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Supplying Space: 3D Printing for Interplanetary Logistics

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Abstract

This case study examines 3-D printing as an effective solution to ensure just in time logistics capability for supporting a crewed colony on Mars. It explores the cost to weight benefits of an advanced shipment sent prior to the crewed mission to ensure on-planet production capacity on arrival and landing for sustained operations with limited resupply from Earth. In order to project a realistic and financially reasonable solution, a quantitative descriptive analysis method is utilized. Data was collected through text research and research tools provided from the United States Government (NASA) and private industry via internet sources. From correlated data, it finds that utilizing additive manufacturing allows for greater flexibility from pre-fabricated items through a secondary shipment separate from a crewed mission, allowing more material to be sent while the crews can carry more essential items for survival. Ideas for consideration and for future research are provided to readers in order to establish a starting point for future work.

Introduction

Mars is the focus of the next long duration or even permanent human presence for exploration. Weight-to-cost ratios in launch and travel phases remain though as a significant obstacle for maximizing the human element of long-term existence outside of Earth's infrastructure. With current technology, the distance to Mars requires a journey of about six to nine months. In an urgent situation during the initial colonization period, this would be problematic if a tool or part is unavailable or even in transit, but a day late. A potential solution to provide flexible, just-in-time logistics is additive manufacturing, better known as three-dimensional (3-D) printing, capability onsite that reduces the time from identifying a need to a physical solution from days or months to hours or minutes. Current technology is based on raw plastic wire filament, it allows for on-site and on-demand production of items needed while limiting waste material. This allows for flexibility in logistics beyond direct support from Earth in interplanetary travel as shown in testing (Prater, et. al., 2018). Using the example of a crewed Mars mission, is 3-D printing an effective solution to the just-in-time logistics question of component replacement and adapting to unforeseen challenges when establishing a colony on another planet?

Background

Logistics is a complex field even on Earth. Variables include but are not limited to: anticipating the needs of the consumer, production lead times, cost versus quantity, storage both post-production and in transit, and shipment methods including costs such as insurance are usually essential to successfully supporting end users. Currently, the International Space Station (ISS) can be resupplied in a matter of days (depending on rocket availability) with both perishable and non-perishable stocks from Earth. Unlike previous human exploration there are few known resources to sustain an initial human presence on another planet. For the National Aeronautics and Space Administration (NASA) or a private company like Space Exploration Technologies Corporation (SpaceX), the small-scale logistics will be as vital as launch systems or travel duration effects on humans to sustained planetary exploration.

Scientifically, 3-D printing has few challenges in off Earth scenarios. The costs and benefits of small-scale production have not been examined widely yet. In that regard it remains uncertain if a technology along the lines of 3-D printing would be the optimal solution. With space operations, generally the largest cost is the launch from Earth. As that is directly tied to the weight of the payload, then it becomes a question of what kinds of items would need to be produced and how much raw material would be needed to supply that for the life cycle of those items as well as subsequent replacements. A similar ratio can be found for cost to time, as in what the difference is of physical interplanetary travel compared to an interplanetary transmission to also support resupply.

Scope

This research is necessarily focused on a broad scope for supporting non-perishable essential capabilities without immediate resupply from Earth to support the larger survival of a colony on Mars. Low Earth Orbit (LEO) and lunar operations are already well established from the ISS and the Apollo missions. While both present their own challenges, logistics support can be measured in a matter of weeks or days with current technology. In contrast, resupply on Mars may take between nine months and three years, making just in time logistics a paramount concern. NASA has a current timeline of the *Artemis* program returning humans to the Moon by 2024 with further exploration to Mars following after 2028 (Dunbar (Ed.), 2019). Since the NASA missions will probably be first, Mars is presumed to be the next step to identify the planetary limitations. *Artemis* uses the *Orion* spacecraft, currently capable of four crew at present (and possibly more) for spaceflight. Based on that size, a colony of 10-12 crew will serve as the baseline for number of people (“Orion Quick Facts”, n.d.). For time, the research will assume a solution of a pre-arrival delivery in parallel to the crewed launch as well as a timeline through the initial establishment of the colony and stabilization of about a year with a possible delivery of added materials at about nine months from establishment.

This research does not address the initial habitat facility, crewed spacecraft, water, and perishable supplies as those challenges need to be answered separately. For *in situ* small-scale production, it is assumed that there are no planetary resources available to produce components, tools, parts, or other items needed to sustain the facility. This will require on-site production from Earth provided supplies, either pre-fabricated items or from a raw material like plastic filaments; the common payload weight number for available projections of this size was 800 kilograms. All monetary figures are presented in US Dollars and as if the mission were happening in 2021, unless otherwise stated, to establish a baseline reference.

Literature Review

The work being done through NASA’s In-Space Manufacturing (ISM) initiative will serve as the basis for logistics during extended human exploration of space beyond Earth and the Moon. In addressing the larger concept, the ability to provide for the capability to produce non-perishable items without resupply will have to be a fundamental consideration for any planned mission. “Missions where cargo resupply is not available or a quick abort scenario cannot be executed require a fundamental paradigm shift in mission planning” (Prater, et. al., 2018, p. 391). This is a matter of survival for crews that take on the task of establishing a colony on Mars to show it can be done, not just an academic exercise. Think ahead on self-sustaining logistics costs in crewed exploration will be a matter of life and death.

With the ISM initiative, the results of experiments and subsequent testing for items manufactured in micro-gravity has produced a foundation of work to move forward from. This basis is not only looking at this capability limited to purely plastic filaments, but to other possibilities as well. The core areas NASA is examining are 3D printing in zero gravity, additive manufacturing that has already been installed and tested on the ISS as of 2016, a Multi-Material Fabrication Laboratory, a related multi-material electronics manufacturing capability, and the possibility of recycling printed products that are broken or beyond service life to be returned to a filament and reused as another printed item (Litkenhous, 2019). This is mentioned to demonstrate the scope and scale that NASA is pursuing additive production to see if these capabilities would be possible in reduced or zero gravity situations. Different materials have varied effects in microgravity, but as demonstrated in the 2014 study for fused filament fabrication (FFF) using plastic, zero (interplanetary flight) and reduced (Martian) gravity should not have a degrading effect for initial production of an item created with this method (Prater, et. al., 2018, p. 391-392). Long term environmental effects on items used, especially outside of an enclosed habitat, will need to be seen once long term facilities are able to be established.

Scientifically speaking, ISM is not the main challenge at this point. The technological capacity, to some extent, has been demonstrated along with continuing evaluation on the ISS (Prater, et. al., 2018, p. 413). From an economic standpoint, utilizing this technology leaves more questions than answers. Neil Leach argues that traditional FFF or additive supplies for printing are cost prohibitive to ship even to the Moon for a colony; he cites shipping an “ordinary brick”[1] with a cost of $2 million to the Moon (Leach, 2014, pg. 110). An approximate estimate from NASA is that it cost roughly $10,000 per pound to launch into Low Earth Orbit (LEO) (Calandrelli, 2016). Spencer Pitman, head of strategy for Made in Space, LLC, the company contracted for ISM capability on ISS, stated that the cost of print to order space production costs are between $6000 and $30,000 for a given item; discounts are available for STEM education groups in the current business model with NASA (Calandrelli, 2016). Those costs reflect the need for a LEO business model that requires it to remain financially solvent for a NASA contractor in offering what is a niche scientific novelty market where the item produced is returned to Earth. It not only reflects the shipping cost to ISS and production (materials, energy, time), but also having to put it into a vehicle that is designed to be recovered safely on returning. As there is an unlisted discount for STEM education, it shows that the at-cost production for non-returning items on a Martian colony would be considerably less (Calandrelli, 2016).

Leach (2014) argues that while Mars is more hospitable for FFF and additive production, the surface is still exposed to harsher conditions than found on Earth, limiting the effectiveness of that kind of production. In response, he goes on to argue for a hybrid of additive production using on-planet resources to create concrete that can then be extruded into a building or habitat that could potentially stand up better to the environment (Leach, 2014). This raises separate ethical questions as to the environmental impact that are not impossible to overcome, but may not be prudent for initial establishment of a colony on Mars and are outside of the scope of this research. However, it does reduce the potential total cost by limiting it to a single launch to deliver the system for constructing larger, permanent structures that will have longer duration in

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[1] This is assuming a size standard brick, 3⅝” x 2¼” x 8”, with an estimated weight of 4.5 pounds or just over 2 kg; Leach does not specify actual size in his article.

the space environment. Leach (2014) also is not addressing smaller scale production for commonly used tools and equipment that will be needed for daily use.

Data for launch costs are limited due to classification for government contracts as well as a desire to protect proprietary processes by most of the companies. However, there is some data for two companies that have launched missions to Mars. United Launch Alliance (ULA) provides one estimate for a Martian launch with their website to build a rocket (ULA RocketBuilder, 2018). A rough estimate for shipping 800 kilograms of filament and back up printers/supplies, comes out to $73 million for an Earth escape orbit to Mars, assuming use of the Atlas V rocket similar to what was done for the *Perseverance* rover.[2] For another similar estimate from a launch service, SpaceX can place 800 kilograms in LEO for $4 million[3] (SpaceX Rideshare). Both the ULA RocketBuilder and SpaceX rideshare had 800 kilograms as a common figure for projected estimations. However, LEO is not entirely comparable for cost. SpaceX has had two launches using the Falcon Heavy system that can serve as a guideline for the cost. The second SpaceX Falcon Heavy demonstration on April 11, 2019, launched Arabsat 6A satellite with a price tag of about $90 million for a reusable system (Brinkmann, 2019). That mission was headed for a geosynchronous orbit, but using the same rocket as the first demonstration flight of the Falcon Heavy. While no cost is listed, the first demonstration launched Elon Musk's Tesla Roadster in a heliocentric orbit around Mars (Gebhardt, 2018).[4] As these two companies have a demonstrated successful track record for reaching Mars with a

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[2] ULA search parameters: Year 2021 only option available; Quarter 4; East Coast Launch, Earth escape orbit; payload 800 kg with 4 meter short fairing; Signature service option; no additional customizations

[3] SpaceX does not yet offer an option on Rideshare for Earth escape orbits and has indicated plans for on-orbit refueling in LEO prior to departing Earth orbit for Mars on future missions. Search parameters: LEO orbit; proposed July 2023 launch; 800 kg.

[4] The Tesla Roadster does not have a published weight. Via a simple search, the unverified curb weight is 2,723 lbs as a possible point of reference. Which would equate to 1235.1 kg for the Falcon Heavy demonstration at $90 million price tag.

similar weight for the estimate, the pricing of $73 million and $90 million will serve as a baseline.

In the last ten years alone, the paradigm for long duration human spaceflight is shifting on a macro scale in concept. That is demonstrated by the varying recommendations in how to address some of the potential costs and problems associated with a mission like this to establish a presence on Mars. One thing that is missing in the body of literature overall is the cost benefit analysis of just-in-time logistics. The scientific aspects are well established following Made in Space, LLC's contract with NASA on ISS to understand the effects of microgravity on ISM capabilities for extended use.

To apply this technology in a practical way requires exploration of how to do so the same as logistics management done on Earth. A $90 million price tag may seem steep, but 800 kilograms is a significant amount of filament to sustain a colony on Mars for a long time in establishing a sustainable life there. At this point, it becomes a question of: how long can it sustain and how many people? NASA for publicly backed exploration and Elon Musk for private industry have both made it clear Mars is the goal within a matter of years. Answering the practical application of logistics support for non-perishable tools will be essential in taking that next step beyond Earth.

Research Method

Sample

The scope of this research is limited to a specific need in answering non-perishable logistics in advance of and during the initial establishment of a colony on another planet, specifically Mars. For this research, the sample is limited to a review of available historical data from previous space flights to other locations, such as the crewed lunar landings and non-crewed

Martian landings. Currently available cost averages, such as launch costs for Earth-to-Mars transit, 3-D printing capabilities, and limits of the available printing capacity will be analyzed. A potential influence on available data, is that companies who provide launch capability to the United States and other countries do not always release details on costs or payload weight due to classification or proprietary rights.

Measures

In interplanetary travel, weight is a key limitation of supporting establishment for even an exploratory colony on Mars. This research is a cursory look at what current, off the shelf technology could be utilized immediately to maximize a crewed colony flight to Mars without sacrificing supply support on arrival. Only those technologies that are currently able to be effectively utilized at low cost will be examined. This is to present objective data to determine if 3-D printing is a cost-effective measure to reduce a nine-month flight, under the best conditions, to a matter of hours while reducing the associated risks with launch windows, development delays, and cost overruns. Due proprietary cost information not being released publicly, observations were limited to open source literature from the United States government and private industry. During the analysis, validity was established through clustering of confirmed historic launch cost data, flight time, cost of 3-D printing equipment, and materials. Reliability of the analysis is generalized due to looking at unrelated resources with different public reporting requirements, the limitations listed, and the comparison to established literature.

Data Collection Procedures

All data collected is open source, from various reports and documents via the internet based on specific questions. No interviews or surveys of individuals were conducted in order to meet time constraints and ethics requirements. The questions presented are focused on specific aspects impacting space flight and colonization limitations to determine the cost benefit analysis of applying available emerging technology in an austere environment. The questions are:

1. What is the average cost-to-weight ratio for a non-crewed Martian launch?
2. What was the average cost-to-weight ratio for crewed lunar launches?
3. What is the current average cost-to-weight ratio for crewed low earth orbit (LEO) launches?
4. How long is the average trip from Earth to Mars on the short side of an orbit? How long is the average trip on the long side of the planetary orbit? What is the average two way signal transmission time?
5. Is there a static, increasing, or decreasing trend in cost of 3-D printing equipment and materials?
6. Are available 3-D printers able to withstand the entire sequence of spaceflight?
7. Will 3-D printers work in different gravity/atmosphere? Can they be calibrated for different planetary environments?
8. How much filament (in kilograms) would be required to adequately supply establishing a colony with tools and other implements with enough for an initial 10% replacement due to breaking or failure?
9. How many printers are needed, including to ensure redundancy in the event of damage, to supply a colony of 10-14 people?
10. What alternatives are there to on-planet production that are comparable?

Data Analysis

A descriptive analysis correlates the data based on operational and conceptual variables. First, it examines the cost-to-weight ratio benefits for 3-D printers as a payload for space flight systems to determine the direct economic impact. Second it will look at the subsequent benefits for reduced time along with adaptability based on specific need rather than anticipated need. This allows for further comprehensive examination while demonstrating the applicability for utilization.

Analysis and Discussion

Flight Cost Considerations

As mentioned previously, the two main companies with the proven rocket capability to reach Mars are ULA and SpaceX. Both have had launches using systems that can reach Mars with cost estimates listed, averaging between $73 million and $90 million respectively for the year 2021. Assuming both cost projections are fixed cost, a launch with 700 kilograms of ABS filament and 100 kilograms for two printers would cost $91,250 per kilogram for a lower cost launch (ULA, Atlas V) and $112,500 per kilogram on the higher cost launch (SpaceX, Falcon Heavy).[5] For comparison, SpaceX also advertises a $4 million fixed price for shipping to LEO, which amounts to $5000 per kilogram. ULA on the other hand, offers no difference in cost for launches to LEO on their RocketBuilder website, with a fixed price of $73 million, retaining the $91,250 per kilogram cost.[6] While other companies offer launch capability, from the available data launching to Mars appears to be limited primarily to two providers with known costs for the time being.

According to The Planetary Society, the *Apollo* missions including Project *Gemini* as part of research and development is estimated to have cost an actual $28 billion at the conclusion of the lunar flights in 1973 (“How Much did the Apollo Program Cost?”, n.d.). By their same estimate, when adjusted to 2020 for inflation, that would have cost an estimated $283 billion.

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[5] Projected fixed rates from ULA and SpaceX divided over 800 to reach the cost per kilogram per launch.

[6] ULA search parameters: Year 2021 option; Quarter 4; East Coast Launch, Low Earth orbit; payload 800 kg with 4 meter short fairing; Signature service option; no additional customizations

Without including *Gemini*, it comes to $269.2 billion. If looking only at the six successful Moon landings, then it cost $44.8 billion per mission.[7] With all 11 crewed missions (including Apollo 13), it reduces the cost to $24.4 billion per Apollo mission in 2020 dollar estimates. Without inflation in 1973 dollars, the six Moon landings would be $4.45 billion per mission; for the 11 crewed Apollo missions, it drops to $2.42 billion per flight. By comparison with the Falcon Heavy if it were certified to launch crews, at $90 million per launch, two separate crews of seven plus two separate logistics support launches for a *total* of four spacecraft (not including cost of payload or crew salaries and benefits) would cost $360 million dollars in 2021; a similar plan with ULA's estimated cost would be $292 million.[8] In returning to the 3-D printing supply, reducing the filament supply to 110 kilograms and 90 kilograms for two printers at 45 kilograms each would allow a reduction to one initial supply craft while still allowing 600 kg of other supplies to be shipped.[9] Two crewed missions and one supply support mission would cost $270 million for the launch and flight capability.

For the NASA *Perseverance* mission, being a non-crewed flight it was able to fly at around 24,600 miles per hour (39,600 kilometers per hour) during cruise flight to cover the 300 million mile (480 million kilometer) distance in about seven months ("Cruise", n.d.). As the most recent successful robotic mission to Mars, this provides a baseline of what the current technology can do in terms of time for supplying or re-supplying a colony on Mars. It also helps for a comparative look at the weight, with *Perseverance* weighing 1,025 kilograms ("Perseverance", 2020). The Planetary Society (2020) reports that the total cost however, as $2.725 billion, with a specific launch service cost from ULA on the Atlas V at $243 million; a

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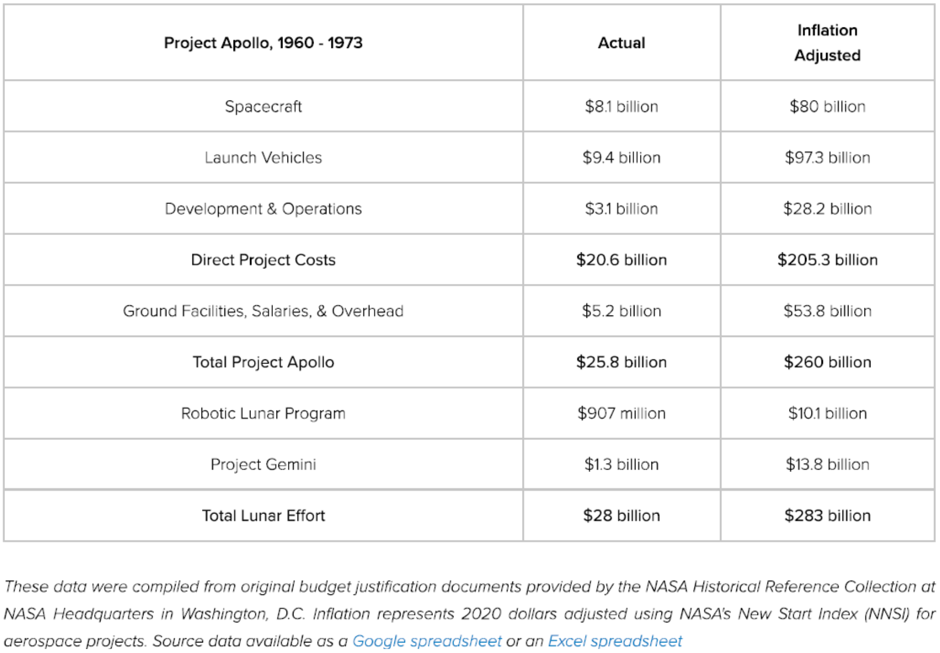
[7] *Apollo* missions minus *Gemini* costs; 11 total crewed, 6 moon landings; 2020 dollars: 283÷6 and 283÷6; 1973 dollars based on The Planetary Society cost table: 24.4÷6 and 24.4÷11

[8] Falcon Heavy with Dragon is estimate as discussed earlier, assuming flat rate similar to Falcon 9; 90 x 4 = 360; ULA with Orion spacecraft 73 x 4 = 292; two of the four are supply craft in each scenario.

[9] The ISS Additive Manufacturing Facility produced by Made In Space weighs 45kg per unit (User Guide, 2016).

significant difference from the $73 million estimate on the RocketBuilder website for an Earth escape orbit.[10] Even under the best circumstances such as SpaceX's Rideshare, a seven month transit flight to Mars can take three to six months prior planning prior to launch. Not requiring as much care to ship components and filament stock would probably reduce that further, however, that is not guaranteed. A three month planning session plus seven months under the best circumstances is still a 10 month delay between identifying the need and being able to deliver an item from Earth. For colonization, this alone becomes time prohibitive and potentially a massive risk to the safety of the crews on Mars. The average however is not seven months, but nine. This pushes it out to one year from planning to delivery on average.



Project Apollo, 1960 - 1973	**Actual**	**Inflation Adjusted**
Spacecraft	$8.1 billion	$80 billion
Launch Vehicles	$9.4 billion	$97.3 billion
Development & Operations	$3.1 billion	$28.2 billion
Direct Project Costs	**$20.6 billion**	**$205.3 billion**
Ground Facilities, Salaries, & Overhead	$5.2 billion	$53.8 billion
Total Project Apollo	**$25.8 billion**	**$260 billion**
Robotic Lunar Program	$907 million	$10.1 billion
Project Gemini	$1.3 billion	$13.8 billion
Total Lunar Effort	**$28 billion**	**$283 billion**

These data were compiled from original budget justification documents provided by the NASA Historical Reference Collection at NASA Headquarters in Washington, D.C. Inflation represents 2020 dollars adjusted using NASA's New Start Index (NNSI) for aerospace projects. Source data available as a Google spreadsheet or an Excel spreadsheet

Figure 1. The Planetary Society *Apollo* Mission cost and inflation comparison. Undated.

An additional flight consideration not yet discussed is the most limiting. Due to the orbital differences between Earth and Mars, launching for an orbit that bisects both orbits around

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[10] Of the estimated cost for *Perseverance*, $2.2 billion out of the $2.725 billion price tag was specifically for spacecraft development. Remaining costs beyond development and launch are $300 million for operations.

the Sun occurs every 26 months for present rocket technology (“How Long Would a Trip to Mars Take?”, n.d.). Potentially, this could extend the lead time for launching logistics support to three years depending on when a need is identified for something as simple as replacement parts to a habitat, tools, or equipment. “The typical time during Mars's closest approach to the Earth every 1.6 years is about 260 days” (“How Long Would a Trip to Mars Take?”, n.d.). This makes it even more challenging as that may not necessarily align with the window every 26 months. In terms of cost effectiveness, having a separate supply mission (or two) launch during the same bi-annual window as a crewed mission to supply humans on arrival provides the widest flexibility to ensure survival without having to rely on short notice requests. Returning to *Perseverance* as an example of current technological capability for comparison, the time of a signal transmission between Earth and Mars, depending on planetary alignment, is estimated to be between five and twenty minutes (“Communications”, n.d.).

Making (Radio) Waves

Speculating that similar or even the same radio technology is utilized for an initial human presence, *Perseverance* remains a good example to draw from. Three antennae provide the connectivity with Ultra-High Frequency (UHF), High Gain, and Low Gain X-Band that provide redundancy and accuracy (“Communications”, n.d.). UHF operates in the 400 megahertz range with a data rates of up to two megabits per second using a relay link where the transmission is sent from Earth to Mars via an orbiter, which allows reduced power usage for communications on the rover as it orbits Mars. For a rough example, a complex 3-D print file that is 40 megabytes formatted for a 3-D printer to utilize at the end of download with a webbing design to maintain structural integrity while conserving filament with a download speed of two megabits per second would take about three minutes (00:03:00) to download on Earth (Download Time, n.d.).[11] On the estimated shorter time, a transmission via UHF of a file using a similar system would take around eight minutes to leave Earth and be downlinked to a Martian base; approximately 23 minutes if the alignment is not as direct.

The two X-band antennae on *Perseverance* (high and low gain) both operate in the seven to eight gigahertz range to communicate directly with Earth via the Deep Space Network (DSN) ("Communications", n.d.). The high gain X-band antenna varies depending on which DSN transmitter it is receiving from in Spain. On the 112 foot DSN dish, it is a 500 bit per second receive rate; from the DSN 230 foot dish, it jumps to 3000 bits per second. Translated to the similar UHF rate, the downlink for information sent is a half a megabit (0.5 Mbit) per second and three megabits (3 Mbit) per second. For the download itself, that becomes approximately 11 minutes 30 seconds (00:11:30 at 500 bits per second) and about two minutes (00:02:00 at 3000 bits per second) respectively based on the times evaluated in figure 2 (Download Time, n.d.). Adding in the transmission time from Earth, transmitting a 40 megabyte file would be about 22 minutes (00:22:00) on the slow end and 10 minutes (00:10:00) on the fast end.[12] The low gain X-band antenna receives at 10 bits per second from the 112 foot DSN dish while receiving at 30 bits per second from the 230 foot dish ("Communications", n.d.). A 40 megabyte file sent from the 230 foot dish would take about three hours ten minutes to download (3:10:00), plus the 5 to 20 minute transmission time from Earth (Download Time, n.d.). The time for a transmission from the 112 foot DSN dish was not calculated for this research.

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[11] Constants are 40 MB file for complexity, plus the longest and shortest transmission time averages drawn from NASA to get a possible range for sending a file one way for printing. Reference file is at: https://www.thingiverse.com/thing:2894267/files as "Catan.stl". The original file is 1 MB of data; the 40 MB represents the "sliced" format that is readable by a printer for executing the print directly.

[12] Times are approximate from interpolating from Download Time result table, plus adding the time it takes for a signal to reach from Earth to Mars one way as discussed in the UHF section.

Modem - Also known as: Dialed-up Internet

ADSL - A form of DSL(Digital Subscriber Line). ADSL stands for Assymetric DSL.

LAN - Local Area Network. Ethernet is one form of this.

Turbo 3G - Third generation mobile interface

4G - Fourth generation mobile interface

Broadband means a download speed of at least 256 kbit/s.

1 byte = 8 bits, which means that if the download speed is 1 Mbit/s then you can download 0,125 MB/s.

File size 40 ○KB ●MB ○GB

Connection type	Download speed	Download time
Modem	28,8 kbit/s	**03:14:10**
Modem	56,6 kbit/s	**01:39:51**
ADSL	256 kbit/s	**00:21:50**
ADSL	512 kbit/s	**00:10:55**
ADSL	1 Mbit/s	**00:05:35**
ADSL	2 Mbit/s	**00:02:47**
ADSL	8 Mbit/s	**00:00:41**
ADSL	24 Mbit/s	**00:00:13**
LAN	10 Mbit/s	**00:00:33**
LAN	100 Mbit/s	**00:00:03**
Turbo 3G	7,2 Mbit/s	**00:00:46**
4G	80 Mbit/s	**00:00:04**
5G	1 Gbit/s	**00:00:00**

Own Speed Own Spee ○kbit/s ●Mbit/s ○Gbit/s

The calculations for download time are purely theoretical. It's rare that its possible to use the entire bandwidth for the download. Also, it is possible that you don't have the bandwidth that you are paying for. Please do a bandwidth test so that you will know what your download speed truly is. Speedtest.net Afterwards you can enter that download speed as "Own configuration" and do a new calculation of download speed.

download-time.com © 2021 Email:webmaster

Figure 2. Download Time results for 40MB file in relation to the *Perseverance* speeds; this data rate table was generated April 18, 2021. Undated.

For the example file at 40 megabytes, on Earth it takes about 18 hours 30 minutes (18:30:00) to print in PLA.[13] Even with the slowest signal transmission, DSN 230 foot dish to low gain X-band, of three hours 30 minutes (3:30:00) means that from sending the signal to having the component or part completed on Mars would be around 22 hours. If it is a repeat part already in the files accessible to the printer without the need for a download time that can be executed by a support controller on Earth, it reduces the time back to the printed time of the file. Conversely, a file requiring crew involvement such as slicing or unexpected errors or printer failures such as replacing the nozzle, would add time. Smaller files, such as the original example file at one megabyte, would transmit faster and can be manipulated by the colony crew on site prior to printing. The transmission time tradeoff for a faster signal download would be on the backend with the crew. That is not inherently a problem as sliced print files are generally locked depending on the programming used, whereas something in a file format of ".stl" can still be

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[13] Print estimate time based on Ultimaker Cura software for a 0.15mm extrusion, wall thickness of 1mm, 10% infill with grid pattern, extruding at 220° C to a heated bed of 60° C at a speed of 60mm/second. Generic printer settings for Prusa i3 used in the software.

manipulated and adjusted. Having that option may vary depending on the specific scenario needed and determined by the colony crew.

If the file is pre-formatted in a way that it can print immediately for remote operation by Earth based controllers, such as during sleeping hours for the Mars crews, then these times can serve as a baseline to compare with shipping pre-made components from Earth. Additionally, not being constrained by the launch window or transit time for a spacecraft enables flexibility not otherwise available. For the cost estimate, looking at if print files were being sent beginning at the time of research, for the remainder of 2021 it would cost $1,353,274; for 2022 to 2024 it would cost $1,901,900 per year to enable regular communication with Mars (DSN Aperture Fee Calculator, n.d.).[14] That has a breakdown of $158,492 per month, or $211.33 per hour.[15] This results in the three hour and 30 minute (3:30:00) transmission to the low gain X-band antenna costing $739.62; for the high gain X-band antenna via the 230 DSN dish would cost $35.30 to send a file that is ready for printing.[16] While it could be estimated as a recurring cost for mission budgeting, each transmission will possibly also only be a one-time non-recurring cost depending on the part and if the crew retains it on site in a database locally.

Transmissions like these probably would be included as part of a larger persistent communications package between Earth ground controllers and a Mars colony crew if the DSN is utilized under contract. A dedicated relay link system similar to the UHF for *Perseverance* would likely reduce costs further as it is part of the non-recurring costs of establishing two crews

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[14] DSN Aperture Fee Calculator inputs for reference; Service Editor: X-band, D/L only, 70 and 34 meter, Relay option, 15 minute set up, 30 minute tear down; Events Editor: User: "MarsBase", Description: "Research for communications with a crewed colony on Mars", Time Range input: Weeks, Range Start Year: 2021, Range End year: 2024, Range Start week #: 16, Range End week #: 52, UTC start and end times (Auto defined); Request Editor: User/Name: "MarsBase", Alias & Alias Filters: X D/L only Relay 70m & 34m, Type: Repeated Daily Pattern Track, Duration: 2 hours, Number per Day: 2

[15] Cost for Years 2022 to 2024 divided over 12 for the monthly cost; Monthly cost divided over 750 hours in a month for the hourly cost.

[16] Low gain: Hourly cost x estimated time of transmission; High gain: (Hourly cost/60) x time of transmission

on Mars. As systems like the *Perseverence* orbiter are already in place and may continue to be utilized for similar communications relays, this could also be factored in if the mission life is extended beyond the original intended operational period, in order to support a colony, as seen with other programs like *Spirit* and *Opportunity*. The UHF cost per transmission was not available for research from the *Perseverance* mission for analysis and is not included; the technology though is a distinct possibility providing a reliable form of contact that reduces end user power for conservation. With similar systems adding intermediate relay orbiting and on the Moon's surface, it will further reduce vital power consumption while increasing reliability between Earth and Mars.

Forecasting Essentials

Something that is possible may not always be practical. Trying to forecast the need for parts, components, tools, and even comfort items for an initial colony on another planet may prove to be like a person trying to hit the bull's eye on a moving target over their shoulder while blindfolded. Accurate logistics forecasting would be entirely based on knowing how many people are being supported and for how long. A permanent presence will look considerably different than an initial one to two year establishment with the intent of sending more crews later. Two crews of up to 14 people would be easier than added crews joining and remaining; replacing would keep the logistics support consistent. Until those questions are definitively answered, projecting what tools are needed will remain a hypothetical at best. Having the ability to better adapt to the needs of crews through additive production, even when those questions are resolved, will help sustain operations on Mars.

Instead of attempting to guess what tools crews and mission planners may decide in the planning phase what they would need, this research takes a two-pronged approach. Having some pre-fabricated items onboard the landing module and accessible during cruise flight, such as screw drivers, will be essential for the first colony crews. Additionally, taking a 3-D printer aboard along with a limited supply of filament would also allow flexibility during flight and on initial landing to be able to produce tools and equipment immediately without having to set up anything additional before establishing a permanent habitable space on the surface. On landing, having the supply craft there would then allow access to the larger supply of filament, replacement parts such as nozzles, and either additional printing capacity or reserve capacity in the event of failure for the printers that travelled with the crews. With that same concept, if the printers fail on the supply ships during initial operational testing after arrival, then the printers brought with the crews will remain functional to provide on-site production. Despite reduced printing capacity, loss or damage of any or some of printers would not cause an end to the mission. Even if all were damaged to the point of being unusable, with enough surviving and supplied replacement parts that can be exchanged between them, another one could be reconstructed on Mars for use.

The ISS Additive Manufacturing Facility (AMF) technology produced by Made In Space, Inc could serve as the basis for 3-D printing both in cruise flight and on landing. The AMF has successfully been on the ISS since 2016 working to support both the station crew and for commercial or research requests. This is currently the only proven and regularly used additive manufacturing capability shown to be able to function in space with a specific design for surviving launch. The concept version, also built by Made In Space, flew in 2014 and was the subject of extensive testing. When samples were returned to Earth for review, it was determined that differences due to human action caused the largest variations, not microgravity. “Overall, scanning electron microscopy (SEM) analysis was not indicative of a microgravity effect on material structure, as both ground and flight specimens from phase I exhibited “filament slump” (i.e., the filament sagging under its own weight during manufacturing)” (Prater, et. al., 2018, p. 393). When compared with phase II prints from a year and a half later, it confirmed the hypothesis that there was no significant difference between the in orbit print tests and the Earth based testing from prior to launch. “Since voids are detected in all specimen sets and there does not appear to be a clear, discernable trend in the size or frequency of voids among specimens, their presence cannot be definitively attributed to operation of the fused filament fabrication (FFF) process in the microgravity environment” (Prater, et. al., 2018, p. 401). This demonstrates that since 3-D printing can be calibrated and operated in microgravity, then it can also be adjusted for reduced gravity on Mars.

Both the 2014 test system with the subsequent and sustained AMF system that remains in use since 2016 (currently five years), 3-D printers similar to the AMF can survive the journey. That is regardless of whether it is a printer in use by the crew in transit or stored in the supply craft. As long as it survives entry to the Martian atmosphere and landing, this would not pose any significant problems to set up or employ on the arrival of the crews. The AMF uses acrylonitrile butadiene styrene (ABS) filament as the primary medium (User Guide, 2016). ABS is a common filament for 3-D printing on Earth, meaning that it is inexpensive and obtainable from commercial sources off the shelf. Since it is so commonly utilized, there is a large body of data to draw from with the 3-D printing community on Earth. “As a thermoplastic polymer, ABS melts and cools without altering its chemical properties. That makes it an interesting 3D printer filament, even more considering the relatively low temperatures required for melting” (Carolo, 2021). Having a material that retains the chemical properties through the heating, extruding, and cooling process means that there will be consistency without degradation over multiple or longer prints. For retail cost, ABS currently costs about $20 per kilogram on Amazon.[17] Even on the upper end of a supply mission with 800 kilograms of filament supply, it would cost an estimated $16,000 going through retail sources.

Since the AMF contract for NASA with Made In Space is proprietary, a cost analysis was not able to be completed during this research. However, the AMF User Guide (2016) does list a nominal resolution size of 0.15 millimeters with an extruder that can be heated between 180°C-375°C and a heated bed. Most of the other technical specifications match common Earth based 3-D printers, meaning most of the components are easily obtainable from commercial sources. For example, nozzles last roughly three to six months depending on usage. Replacement nozzles of 1.75 millimeters by 0.15 millimeters cost about $18 per nozzle on the retailer MatterHackers.[18] Since 1.75 millimeters is a common input size for where the filament goes in from the extruder, this seems the most likely size with the 0.15 millimeter at the printing end to be what would be utilized. Running at $18 per nozzle, and each nozzle needs to be replaced every three to six months, that is about 12 nozzles for the first three years for one printer assuming a three month replacement rate, depending on when the first resupply mission can be launched after 26 months. To support four printer systems, that would be 48 nozzles (one per crewed mission and two on the supply craft). Adding in ten percent for overage, would put it at a stock of 53 nozzles; at $18 per nozzle, that would cost $954 for the initial colonization.

As Made In Space's AMF is the only proven and utilized NASA contractor for small scale additive manufacturing in flight for the time being, a cost trend analysis is not possible at this time. While that may be the case, estimating the cost of technology from similar Earth based

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[17] Simple Google search for "ABS filament", selected Amazon for reference. URL: https://www.amazon.com/ABS-filament/s?k=ABS+filament

[18] Google search for "0.15mm nozzle 3D printer", returned result for MatterHackers. URL: https://www.matterhackers.com/store/l/e3d-v6-extra-nozzle-175-x-015/sk/MCHGCDFV

hardware can be developed. Looking at the historical trend between the introduction and 2016 has seen a significant decrease in price for reliable printers on the market. “Back then [1987] it would cost you somewhere in the vicinity of $300k to purchase one. How does that translate to 2016? Well, accounting for total inflation of 116%, that $300k printer would cost nearly $650k today. So it wasn’t really an inexpensive hobby that people were investing in. Up until 5 years ago, the average cost of a 3D printer was floating around the $50k mark. But, due to consumerism and an increase in demand and, subsequently, production, you can now purchase a respectable 3D printer for the substantially lower cost of $1800” (Miller, 2016).

Figure 3. Additive Manufacturing Facility module that is currently installed on the ISS. 2016.

This means from this kind of technology being introduced to the market until 2011 it saw a price decrease of $600,000, with an acceleration of the decrease to $1800 in the five years after that. “Just like every other industry under the sun, the 3D printing industry is affected by the trend of more, faster and for less. It’s the modern matter of cost versus convenience” (Miller, 2016). This is still holding true in 2021; for reference, producer Prusa lists the flagship consumer i3 Mark 3S+ kit and pre-assembled printers at $749 and $999 respectively that can print from two reels or more of filament.[19] With the trend of inflation for prices being expected, this shows that the proliferation of the technology to homes and individual consumers that the trend Miller mentions has put downward pressure on the market. That market may be stabilizing as the reduction of price is not as drastic as even the 2011 to 2016 period compared to the 2021 pricing.

With a colony of 14 crew, four printers is one printer for every three and a half people. The one AMF unit on board the ISS has been supporting average crews of six since 2016 without failure. However, there is no public data available with regard to how often that is supported by resupply from Earth for things like filament, nozzles, or other replacement parts. The User Guide (2016) does state that it is designed to support ISS functions and missions for the remainder of the life of the station, estimated through 2024, which would give the AMF an eight year lifespan. Three years on Mars with each printer supporting roughly half the people the current one does would seem optimum. Being that a system like that has not been tested with dust and atmospheric conditions (less than optimum) on Mars, it remains unknown how long components will last. If Martian soil is like lunar dust was to the *Apollo* astronaut's suits, it would most likely shorten the lifespan of components and printing capability. Carolo (2021) states regarding the use of ABS, "ABS is UV sensitive, so it can sustain damage by direct sunlight. For this reason, it's not really recommended to print outdoor parts with ABS." Since Mars has a thinner atmosphere, parts used for the exterior of a habitat would also face degraded lifecycles requiring regular replacement due to ultraviolet exposure. With the unknown elements of how Martian weather will affect the plastic over time, it is difficult to project the lifecycle until further testing is done.

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[19] Prusa retail URL: https://www.prusa3d.com/original-prusa-i3-mk3/

Alternative Routes

Due to the challenges of interplanetary travel to Mars, alternatives are limited. The main one is having to project for all possible scenarios and carry possibly unnecessary equipment, tools, or parts along with the crew or on separate supply missions. Considering the 26 month window gap, this could be impossible if something goes wrong or the shipment is lost in transit (such as from a space debris impact). Another alternative is *in situ* resourcing for available materials on Mars. While not impossible as the iron content is so high, it would require sending equipment ahead to mine the materials first through robotics to have an adequate supply on arrival. The same would apply with silicates; while those have been noted there, the infrastructure to collect and refine them into plastics or other usable materials would be difficult without a human presence. Leach (2014) raises good points about concrete 3-D printing for habitat building, but that does not account for small scale needs. In effect, this creates a “chicken and egg” scenario to determine whether having a human presence on the planet is needed first to develop the resources. While robots are reliable for some tasks, this level of performance remains beyond the current scope of what most can handle. Adding in a different planet and communications delay of up to 20 minutes could be disastrous in trying to build stocks for supplying crews before arrival. Even with robotic artificial intelligence operating independently for sustained periods of time, it presents different risks that need to be examined separately as an alternative for utilizing local resources on Mars.

Recommendations

While the technology has been demonstrated as capable on the ISS, it remains an emerging technology with questions that remain to be answered. For flight, the Falcon Heavy only has had three flights; despite all three being successful, there are always limits to systems that have yet to be seen. With ULA, despite efforts like RocketBuilder, their transparency remains a lot to be desired for enabling successful missions and prices. That may seem like a minor problem from a research standpoint. But that allows opportunity for mission creep to steadily increase pricing for launch services that could delay or cancel missions altogether due to becoming cost prohibitive.

For NASA and private entities to move forward with establishing a presence on Mars, the first step would be defining the ideal colony crew sizes within the limits of the current technology. From that, everything else can fall into place. As *Orion* and *Dragon* both have capacity over five people, two crews appears to be an ideal size for long term for the initial settlement of Mars. To best support those crews, two separate supply missions launched during the same bi-annual window would ensure survival during the first three years on Mars until replacements and resupply can arrive. With providing crews the flexibility through additive manufacturing, $16,954 for 800 kilograms of raw materials and the most common part requiring replacement is a cost effective way to support logistics on planet without losing quality. One thing to consider that was not looked at is alternative filament stock. Anecdotally, there are plastic (ABS, PLA, etc) filaments with metal incorporated to it. On printing, it can be placed in an oven at over 450^{o} F where the plastic cooks out and the metal remains bound in a solid piece. This may not yet be mature enough yet for practical use but should be considered in further research and testing for limitations.

The downside to this possibility is that the metal in the filament tends to wear out nozzles faster. However, rate of degradation and lifecycle length have not been studied with these types of filaments. Other forms of additive printing, including metal and concrete on larger scales have been developed. Leach’s (2014) idea that *in situ* resources can help with larger scale production is something that should be pursued. For smaller scale printing from metal stock, the drawback in terms of weight for launch cost and size are prohibitive enough that it has not yet been tested in space, but should also be explored moving forward. If flat rate launch costs are possible, then it may open this type of printing as a possibility if the raw stock material is inexpensive to send. With only plastic based stocks having been tested in space, this limits other materials until they can be shown to retain the chemical and physical properties through the extrusion process.

Another area that needs to be considered for added research and expansion is with the demonstrated technology of the AMF. The User Guide (2016) lists a print volume in millimeters of 140 (Length) x 100 (Width) x 100 (Height), or 5.5 inches x 3.9 inches x 3.9 inches. These are incredibly small pieces as prints must remain within that configuration. While size will always be limited, the Prusa i3 mentioned previously can print pieces in sizes up to 9.84 inches x 8.3 inches x 8.3 inches, nearly double the size of the AMF (Prusa, n.d.). For longer duration missions, the printing size will need to be larger for components, parts, dishes, tools, medical support instruments like casts for broken bones, or anything else a crew might need to produce with time constraints. Retaining such a small volume would extend a print out longer as it has to be constructed from smaller parts and may also degrade the structural integrity as it is not in a single completed product from the manufacturing process.

Figure 4. AMF module with door open demonstrating volume size. The door seals when shut to prevent hazardous fumes from escaping into the station during printing. 2016.

The final area not addressed that needs further research is the long term lifecycle of items produced using this technology. Reuse and recycling will be the most efficient way to return the filament to a stock state through grinding or melting with an extruder that can return it to wire form. While this is possible, it has not yet been tested on a large scale with continued use. Plastics as well have limitations on life for reuse through reheating to return it to a stock state for reuse in other products. How many cycles that can go through is not yet known, especially if there has been any sustained ultraviolet or radiation exposure as well as the dust content if it has been outside of the habitat facility. It may result in some things being single use plastic items that cannot be reused due to safety reasons where the Martian dust would alter the chemical composition during the recycling process. Only testing under conditions similar to what will be found on Mars, like the testing done for printing on the ISS for initial print results, will determine if this kind of logistics support is viable.

Conclusion

No technology is ever fully perfect, especially if it continues evolving in ways that can better support humanity in adapting to new situations. To mount a hypothetical mission, a four launch mission without accounting for salaries or the cost of perishable supplies (assuming those are launched with one of the supply missions, the launch cost is covered), with flat rate non-recurring launch services and utilizing a three year contract with the Deep Space Network for communications, establishing a colony would cost an estimated $385,722,654 to include being able to sustain logistics for non-perishable goods for a three year period. It is understood however that this is a raw estimate which is not entirely reflective of actual prices due to inaccessible proprietary cost information. For example, four launches could be seen as a recurring cost along with the cost of future resupply missions that due to quantity of supply on the launch service side could drive prices down. Conversely, the fact that the AMF is the only printer currently providing this technology in space would require development for larger systems that will increase costs substantially to account for conditions on Mars.

From a logistics and pricing standpoint, 3-D printing appears to provide the most flexibility due to the fact that every piece is custom made to order on demand. By utilizing an additive manufacturing system where the raw materials are able to be sent at a flat rate, a cost of $90 million to ship 800 kilograms of materials and printers keeps the cost at a set rate. Additionally, by providing that payload via a separate supply or resupply flight offsets that weight from crewed missions, allowing more to be carried with the crews to meet survival needs. ABS filament has shown that it can be used in production under less than ideal conditions is a good place to start examining for cost planning on future missions as was shown in the *Printing in Zero G* demonstrated (Prater, et. al., 2018). "…work performed under the ISM umbrella may serve to accelerate the shift from traditional earth-dependent approaches to logistics for long-duration crewed missions to a space where manufacturing systems operated inside the crew habitat provide spares on-demand, enable adaptive and rapid response to unforeseen operational scenarios, and facilitate the use and repurposing of nuisance materials (such as trash recyclables)" (Prater, et. al., 2018, p. 414-415). Moving forward, in parallel to the technological development, the examination of practical application along with cost impacts need to be more widely discussed. That is what will move 3-D printing out of the theoretical and into the practical for enabling long duration missions for the next steps beyond Earth.

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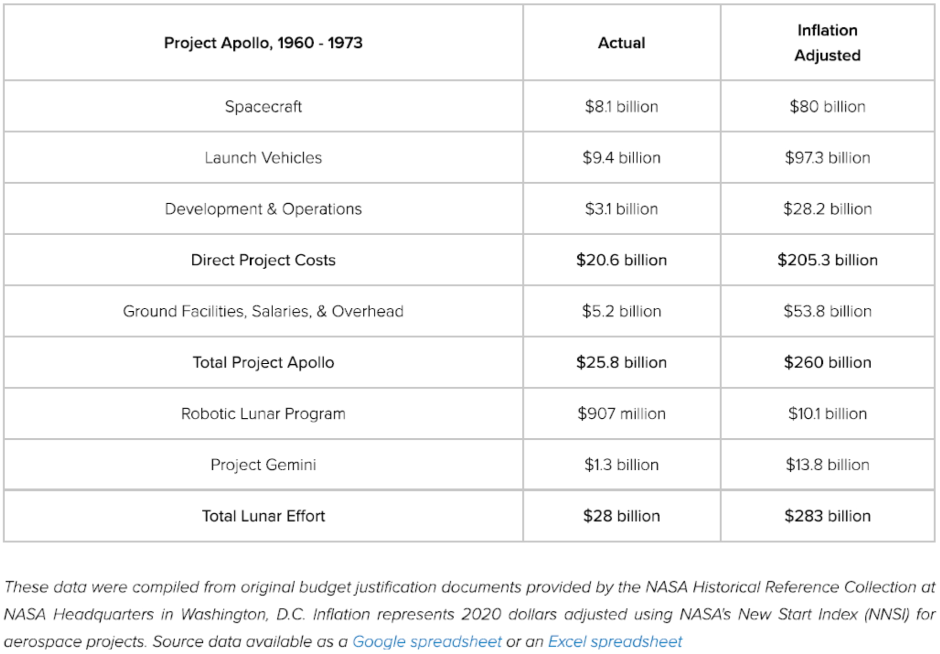
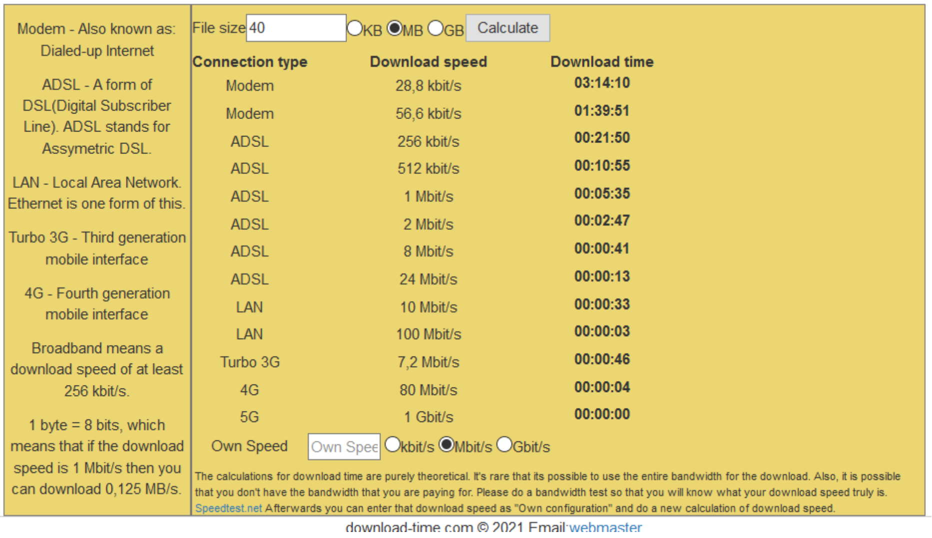
Figures



Project Apollo, 1960 - 1973	Actual	Inflation Adjusted
Spacecraft	$8.1 billion	$80 billion
Launch Vehicles	$9.4 billion	$97.3 billion
Development & Operations	$3.1 billion	$28.2 billion
Direct Project Costs	**$20.6 billion**	**$205.3 billion**
Ground Facilities, Salaries, & Overhead	$5.2 billion	$53.8 billion
Total Project Apollo	**$25.8 billion**	**$260 billion**
Robotic Lunar Program	$907 million	$10.1 billion
Project Gemini	$1.3 billion	$13.8 billion
Total Lunar Effort	**$28 billion**	**$283 billion**

These data were compiled from original budget justification documents provided by the NASA Historical Reference Collection at NASA Headquarters in Washington, D.C. Inflation represents 2020 dollars adjusted using NASA's New Start Index (NNSI) for aerospace projects. Source data available as a Google spreadsheet or an Excel spreadsheet

Figure 1. The Planetary Society *Apollo* Mission cost and inflation comparison. Undated.



Modem - Also known as: Dialed-up Internet

ADSL - A form of DSL(Digital Subscriber Line). ADSL stands for Assymetric DSL.

LAN - Local Area Network. Ethernet is one form of this.

Turbo 3G - Third generation mobile interface

4G - Fourth generation mobile interface

Broadband means a download speed of at least 256 kbit/s.

1 byte = 8 bits, which means that if the download speed is 1 Mbit/s then you can download 0,125 MB/s.

File size 40 ○KB ●MB ○GB Calculate

Connection type	Download speed	Download time
Modem	28,8 kbit/s	**03:14:10**
Modem	56,6 kbit/s	**01:39:51**
ADSL	256 kbit/s	**00:21:50**
ADSL	512 kbit/s	**00:10:55**
ADSL	1 Mbit/s	**00:05:35**
ADSL	2 Mbit/s	**00:02:47**
ADSL	8 Mbit/s	**00:00:41**
ADSL	24 Mbit/s	**00:00:13**
LAN	10 Mbit/s	**00:00:33**
LAN	100 Mbit/s	**00:00:03**
Turbo 3G	7,2 Mbit/s	**00:00:46**
4G	80 Mbit/s	**00:00:04**
5G	1 Gbit/s	**00:00:00**

Own Speed ○kbit/s ●Mbit/s ○Gbit/s

The calculations for download time are purely theoretical. It's rare that its possible to use the entire bandwidth for the download. Also, it is possible that you don't have the bandwidth that you are paying for. Please do a bandwidth test so that you will know what your download speed truly is. Speedtest.net Afterwards you can enter that download speed as "Own configuration" and do a new calculation of download speed.

download-time.com © 2021 Email:webmaster

Figure 2. Download Time results for 40MB file in relation to the *Perseverance* speeds; this data rate table was generated April 18, 2021. Undated.

Figures (Continued)

Figure 3. Additive Manufacturing Facility module that is currently installed on the ISS. 2016.

Figure 4. AMF module with door open demonstrating volume size. The door seals when shut to prevent hazardous fumes from escaping into the station during printing. 2016.