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In-Space Economy in 2023 - Statistical Overview and Trends

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Abstract

A new in-space economy is emerging, with the nascent industries including orbital transfer vehicles, commercial space stations, in-space manufacturing, satellite servicing, commercial rovers, and many more.

Factories in Space is the most extensive online database of commercial entities operating in the in-space economy, space resources, and in-space manufacturing sectors. Launched in 2018, the directory includes 825 entries, more than double from the previous version presented at IAC in 2021. Seraphim recently published their version of the in-space economy ecosystem map, further indicating growth and interest in this field.

The first part of the paper will update the definition of the in-space economy, including its classification and glossary. There continues to be a great deal of variation in how these new space industries are grouped and defined, making it more challenging to determine competitors and estimate market sizes.

The second part of the paper will present an updated statistical overview of the companies that are currently active or aspire to be active in the emerging in-space economy. Within each classification, a comparison will be made between the development status, geographical distribution, and funding. Based on a previous publication from 2021, some trends and space market booms are apparent. For instance, microgravity flight services and re-entry capsules appear to experience a proliferation, more space tugs are being announced, and space-based solar power has become an active topic. Redwire announced a crystal grown in space as their first microgravity-manufactured product to be sold, and ispace launched the first commercial lunar lander. However, while the number of startups in the new space economy is rapidly increasing, only a few new services have been demonstrated in space.

The third section delves deeper into selected markets. Despite a proliferation of startups in these sectors, revenues appear to be growing at a slower pace. Market analyses, including those focused on in-space transportation, satellite servicing, and space stations, have been published, and the paper will examine the estimates made. It is worth noting that the number of companies operating in these markets may not necessarily correlate with the market opportunity, and there may be signs of new market bubbles forming.

Comprehensive analytical overviews and taxonomies for the emerging in-space economy continue to be rare as far as the author knows. The aim of this study is to conduct a thorough industry survey and analyse the developments in this dynamic in-space economy field bi-annually to leave snapshots.

Keywords: in-space economy, space-based economy, beyond-Earth space economy, on-orbit economy, cislunar economy, in-space manufacturing

1. INTRODUCTION

Factories in Space has tracked new in-space economy entities since 2018. This paper is an updated and improved survey and a statistical overview about the commercial organisations in the in-space economy from 2021 by the author.[1]

There are 825 entries in this study and in the database as of August 2023, likely making it the largest public database. This is over double compared to the 472 entries in the 2021 study.[1] Number of unique companies is about 755 because some have multiple entries due to being active in separate fields according to the taxonomy presented here.

In-space economy is the new extraterrestrial space industries.[2] In-space economy means generating revenue in space using assets in orbit or beyond Earth. Sometimes called as space-based economy and in narrower definitions on-orbit economy, space-for-space economy, low Earth orbit economy, beyond-Earth space economy. It also encompasses cislunar economy, Moon and Mars. M. Weinzierl and M. Sarang called it as space-for-space economy and defined it as goods and services produced in space for use in space, such as mining the Moon or asteroids for material with which to construct in-space habitats or supply refuelling depots.[3] For clar-

ity, excluding satellite constellations for terrestrial purposes and Earth-to-space launch vehicles.

New in-space economy entails space stations, commercial landers, in-space manufacturing, and much more. Fields that often started emerging commercially in the 2000s and generally have had small revenues. New space economy and specifically in-space economy terms were formed to distinct the new areas and to be able to follow them without existing large space industries inflating the numbers.

Literature reviews have been performed and studies about the broader new in-space economy continue to be relatively sparse. The previous study from 2 years ago includes a longer literature review for older publications and also includes estimations about the size of space economy. In case of interest, please see that survey from IAC 2021 to avoid duplication.[1] Broad studies may be rare but writings about more specialized in-space economy industries are becoming much more common.

Since 2021, the author has published a survey on In-Space Manufacturing commercial entities at IAC 2022.[4] The author also presented the history and future vision of semiconductor manufacturing in microgravity at Stanford University in March 2023.[5] For Space Resources Week 2023, the author created a poster titled "Enabling Infrastructure Ecosystem for Space Resources".[6]

H. Shipman's book "Space 2000: Meeting the Challenge of a New Era" was published in 1987 and covers many early in-space economy and in-space manufacturing activities and ventures.[7]

Seraphim Space published their In-Space Economy Ecosystem Map 2023 in February.[8] ESA's The Business in Space Growth Network published Low Earth Orbit Value Chain[9] in August 2023. Chad Anderson, founder of Space Capital, published a book called The Space Economy in 2023.[10] The classifications of industries continue to be different and there is more work to do to align them.

U.S. national security space organizations released a report in November 2021 "State of the Space Industrial Base 2021", which noted that there is too much emphasis and investment in launch, but too little capital going into other sectors of the industry such as in-space logistics and manufacturing that will be essential to build a space economy.[11]

Moon Village Association published "The Lunar Commerce Portfolio" in November 2022.[12] Munich Re Ventures published blog post "In Space for Space: The Next Wave of the Space Economy Needs "Picks and Shovels" in Jan 2023.[13] Philip T. Metzger published a paper on "Economics of in-space industry and competitiveness of lunar-derived rocket propellant" with the latest revision in February 2023.[14]

DARPA announced a 10-Year Lunar Architecture (LunA-10) project in August 2023, seeking ideas from potential developers of lunar power, communications, navigation, and other infrastructure as well as users. Plan is to select a group to work together on new integrated system-level solutions that span multiple services and be commercially available by 2035. The study will also define a commercial end state for lunar infrastructure in 10 years, where there would be self-sufficient lunar economy, from which it would be possible to work backwards to identify and solve technology and economics gaps.[15]

J. Foust published an article discussing ZBLAN and space station markets titled "Manufacturing a low Earth orbit economy" in September 2022.[16]

K. Madasamy published an article in January 2023 about space economy being here to stay and also discussed manufacturing in space and lunar economy. They quoted Ronald Reagan's 1985 State of the Union speech and him describing how manufacturing in space could enable technological breakthroughs in supercomputers and medicine. They also quoted McKinsey, which found that the number of patents mentioning "microgravity" increased from 21 in 2000 to 155 in 2020.[17]

We continue to need new economic drivers for spaceflight. Something new and potentially larger than any existing space industry, such as telecommunications, remote sensing, launch and research. The following supporting macro trends for in-space economy are ongoing:

- Decreasing launch costs. Now about 2-3 times less according to P. Lionnet,[18] but potentially 10-100 times lower in the future, e.g. Starship.
- Commercialization of space and LEO.
- Commercial services and infrastructure.
- ISRU and space resources advancements.
- Pollution and climate change on Earth.
- Increasing momentum for space settlements.
- NewSpace iterative mindsets and affinity for bolder risks, also from long-term investors.

First part of this paper defines taxonomy for the organisations in space-based economy to be able to group them. Second part presents statistical overview of the 825 surveyed in-space economy entities. Third part of the paper takes a deep-dive into some of the new in-space economy markets.

2. RISE OF NEW IN-SPACE ECONOMY

Here follows a non-exhaustive chronological overview of some of the latest advances and companies in the in-space economy fields.

2.1 Commercial Space Stations

Space Industries Incorporated was founded in the early 1980s and planned to develop a commercial space facility called the Industrial Space Facility (ISF) to be launched in the early 1990s. Reagan administration agreed to become an anchor customer with up to $700 million in funding, but the request was not approved by the US Congress.[19,20]

Bigelow Aerospace was founded in 1999 to develop expandable orbital station modules. The first free-flying technology demonstrator Genesis I was launched in 2006 and Genesis II in 2007.[21] BEAM module was launched to the ISS in 2016 under a $17.8 million NASA contract[22] and is still attached. Bigelow has developed numerous designs for large commercial space stations, space hotels and lunar bases including the BA330 and BA 2100.[21] In early 2020, SpaceNews reported that Bigelow decided not to pursue NASA competition for a commercial ISS module because of funding concerns.[23] In March 2020, Bigelow laid off all employees and it is unknown whether activities will resume.[24]

Private and cost-effective human spaceflight has always been a challenge for space stations and a relatively large expense in general. Once SpaceX demonstrated crewed flight in May 2020 (Demo-2) and NASA started seeking commercial International Space Station (ISS) modules in June 2019,[25] Bigelow seems to have been unable to take advantage of the finally positive trends and emerging ecosystem, after 20 years and well over $250 million invested.[26]

In 2007, Galactic Suite Project was announced, which planned luxury orbital getaways by 2012.[27]

In 2010, Russian company Orbital Technologies announced Commercial Space Station to be launched in 2015 in partnership with RSC Energia.[28]

Axiom Space was founded in 2016 and had raised over $150 million by 2021.[29] In early 2020, NASA awarded Axiom the NextSTEP contract for the first commercial ISS module.[30] The construction of the first two modules was contracted to Thales Alenia and was planned to be launched in 2024 and 2025.[31] The modules will be separated into a free-flying commercial orbital platform before the ISS is deorbited.

Orion Span was founded in 2017, but fell short of their $2M crowdfunding campaign in early 2019.[32]

In February 2021, Orbital Assembly Corporation announced plans to start building the Voyager Station with artificial gravity in 2025.[33]

In March 2021, Sierra Nevada Corporation (SNC, now Sierra Space) announced LEO space station plans with inflatable pods, which would be supplied by their Dream Chaser spaceplanes.[34]

During 2021, NASA was seeking solutions for free-flying commercial space stations and did receive about a dozen proposals.[35,36]

Nanoracks CEO Jeff Manber said they have lost business to China's Tiangong Space Station.[37]

Lunar Gateway will likely also have commercial services for satellite deployment and internal and external platforms for commercial payloads.

In October 2021, Nanoracks, Voyager Space and Lockheed Martin announced Starlab, a commercial space station which could launch as early as 2027.[38]

A few days later, Blue Origin and Sierra Space with Redwire Space, Boeing and Genesis announced Orbital Reef, a space station that would be ready in latter half of the 2020.[39] Sierra Space seems to be pausing its independent plans from March 2021.

Since October 2021... In December 2021, NASA selected 3 companies to develop commercial destination in space. Blue Origin received $130M, Nanoracks got $160M and Northrop Grumman was awarded $125.6M. This is the first phase continuing through 2025. Blue Origin and Sierra Space develop Orbital Reef. Nanoracks collaborates with Voyager Space and Lockheed Martin on Starlab.[40]

In 2022, NASA and the commercial LEO destinations it selected are counting on a booming commercial market in LEO.[41]

J. Foust quoted Blue Origin's Erika Wagner in October 2022 from the ASCEND conference "we don't know what markets will be successful on commercial space stations; if we did, we would be doing them on ISS. Have to foster new markets. So, we need to design stations like Orbital Reef to be flexible to set us up for success".[42] He also published an article about commercial space station developers seeking clarity on regulations.[43]

In Nov 2022, Gravitics raised $20M after being founded in 2021 to create approx 8 m diameter space station modules with a planned delivery in 2026.[44]

E. Berger wrote in January 2023 that the ISS will likely fly through 2028, and potentially to 2030. During the last two years, NASA has awarded over half a billion dollars to four groups to start the design and construction of private space stations. When operational, NASA will likely spend about $1B annually on commercial station services.[45]

Axiom Space announced in August 2023 that it has raised $350 million Series C for a total of over

$505 million and said said it has more than $2.2 billion in customer contracts.[46] However, the first Axiom module is now scheduled to launch 2026.[46]

In May 2023, Vast announced its first space station Haven-1 will fly on Falcon 9 in 2025. Vast was founded in 2021 and has a goal to operate a 100-meter-long multi-module spinning artificial gravity space station launched by SpaceX's Starship.[47]

In August 2023, Voyager Space and Airbus created a joint venture called Starlab for the space station development. The Starlab team recently finished a system requirements review with NASA.[48]

In September 2023, Michael Sheetz from CNBC reported that the Orbital Reef partnership between Blue Origin and Sierra Space is having troubles.[49]

In early October, Northrop Grumman stopped plans for its own space station and is withdrawing from the NASA contract.[50] E. Berger from Ars Technica reported that Northrop was uncertain about the commercial demand besides NASA astronauts. He further reported that Blue Origin's Orbital Reef may be internally de-prioritized.[51]

2.2 Asteroid Mining (Space Resources)

The first wave of commercial asteroid mining has already come and gone.[52]

Planetary Resources (Arkyd) was founded in 2009 by high-profile backers with the intention to mine asteroids for profit. CubeSats were launched in 2014, 2015 and 2018, and over $50M of capital was raised.[53] There were plans to create mid-wave infrared Earth Observation constellation for near-term revenue generation,[54] but the company was sold in 2018 after failing to raise further funding.[55,56]

Deep Space Industries (DSI) was founded in 2013 with the goal of prospecting and extracting space resources and raised over $3.5 million.[52] In the end, they were unable to launch a demonstration mission, business model was pivoted to deep-space smallsats and water-based thrusters, and the company was sold to Bradford Space in late 2018.[57]

There are others, including Asteroid Mining Corporation[58] in the UK and Origin Space from China, latter of which launched a test spacecraft in 2021.[59]

At the end of 2020, NASA selected four companies to collect space resources and transfer ownership to the agency: Lunar Outpost, Masten Space Systems, ispace Europe and ispace Japan, paying from $1 to $15000 for small amounts of lunar regolith.[60]

Since October 2021... AstroForge and ExLabs have emerged.

AstroForge plans to launch the Brokkr-2 flyby mission in late 2023 to a small near Earth asteroid to collect data to determine if the asteroid is metallic using a 100-kg class platform from Orbital Astronautics (OrbAstro). They are not planning to generate any revenue before and besides mining an asteroid. AstroForge raised a $13M seed in May 2022 and launched a 6U CubeSat from OrbAstro in April.[61]

Argo was founded in 2021 and closed a $2M round in April 2023. They are aiming to build an in-space transportation network, using reusable spacecraft propelled by water. Lunar water is planned to be harvested and stored in-space for refueling. Goal is to be on the Moon, processing regolith and turning it into water in the late 2020s.[62]

In June 2023, Exploration Laboratories, ExLabs announced it has been selected by SpaceWERX for a $1.7M contract. They are developing next-generation spacecraft for capture and control operations for orbital debris clean-up, paving the way for deep space missions for natural resource retrieval. Broader mission is to unlock the vast resources of space in support of human sustainability.[63]

Karman+ first asteroid mining mission is scheduled to launch in early 2026.[64]

In September 2023, Starpath Robotics emerged from stealth and raised $2.5M pre-seed to build machines to mine and refine water for rocket propellant using resources on the Moon and Mars.[65]

In 2022, Michael Mealling proposed "Strategic Commodities Reserve", where the US Government would act as an in-space commodities market maker by purchasing a set number of commodities at specific transportation nodes within cislunar space.[66] Second similar idea from 2022, Tory Bruno et al. published a study titled "Creation of a U.S. Strategic Propellant Reserve" to create a Strategic Propellant Reserve using lunar-derived propellant.[67]

2.3 Surface Habitats

The Lunar Resources Company (now The Moon Society) designed a commercial Lunar Settlement plan in the 1990s called The Artemis Project.[68] Started in 1993, the first description and architecture was published in 1995 in Analog Magazine.[69]

Mars One organization was announced in 2012 and planned to send a crewed mission to Mars on a one-way ticket to establish a human settlement in 2023.[70] After many controversies[71] and much scepticism, the project eventually failed to attract enough funding and went bankrupt in 2019.[72]

The overall trends and technological capabilities were not there, thus making the plans too early at the time. As of 2021, SpaceX's Starship and NASA's Artemis program are starting to provide a much

more favourable environment. ICON, Interstellar Lab and Astreia are further discussed in Section 5.3.

Since October 2021... Only limited updates in this field. Astreia was shut down in 2023.[73]

Spartan Space was founded in 2021 and has been studying and prototyping multiple Lunar habitat concepts such as EUROHAB, L.I.S.E. and ILOTS.[74]

Lockheed Martin is developing inflatable habitats for planetary surfaces and space stations.[75]

2.4 Commercial Landers

In 1998, SpaceDev claimed to be the world's first commercial space exploration and development company and intended to launch the first privately financed spacecraft to land on another planetary body. It was selling rides for scientific instruments to a near Earth asteroid with the intention to sell that data as commercial products.[76]

The $20M Google Lunar XPrize was announced in 2007. The goal was to land a private robotic spacecraft on the Moon, travel at least 500 meters and transmit high-definition video. The initial deadline of 2012 was extended multiple times until 2018, when the challenge ended with no winner.[77,78]

Beresheet was a lander from Israel's non-profit SpaceIL and their entry to XPrize, which was of 2021 is the only one which had been launched, and which made an unsuccessful landing attempt in 2019.[79] While most of the other XPrize finalists are still active with missions booked, none have launched after more than 3 years from the initial deadlines.

In 2018, NASA launched the Commercial Lunar Payload Services Program (CLPS) to use commercial lander services for payloads.[80] In May 2019, Astrobotic was awarded $79.5M, Intuitive Machines $77M and OrbitBeyond $97M.[81] Launches were supposed to happen in 2020-2021. OrbitBeyond later asked to be released from the contract.[82] In 2020, NASA awarded $75.9M to Masten for for a mission in 2022.[83] Also in 2020, NASA awarded Astrobotic $199.5M to deliver the VIPER rover to the Moon.[84] In 2021, NASA awarded CLPS contract worth of $93.3M to Firefly Aerospace to deliver a suite of 10 payloads to the Moon in 2023.[85]

Since October 2021... Lunar lander launch delays have continued.

In September 2022, Intuitive Machines announced it will go public via SPAC at close to $1 billion valuation.[86] The deal closed in February 2023 but had a very large amount of redemptions resulting in much less funding raised. They projected revenues of $759 million by 2024, up from $73 million in 2021, through diversified services for the moon, including landers, data access, infrastructure and in-orbit servicing. Planning to develop a much larger lander Nova-D, capable of carrying 500-750 kilograms of payload to the lunar surface.[87]

ispace HAKUTO-R launched in Dec 2022 and attempted landing in April 2023 but did not achieve a soft landing. Next launch is planned in 2024.[88] ispace became a public company.[89]

In March 2023, NASA awarded Flyfly second CLPS contract worth $112M to launch in 2026.[90]

In July 2022, Impulse Space and Relativity Space announced first commercial Mars lander mission launching in 2024.[91] As of May 2023, they are now targeting 2026 due to Terran R readiness.[92]

NASA awarded Draper $73M to land near lunar south pole in 2025. The Series-2 lander is designed by ispace U.S.[93] In Sept 2023, ispace changed the lander design to APEX 1.0 and launch to 2026.[94]

More in July 2022, Masten filed for bankruptcy and most assets were bought by Astrobotic.[95,96]

Non-commercial missions have also launched. India's Chandrayaan-3 and Pragyaan rover successfully landed in August 2023[97] after Chandrayaan-2 lander did not succeed in September 2019. Russia's Luna-25 crashed in August 2023. Japan's Smart Lander for Investigating Moon (SLIM) lightweight lunar lander was launched in September 2023 but will take months to reach lunar orbit.[98]

Intuitive Machines is planning November launch for their IM-1 Nova-C lander as of October 2023.[99]

Astrobotic's Peregrine is scheduled on the inaugural launch of ULA's Vulcan Centaur, which has been likely delayed to 2024. Second larger Griffin mission will take VIPER to the lunar south pole on Falcon Heavy in late 2024. In April 2023, another Falcon Heavy was booked for a third mission in 2025.[100,101]

2.5 Commercial Rovers

The first wave of in-space economy companies happened in the late 1990s and early 2000s during the first wave of communications constellations and Internet companies.

BlastOff! Corporation operated from 1999 to 2001, peaked at 50 employees and planned to send a robotic lander and rover to the Moon in 2001.[102] TransOrbital got permission for the first private Moon landing in 2002 and planned to send an imaging satellite and a time capsule as early as 2003.[103]

Google Lunar XPrize kicked off the development of plethora of rovers, because one requirement was to travel 500 meters and capture HD-video.[77]

Astrobotic was awarded $5.6M in 2019 by NASA to develop MoonRanger rover, which could fly in 2022 on Masten XL-1 lander.[104] In 2018, Astrobotic announced that it established CubeRover subsidiary in Luxembourg,[105] but does not seem to have happened and website now redirects to Astrobotic.

Since October 2021... Lander delays and failures continue to hold back this field.

In August 2022, Astrobotic won NASA funding to fly CubeRover as soon as 2025.[106]

As of February 2023, ispace Mission 2 scheduled for 2024 will carry ispace's own micro rover.[107]

Intuitive Machines second mission IM-2, likely now scheduled for 2024, will launch Micro Nova (μNova) Hopper, which will be able to hop as far as 25 km across the surface.[108,109] It received $41.6M NASA Tipping Contract funding award in 2020.[110] A couple of other startups developing lunar hoppers have started to emerge.

STELLS was founded in 2021 and is developing MPR-1 Mobile Power Rover, which is a medium size rover scheduled to launch in 2024 to the Moon's South Pole, and provide power to other missions.[111]

GITAI announced R1 lunar rover in late 2021, which is scheduled to launch in 2025.[112]

Dymon's YAOKI is a 0.5 kg rover and scheduled to launch on the first Astrobotic mission.[113]

Astrolab said in March 2023 that it booked to fly the Flexible Logistics and Exploration (FLEX) rover on a Starship lunar lander mission as soon as mid-2026 and it will include 1000 kg of payloads.[114]

Lunar Outpost announced it integrated 3 MIT's payloads into the Mission 1 MAPP Rover, which will fly on Intuitive Machines Nova-C lander.[115]

2.6 Commercial Cargo

In 2004, NASA awarded Kistler, which by that time was in bankruptcy, a $227 million contract for a fully reusable launch vehicle K-1's flight data. SpaceX protested and argued that other companies should have been given the opportunity to compete. NASA cancelled the award after it became clear that the Government Accountability Office (GAO) would rule in favor of SpaceX.[116,117]

NASA Commercial Orbital Transportation Services (COTS) consisted of two phases. Phase 1 was demonstrations and Phase 2 was a competition for cargo services to support the ISS. NASA payments were made only upon completion of progress milestones.[118,119] SpaceX and Rocketplane-Kistler were selected in August 2006.[120] The agreement with Kistler was terminated in September 2007 after it failed to complete financial and technical milestones.[121] A competition was held to select a new partner, which resulted in the selection of Orbital Sciences Corporation (OSC) in February 2008.[118]

In 2008, NASA announced the Commercial Resupply Services (CRS-1) awards. SpaceX received $1.6 billion for 12 cargo Dragon flights and $1.9 billion went to Orbital Sciences for eight Cygnus flights.[122] SpaceX performed the first demo mission to ISS in 2012 and Orbital in 2014. In December 2015, NASA extended CRS-1 to twenty flights for SpaceX and ten flights to Orbital ATK.[123]

Second CRS-2 contracts were awarded in January 2016 to Orbital ATK, SpaceX (Dragon-2) and SNC (Dream Chaser) for flights starting in 2019 and lasting through 2024. Cygnus and Cargo Dragon have been flying since 2019-2020. The first SNC Dream Chaser Demo-1 launch was planned for 2022 on a Vulcan rocket, which has not flown yet.[124]

SpaceX was awarded one-way cargo transportation services called Gateway Logistics Services in March 2020 for the Lunar Gateway, using a new Dragon XL launched on Falcon Heavy.[125] As of April 2021, the contract start has been delayed.[126]

Chinese startup Interspace Explore is developing reusable spacecraft capable of supplying China's Tiangong space station with a first small-scale demonstration mission planned for 2022. The mission does not seem to have happened yet.[127]

Since October 2021...

In 2022, NASA ordered 12 further ISS cargo missions, six each to Northrop Grumman and SpaceX, to last through 2026.[128] As of now, the last Cygnus mission was NG-19 and CRS-28 for SpaceX.

Sierra Space's Dreamchaser is now likely scheduled for 2024.[129] In November 2021, they raised $1.4 billion at $4.5 valuation.[130] In September 2023, they raised $290M at $5.4B valuation.[131]

In May 2023,[132] European Space Agency announced Commercial Cargo Transportation Initiative to find commercial providers to deliver 2 tons to the ISS by 2028 and be capable of safely returning 1 ton to Earth. Also in May, China Manned Space Engineering Office announced a "Low-cost Cargo Transportation System" plan to hire companies to deliver at least 1800 kg of cargo to Tiangong space station and would pay no more than $17.2 million per ton of cargo delivered.[132]

In September 2023, The Exploration Company signed a preliminary cargo delivery agreement with Axiom Space. They also raised $44M in February.[133]

Rocket Factory Augsburg submitted Argo resupply vehicle to the ESA cargo initiative. It uses inflatable atmospheric decelerator for the re-entry module. The consortium includes Atmos Space Cargo,

Sener, OHB and MT Aerospace.[134,135]

China Manned Space Engineering Office down-selected 4 proposals out of 10 for the commercial cargo system. However, all of them belong to state-owned organisations, and for example AZSpace, InterSpace Explore, Orienspace were not selected.[136]

2.7 Commercial Human Spaceflight

At least two firms entered into negotiations to buy and operate a fifth Space Shuttle in 1980s.[137,138]

In 2009, Excalibur Almaz announced they will be using Soviet Almaz reusable space capsules to launch tourists to orbit and Moon. Flights were first planned to start in 2013 and later pushed to 2015. The company went defunct around 2016.[139–141]

Space Adventures has sent 7 space tourists, or space flight participants, on 8 flights to the ISS between 2001-2009 using Sojuz.[142] In 2011, Space Adventures announced that one ticket for a circumlunar Sojuz mission in 2015 had been sold at a price of $150 million,[143,144] but that mission has not come to fruition. Commercial visits to the ISS will continue in December 2021 using Sojuz, with a two-week mission including Yusaku Maezawa.[145] Space Adventures also announced a free-flying SpaceX Crew Dragon capsule mission but it was paused.[142,146]

In 2013, two-time space tourist Dennis Tito announced Inspiration Mars foundation and a private Mars flyby mission in 2018.[147] Trouble started when a mission study showed that commercial vehicles would not be suitable and NASA's SLS (Space Launch System) would be required plus extensive support.[148] In 2014, liftoff was rescheduled to 2021,[149] but organization went dormant in 2015.

Commercial Crew Development (CCDev) Phase 1 awards were announced in early 2010 with funding for concept and technology development.[150] The final phase of CCDev program concluded in September 2014.[151] SpaceX was awarded $2.6 billion and Boeing was awarded $4.2 billion.[152] SpaceX performed the first uncrewed flight in 2019, crewed demo flight in 2020 and many missions followed.[153]

Boeing's Starliner performed a partially successful first mission in December 2019,[154]

In 2016, SpaceX announced plans for a circumlunar mission paid by Yusaku Maezawa with the Crew Dragon flying on Falcon Heavy.[155] In 2018, the plans were switched to Starship with the lunar flyby mission "dearMoon" currently scheduled for 2023.[156]

In September 2021, Inspiration4 mission performed a 3-day flight on SpaceX Crew Dragon, which did not have any professional astronauts onboard.[157] There have been all-civilian and private missions before, but they always had at least one professional astronaut part of the crew, making this the first all private sector and citizen mission.

NASA announced Artemis program in 2019 to send the first woman and the next man to the Moon by 2024 and to develop a sustainable human presence on the Moon by 2028.[158] NASA announced competition for the Human Landing System (HLS) in 2019, which would perform the human lunar landing in 2024. In the first study phase announced in April 2020, Blue Origin was awarded $579M, Dynetics $253M and SpaceX $135M.[159] In April 2021, SpaceX won the $2.89B contract with Starship for the first return lunar landing mission.[160] Further regular flights will have a new competition and possibly 2 service providers. In Sept 2021, NASA awarded $146M for further sustainable human lander technology development.[161]

Since October 2021...

Since late 2021, ESA is interested in human spaceflight program, but it will depend on member states and decision may come in 2025.[162] Commercial cargo initiative is the first step towards that.

Early 2022, Jared Isaacman bought three more flights as part of the Polaris program, where the first launch is now likely scheduled for 2024.[163]

Blue Origin performed multiple sub-orbital missions throughout 2022 until September, where during an uncrewed flight the booster failed about a minute after launch and they may resume launches after a year in October.[164]

Virgin Galactic performed a research mission in June 2023, private astronaut flight in August and third astronaut flight in September.[165]

Axiom has been flying a series of private astronaut missions to the ISS on SpaceX Crew Dragon spacecraft. The second of those missions, Ax-2, went to the ISS in May 2023 and included two Saudi astronauts. The next, Ax-3, is planned for early 2024.[46]

Starliner second uncrewed test was in 2022 and the first crew mission has been delayed to 2024.[166]

Starship performed unsuccessful maiden flight in April 2023 and is not yet cleared for second flight.[167]

In May 2023, NASA selected Blue Origin as the second Artemis human landing system provider and awarded $3.4 billion.[168]

2.8 Re-Entry Capsules

Small re-entry capsules for on-demand return from space (stations) is a decades old idea with many missions flown.[169] The idea had more support during the retirement of the Space Shuttle when the ISS was supplied with expendable Progress, ATV and

HTV and only a limited downmass capability existed with Sojuz capsules. With the recent emergence of regular commercial crew and returnable cargo flights every 2-3 months, the practical necessity and business case to save approximately a month of time for a considerably more cost has not been proven. Similar unproven case is with dedicated (reusable) satellites for microgravity manufacturing and research.[170]

VBK-Raduga was a reentry capsule that flew 9 or 10 flights between 1990-1994, returning materials from Mir.[171] In 2000, European Space Agency (ESA) with international partners tested inflatable re-entry technology with the ISS payload download seen as one promising application due to the Space Shuttle costs.[172] Around 2005, ESA and EADS (Airbus) studied PARES (Payload Retrieval System) that would have been launched from the expendable Automated Transfer Vehicle (ATV) and could bring back 220 kg with a design that was 70 cm in diameter and 2.28 m in length.[173]

Small re-entry capsules were commonly used for military Earth observation satellites to return the film. Soviet lunar sample return missions had a small re-entry capsule and performed the first 3 successful robotic missions in 1970-1976. BREM-SAT 2 was studied around 1996 and planned be capable of re-entry using a deployable heat shield.[174] The next extraterrestrial samples were returned on Genesis, Stardust, Hayabusa, Hayabusa2 and Chang'e 5 missions while OSIRIS-REx is ongoing and many planned including Martian sample-return.

Foton and Foton-M are a Russian series of spacecraft with re-entry capsules. First mission was in 1985 and the last mission was performed in 2014.[175]

In 2014, NASA awarded Terminal Velocity (SpaceWorks) SBIR Phase 1 and Phase 2 contracts for low-cost small payload return with a capsule-series called RED (Reentry Device, RED-25, RED-4U).[176–178] The data recorder version RED-Data2 flew in 2017 on Cygnus OA-7.[179]

In 2015, Shackelton Energy signed an agreement with CASIS to develop Oryx series of aerobraking re-entry capsules for on-demand rapid return of time critical experiments from the ISS.[180]

Around 2018, Intuitive Machines advertised their URV (Universal Reentry Vehicle) capable of returning cargo from LEO and Moon, but it has since been removed from the website.[181]

HTV Small Re-entry Capsule (HSRC) performed a successful demonstration returning cargo from the ISS in November 2018, but has not flown again. The capsule has a mass of 180 kg and is 85 cm in diameter and 66 cm in height with internal volume of 30 litres and 20 kg payload capacity.[182]

New commercial solutions in development include Varda Space, Space Forge and many others.

Since October 2021...

InterSpace Explore signed a deal in August 2021 for launch of the Zengzhang-1 returnable satellite on a Ceres-1 rocket in 2022.[183,184] As of September 2023, it does not seem to have happened yet.

Inversion raised $10M in November 2021.[185]

Outpost raised $7.1M seed in August 2022 and plans to to start building a fleet of returnable satellites called Ferries in 2024.[186,187]

In late 2022, Space Cargo Unlimited contracted Thales Alenia Space to develop REV1 floating space factory, which shares technologies with Space Rider, and is scheduled for launch in late 2025.[188]

In early 2023, The Exploration Company raised $43.6M Series A to develop full-scale capsule, Nyx, planned for launch in 2026. The first small demonstrator is scheduled to launch in 2024.[189]

Varda launched its first space-capsule in June 2023 and grew crystals of the drug ritonavir.[190] As of late September, FAA and US Air Force have denied reentry landing requests and the capsule was launched without a reentry license.[191]

Atmos Space Cargo raised $4.3M seed in June 2023 and the first demo mission is scheduled for 2024. They are developing Phoenix return capsule with a payload capacity of 100 kilograms.[192]

ESA's Space Rider has been delayed to 2025. Announcement for flight opportunities in Oct 2021 brought over 40 applications. 16 payloads are scheduled to be on the maiden flight. The pricing has been $40,000/kg but it is under consideration.[193]

2.9 In-Space Manufacturing

The first space processing and space manufacturing symposiums were held in 1968 and 1969.

Many space manufacturing experiments were performed on Skylab in 1973, incl. semiconductors. First Space Manufacturing Conference was in 1977. The early 1980s was the first age of in-space manufacturing, with many studies published for profitable materials, as part of the beginning of regular Space Shuttle flights and for future usage of the planned Freedom Space Station.[194–201] None of those forecasts came true.

Microgravity Research Associates was founded in 1979 and planned to grow crystals in space, starting with gallium arsenide. The high-quality gallium arsenide crystals could be used to make chips that would be much faster than silicon chips.[202]

Around 1984, John W. Vanderhoff, a chemistry professor at Lehigh University, worked with NASA

to design Monodisperse Latex Reactor (MLR) instrument. A plastic mixture contained in four furnaces congeals and grows around tiny seeds to produce plastic spheres of uniform size. In one space shuttle experiment, these furnaces produced ten billion identical tiny spheres. The National Bureau of Standards certified that the size of these spheres is ten micrometers in diameter, varying by only a tenth of a percent. One could buy these in a 5-milliliter vial for $384. The plastic beads were worth between $4-12 million per kilogram. The idea of making spheres in space was behind one of the oldest proposals for space manufacturing: making ball bearings in space (drop towers). NASA planned to make more latex balls in larger sizes. Estimates were published that the market for larger 100-micron spheres could be $200-300 million annually.[7]

In the mid-1980s, EOS (Electrophoresis Operations in Space) was a joint venture of McDonnell Douglas and Johnson & Johnson. They planned to make a drug called erythropoietin in space. Before, it was available in very small quantities for research and had not been used clinically. The first flight in June 1982 demonstrated that the expected improvement in volume and purity of product would happen. In April 1985, 1 gram of drug was produced, and testing started. In July of 1985, McDonnell Douglas planned to fly an EOS production unit in the payload bay of the Space Shuttle. They had a shopping list of 20 drugs for space manufacturing. However, "Johnson & Johnson seems to have got discouraged."[7] The news seem to have stopped after the Space Shuttle Challenger disaster.

ACME Advanced Materials was founded in 2014 to develop and produce unique materials in a microgravity environment. They announced first production of superior Silicon Carbide wafers in microgravity in 2014, which is another promising product. They raised funding of €400,000 in 2015. Seems to have become dormant around 2018.

Optical fibre ZBLAN was started to be publicly touted as the first profitable product made in space in about 2016-2017.[203–205] One of the first studies about ZBLAN manufacturing in microgravity was released in 1995.[206] News already in 1998 estimated ZBLAN commercial potential at $2.5 billion.[207] NASA's has awarded optical fiber related contracts to FOMS, Physical Optics Corporation, Apsidal and DSTAR starting from 2016.[208–211] Made in Space launched internally funded ZBLAN demonstration missions in 2017 and 2019.[212,213] FOMS reported high-quality production on ISS in 2019.[214] Flawless Photonics is developing ZBLAN production system in Luxembourg.[215] After all the news, progress seems slower than expected in the recent years and Redwire (Made In Space) seems to be focusing elsewhere[216]

Made in Space, founded in 2010, has been testing large-scale in-space assembly and construction technologies and additive manufacturing. They launched first 3D printer to ISS in 2014.[217] In 2019, NASA awarded $73.7M for Archinaut One to manufacture 10-meter beams and unfurl solar arrays.[218]

Varda Space was founded in 2020 and is developing reusable satellites with re-entry capability for in-space manufacturing and other services.[219] Space Forge, founded in 2020, is working on re-usable ForgeStar satellites with return-to-Earth capability for microgravity on demand.[220]

Since October 2021...

J. Foust published an article titled "Manufacturing a low Earth orbit economy" in September 2022 discussing ZBLAN and space station markets.[16]

The Workshop on Semiconductor Manufacturing in the Space Domain was held at Stanford in March 2023 and a whitepaper will be published soon.[5,221] Purdue University held a workshop on the same topic in July and more are planned.[222]

Varda announced in early July that they have grown crystals of the drug ritonavir in microgravity but the capsule has yet to return to Earth.[190,191]

In June 2022, Redwire announced the first sale of its space-manufactured optical crystal to researchers at The Ohio State University. Two grams were sold and have an approximate value of $2 million per kilogram. The crystal was produced in Redwire's Industrial Crystallization Facility (ICF) on the ISS.[223] They said this is the first time that a space-enabled materials product has been sold on Earth. However, the latex spheres were the first in the 1980s.

In September 2023, Redwire announced it 3D bioprinted the first human knee meniscus on orbit using its upgraded 3D BioFabrication Facility (BFF) on the ISS. This milestone opens the door to improved treatments for meniscal injuries.[224]

As of September 2023, biotech in space may be the next wave for in-space manufacturing. However, the "killer app" for in-space manufacturing is still yet to be found or published.

2.10 Microgravity Flight Services

There are many commercial services on the ISS to perform experiments, demonstrate payloads and in-space manufacturing processes. For example, Nanoracks Nanolab, Space Applications Services ICE Cubes, Airbus Bartolomeo, Space Tango CubeLab and Yuri.

Airbus Bartolomeo was mounted externally on the ISS Columbus module in April 2020.[225] In Sept 2023, the multi-Needle Langmuir Probe was moved to the Bartolomeo platform and is the first experiment to use one of the 11 slots.[226]

Space DOTS announced $1.5M pre-seed in July 2023 to develop the Barnacle DOT, a materials testing payload the size of a phone that can test the tensile strength and other properties of materials in space. They plan to have a first flight in 2025.[227]

2.11 In-Space Transportation (Space Tugs)

There was a time when the Space Shuttle was planned to be the only launch vehicle of the United States and thus an upper stage would have been required for many types of spacecraft to get to their final orbits. Already by 1972, NASA and DOD had studied a variety of upper stage approaches including expendable stages and recoverable space tugs, which included in-orbit servicing.[228]

By 1984, several companies had developed upper stage vehicles designed to place payloads in high orbit. McDonnell Douglas and General Dynamics manufactured the Payload Assist Module and the Centaur. Boeing and Orbital Systems Corp were developing similar upper stage vehicles.[137]

Studies and proposals continued.[229,230] In 1986, TRW was awarded contract for one orbital manoeuvring vehicle, because NASA viewed space tugs as essential components of the proposed Freedom Space Station to retrieve and return satellites.[231] McManus et al studied over a hundred possible orbital transfer vehicle designs in 2003.[232]

Space tugs are now one of the most popular new in-space economy fields thanks to the popularity of nano- and microsatellites and low-cost rideshare missions. Spaceflight (Andrews Space) announced SHERPA in 2012 and first mission was planned for 2014, but happened in 2018.[233,234] Momentus was founded in 2017 to provide last-mile transportation service for satellites. They raised over $140 million and then went public through SPAC.[235] In September 2021, SpaceX founding member Tom Mueller announced Impulse company with the goal to provide agile economical access to any orbit.[236]

Since October 2021... This continues to be one of the most popular and active in-space economy fields. Many more startups have been created, and some are developing reusable orbital transfer vehicles, but uncertainties about the economic sustainability and market size remain.

D-Orbit announced plans to go public via SPAC in early 2022 but cancelled by August 2023.[237] In June 2023, they launched their 11th ION Satellite Carrier mission after starting in September 2020.[238]

Momentus first mission Vigoride-3 launched in May 2022 but had anomalies. Second mission started in January 2023 and third in April 2023.[239] Momentus reported $1.7M in revenues for the first half of 2023. They also announced a satellite platform product line based on Vigoride.[240]

Launcher flew the first Orbiter space tug in Jan 2023 and second in June 2023 but both missions had anomalies.[241,242]

2.11.1 Satellite Servicing

The first satellite servicing was performed in 1984 to Solar Maximum Mission spacecraft during the Space Shuttle mission STS-41-C.[243]

Orbital Recovery was founded in 2001 and was planning the first life extension mission in 2004, which was rescheduled to 2007 before closing.[244]

Mission Extension Vehicle (MEV) concept got started around 2010 in ViviSat.[245,246] After mergers, the project continued in Orbital ATK and then in SpaceLogistics, subsidiary of Northrop Grumman.[247] First commercial servicing mission MEV-1 launched in 2019 and attached to Intelsat-901 in geostationary orbit in 2020.[248] MEV-2 launched in 2020 and attached to Intelsat 10-02 in 2021.[249] As of 2021, SpaceLogistics is developing a new vehicle with a robotic arm that will install propulsion packs on dying satellites. Six undisclosed customers have signed up for servicing by the Mission Robotic Vehicle (MRV), projected to launch in 2024.[250]

MDA announced servicing spacecraft concept in early 2010.[251] In 2017, a subsidiary called Space Infrastructure Services was created and majority was sold to Finance Technology Leverage.[252]

Astroscale, better known for debris removal, started in 2013 and has raised over $191M.[253,254]

Orbit Fab, founded in 2018 and offering refuelling services in space, is planning to launch a propellant tanker payload on Spaceflight Sherpa-ES orbital transfer vehicle to geostationary orbit, with the launch projected for late 2022 or early 2023.[255]

Starting from 2021, work is ongoing to establish satellite servicing standards and regulations.[256–258]

Since October 2021... Launch delays have meant that new missions are yet to launch.

In January 2022, Orbit Fab signed a deal with Astroscale to refuel their geostationary satellite servicing spacecraft LEXI (Life Extension In-Orbit) projected to launch in 2026 by supplying up to 1000 kg of Xenon.[259] In August 2022, they announced in-space hydrazine refueling service for satellites in geo-

stationary orbit as soon as 2024 at a price of $20 million for up to 100 kg of hydrazine.[260] In April 2023, they raised $28.5M at a valuation of over $100M.[261] In May, they selected orbital vehicle from Impulse Space to host a fuel depot for an in-orbit refueling demo in 2025 funded by the U.S. military.[262]

In November 2022, ClearSpace announced a mission to extend the life of an Intelsat satellite before it runs out of fuel around 2026-2028.[263]

Astroscale was awarded funding in early 2022 to advance on-orbit servicing interface technologies.[264] At the end of 2022, Astroscale and JAXA started studying satellite refueling service.[265]

Starfish launched Otter Pup in June 2023 but anomalies with Launcher's space tug will not allow docking experiments.[242] In March 2023, they raised $14M for its planned satellite life extension and debris removal service.[266] In late 2022, it was targeting late 2024 or 2025 for the first Otter mission.[267]

Northrop Grumman (SpaceLogistics) licensed three satellite servicing technologies from NASA in early 2022.[268] In June 2023, Intelsat ordered the third and last pod available on first Mission Robotic Vehicle (MRV). The MRV is a 3000 kg spacecraft and first mission will have three MEPs (Mission Extension Pods), each about 400 kg. The first MRV mission is now scheduled for 2025.[269,270]

In May 2023, Italian Space Agency awarded Italian companies $256M for in-orbit servicing demonstration to launch in 2026. The group includes Thales Alenia, Telespazio, Avio and D-Orbit. Servicer and target satellite will be launched together and both will include a refueling interface.[271]

Rogue Space Systems announced two contracts worth $3M in total to develop a more universally compatible CubeSat dispenser and a magnetic system for stabilizing tumbling space objects.[272]

In April 2023, NASA created a consortium for In-space Servicing, Assembly and Manufacturing (ISAM) called COSMIC.[273,274] It aligns with the ISAM National Strategy[275] and National ISAM Implementation Plan[276] both published in 2022.

In September 2023, U.S. Space Force awarded Astroscale $25.5M to deliver in 2 years a "manifest ready" prototype capable of refueling a satellite.[277]

Also in September, Astroscale said its ADRAS-J mission to inspect the H-2A upper stage is technically ready for launch on Rocket Lab's Electron.[278]

2.11.2 Space Debris Removal

In late 2020, ESA signed a €86 million contract with ClearSpace to remove part of Vega rockets upper stage in 2025.[279] In January 2023, they raised €26.7M Series A and ClearSpace-1 is now scheduled to launch in 2026.[280]

In May 2022, Astroscale was awarded $16M from ESA for a demo mission launching in 2024 to remove what will likely be a OneWeb satellite.[281] They are also working on UK mission study to remove two defunct British satellites by 2026.[282]

In September 2022, FCC approved a rule that spacecraft have to deorbit no more than 5 years after the end of their mission, which previously was 25 years.[283] In 2023, they are working on rules to limit lifetime of upper stages in orbit.[284]

NASA Office of Technology, Policy, and Strategy published report on "Cost and Benefit Analysis of Orbital Debris Remediation" in March 2023.[285]

In September 2023, NASA issued a call for proposals for ISS deorbit module called the United States Deorbit Vehicle (USDV).[286]

iMetalX is developing debris removal products and was selected to Techstars 2023 accelerator.[287]

2.12 Space Utilities

2.12.1 In-Space Internet

Audacy was founded in 2015 to build inter-satellite communications relay network. In 2018, they announced MoUs and pre-service agreements for over $100M.[288] However, they closed during 2019 after failing to find new investors.[289]

Kepler Communications was founded in 2015. In April 2023, they raised $92M Series C to start deploying an optical data-relay constellation in 2024 to provide real-time connectivity for LEO satellites.[290]

In 2020, SpaceLink was established to develop a constellation in MEO to relay data between ground and LEO. They also acquired Audacy's assets. However, in late 2022 they winded down operations due to not being able to attract new investors.[291]

In September 2021, ESA signed a contract with Surrey Satellite Technology (SSTL) to be the anchor customer on a Lunar Pathfinder lunar communications satellite, currently scheduled for 2025.[292,293]

In January 2022, Plus Ultra Space Outposts announced collaboration with ispace for help to deploy their Harmony lunar communications and navigation constellation as soon as 2024.[294] However, Plus Ultra shut down in mid-2022.[295]

In March 2022, Aquarian Space announced raising $0.65M seed to deploy a high-speed communications network for the Moon starting in 2024.[296]

In December 2022, Quantum Space published the raising of $15M to build a constellation of satellites to provide services in cislunar space, such as communications and navigation.[297]

In March 2023, Lockheed Martin announced the creation of a subsidiary, Crescent Space, to offer communications and navigation services around the Moon. Service is called Parsec and first satellites should launch in 2025.[298]

2.12.2 Space Energy & Energy on the Moon

NASA's Watts on the Moon power-beaming challenge was initiated in 2020.[299] Similarly to the Google Lunar X Prize, many space energy and power beaming startups were established or supported by it, and some have continued to progress.

Astrobotic announced in July 2023 that it won a $34.6M NASA Tipping Point award to demonstrate power transmission on the lunar surface. LunaGrid-Lite will transmit power from a lunar lander to a tethered rover. During the demo, an Astrobotic 6U CubeRover will unreel 1 km of cable from an Astrobotic lunar lander and receive the first high voltage power through a cable across the lunar surface. The demo will serve as a pilot for the LunaGrid service to deliver commercial power service. The full LunaGrid could use the 20-meter-tall Vertical Solar Array Technology (VSAT).[300]

In September 2023, the U.S. Air Force Research Laboratory awarded contracts to Intuitive Machines, Lockheed Martin and Westinghouse to advance technologies for nuclear powered spacecraft.[301]

2.12.3 Space Solar Power (SSP)

Space-based solar power seems to be taking off in a significant way in the last two years. Major difference to many space industries is that the terrestrial energy market is very large and already exists.

In November 1968, Peter Glaser proposed the first technical concept of space solar power to provide energy for terrestrial use.[302]

Solaren was founded in 2001 to make space solar power reality. In 2009, California's biggest energy utility (Pacific Gas & Electric) announced a 15-year deal to purchase 200 MQ of electricity that would be beamed to Earth from space, beginning in 2016. Solaren's system would be "competitive in terms of performance and cost with other sources of baseload power."[303] In June 2023, they announced raising $2.5M in an initial Series D round.[304]

Space Energy was established in Switzerland in 2008 and by 2010 it had offices in five countries. Funding totalled about $4M. Until 2013, they continued to pursue ground and space-based projects. As a side business, they sold IT equipment. The company was then targeted by criminals and it caused a debt from which they did not recover.[305]

In 2010, Astrium (now Airbus) was seeking partners to help fund solar power beaming demonstration. After in-house review and a small ground demo, they started seeking the interest of European governments for a large satellite in GEO. Applications foreseen were providing power from space to ships at sea or other fixed or mobile users.[306,307]

ESA started re-exploring space solar power around 2020, which has continued. In early 2022, ESA commissioned two cost versus benefits studies from Frazer-Nash and Roland Berger.[308] In November 2022, the SOLARIS 2-year program was officially announced to develop technologies.[309] In April 2023, ESA awarded study contracts to develop new reference-design space solar power architectures for large-scale terrestrial use to Arthur D. Little and Thales Alenia Space Italy.[310] In July 2023, Astrostrom completed their ESA-funded study investigating the feasibility of a "Greater Earth Lunar Power Station" (GEO-LPS) manufactured on the Moon and assembled at the Earth-Moon Lagrange Point 1, to provide power from lunar orbit to operations on the surface of the Moon.[311]

In June 2022, A. Jones wrote in length about China's SSP plans in SpaceNews. The China Academy of Space Technology (CAST) plans to conduct a "Space high voltage transfer and wireless power transmission experiment" in LEO in 2028. The satellite will generate 10 kW and test power transmission over 400 km from orbit. The plan also involves building infrastructure on the ground for receiving. Phase 2 in 2030 would be launched into geostationary orbit. Phase 3 in 2035 would scale to 10 MW and Phase 4 in 2050 to 2 GW.[312,313]

In June 2023, UK announced £4.3M in grants to space solar power technologies.[314] Space Solar was spun out from the Satellite Applications Catapult in the UK in April 2022 and is planning a demo of MW-scale power beamed from space by 2029.[315]

Caltech announced in 2021 that they received a $100M donation in 2013 to form the Space-based Solar Power Project.[316] They launched a mission in January 2023 as a hosted payload on Momentus spacecraft. Wireless power transfer was demoed in March, including detecting energy on Earth.[317]

In June 2023, The U.S. Naval Research Laboratory's Space Wireless Energy Laser Link (SWELL) surpassed 100 days of operations and it should be the first laser power beaming demonstration in space.[318]

Emrod demonstrated wireless power transmission in September 2022.[319] Virtus Solis demonstrated 100 m power beaming live in March 2023.[320]

3. MARKET SURVEY

3.1 Survey Criteria

The survey criteria, which has resulted in the 823 entries currently, is the following:

- Belongs to the in-space economy, as defined in the next section of high-level classifications and sub-categories.
- More precisely "new in-space economy". For example, excluding launch vehicles, unless they are also meant for interplanetary flight like Starship; excluding satellite manufacturing, unless they will be reusable; excluding satellite fleets and constellations around Earth; and more.
- Commercial entities or at minimum offering commercial services to the public markets.
- Discovering the new startups is a main challenge and many might be missed for some time.

3.2 In-Space Economy Classification

One goal of this paper is to continue iterating on the taxonomy for the commercial entities in the in-space economy to be able to group them.

Until such categories are defined and widely accepted, the activities will continue to be called with different names as per personal preferences, which makes it more challenging to determine competitors and estimate market sizes. The categories have been limited to 10 to make the figures more practical to read, but this may change in the future.

The following classification is preliminary and author expects it to improve greatly thanks to feedback, independent iterations, and especially over the upcoming years as the new space-based industries continue to grow and become established.

Figure 1 illustrates the in-space economy fields and has been updates in 2023.

The in-space economy high-level categories:

1. **Human Spaceflight & Landers**
2. **Cargo Transportation & Landers**
3. **Surface Spacecraft**
4. **Space Stations & Habitats**
5. **Surface Habitats & Structures**
6. **In-Space Manufacturing**
7. **Space Resources**
8. **Space Utilities**
9. **In-Space Transportation**
10. **Miscellaneous**

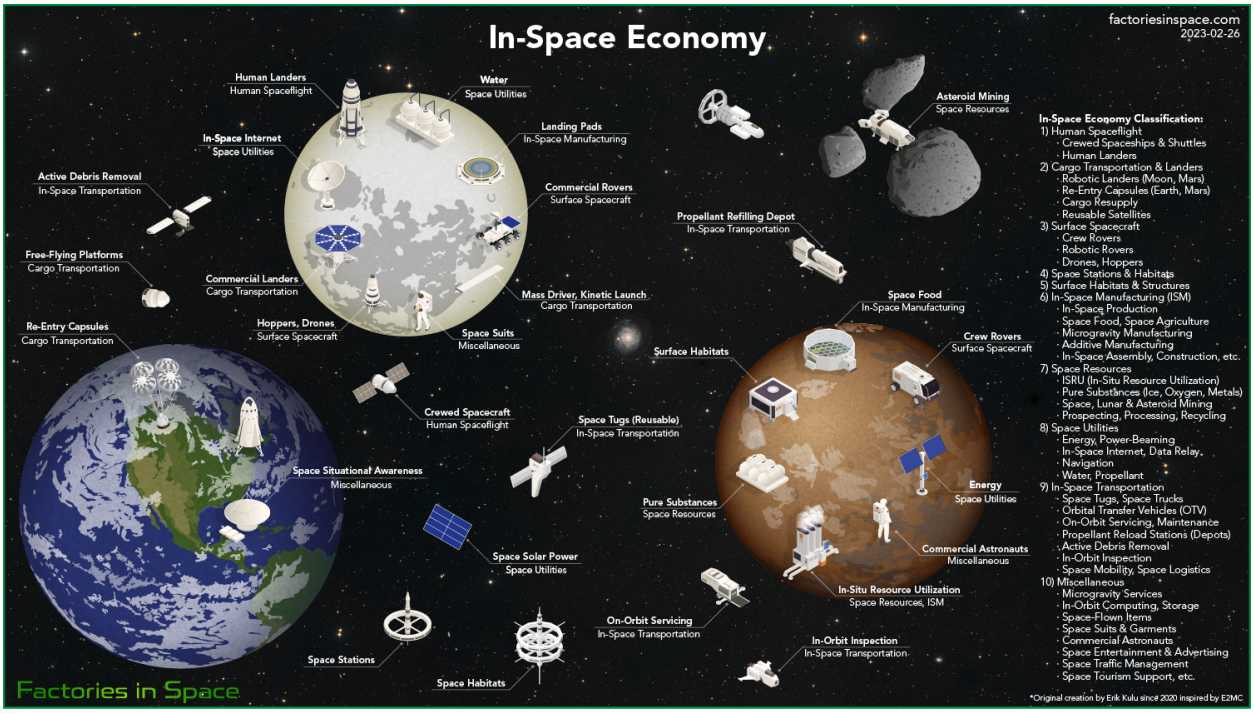

Figure 1: In-Space Economy

4. IN-SPACE ECONOMY TAXONOMY

Here follows the terminology and definitions for the primary classifications. The following list of keywords, alternative terms, applications and fields is not exhaustive. Feedback is very welcome and author expects the terminology to evolve greatly as in-space economy markets develop.

1. **Human Spaceflight & Landers** - Space vehicles designed for any kind of human flight. Also referred to as crewed spaceflight.[321] It is a separate category due to difficulty level, but could be merged in the future.
    - Human-Rated Spacecraft, Spaceships & Shuttles - Minimum criteria is an orbital flight in LEO.[321] Includes space transport ships to Moon, Mars and beyond.
    - Human-Rated Landers - Moon and Mars landers and reusable shuttles.
2. **Cargo Transportation & Landers** - Spacecraft transporting goods from and to Earth, Moon and Mars.
    - Cargo Resupply - Space station cargo resupply services.
    - Landers - Commercial non-reusable Moon, Mars and asteroid robotic landers.
    - Reentry Capsules (Earth, Mars) - Dedicated free-flyer spacecraft capable of atmospheric return. Many have been and again are in development.
    - Reusable Satellites - the term is also used under In-Space Transportation, but in this context it would have re-entry capability.
3. **Surface Spacecraft** - Spacecraft operating on the surface or near the surface of a planetary body. Includes rovers, drones, hoppers.
    - Rovers - Wheeled or rolling robotic vehicles. To be used for exploration, prospecting and transportation.
    - Drones - Rocket-powered flight on the lunar surface to reach difficult locations and winged and rotary aircraft on Mars, Venus and Titan for example.
    - Hoppers - Hopping might become a transportation method on Moon and asteroids.
    - Human-Rated Rovers - Sub-set of rovers designed for human-use, often larger scale and stricter safety requirements.
4. **Space Stations & Space Habitats -** Free-flying space stations and very large space habitats. Can be called space platform, orbital colony, space colony, and space settlement. May be located in orbit around the Earth, Moon, Mars, Venus and in Lagrange points. Could be rotating to achieve artificial gravity.[322] Merriam-Webster defines space station as a large artificial satellite designed to be occupied for long periods and to serve as a base.[323] K. Kennedy et al defined space habitats as a recreation of Earth environment for the purpose of sustaining life, and that habitats are pressurized crew volumes including laboratories, living quarters, and maintenance facilities.[324]
5. **Surface Habitats & Surface Structures -** alternatively surface facilities. Facilities on the surface of Moon and Mars for habitation, storage and manufacturing. Structures can include physical infrastructure, antennas, various plants, factories and more.
6. **In-Space Manufacturing** (ISM) - alternatively Off-Earth Manufacturing[325] and Space-Based Manufacturing.[326] ISM divides into 2 large areas. First area is manufacturing products in microgravity for Earth, which will be brought back to be sold on terrestrial markets. Second area is manufacturing large-scale space structures that will remain in space. Author presented a dedicated paper on ISM in 2022 including many new subcategories.[4]
    - In-Space Manufacturing - In narrower definition it means making products and materials in microgravity, which cannot be made on Earth, or which are better.
    - In-Space Production - Same as the narrow definition of in-space manufacturing. ISS National Lab is using this term.[327]
    - Space Food or Deep Space Food - Space agriculture to supply fresh food to workers, settlers and tourists, both in-space and on Moon, Mars and beyond.
    - Microgravity Manufacturing - Alternative name for in-space manufacturing and in-space production.
    - In-Space Construction - Large-scale construction in space and on Moon & Mars.
    - In-Space Assembly (ISA) - Subset of in-space construction, which will likely be the first step before the very large-scale end-to-end construction in space. Xue et al. defines ISA as the assembly activities completed in the target orbit and extraterrestrial space, which is to assemble modules in space in order to form a larger functional element, or to recombine one or more structures after separation.[328]

- In-Space servicing, Assembly and Manufacturing (ISAM) - Broader term.
- Additive Manufacturing - Subset of in-space manufacturing, also 3D printing.
- Parabolic and Suborbital Flights - Some microgravity manufacturing can happen during short flights and due to that has been included here for completeness.

7. **Space Resources** - Deals with the prospecting, mining, beneficiation, processing, ISRU and recycling of natural or artificial resources in space, incl. Moon, Mars and asteroids.[2,329] Some processing and ISRU activities could also be considered to be in-space manufacturing.
    - ISRU (In-Situ Resource Utilization) - Any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration.[2] Encompasses exploration, mine planning, mineral processing, metallurgy and sale of off-Earth resources.[2]
    - Prospecting - Determining the composition of asteroids, moons and planets using remote sensing and in-situ measurements for mining and ISRU.
    - Space Mining - Also Off-World Mining[330] and includes Moon and Mars mining. Extracting and collecting the raw resources from planetoids or planetary surfaces.[331]
    - Asteroid Mining - Sub-set of space mining, focused on asteroids in space together with basic processing to reduce the mass of the materials to be transported.
    - Lunar Resources - Subset of space resources.
    - Pure Substances and Raw Materials - Selling processed materials like ice, water, oxygen and metals.
    - Recycling - Reprocessing artificial objects including satellites and spent rocket stages into raw materials or reusing parts of them.
    - Processing or Beneficiation - Separating valuable minerals from waste rock.
    - In-Space Metal Processing.
8. **Space Utilities** - alternatively In-Space Utilities. There will exist distinctive supply chains and physical infrastructure for common goods like energy, internet, navigation and water.
    - Energy - Includes space-based solar power, nuclear power and wireless transmission. Electrical energy will have a more centralized infrastructure on Moon and Mars. Currently often served by independent solar panels, but solar power stations could supply other satellites and vehicles and outposts on the ground.
    - In-Space Internet - Communications will be a critical infrastructure across the solar system and on the surfaces. More broadly, this is In-Space Communications or Data Relay Communications.
    - Navigation - Navigation in space and on Moon and Mars. Possibly required for future landers and surface vehicles.
    - Water - Water in space and on the Moon and Mars, to be used for human consumption, air, propellant and likely radiation protection.
9. **In-Space Transportation** - Broad category about multi-functional spacecraft providing services to other spacecraft in direct contact or short-distance away and capable of sizeable orbit changes. There are many similarities between the following sub-categories, because all those spacecraft must be capable of significant orbital velocity changes. It is very likely that same entities will offer multiple services thanks to the underlying technologies. Similar to terrestrial applications, where trucks and pick-ups serve multiple roles, all requiring only small modifications if at all. Key difference with Cargo Transportation is that these vehicles will stay in space and do not have reentry and/or landing capability.
    - On-Orbit Servicing (OOS) - or In-Space Servicing. Spacecraft with the means to go nearby other spacecraft and dock with them for propellant loading, orbital repositioning or to stay attached and augment capabilities. J. P. Davis et al. defines OOS as on-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object. These activities include non-contact support, orbit modification (relocation) and maintenance, refuelling and commodities replenishment, upgrade, repair, assembly, and debris mitigation.[332]
    - Mission Extension, Life Extension - Extending the operational life of spacecraft trough servicing.
    - Satellite Maintenance - Alternative term for in-space servicing and repair.[333]
    - In-Orbit Inspection - Sub-set of on-orbit servicing. Spacecraft capable of travelling nearby to other spacecraft and inspecting

them for damages, status, intelligence.
- Orbital Transfer Vehicle (OTV) - Spacecraft capable of transporting other spacecraft between different orbits. Capabilities can vary greatly. Starting from small altitude and inclination changes in LEO, to taking spacecraft from LEO to GEO, and to Moon, Mars and further.
- Space Tugs - Alternative name for Orbital Transfer Vehicles.
- Space Trucks - alternative name of OTVs when comparing to utility vehicles.
- Space Transportation Node - Alternative name for Orbital Transfer Vehicles.
- Orbital Manoeuvring Vehicle - Alternative term for OTVs and Space Tugs.[334]
- Propellant Reload Station - Includes propellant refuel stations, propellant depots, orbital refuelling, and propellant tankers.[255]
- Active Debris Removal (ADR) - Spacecraft with the means to go nearby other spacecraft and help them de-orbit faster.
- Reusable Spacecraft - or reusable satellites. Primarily adding propellant reloading. Sharing many technologies with OTVs. Future uniqueness will be on modular exchangeable payloads changed in space.
- Space Logistics - Another terms for In-Space Transportation that might become widely used. AIAA defines space logistics as the science of planning and carrying out the movement of humans and materiel to, from and within space combined with the ability to maintain human and robotics operations within space.[335]
- Space Mobility - another popular term.

10. **Miscellaneous** - Supporting and connected services to the in-space economy, which largely would not exist without it. Some of them may not strictly generate revenue in space.
    - Microgravity & ISS Flight Service - Broad term for service providers and brokers offering access microgravity environment. They can use and have facilities on the ISS and upcoming space stations or on dedicated free-flyer spacecraft. Organisations can have their own hardware, but do not perform ISM for own purposes nor do they develop their own space capsules or space stations for example.
    - Space Suits & Garments - Space suits and space clothing will be required for every astronaut, settler and tourist.
    - Commercial Astronauts - Privately employed and trained astronauts to help with large-scale commercial activities in space and on the surfaces.[336,337]
    - Space Tourism, Suborbital Space Tourism - Wider terms encompassing human spaceflight and habitation services. Suborbital Space Tourism companies have been included under miscellaneous. Space tourism is considered to be one of the potential customer segments for multiple in-space economy fields in the future.
    - Space Tourism Support Activities - Space tourists, but also commercial astronauts, will require some training and support for the foreseeable future. This can also include space-themed experiences on Earth.
    - Space Entertainment - In-space economy will likely start a new form of entertainment, where the activities will happen in space. Starting with variations of or new types of sports, space casinos, performance shows, and other entertainment activities.
    - Space Advertising and Marketing - Advertisements in space, Moon and Mars.
    - Space Traffic Management - Very active and common human spaceflight activities between Earth, Moon, Mars and space stations will likely need some coordination. This also includes Space Situational Awareness (SSA), which US Air Force now calls Space Domain Awareness (SDA).[338]
    - In-Orbit Computing - Edge computing and server farms in space.
    - Space Robotics - Can be covered by in-space construction, in-space manufacturing, surface spacecraft and satellite servicing, but also robotic humanoid robots.
    - Moon and Mars Remote Sensing - Imaging in different wavelengths for choosing landing and base sites, cartography and resource mapping.
    - In-Space Infrastructure - Wider term that would encompass many of the top-level categories like transportation, utilities and stations. No companies in the data have this classification currently and has been only listed for completeness. S. P Sharma and C. Moore define in-Space infrastructure as consisting of the systems and services operating in Earth's neighbourhood to facilitate commerce, exploration, and scientific discovery.[339]

5. 2023 STATISTICAL OVERVIEW

This section presents the statistical overview of the 823 entries included in this new in-space economy survey of primarily commercial space entities.

5.1 Classifications with Status

Figure 2 shows the classification of in-space economy companies. Many companies now have multiple entries in the database.

Overall, approximately 1/3 of entities are in dormant, concept or early stages. About 1/3 are in active development. About 10% of companies have launched some technologies to orbit and thanks to that they can be given the demonstrated status.

Human Spaceflight is expensive and technologically challenging to develop, and as such, it is difficult to enter this market, which has resulted in a small number of entities. SpaceX is active in the human orbital spaceflight category and cargo transportation. Blue Origin is active in the suborbital human spaceflight and Virgin Galactic started regular missions in the summer 2023.[340] Northrop Grumman is active in Cargo Transportation with Cygnus.[341]

None are active yet in Surface Habitats (increased from 19) and surface spacecraft (up from 21 from 2 years ago) and few updates in the last 2 years. Among Space Stations (increased from 25), Nanoracks launched a commercial ISS airlock in 2020[342] and many new developers such as Vast and Gravitics.

In-Space Transportation with 95 entries (up from 71 from 2 years ago) is popular due to a large increase in orbital transfer vehicle (space tug) startups. This category also includes satellite servicing, active debris removal and propellant reloading, because of the large overlap in spacecraft technologies. Northrop Grumman (SpaceLogistics), D-Orbit and Spaceflight are active in the in-space transportation category because they have launched space tugs for servicing or satellite deployment. Launcher and Momentus have now also launched since 2 years ago.

Number of entries in the Space Utilities classification has grown from 54 two years ago to 96.

In-Space Manufacturing with 167 entries (up from 92 from 2 years ago) is again the most popular single category. This classification also includes numerous companies which have performed demonstrations, done research or made limited quantity of novelty products such as space whisky and space beer. There are only a few in-space manufacturing entities making products and materials regularly for Earth or space. Varda will be marked demonstrated once the capsule returns. Redwire has performed multiple demonstrations too.

Miscellaneous includes multiple non-space hardware or space advocacy organizations that are active due to lower barriers of entry. Previously, In-Space Manufacturing included the ISS-based and other microgravity testing providers, which are actively offering services, but have been moved to Miscellaneous.

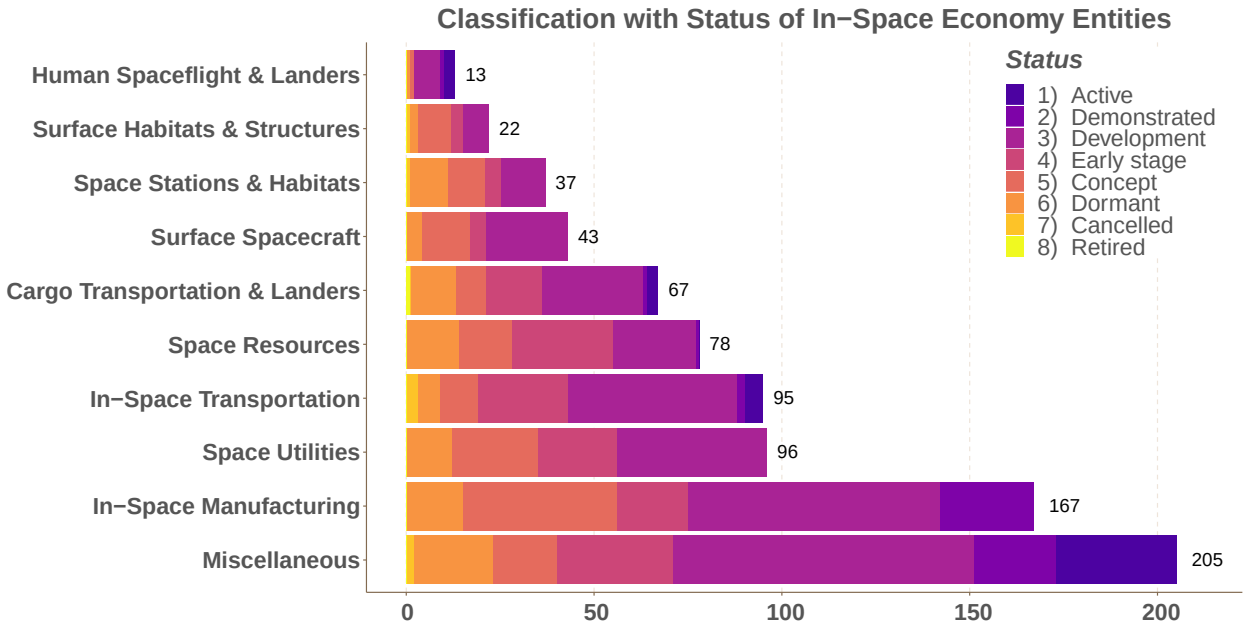

Figure 2: In-Space Economy Classification by Status

5.2 Founded with Status

Figure 3 lists the founding years of organisations together with the status categories.

Establishment of a company does not correlate to a successful long-term business or to demonstration missions, because most will become dormant before. As seen from the chart, many commercial organizations are in the early stages, where the visible progress could be limited to a website and a small partially committed team. Only a small part of companies have performed orbital demonstrations or are active. It shows there is still a long path for many in-space economy services to become commonplace.

The figure shows well the arrival of NewSpace. The amount of new space companies being created has increased rapidly in recent years when compared to 10 years ago. Between 2008-2010, SpaceX succeeded in launching rockets to orbit. CubeSats started to be taken seriously around the same time.

There are 823 entries and about 755 unique entities in this study, more than double compared to the 472 entries in the 2021 study.[1] In the previous 2021 chart, there was a peak in 2018 and a subsequent decline. It was discussed that there may have been a boom, which had slowed down. Because most of the fields do not have existing markets, new players might be in waiting mode, or startups could be in stealth mode or early stages, and as such the author has not become aware of them. A lot of them have been backfilled and the founding peak is now in 2021 instead. Some increase can also be attributed to many companies now having multiple entries.

The start of the increase and new wave of companies founded between 2017-2019 is likely correlated to SpaceX's Starship and NASA's Artemis program announcements, because of the very high payload capacity and low-cost rideshare missions improve the business cases, and returning to the Moon is creating new markets for many in-space economy fields.

While there was a decline in 2021, the author continues to forecast that successful Starship missions and return to the Moon will kick off another startup founding wave in about 2-3 years. There may remain a slight decrease for 2022-2023, because Starship has been delayed, but afterwards the in-space economy is likely to continue to get larger.

Next are some startups, which were founded or added after October 2021 and not named in Section 2. Founded in 2022 are for example Diatomic (producing oxygen on lunar surface), InspeCity (satellite servicing), KINETIK (robotic arm), IX (fusion power), LodeStar (additive manufacturing), Orbital Matter (additive manufacturing), Prometheus Life Technologies (human tissue production) and Overview Energy (space power). Founded in 2023 are for example ASTROLAB (microgravity experiments platform), Paladin Space (reusable satellites), Stellar Luxuries (orbital distillery for whiskey) and BioOrbit (large-scale protein crystallisation).

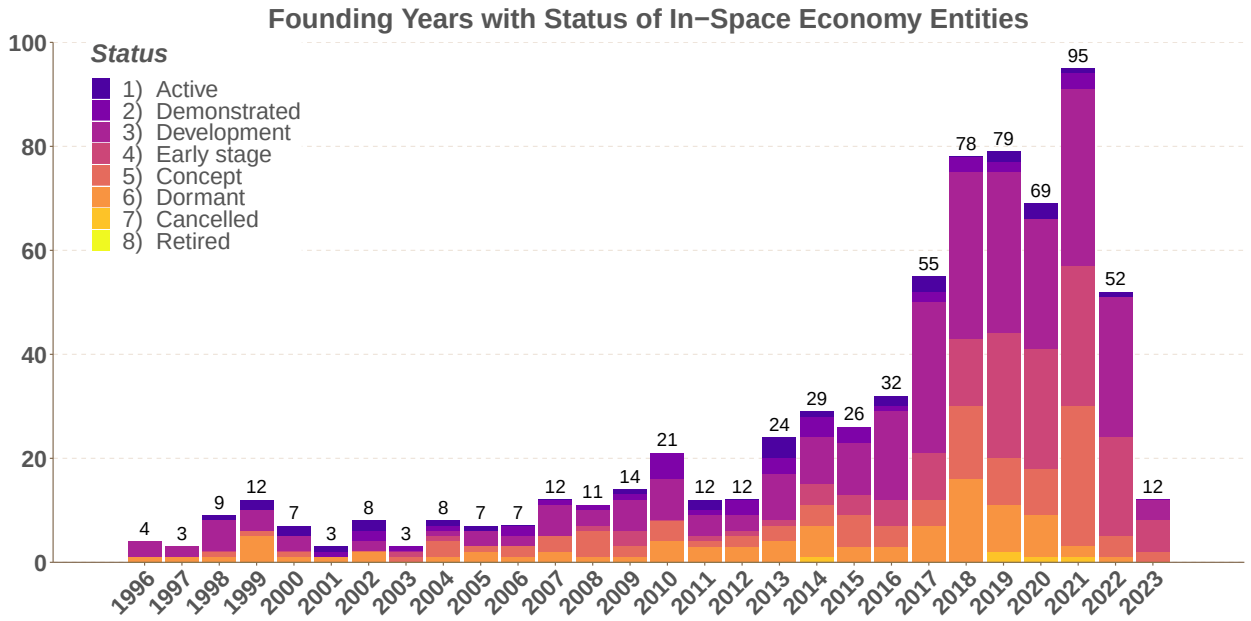

Figure 3: In-Space Economy Founding Years by Status

5.3 Founded with Classification

Figure 4 plots the founding years of entries in the database together with the classification.

Among human spaceflight providers, Blue Origin was founded in 2000 and SpaceX in 2002.

Competitions and challenges are a great way to create new startups or gain momentum. NASA's Watts on the Moon" power-beaming challenge was initiated in 2020.[299] ESA's Moonlight project started in 2021 and is bringing connectivity to the Moon.[343] NASA's Deep Space Food Challenge started in 2021.[344]

Google Lunar XPrize started in 2007[77] and inspired many lunar lander and lunar rover companies in the following years. In 2021, Beresheet was the first non-governmental Moon lander, which made a landing attempt in 2019. ispace made a landing attempt in April 2023 but it also failed. Lack of lunar landing opportunities and delays has also slowed down the launches of commercial rovers, surface habitats, and space resources demonstrations.

Starting from 2017 and continuing, there has been a large increase of in-space transportation companies, which include space tugs, debris removal and satellite servicing. Likely coinciding with the first public Starship announcements and successful reusability of Falcon 9, because both are aiming to lower the costs of space access, which may enable the new business cases using rideshare missions.

Companies developing ISRU solutions and surface habitats have been increasing too but not in the recent years. The initial motivation was likely thanks to NASA's Artemis announcement in 2019 with related funding opportunities and SpaceX's long-term vision for a self-sustaining Mars settlement. Surface habitat companies continue to be focused on sustainable housing or farming on Earth, but plan to expand to Moon and Mars when the time is right. There has been little growth in this field in 2 years. For example, ICON was founded in 2017,[345,346] Astreia in 2019[347] and Interstellar Lab in 2019.[348] However, Astreia shut down in 2023.

During 2021, numerous commercial space station proposals were presented and announced. NASA's Commercial Low Earth Orbit Destinations program received 11 proposals, many from new startups.[349]

Space utilities in LEO include for example in-space internet and wireless electricity. Kepler Communications was founded in 2015, has planned in-space internet from the beginning[350] and their optical network is scheduled to launch in 2024.[290,351]

For in-space manufacturing, plethora of small reentry capsule companies have been founded in the last years, for example, Space Forge in 2018,[220] Varda Space in 2020,[219] Outpost in 2021,[352] Inversion Space in 2021[353] and The Exploration Company in 2021.[354] Even more return-capable spacecraft have been announced since 2021. Organisations aiming to perform in-space manufacturing directly have gotten more numerous too.

Space Situational Awareness (SSA) is under Miscellaneous and has also seen large growth. It is easier to enter but the market opportunity seems unclear.

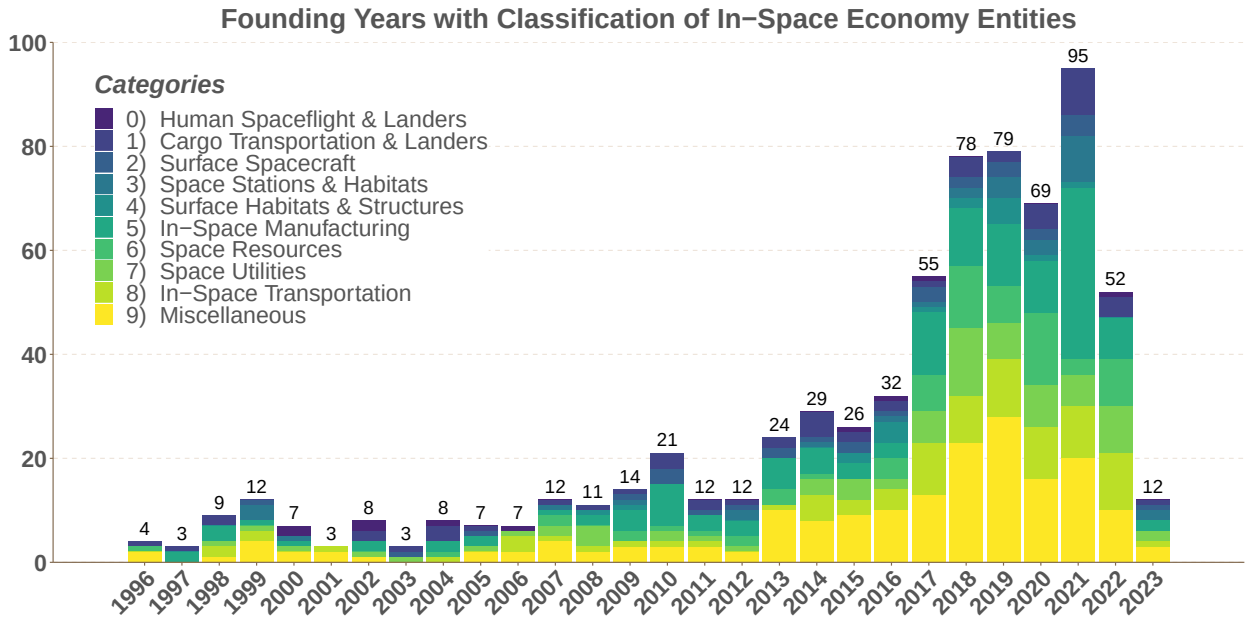

Figure 4: In-Space Economy Founding Years by Classification

5.4 Funding with Classification

Figure 5 collects funding in the defined ranges with categories. Here, organisations with multiple entries also have the funding duplicated. Thus, it would be wrong to add the funding amounts to get the overall total. An alternative would be to present funding once per company, but then many categories would seemingly have no funding.

The funding levels are the total amounts and the exact investments for in-space economy may be unknown in case of larger companies. "Yes, but amount unknown" commonly means an established space company, but it has not been made public of how much they are investing in those specific new fields. The "Unknown" category is for entities which have not announced funding and it is likely they have no or very small amount of capital.

Over $1 billion in private and awarded funding have received e.g. SpaceX, Boeing, Blue Origin,[355] Relativity Space[356] and Sierra Space.[130]

Some in-space transportation services have accumulated large funding, e.g. Astroscale with over $390M.[357] Momentus went public via SPAC in 2021 and has raised over $145M.[358]

Commercial space stations are capital intensive. Axiom has raised over $505M.[46] Bigelow spent about $250M over 20 years but shut down in 2021.[26] In 2021, The Orbital Reef from Blue Origin, Starlab from Nanoracks and Northrop Grumman were awarded $130M, $160M and $125.6M, respectively.[359]

Many startups in the lunar, space resources, and ISRU fields have received awards from NASA, related to the Artemis program. Moon lander companies and funding amounts are for example: Moon Express with $65.5M,[360] non-profit SpaceIL with approx over $160M,[361,362] Astrobotic with $212M,[363] Firefly over $175M,[364] ispace over $195.5M,[365] Masten Space Systems considerably over $75.9M[366] but they went bankrupt in 2022.[95]

Redwire bought Made In Space, Techshot and others, and went public raising over $100M.[367,368] Voyager Space Holdings has acquired Pioneer Astronautics and many others.[369]

Among in-space manufacturing and particularly small re-entry capsules are: Varda has raised $51M,[219] Space Forge has raised over $10.8M,[370] Inversion Space raised $10M[353] and The Exploration Company has raised over $50M.

Most surface habitat company investments are limited, but that ecosystem is also early. Relativity Space is an exception with $1.3B[356] and they have stated they want to build first structures on Mars.[371] ICON has raised over $451M for 3D printed homes and has concepts for lunar bases.[345,346]

Aleph Farms has raised over $130M[372] and grew cultured meat on the ISS in 2019.[373] GITAI from Japan has raised over $66M to build space robots and rovers.[374] Kepler has raised over $200M to bring the Internet outside of Earth.[290]

Largest VC rounds since 2021 have been Sierra Space with $1.4B[130] and Axiom with $350M.[46]

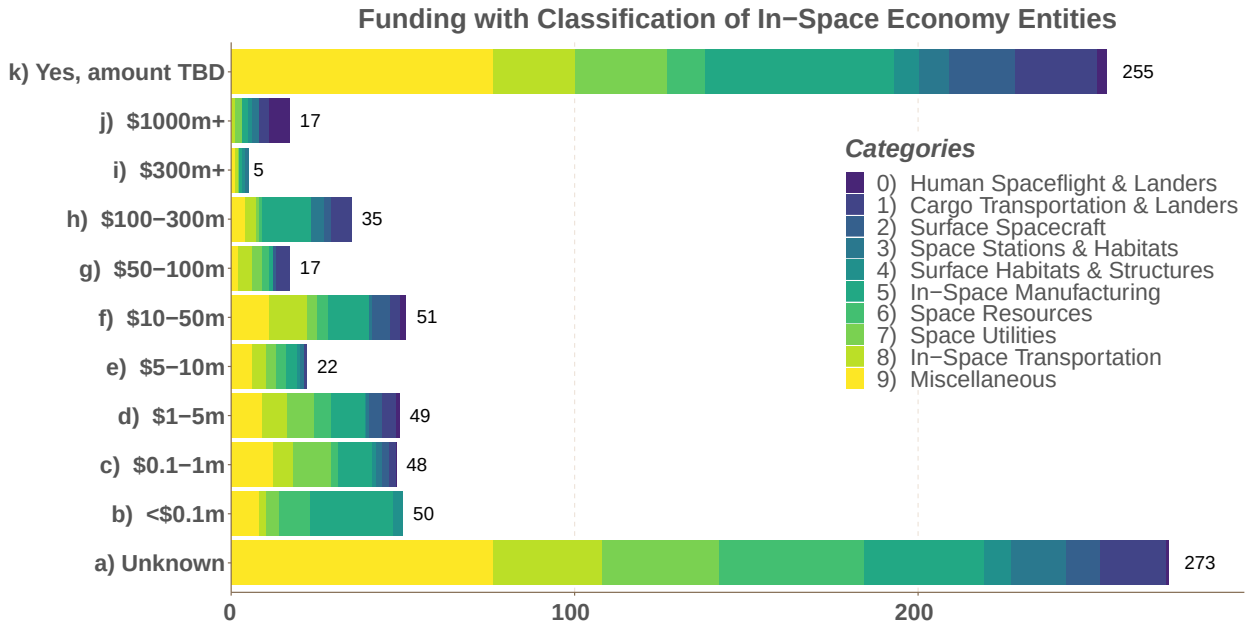

Figure 5: New In-Space Economy Status

5.5 First Launches

The year of first missions and demonstrations in space have been plotted on Figure 6. The goal in this section is to collect the maiden launch year of the activity most relevant to the in-space economy fields. Henceforth, entities may have launched hardware to space before the years referenced here.

Knowingly cancelled and dormant entities have been marked with "Dormant". "Not applicable" includes organizations, which are not performing own space missions. "Not announced" are companies that do not seem to have announced a planned year for their first missions or activities in space. The large unknown amount correlates to the prevalence of companies in the idea and early stages.

Example first launches in 2020-2021 were Astroscale's debris removal test,[357] D-Orbit's space tug,[375] Airbus Bartolomeo's external payload hosting on the ISS.[376] Hewlett Packard's The Spaceborne Computer launched to the ISS in 2017[377] and second in 2021.[378] Inspiration4, the all private sector and citizen mission, happened in September 2021.[157]

In the 2021 survey:

- Example missions scheduled for 2022 were lunar landers from Astrobotic,[379] Intuitive Machines,[380] ispace;[381] Space Forge;[382] space tugs from Launcher[383] and Momentus;[384] Starship.[385]
- Planned launches for 2023 included for example Firefly's[386] and Masten Space's[387] Moon landers; Kepler's in-space data relay constellation;[351] Inversion's[353] and Varda's[388] small re-entry capsules, and ESA's Space Rider.[389]
- Planned launches for 2024 were for example lunar robotic outpost from Quantum Space,[390] Axiom Orbital Segment,[391] Space Entertainment Enterprise's SEE-1[392] commercial film studio module, SSTL's Lunar Pathfinder[393] mission to Moon and The Exploration Company's reusable orbital vehicle Nyx.[354]

In reality, as the launches happened or currently planned schedules:

- First launches in 2022 were ispace, Momentus, Nanoracks (cutting demo), Mercury Systems (ZBLAN manufacturing), Cedars-Sinai (stem cell production) and others.
- First launches in 2023 have been Epic (space tug), Launcher, Redwire's multiple missions, Starship, Starfish Space, Varda and others.
- Planned launches for 2023 have Intuitive Machines, AstroForge (asteroid prospecting), Exotrail (space tug), Space Forge, and others.
- Notable future launches are Vast Haven-1 space station in 2025, Crescent Space lunar spacecraft in 2025, Astrolab lunar rover in 2026, commercial Mars lander in 2026, and others.
- Notable delays during 2 years are Axiom space station module to 2026, Astrobotic lander likely to 2024, SSTL's Lunar Pathfinder delayed to 2025, Space Rider to 2025 etc.

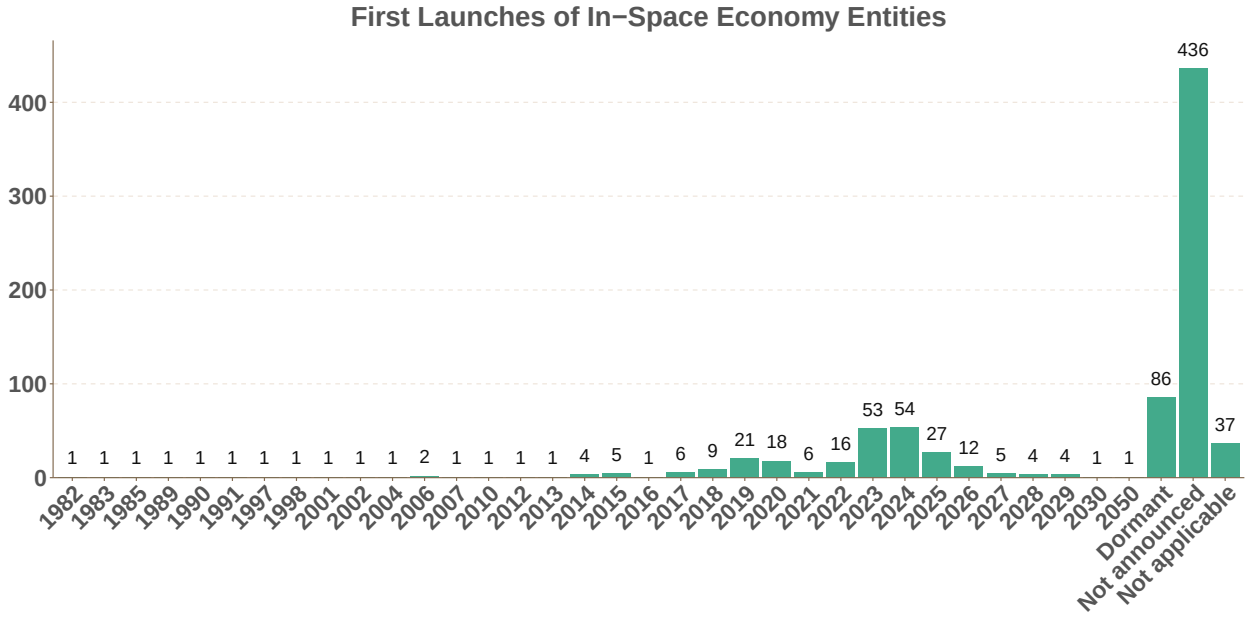

Figure 6: In-Space Economy First Space Launch Years

5.6 Geographical Distribution

Distribution of the in-space economy companies by locations of headquarters is on Figure 7.

Approximately half of the 823 entries have headquarters in the United States. Largest founding rounds are also skewed towards the United States. Many in-space economy fields are very capital intensive, and at the same time do not have large existing or immediate markets, making them higher risk.

Example entries from the 73 in the UK are Space Forge, Lunasa Space (reusable space tug), Space Entertainment Enterprise, Spacebit (lunar rover), SSTL (lunar spacecraft), LodeStar (additive manufacturing), Metalysis (space resources), Space DOTS (microgravity testing), Space Solar (space solar power), Space Power (in-orbit wireless power) and others.

Based in Germany and among the 40 entries are for example The Exploration Company, yuri (ISS payload hosting), PTS (lunar lander), Exolaunch (space tug), ATMOS Space Cargo (reentry capsule), DCUBED (in-space manufacturing), Orbital Matter, Okapi:Orbits (SSA) and RFA.

France's 39 entries include Space Cargo Unlimited (microgravity platform, space wine), Spartan Space (habitats), Thales Alenia, Airbus, MaiaSpace, Interstellar Lab and Gama Space (solar sail).

Italy's example entries include Argotec (space coffee, data relay), D-Orbit, Kurs Orbital (docking system) and many other large companies, which have offices in several countries.

China's 8 entries include for example Origin Space (space resources), Space Craft Beer, Interspace Explore (commercial resupply), AZSpace and Rocket Pi (orbital biology lab).

Japan has 28 entries, which include for example Astroscale and ispace, but both have offices around the world. Further entities are GITAI (robot astronauts and rovers), Dymon (lunar rover), Elevation Space (microgravity services), IDDK (microgravity platforms) and Mitsubishi Electric (additive manufacturing). Car manufacturers like Toyota, Lexus, Nissan and Honda have also researched lunar rovers.

Canada's example entries among the 36 include Kepler Communications (data relay), Canadian Space Mining Corporation (space resources), Eternal Light (power beaming), NorthStar (SSA), STELLS (lunar rover and wireless power) and Canadensys Aerospace Corporation (lunar rover).

Australia has 31 entries, which include e.g. Space Industries (lunar rover, space resources), HEO Robotics (in-space inspection and SSA), Mawson Rovers, Nebula Interplanetary Systems (in-space manufacturing), Paladin Space (reusable satellites), Reach Robotics (robotic arm), Space Machines Company (space tug), Solar Space and Metakosmos (space suit).

Aleph Farms (space food) and SpacePharma HQ are based in Israel. UARX (space tug) is based in Spain. Emrod (power beaming) started in New Zealand. Four Point (space mining) is based in Poland. Maana Electric (ISRU solar cells) is based in Luxembourg.

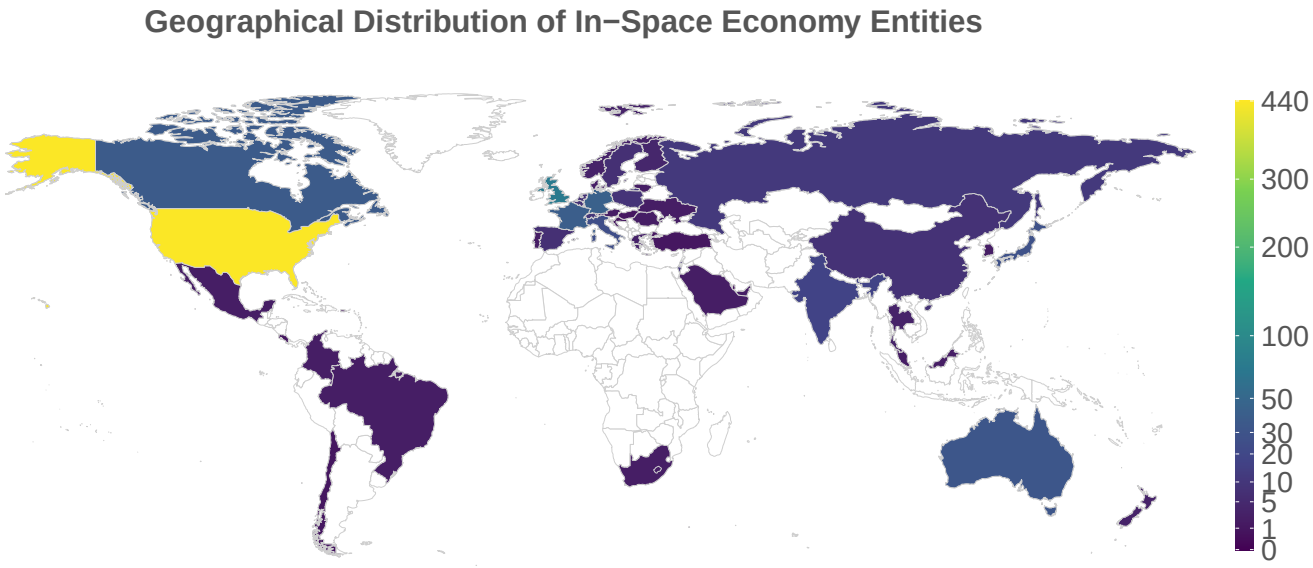

Figure 7: New In-Space Economy Map

6. IN-SPACE ECONOMY MARKETS

There are many space industries with large existing markets, such as launch vehicles, telecommunications and spacecraft manufacturing. It is possible to measure the revenues and calculate Total Available Market (TAM). There are limitations, thus Serviceable Available Market (SAM) and Serviceable Obtainable Market (SOM) provide more realistic estimations. It is also possible to determine the unit economics, take advantage of economies-of-scale, and capture part of the market through various competitive advantages. However, even in those established fields, most new actors experience delays, cost overruns and strong competition.

Unfortunately, for almost all the fields in the new in-space economy, the markets are small or do not exist. Especially when considering commercial customers. Non-existing or small markets also tend to grow slowly. In other cases, even if the monetary amounts are relatively large, then the amount of customers may be very small, often in single digits. Many in-space economy industries are also connected, with many being the leading potential customers to other. This creates a high risk scenario, where the failure of one entity could create a chain-reaction of failures through many areas.

To conclude, the primary challenge continues to be the lack of or very small number of customers and medium-term economic viability for most of the specialized in-space economy services.

6.1 Market: Space Stations

In the 2017 report "Market Analysis of a Privately Owned and Operated Space Station", authors concluded that a low estimate for revenue from activities on a space station is $455M and the high estimate is $1187M. In the high estimate, manufacturing products in space, specifically optical fibers, accounted for over a third of revenues. Satellite assembly in orbit was close to it."[394] Manufacturing optical fibers in space profitably is not a proven business idea and may easily not come to fruition.

M. Kokorich, founder of Momentus and several space companies, wrote in Aug 2020 that "The future market opportunities enabled by the disruption in space transportation are enormous. Even without space tourism, space habitats will be almost a two trillion dollar market in 10-15 years."[395] Three years later, it does not seem to happen in that timeframe.

J. Foust quoted Blue Origin's Erika Wagner in October 2022 from the ASCEND conference "we don't know what markets will be successful on commercial space stations; if we did, we would be doing them on ISS. Have to foster new markets."[42]

J. Foust further wrote at length about the uncertainty of markets for commercial space stations in June 2023 and most of the developers agreed.[396]

6.2 Market: Space Tourism

Grand View Research estimated the global space tourism market size at $695.1M in 2022.[397] The year 2022 saw Axiom Mission-1 launch and 3 crewed Blue Origin sub-orbital launches. This market may also include training and other astronaut services. However, it seems to be a considerable overestimation.

NSR's Space Travel & Tourism Markets, 4th Edition report forecasts the opportunity for flying passengers beyond Earth, on commercial vehicles, to exceed $9.2 billion by 2032, with nearly 90 astronauts, researchers, and tourists to be flown. These revenues only cover ticket sales, whose prices are expected to average $100M per person over the decade.[398] The average price seems high.

6.3 Market: In-Space Transportation

Momentus reported $1.7M in revenues for the first half of 2023. They also announced a satellite platform product line based on Vigoride.[240]

Euroconsult predicts on-orbit services will generate more than $4B in 2031 in the report "Space Logistics Markets, 2nd edition" released in April 2023.[399]

Allied Market Research reported on space robotics market in Feb 2023 with estimation that "the global space robotics market size was valued at $4.3B in 2021, and is projected to reach $8B by 2031."[400]

6.4 Market: Satellite Servicing

Satellite servicing is a market thanks to two MEV missions flown by Northrop Grumman (SpaceLogistics) in 2019 and 2020 and more contracted.[401]

BIS Research forecasted in 2022 that the in-orbit refueling market will reach $1.09B by 2032.[402]

NSR's In-Orbit Servicing Markets, 2nd Edition from 2019 forecast $4.5B in cumulative revenues by 2028. The growth will be over all applications in all orbits with GEO life extension the largest share.[403]

NSR's In-Orbit Services: Satellite Servicing, ADR, and SSA 6th Edition report from 2023 forecasts over 4,500 satellites could be serviced via Last Mile Delivery service providers. However, the actual market demand reaches only 1,350 satellites, generating over $1.8B in cumulative revenues by 2032.[404]

Markets and Markets report from May 2023 estimated the on-orbit satellite servicing market to be $2.4B in 2023 and projects to reach $5.1B by 2030.

Considering that no new mission extension or satellite servicing flights were performed, and only a few may have been partially booked, it is difficult to see how such large numbers were deduced.

6.5 Market: Space Debris Removal

Market Business Insights estimated in April 2023 that "the active space debris removal market size will grow from $26.50M in 2021 to $452.65M by 2030."

Fortune Business Insights projects the global space debris monitoring and removal market to grow from $942.3M in 2022 to $1527.7M by 2029.[405]

NASA Office of Technology, Policy, and Strategy published report "Cost and Benefit Analysis of Orbital Debris Remediation" in March 2023.[285] J. Foust of SpaceNews wrote that NASA billed the report as the most rigorous cost-benefit analysis to date of orbital debris remediation, noting that debris removal analyses had largely focused on sustainability and "moral responsibility" for doing so. The report found that laser-based debris removal systems create benefits that exceed costs within a decade, but other systems will likely need over 20-30 years to break even. He also noted a finding that space debris imposes only relatively small costs on satellite operators today through avoidance manoeuvres and collision damage. The model NASA developed, which was limited to U.S. operators, estimated annual costs of only $58M a year.[406]

6.6 Market: Lunar and Cislunar

Moon Village Association published "The Lunar Commerce Portfolio" in November 2022. The members of the MVA's Working Group on Lunar Commerce and Economics compiled the full range of potential lunar businesses, and their interactions, that are anticipated in the near term and long term; both on the Moon and in lunar orbit. The best assessments of prices for commercial products and services on the Moon, and the resulting revenue projections, were also collected.[12]

Philip T. Metzger published a paper on "Economics of in-space industry and competitiveness of lunar-derived rocket propellant" with the latest revision in February 2023.[14]

NSR published "Lunar Markets, 3rd Edition" market report in March 2023.[407]

NewSpace Global published a market report "Cislunar Market Opportunities".[408]

7. CONCLUSIONS

A statistical overview of 823 in-space economy entries and about 750 unique organisations has been presented. This is almost double compared to the first and previous publication in 2021.[1]

All the activity areas have been classified into a high-level ten category taxonomy of in-space economy. A glossary with sub-categories, definitions, example entities and projects was updated. A short historical overview about the primary in-space economy fields was kept and updates with advancements from the last 2 years were added.

A goal was to leave a second snapshot from 2023, after the first publication in 2021,[1] to be able to continue discovering trends and popular new space industries over the coming decade.

- New in-space economy entities are continuing to emerge and the pace is increasing, but the number of launches to space or commercial revenues remains relatively small.
- There has been an overall large growth during the previous 2 years. Number of public database entries increased from 472 to 823 with some discovered and many founded.
- Business ideas are converging in cases where the core technologies are similar. Primarily due to small or non-existing markets in the original niches. For example, space tugs entering satellite manufacturing, satellite servicing, and active debris removal markets.
- First space launches are often being delayed. Possibly even more in these fields compared to small launchers and constellations.
- Commercial human spaceflight has been demonstrated with Inspiration4 and Axiom and regular suborbital missions.
- Many commercial space station and module providers have large funding and are actively developing. Vast emerged in the last 2 years. However, uncertainty about commercial markets has been a concern. Very recently, Northrop Grumman cancelled its own plans and Blue Origin may be re-prioritizing Orbital Reef.
- The first commercial Moon lander from ispace failed to have a soft landing in April 2023. Intuitive Machines should launch in 2023. The rest have been delayed to 2024 and beyond. Masten went bankrupt.
- Lunar rovers are now planned to fly in 2024.

- In-space manufacturing has many microgravity service providers and numerous small reentry capsules have been announced. However, recurring commercial in-space production for Earth and in-space construction has not yet started. Varda launched their first capsule and manufactured a drug. Redwire sold an optical crystal as their first made-in-space product.
- Satellite life extension has been demonstrated, and is a market, but only in GEO for now.
- In-space transportation is very popular by the amount of organisations building and launching space tugs, but the ecosystem may not be able to support all of them in the near-term. D-Orbit, Momentus and Launcher have launched two or more missions each.
- Starship is expected to have a major role in the future of the in-space economy thanks to lower launch costs together with large volume, upmass and cadence. First test launch in April 2023 failed and second should happen soon.
- Space solar power has re-emerged in the last 2 years, partially thanks to ESA, and may become one of the largest space industries thanks to very large terrestrial energy markets.

The intention is to keep repeating this study annually as a whole or as deep dives into specific categories, e.g. in-space manufacturing,[4] space solar power,[409] space habitats, and surface spacecraft.

The database and figures are viewable online and planned to be updated multiple times per year.

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