11 The Longer Term Future of Launch and Propulsion Systems

Introduction

In the previous chapter the remarkable progress that is being made to increase the reliability, performance and cost effectiveness of launcher vehicles was presented in some detail. This particularly stressed the progress that is being achieved with reusable launch systems. SpaceX Falcon launchers, Blue Origin New Shepherd and planned New Glenn and Sierra Nevada's Dreamchaser vehicle that would provide resupply services to the International Space Station are just some of the new advances that are being achieved. Advances in 3D printing, additive manufacturing and other new production systems are not only resulting in spacecraft operating more efficiently and cost effectively, these new techniques are also serving to reduce the cost of launch vehicles as well. The advances of today will not be the advances of tomorrow, though. The space revolution will continue in the form of new and better forms of space transport.

In the 2020s and 2030s even more innovative systems will provide dramatic improvements in our ability to get systems to orbit. Deep space transportation will improve the most, as we find even more efficient ways to propel systems into the cosmos. We have found that Earth orbit and deep space systems diverge in that those systems needed to climb out of Earth's gravity well need to build up velocity via constant acceleration over weeks, months or even years for deep space missions.

Deep Space Systems

There are many ideas about how to create new and innovative systems optimized for deep space travel. These systems would include those that have the ability to fly to other stars and to leave the Solar System on interstellar flights. There are at least four basic concepts that have been seriously considered that could attain velocities sufficient to travel outside the Solar System. These concepts involve: (i) solar sail systems that could also be augmented by gravity assist; (ii) laser driven or directed energy systems that likewise could be aided by gravity

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assist; (iii) nuclear fusion-powered vehicles; and (iv) systems that would combine water-ice fuel systems with protective shielding against collisions with particles while traveling at substantial velocities near light speeds.

Solar Sail-Powered Craft

The idea of solar sail-powered craft is hardly a new idea. In recent years, though, there been practical experiments seeking to determine the possibility of using such propulsion systems to reach sub-light speeds that would be needed to travel to other stars. The Planetary Society has attempted several experiments with its "LightSail" approach that deployed small objects from a nanosat. These experiments to date have had limited success.

The Japanese agency (JAXA) with its IKAROS experiment in 2010 was the first to prove that solar-powered light sails indeed could work. This light sail was composed of a polyimide with a reflective surface and was 200 square meters in size. It traveled to Venus and then traveled on to the far side of the Sun.

The European Space Agency had their Gossamer De-Orbit Sail experiment in 2013. Currently NASA has its Near Earth Asteroid Scout that is scheduled to fly on the Solar Launch System (in 2019). JAXA has its OKEANOS experiment that will seek to fly to Jupiter's Trojan asteroids in the late 2020s (https://en.wikipedia.org/wiki/Solar_sail#Breakthrough_Starshot).

The most exotic and ambitious project of all is known as Breakthrough Starshot which is privately funded. This light sail experiment, which is headed by ex-NASA Ames Chief Gen. Peter Worden, would seek to achieve an incredible speed of 20% of the speed of light (60,000 kilometers per second or about 134,000,000 miles an hour). In short, this fantastic spacecraft would be gradually accelerated until it would be going really, really fast.

This amazing craft would be composed of lightweight elements for its light sail. It would not be driven by solar radiation but instead will be powered by a number of Earth-based lasers that would drive a nanocraft carrying miniature cameras. This 'Starshot' project would seek to go to Alpha Centauri, the closest star to Earth, which is some 4.4 light years away (about 40 trillion kilometers distance). That is equivalent to about 27,000 trips to the Sun – or a very long, long way.

There have been many different materials proposed for the structure of a solar sail vehicle (i.e., lithium or polyimide), for an effective reflective surface (i.e., aluminum) and for a good emissive surface (i.e., chromium). There are variations on the theme of light sails. One option is also the use of the solar wind (or particles emitted from the sun to create a magnetic field) or a magnetic sail that could be used to generate power to support electrical propulsion. One can also embed high-efficiency solar cells in the light sail to generate electricity for ion propulsion. Finally it might be possible to use the gravitational field of perhaps Jupiter or Saturn to slingshot a light sail craft to a higher velocity.

Today the feasibility of light sail systems for scientific or commercial purposes remains to be proven. The continuing efforts by NASA, ESA and JAXA to test light sails together with the private initiatives of the Planetary

Society and the ambitious Breakthrough Starshot initiative suggest a high level of interest in a light sail starship. If you believe that all of these space scientists in their mission to make light sails work are not bonkers, then one of these projects may truly succeed. One can at least hope that they are not squandering their efforts by chasing bogus photons – the modern version of tilting at windmills. All of this effort seems to suggest that there is truly something there. We must at least hope that one of these efforts will eventually be proven to be correct and true starships created. The physics and the theory are clearly there already. Perhaps we will find the way to create workable light sail starships within the next decade or so. Figure 11.1 shows how laser signals can be used to drive a human-designed craft up to the highest velocity ever known.

Laser or Ion Driven Spacecraft

The light sail systems envisioned to date would use either photons from the Sun or an Earth-based laser system. Some scientists have envisioned that photons or electrically charged ions generated on board a spacecraft can achieve great speeds over time. This type of system would not need to depend on the Sun or laser or directed-energy systems situated on Earth, but rather could travel with the spacecraft to accelerate it to ever greater velocities. Again the

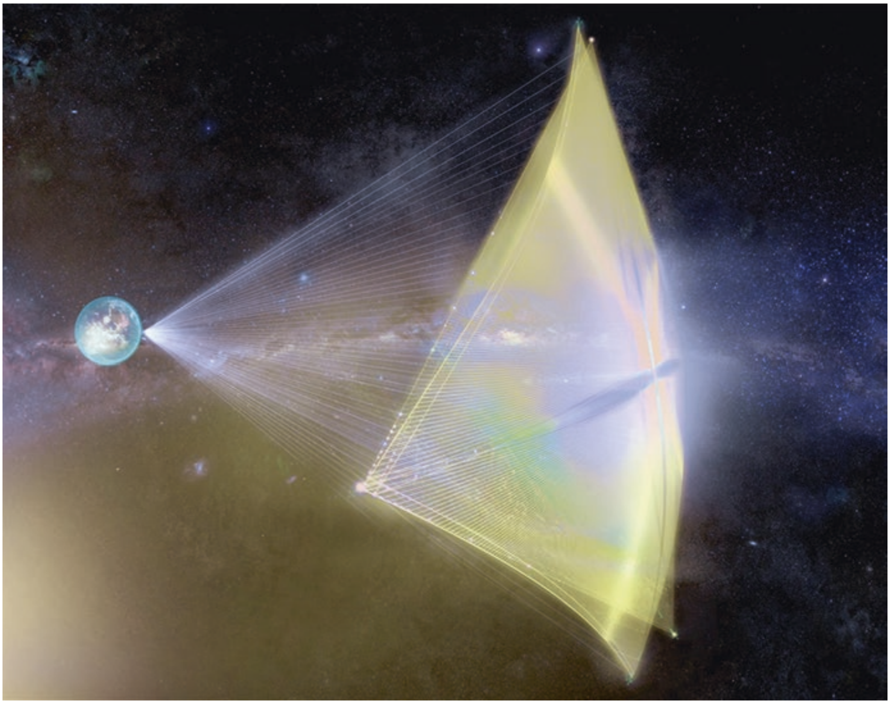

Fig. 11.1 Artist representation of Earth-based laser system connecting with a starship. (Graphic courtesy of Breakthrough Starshot.)

concept is not that of great bursts of speed but the steady accumulation of velocity through constant acceleration for long periods of time. If such a system could only achieve a tiny acceleration of 1 cm/sec^2 it would nevertheless add up over time. The acceleration of gravity at ground level is 9.8 m/sec^2, and thus this acceleration would be 980, or nearly a thousand times less than the force of gravity on our planet's surface. Over time this modest acceleration would add up. There are 86,600 seconds in a day and 31,586,600 seconds in a year. Thus the distance traveled in a year would be about 50 million kilometers – not even half way to the Sun. But in two years it would have gone 200 million kilometers, in three years 800 million kilometers, in four years 1.6 billion kilometers, and by the end of five years about 3.2 billion kilometers. The squared part of the formula relating to acceleration adds up over time.

The key would be to design an on-board system that can last for many years, one that can generate electrically charged ions or emit photons for many years at a time so that the velocity can build up to a speed sufficient to travel to the stars. The Breakthrough Starshot initiative has based its mission design on using a very high-powered ground-based laser, but there is no particular rule that says that a combination of technologies could not be used. It might be possible to use an interesting combination of thrust systems. One might use a ground-based laser, an on-board laser system, an on-board ion thruster or even a chemical thrust system to maneuver around the orbit of Jupiter or the Sun to create a gravity-assisted boost to a spacecraft's velocity that might be the most efficient. Indeed it might be hybrid systems that use a combination of thrust technologies that prove the most effective way to achieve the maximum speeds and still have the maneuverability that is needed to avoid obstacles and use gravity assist as part of the process.

Nuclear-Powered Vehicles

The U. S. Defense Advanced Research Projects Agency (DARPA) and the British Interplanetary Society have been considering the feasibility of nuclear-powered transportation systems for a half century. It has been suggested that nuclear fission or even nuclear fusion systems have sufficient concentrated power to allow for efficient long-range space travel. There are today many feasible and efficient spaceship designs for different ways to use nuclear energy for propulsion.

Although we are not expecting to create starships such as in *Star Wars* or *Star Trek*, with craft that can make hyperspace leaps from one part of the cosmos to another and exceed the velocity of light speed limit, there is still enormous potential for a nuclear-powered craft that might be continuously accelerated until it did reach enormous speeds.

The first steps in the use of nuclear energy in space were to use isotope-based and plutonium-based power supplies for long-term operation of spacecraft. The so-called Radioactive Thermo-electric Generators (RTGs) have been proven on spacecraft for many years. In the case of RTGs they simply convert heat from plutonium-238 decay into electricity, using thermocouples. The RTG on the Navy's Transit 4A satellite produced only about 3 watts of electrical power. In the late 1960s, NASA launched the RTG-powered Nimbus III, which lasted decades in orbit due to its nuclear power supply.

There has been continuing research and development in the area of rocket propulsion that goes beyond simply powering a spacecraft in its operation. There are several options that are subject to current R & D. They fall into categories such as: (i) nuclear pulse propulsion; (ii) nuclear thermal rocket propulsion; (iii) nuclear electric propulsion; (iv) direct nuclear propulsion; and (v) nuclear-powered ramjet propulsion.

Nuclear Pulse Propulsion This type of approach to nuclear propulsion traces its history to the Orion (DARPA) and Daedalus (British Interplanetary Society) research projects back in the 1960s and 1970s. The most recent concepts for a starship designed with nuclear pulse propulsion involve what is called catalyzed antimatter. This is a variation of nuclear pulse propulsion based upon the injection of antimatter into a mass of nuclear fuel as a means of reducing the size of the nuclear pulse propulsion system.

Nuclear Thermal Rockets This is another type of nuclear fission reaction propulsion system and can be used to create propulsion in a variety of ways. It would typically not be used for liftoff from Earth, but for efficient station-keeping operations that would be more efficient than chemical propellants. Nuclear thermal rockets can provide great performance advantages compared to chemical propulsion systems. Nuclear power sources could also be used to provide the spacecraft with electrical power for electrical ion thrust.

Direct Nuclear Propulsion Again there are many variations on this basic concept. One of the prime concepts would involve a core reactor that directly propels the rocket by the exhausted coolant in a gaseous fission reactor. The nuclear fission reactor core could be either a gas or plasma. This type of direct nuclear propulsion could possibly create specific impulses that would be in the range of 30 to 50 kilo Newton-seconds/kg of fuel. It would be based on exhaust velocities that could be as high as 50 kilometers/second. This exhaust plasma or gas would create sufficient thrust for fast planetary or even interplanetary travel. In some designs hydrogen coolant becomes the propellant. The hydrogen serves to cool the reactor and its various structural parts. Once the hydrogen passes through the core region, it is exhausted at the indicated velocities. If cooling from the propellant is not enough, external radiators can be used for the reactor as a supplement. In some other designs, fissioning gas plasmas are used to heat a low mass propellant.

Nuclear Ramjet Propulsion This is the approach to use nuclear power to create a ramjet approach to a cruise missile or aircraft. Project Pluto is one such development project. This type of system only works inside Earth's atmosphere. The principle behind the nuclear ramjet is actually quite simple. The velocity of the missile sucks air into intake vents at the front of the vehicle. This is known as the ramjet. The innovation is to use a nuclear reactor to superheat the compressed air that has already experienced the ramjet effect. The super-heated air exhausts at high speed out through a nozzle to create thrust sufficient to result in hypersonic speeds.

In the future there are many potential applications of nuclear fission or fusion-based space transportation systems. Propulsion systems that allow for efficient station-keeping operations using electric ion propulsion systems that outperform today's xenon ion propulsion systems in terms of long-life performance are the most likely near-term application. Today's chemical propulsion systems are quite adequate to get to the Moon and the closer planets, and gravity assist can help to get to even the outer planets.

Even so NASA has at least argued that a nuclear-powered rocket could be half the size of a chemically powered rocket to support missions to Mars. Figure 11.2 shows a nuclear thermal propulsion system that was proposed to the U. S. Congress in 2016. At the time, NASA administrator Charles Bolton proposed that it could create such nuclear fission-based craft by 2033. They provided testimony as to why it could halve the size of a chemically powered rocket system. Such a program has not been authorized for funding [1].

At this time it seems that true nuclear rocket systems will have to await future space missions. Only such objectives as planetary defense against potentially hazardous asteroids, Mars colonization, or asteroid mining might convince legislative bodies to fund such a difficult and expensive program. This is in spite of the cost efficiencies that have come from NewSpace commercial programs that have seemingly produced far more effective technology at lower cost in recent years.

The bottom line is that it seems that there will need to be more powerful economic incentives to develop either direct nuclear propulsion or nuclear pulse propulsion systems in coming years by NASA or any other space agencies. There is always, of course, the latent goal of developing nuclear-powered rocket systems for objectives related to

Fig. 11.2 Proposed nuclear thermal propulsion craft called Copernicus, envisioned by NASA to go to Mars. (Illustration courtesy of NASA.)

national defense. Such a step would be a step backwards for commercial development of space and the peaceful uses of outer space.

H_2-O_2 Defined Star Craft

Most studies of starships using nuclear propulsion focus on the most pertinent issue of how to achieve sufficient thrust to generate velocities that represent a significant fraction of the speed of light, especially when it is understood that Lorentz contraction also means that mass increases as it moves to higher and higher speeds. But even if we humans can design interplanetary craft that can move at speeds such as a third of the speed of light, there will be other problems to be addressed and solved. One of these key issues is how to protect a star craft that is moving at such enormous speeds. If such a spacecraft should encounter a substance such as ice formation in the Oort Cloud moving at enormous relativist speed the result would likely be disastrous. A magnetic shield might help to divert ions, but some form of physical shield or buffer would seem to be required for objects that hold no electromagnetic charge.

Brian McConnell in his book about water-based "spacecoaches" has made a credible technical case for a starship that is essentially made of frozen water as its essential makeup, with an ice-shield against cosmic accidents. This is an idea perhaps first put forward by Arthur C. Clarke, in which a star cruiser has to land to restock on ice. McConnell has stated his arguments for his water-based design as follows: "The water is used for many purposes before it is superheated via electro-thermal engines to generate thrust, uses which include radiation shielding, thermal management, life support, crew consumption and attitude control." The most important use of all, however, might be a protective ice shield that would protect the pursuing spacecoach [2].

Tethers, Space Elevators and Space Funiculars

The nearer term future may look to the more expanded use of tethers and then, over the longer term, ultimately of space elevators or funiculars. The use of tethers or long extended structures in Earth orbit can be used both to lift objects to higher orbits and also to generate electricity within the geomagnetosphere to create the energy needed to restore the tether lifting system after the transfer orbit has been achieved. Several experiments by NASA, JAXA and ESA have demonstrated the feasibility of momentum exchange to lift objects to higher orbits.

NASA is currently working on an experiment known as the Momentum-Exchange Electrodynamic Reboost tether propulsion system, or MXER tether. The object of this experiment is to deploy a very long tether, some 100 to 150 kilometers in length, that would be able to go through a momentum exchange to lift a satellite from low Earth orbit to a transfer orbit that that would have an apogee at GEO orbit. The NASA explanation of how this process would work is as follows:

> *Momentum-exchange tether propulsion transfers momentum from one object to another by briefly linking a slow-moving object with a faster one. Much the same way as ice skaters play "crack the*

whip," the slower object's speed could be dramatically increased as momentum and energy is transferred to it from the faster object. Similarly, a spinning tether facility in an elliptical Earth orbit might snare slower-moving spacecraft in low-Earth orbit and throw them into much higher-energy orbits [3].

This type of momentum exchange lifting system, if proven in practice, could significantly reduce the cost of launching satellites to GEO orbit and would require large communications satellites to be launched to LEO, where this tether lift system would raise them to a transfer orbit before final deployment in the correct circular orbit.

Previous experiments have involved tethers of much shorter lengths. The MXER experiment, however, would require a much greater length to generate enough electrical energy to restore the system to its original orbit so that it could repeat the lift sequence over and over again.

The idea of using Earth's magnetic field to generate electricity is not only foreseen as a way to lift satellites to higher orbits. The so-called EDDE systems (Electrodynamic Debris Eliminator) envision a system that is used to throw a net over space debris to hasten its de-orbit and operate in orbit over the longer term by generating electric propulsion derived from Earth's magnetic field as well [4] (Fig. 11.3).

An in-orbit momentum exchange lift system that would be up to 150 kilometers (94 miles) in length represents the most ambitious tether experiment to date. Yet this is far, far short of the idea of creating a space elevator or space funicular to GEO orbit. In this case the

Fig. 11.3 Artist representation of the Momentum Exchange Lift System (MXER) experiment by NASA. (Graphic courtesy of NASA.)

tether or cabling system would not only need to reach from Earth's surface out to GEO orbit but considerably beyond to create a lift capacity – or 'negative weight' – that would offset the gravitational pull of a giant tether system that reaches 35,870 kilometers (22,230 miles) out to GEO orbit. From this perspective, the momentum exchange system that would lift a LEO satellite to a transfer orbit, then to GEO seems a much more feasible and cost-effective solution.

Mass Drivers and Rail Guns

Other advanced space transportation systems that have been considered for some time are mass drivers or rail guns. Again the key force involved is electromagnetism. There have been proposals put forth, from Maglev trains to the HyperLoop and rail guns, for years.

The basic idea with rail guns or coil guns is to use magnetic force to accelerate transport vehicles or units to high rates of speed. Gerard O'Neil in his book *The High Frontier* explained how a Maglev system on the Moon could send excavated materials from the Moon into orbit with relative ease due to the Moon's low gravity and lack of an atmosphere. The materials sent could be used to supply basic building materials to create a space colony. Creating a Maglev system that would attain sufficient speed to gain orbit from Earth is a much more difficult feat.

Rail guns or coil guns create an electromagnetically induced acceleration along its rails (or coils). If the projectile or launching device (i.e., sliding armature) is magnetically active the speed will increase exponentially as power is increased. If the rails are many kilometers long, very high velocities can be reached – especially in a vacuum where there is no resistance.

The practical aspects of coping with the problem of g-forces and atmospheric drag currently suggest that a rail gun or coil gun would be used for launching materials or cargo into space rather than subjecting humans to excessively high g-forces or trying to cope with atmospheric drag. Another option would be to design a rail gun or coil gun system that might be used to assist with a spaceship launch. It has been suggested that one might create a rail gun that could be operated from a very high mountain or elevated structure that might be able to launch a stream of pellets or even propel a vehicle into space [5] (See Fig. 11.4).

Current understanding of the technical constraints suggest that human launch from Earth would not be possible. Use of this concept to launch humans from the Moon, Mars or other planetary bodies with limited gravitational force and little or no atmosphere, however, could be possible.

A rail gun or coil gun could, of course, be used as a weapons system. In this case, the objective would be to create very high speed targeted projectiles rather than putting cargo into space. Tests of a rail gun weapons system with energy levels that involve many mega Joules of power have been tested, but only in experimental tests. Such projective firings would not be to support launch operations but as longer range destructive cannon-type systems.

There is also the idea of accelerating plasma via a helical rail gun design with sufficient temperature to even achieve and sustain nuclear fusion. This is one of the concepts that is being explored to create a sustained nuclear fusion process. This sort of idea, however, has to be considered as a much longer-term

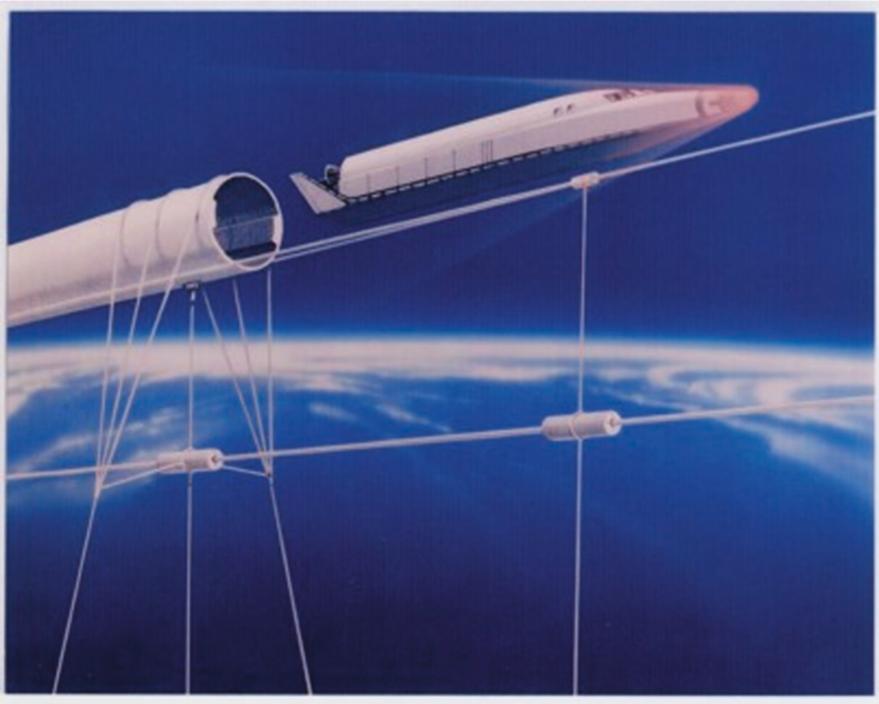

Fig. 11.4 Artist concept of a coil gun or Maglev system that could assist with the launch of a spaceship (Illustration courtesy of NASA.)

research activity and not a near-term concept.

Space Shields and Large-Scale Construction Projects in Space

For many years, the idea that one might create large-scale construction of infrastructure in outer space has been considered science fiction for several legitimate reasons – extremely high cost; technical, scientific and engineering difficulty; extremely harsh space environment; higher priorities here on Earth; and lack of an international regulatory framework or global space governance process under which to undertake such an initiative.

Today the rate of scientific and technological progress in space systems is hitting new heights. The sky is no longer the limit. Soon the James Webb Telescope will be launched, and we will be able to see back virtually to the Big Bang. The International Space Station (ISS) has set a precedent for international cooperation by dozens of countries working together to create and operate a complex facility in space to advance scientific knowledge and foster global cooperation in outer space. The opportunity now exists to create new space systems to protect our world from devastating cosmic hazards.

There are new types of infrared telescopes that could detect potentially hazardous asteroids down to 30 meters in size (city killers) as opposed to systems that can spot hazardous asteroids only 140 meters and larger. There are new systems that might allow us to create magnetic shields that could protect us from devastating coronal mass ejections from the Sun that could wipe out our electric power grids, our pipelines and vital space systems. We now have the technology and the knowledge that could protect our planet from devastating 'black swan' events that could do trillions of dollars of harm to the world economy. New types of technologies can allow us easier and more cost-effective access to space with new ways to protect the global economy from devastating cosmic hazards and preventing huge loss of life. It has been assumed for many years that we can only suffer the losses that come from killer asteroids, solar storms that destroy our vital infrastructure and cosmic hazards. Today we are developing new space technologies that show us a pathway to safeguarding Earth in new and innovative ways.

Conclusions

The majesty of launch vehicles propelling spacecraft into space is an awesome and exciting sight. New launch systems are becoming more reliable, effective and cost-efficient. Yet the subjects discussed in this chapter suggest there are important new technologies in the pipeline that could be safer and more efficient. The idea that the best way to put people into space by putting them on top of a controlled bomb will be likely become passé within the next three decades. It is not only dangerous, but there are environmental hazards that come from spewing noxious chemicals from more and more rockets launched at an ever increasing pace.

We need to find ways to do more in space even more efficiently. We need to build new space infrastructure to create clean electrical energy systems, protect our planet and provide better space-based services. We can accomplish this by developing the latest and best new means to get stuff into orbit. We still have a long ways to go to find and perfect the best ways to do this in the most efficient ways possible. If we can use tethers to flip spacecraft from LEO to GEO, the environment and the space industry will benefit. Nuclear propulsion, electric ion propulsion, solar sails, rail guns, and perhaps ultimately space elevators will create a new and even more exciting new space age in the decades ahead. The short story is that the coming trillion-dollar space industry will be built on the base of a host of new space technologies and exciting new ways to get spacecraft into Earth orbit.

References

1. Zolfagharifard, E.: NASA wants to use nuclear rockets to get to Mars: space agency claims the technique is 'most effective way' of reaching red planet. Dailymail.com (2016). http://www.dailymail.co.uk/sciencetech/article-3499441/Nasa-wants-use-nuclear-rockets-Mars-Space-agency-claims-technique-effective-way-reaching-red-planet.html
2. McConnell, B.: A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach. Springer, Cham (2015)
3. NASA: momentum exchange tether propulsion. https://www.nasa.gov/centers/marshall/pdf/100415main_momentum.pdf. Accessed 30 July 2018
4. ElectroDynamic debris eliminator. http://www.star-tech-inc.com/id121.html. Accessed 30 July 2018
5. Atkinson, N.: NASA Considering Rail Gun Launch System to the Stars. Universe Today (2010)