
Print Volume	**6 cm x 12 cm x 6 cm**
Mass	**20 kg (w/out packing material or spares)**
Est. Accuracy	**95 %**
Resolution	**.35 mm**
Maximum Power	**176W (draw from MSG)**
Software	**MIS SliceR**
Traverse	**Linear Guide Rail**
Feedstock	**ABS Plastic**

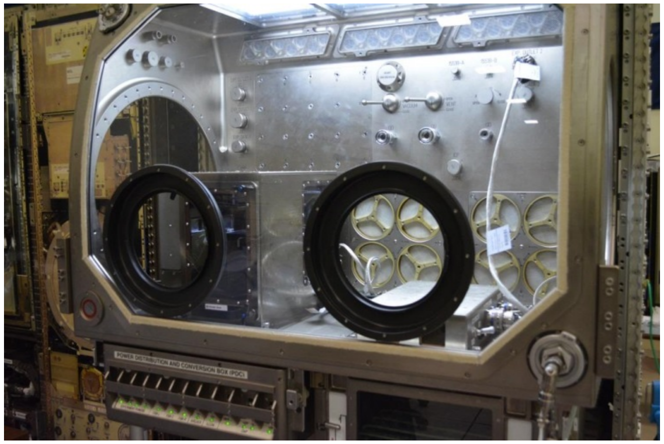
3D Print Roles and Responsibilities

- MIS, 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
  - To integrate the delivered MIS printer into the ISS MSG
  - To perform integrated development testing and final V&V testing of the delivered flight hardware
  - 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.

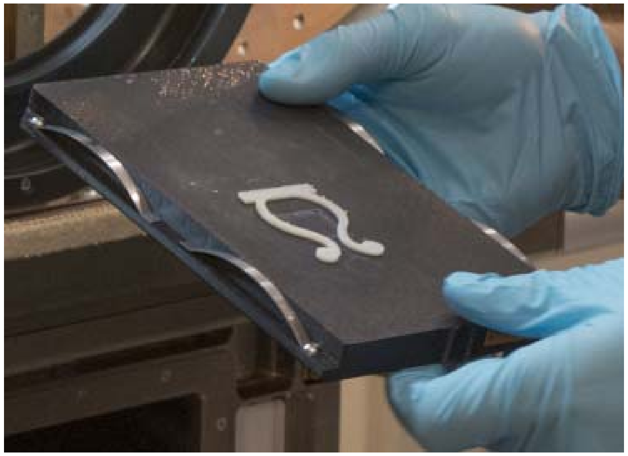
3D Print



Computer Aided Design (CAD) model of the 3D Print printer and electronics box in the MSG



3D Print Flight Unit within the MSG Engineering Unit at MSFC printing the final set of parts prior to launch



Testing of Print Tray removal inside MSG Engineering Unit at MSFC

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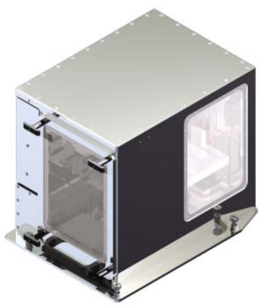
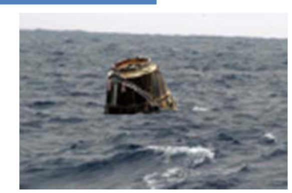
Concept of Operations Overview

Pre-Launch Setup → Deliver to ISS → Stow in ISS until use → Unpack and Install in MSG → System checkout / Commissioning

-Pack into CTB



Print samples will be returned home as descent flights allow.



Nominal Ops: Printing → Uninstall & Stow → Decommissioning → Return to Earth

-Pre/Post Print Procedures

-Ground analysis
-Lessons learned

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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

Cube Sat Parts *Optimized Structures*

Related Projects

- 3D Printed Toolbox – flight qualified Ultem
- POP3D – ESA's 3D printer, uses polylactic acid feedstock, prints a single part
- Feedstock Recycler – in SBIR Phase I
- RP+M – Materials characterization needed to qualify AM parts for spaceflight
  - NASA/America Makes award
- ASME Space Act Agreement for E/PO activities
- Heat compactor, Xhab, Recycler SBIR…
- Many, many more…

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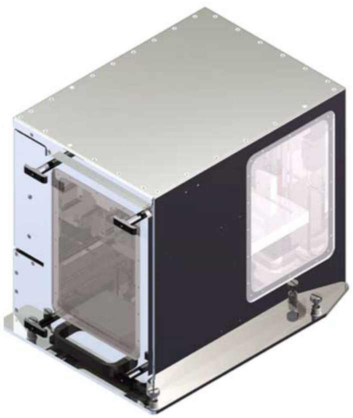
In-space Manufacturing on ISS: The Bridge to Exploration

3D Printing in Zero-G ISS Tech Demo

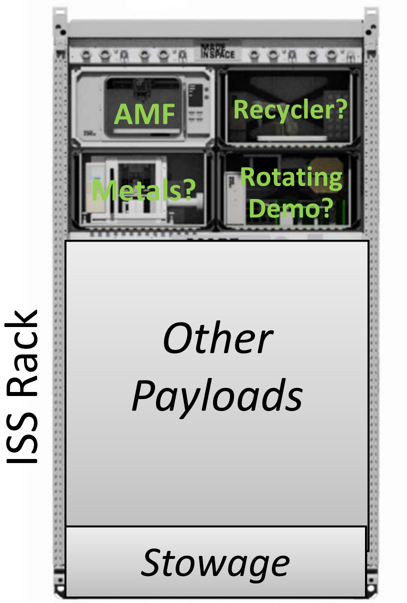
3D Print is the foundation for In-Space Manufacturing



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

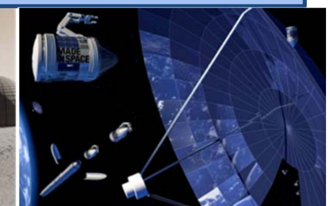
Additive Manufacturing Facility

ISS Rack



- 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

BACKUP

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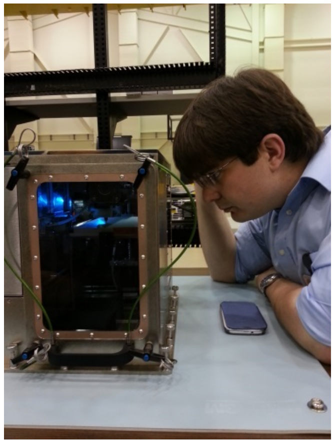
MSFC Developmental Testing

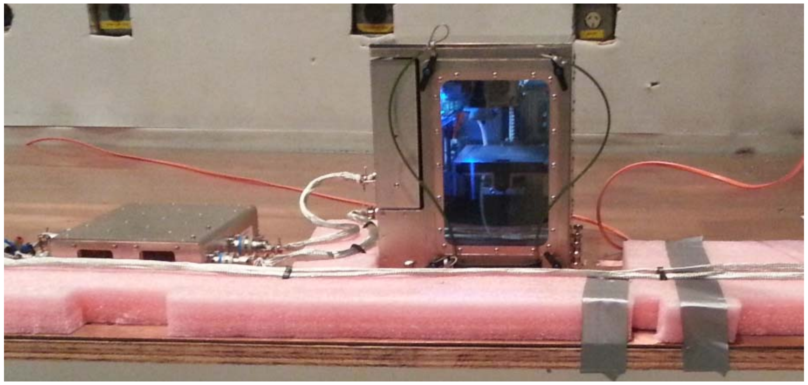
Tested ETU and GTU Hardware at MSFC

- Functional Print Tests (A)
- Fit Checks in MSG (B)
- EMI/EMC/Shock/Acoustic (C)
  (covered in Electronics Section)
- Launch Vibration Testing (D)
- Vibration Emissions (E)



A

B



C

D

E

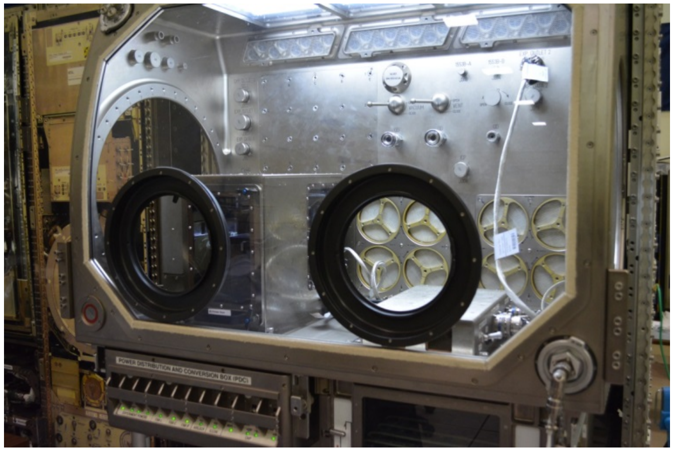
MSFC Flight Testing

Tested Flight and Flight Backup Hardware at MSFC

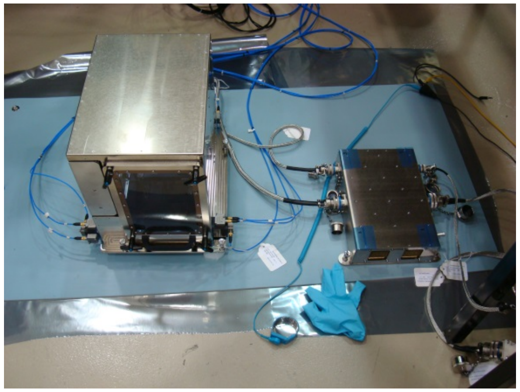
- Functional Test Prints (A)
- Printing in MSG (B)
- EMI/EMC/Shock/Acoustic (C)

  (covered in Electronics Section)
- Launch Vibration Testing (D)
- Human Factors Integration Team Inspection (E)

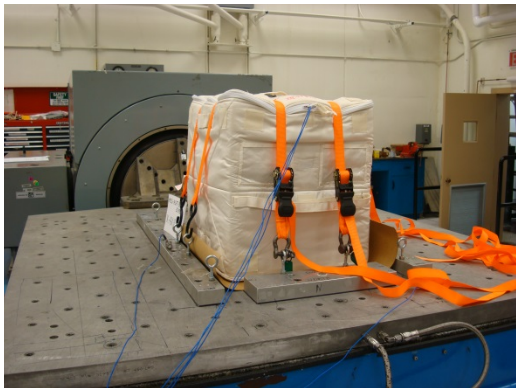
A



B



C



D

E

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Press

Public interest and response to 3D Printing in space has been phenomenal. In just the last year, more than 300 media articles and interviews *specifically related to this project* have been published nationally. Below is a sampling of some recent publications.

- *"Printing in Space",* TED-X Brussels Talk, 11/02/13
- *"Printing on ISS"*, ISS Live Interview, 10/30/13
- *"The New Space Race"*, Stanford Daily, 10/10/13
- *"NASA To Launch 3-D Printer into Space, SciTech Today"*, 10/08/13
- *"3D Printers in Space"*, Engineering.com, 10/02/13
- *"Space launch of 3D printer to ease supply, safety concerns"*, The China Post, 10/01/13
- *"NASA to Begin 3-D Printing in Space"*, ABC News, 9/30/13
- *"First 3D printer will launch to International Space Station in 2014"*, CBS News, 9/30/13
- *"NASA 3D printer: The next revolution in space?"*, The Christian Monitor, 9/30/13
- *"In Space, 3-D Printer Will Make Satellites On The Fly"*, Time Magazine, 9/30/13
- *"NASA to launch 3D printer into space to help supply astronauts"*, Fox News, 9/30/13
- *"'Maker' Ideas Wanted for First 3D Printer In Space"*, Space.com, 9/23/13
- *"NASA and 3D printing -Sky-rocketing"*, The Economist, 9/03/13
- *"Space Station Astronauts to Test 3-D Printing in Microgravity"*, Scientific American, 8/26/13
- "NASA sending a 3-D printer into space", CNN, 8/1/13
- *"3D Printing is Headed to Space"*, Popular Mechanics, 8/1/13
- *"3D Printing in Zero-G"*, NASA MSFC TV, 8/12/13
- *"NASA News: 3D Printing in Space Brings 'Star Trek' Replicator to Life"*, Design & Trend, 8/14/13
- *"NASA researchers looking to take additive manufacturing into space*", PhyOrg, 7/24/13
- *"Made-in-space parts could become new norm"*, CBS News, 7/23/13
- *"Get ready, 3D printing may be coming to a planet near you"*, Washington Post, 6/27/13
- *"Made In Space? 3-D Printer Fit for Microgravity"*, Discovery News, 6/12/13
- *"Houston, we don't have a problem"* – Zero-gravity 3D printing heads for space", Gizmag, 6/9/13
- *"NASA Wants To Bring 3-D Printers To Space"*, Popular Science, 6/5/13
- *"3-D Printing: NASA's Next Frontier"*, Wall Street Journal, 6/02/13
- *"3D Printer Launching to Space Station in 2014"*, Yahoo News, 5/24/13