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Commercial Space In The Age Of "New Space", Reusable Rockets and The Ongoing Tech Revolutions

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Abstract

A plethora of converging frontier technologies are reducing the costs of space access and utilization, enabling major growth going forward in commercial space, both in orbits up to Geosynchronous Earth Orbit (GEO) and in "Deep Space" beyond GEO. This paper reviews these frontier technologies and enabling technological approaches, the landscape of enabled emerging commercial applications, their issues, and in some cases their competition and outlook, along with the attendant "hard problems". Major issues include mitigation of the in-space human health issues, reliability and safety, details regarding on body space resources, and a closed competitive and timely business case.

Introduction [refs. 1-9]

There are a myriad of reasons for humans to go into Space:

- Hedge the bets of the Species with respect to serious Asteroid Impact, e.g. becoming a multi-planet species and beyond-Earth colonization
- Positional Earth Utilities, a long standing and thriving commercial space industry, GEO and below.
- National Security
- Science

Projections by market analysts for Commercial Space include ten times more satellites in orbit within a few years and expansion beyond GEO ("inner space") into Outer Space/Deep Space with an overall valuation between $1 to $3 Trillion per year by 2040. [4-8] There are two distinct commercial space activities: commercialization of government activities and instances where the customer is another commercial or private entity. Thus far, the preponderance of commercial space activities has been “near Space, GEO, and below Earth Utilities with increasing activity in commercialization of government functions. What has largely been missing thus far is beyond GEO, “outer/ Deep Space” “real” commercial business. This latter activity is a result of the techs and approaches discussed herein, presently on a growth curve, initially involving space resource acquisition/ utilization including for fuel and manufacturing and toward colonization of moon(s), Mars and eventually more exotic places such as the poles of Mercury, the upper atmosphere of Venus and Titan.

Some of the basic precepts driving much of this increase in outer space commercialization include reusability, in-situ resource utilization (ISRU), Resiliency, Cost reductions / ROI, competition and leveraging. The myriad extant space resources include CO2 (Mars), water (moon, Mars, asteroids), minerals, Solar Energy, Volatiles, Microgravity, “Space”, vacuum, and low temperature. The option spaces include reusable or expendable, robotic and/or Humans, solar/chemical/nuclear/positron energetics and resupply or ISRU.

The purpose of this report is to indicate the breadth of announced commercial space planning, the associated frontier enabling technologies and approaches, the major issues going forward, and the potential impacts of these technologies. In addition, the report will provide commentary observations and highlight the “hard Problems” and envisaged longer term “frontier” activities and goals. Overall, the intent is to identify needed R&D to ensure success going forward as space commercialization ventures into “deep” or “outer” space and supports the call to “focus on problem definition” to accelerate entrepreneurial space.

Commercial Space Planning/ Possibilities [refs. 2, 3, 10-16]

A. Major LEO constellations of small satellites for high-speed internet and Earth observation, expanding the number of Satellites from the order of 5,000 now to some 20,000 plus in 10 years. The Earth observation satellites could enable “staring” anywhere 24/7/365.

B. “Utilities” for beyond GEO to service both public and private customers, including communications, energy/fuel, transportation, maintenance/ repair, life support, etc.
C. Mining writ large – Moon, Mars, and Asteroids for anything commercially viable such as water, minerals, HE3, rare earths, volatiles, “mass”, etc. There are purportedly some 1,100 sizable near-earth asteroids larger than a kilometer in diameter and more than one million larger than 40 meters in diameter at lunar distances from earth or less.
D. Entertainment – including 5 senses virtual reality (VR), videos, etc., virtual presence, to enable spending an evening exploring Mars from your living room, etc.
E. Collect anti-protons – these are present in the solar wind and become entrained in the Earth’s magnetosphere. Anti-protons are exceedingly expensive and, in terms of energetics produced by their 100% matter-antimatter annihilation, are some 9 orders of magnitude greater than chemical options.
F. Asteroid Defense, detection, tracking diversion of threats deemed capable of causing grievous harm.
G. Space Solar Power – including for planets, moons, asteroids, in space, delivered via energy beaming using microwave or lasers.
H. “Space Beach Combing” – the identification, collection, destruction, repurposing, remanufacture of space debris. Of special interest is boosting ISS, in due course, into a parking orbit and scavenging its parts and by the piece.
I. Trash Dump – putting “trash” in parking orbits for “safe Storage”, including possibly some components of nuclear waste. This will depend on if it could be certified “launch indestructible”.
J. Space Manufacturing, in orbit, in-space or on other “bodies” or enroute. This could include possibly pharmaceuticals, fiber-optics, ball bearings, LEDs, solar panels, organs, hearts, protein crystals, fuels, on planet/body human commercial space equipage, anything that makes financial, economic “sense”, for use in space or on earth.

K. Space Hospitals – if microgravity or other in space conditions prove to be efficacious for specific human ills.
L. Space Tourism and/or colonization – Moon(s), Mars, Titan, poles of Mercury, upper atmosphere of Venus, asteroids, in space. This could include servicing and equipage.
M. Quantum Technologies and quantum computing – utilizing the "quiet" conditions in space, vacuum, low temperature, etc. to delay de-coherence and stabilize quantum states.
N. Positional Earth Utilities – telecom writ large, internet, Navigation, weather, imagery/ Earth observation, resource monitoring, etc.
O. Space weather forecasting,

The balance of this report will consider the frontier technologies applicable to these various commercial space activities along with evaluations and projections going forward.

Frontier Space Technologies and Approaches [refs. 12, 17-35]

A. Reusable Rockets for increased launch tempo and cost reductions. Analyses indicate that the upside for reusable rockets is a factor of 14 or greater reduction in launch costs. This capability is now operationalized and based on success thus far, rapid utilization is projected. This significant space access cost reduction will, going forward, have massive impacts upon all commercial space, changing what is feasible.

   The lowest contributing cost for space access using rockets is the cost of fuel, which is only some .4% to 1% of the current total cost. The other some 99% is the cost of the rocket amortized over many flights via reusability and "operations" of all flavors. A major overall cost reduction approach is to replace humans with "robotics"/ AI writ large for "everything", including manufacturing. Other, additional cost reductions include printing manufacture technologies (especially the potential 5x reduced based on nano-printing technologies) and greatly improved microstructure materials to reduce dry weight and increase payload fraction.

In actuality, adoption of new technologies has only begun to reduce space access costs, which is the Sine qua non for more profitable space commercialization through GEO and into deep space.

B. Miniaturization writ large – nearly everything except humans and the equipage that scales with their size has, thanks largely to the IT and other tech revolutions, long been reducing space equipage in size and mass. This is a process that is still ongoing. New technologies are reducing satellites that in some cases were the size of “school buses” to much smaller payloads. Also, this miniaturization has enabled cooperative constellations that are more survivable and, in some cases, have greater resolution. The usual metric of dollars per pound to orbit is being replaced by value per pound.
C. Energetics for in-space, on-planet, and in-orbit propulsion – including down sized reactors such as kilopower. These can provide orders of magnitude more energy dense nuclear batteries, such as NTAC, and positrons that can now be stored, 9 orders of magnitude times chemical, energy power beaming, magnesium/CO2 rockets for Mars (there is considerable magnesium on Mars), solar photovoltaic (PV) with increased efficiency, Space-based solar power (SBSP), and chemical fuels made in space from various resources.
D. Electric Propulsion, high thrust magnetohydrodynamic (MHD) such Variable Specific Impulse Magnetoplasma Rocket (VASIMR) field reversed configuration (FRC) propulsion, mass drivers, E-M tethers, Slingatron, solar electric propulsion (SEP), and Hall Thrusters.
E. Cyclers, “Slo Boats” as “freighters”, sails including photon, magnetic, laser, particle sails, other ultra-efficient propulsion
F. Tethers , electro-magnetic (E-M), Mechanical
G. AI/ Autonomous Robotics – The progress with respect to these arenas and what they will be able to accomplish is nothing short of astounding. Recent work indicates robots can invent, ideate, they know far more, and when overall compared to humans, they are

usually far less expensive, exclude operational human error, have more functionalities, far less latency, far longer duty cycle, and are faster, efficient, durable, and patient. They also preclude the expensive and weighty equipage required to keep humans healthy. They are not affected the way humans are by radiation and microgravity.

For cost and schedule reasons, space has nearly always been explored robotically. The nominal cost differential between robotic vs. humans is greater than 2 orders of magnitude. Capability improvements for AI/ Robotics are on an exponential growth curve. At a minimum, they could perform the initial preparation either in-space and on-body, and can (via ISRU) produce most of the equipage required for themselves and by humans given the extant requisite resources such as are available on Mars. In addition, the Nano tech revolution is increasingly improving robotic mechanization / capabilities.

H. Materials / printing manufacture – Printing is becoming the most efficacious in-space manufacturing approach. Also, recent printing at the Nano scale has produced 5x materials via superb microstructures with greatly reduced dislocations and grain boundary issues, with up to 10x potential. Nanotube composites are being worked with an upside of 11x impact in materials. These materials could possibly greatly reduce payload weight and rocket dry weight, further reducing space access costs perhaps by another factor of 2 to 3 or more.

I. Synthetic Biology – for producing food, materials, electronics, biocement, biopolymers, bioadhesives, life support, biofuels, biomining, pharma, biophotovoltaics.

J. Inflatables – including rigidization, imbedded sensors, actuators, AI, for localized shape changing, 12 different equipage writ large applications, reduces weight, increases functionalities, capabilities, also brilliant membranes.

K. Radiation Protection – low Z materials to minimize secondary effects, active approaches including magnetics, fast transits, biological countermeasures (BCMs), 5 meters of Regolith, Ice Igloos

L. Optical and Quantum Communication – increasing utilization of free space optical communication for greatly increased band width, quantum vector/ scaler potential communication is patented but nascent, and purportedly is applicable to planetary distances at high band width.
M. Powered EDL – for Mars, the current SOA for EDL is inflatable heat shields to increase drag area. With Reusable rockets/ “cheap space”, or Variable Specific Impulse Magnetoplasma Rocket (VASIMR), 6,000 seconds of specific impulse (Isp), missions could perhaps afford direct propulsive deceleration such as is used on planets, bodies without atmospheres.
N. Humans becoming cyborgs – artificial retinas, hearts, limbs, organs, and brain chips, direct brain to machine communications.
O. Increasing Knowledge of in space and on body resources – including water, minerals, lakes, lava tubes, atmospheric composition, etc.
P. Reusability and repurposing – of rockets, radiation protection overcoats, and everything else possible
Q. Tele-Everything – including tele-Medical, robotic surgery, tele-manufacturing, holographic crew members for psychological support.
R. Reliability Engineering – Fail safe-safe, redundancy, dual use, digital twin, Integrated vehicle health management (IVHM), self-repair, etc.
S. In Space Assembly and repair/ replacement – allows assembly of large systems placed by multiple launches. This also includes use of piece parts manufactured in space.
T. Artificial gravity – From crew quarters to entire spacecraft for Spaceflight Associated Neuro-ocular Syndrome (SANS), other non-mitigated effects of low to micro g.

Needed Space Technologies

A. Dust, Contamination Control/ mitigation/removal for Mars/Moon – Humans.
B. Propellant Resupply in-orbit and on-surface
C. In-Space Assembly for Staging and Manufacturing
D. Landers
E. GCR Shielding, Microgravity Countermeasures, and Fast Transits
F. ISRU

Commercial Space Issues [refs. 20, 26, 34, 36-41]

A. Reliability/Insurance – the hard problem is the historical launch accident rate versus the safety record of commercial aircraft, which are orders of magnitude different. This is an issue particularly germane to space tourism with respect to "How Safe is Space Travel".
B. Human health in space: [from ref. 26]

Our current understanding of long-duration flight effects on human health stems from many years of astronaut experiences on the International Space Station. Flights lasting six months began around 2005 and continue to present day. During this time, a wealth of knowledge and advances in technology have contributed to our understanding of the human adaptation to the space environment in Low Earth Orbit and have produced suitable countermeasures to mitigate many unwanted side effects to microgravity and space radiation that on ISS are 45% of deep space values.

Unmitigated musculoskeletal deconditioning begins immediately and continues unabated over time, with resultant losses or maintenance dependent on exercise countermeasures and adequate nutrition. Current countermeasures available on the ISS are able to minimize losses of bone density, muscle mass and strength, and aerobic deconditioning to acceptable levels during the standard 6 month tours. Astronauts maintain muscle and bone strength by exercising for two-and-a-half hours a day, six days a week, guided by strength coaches. Although the bone rebuilds mass, it may not rebuild in the original places, possibly affecting the overall strength of the rebuilt bone.

Not all problems have a solution currently. Some, such as anthropometry, fluid regulation, and red blood cell mass adjustments, adapt completely to space conditions within a week to 10 days and remain about the same throughout the mission. Neurosensory deconditioning accompanies adaptation to weightlessness, but is maladaptive during and after return to a gravity environment; this challenges performance involving motor control and positional sense during the sensitive phases of entry, landing, and postflight. No countermeasures are available at this time, but these are under investigation. Neurosensory re-adaptation does occur after Earth return and leaves no lasting adverse effects, but does take as much as a month to recover. Other changes in humans associated with long duration spaceflight include highly altered but functionally adaptive cardiovascular system regulatory alterations, immune changes, and gastrointestinal function.

There are changes that seem to be less adaptive and more harmful. The recently recognized entity known as Spaceflight Associated Neuro-ophthalmic Syndrome (SANS) involves changes in critical neuroanatomy (optic nerve sheath, optic disk, retinal surfaces, intracranial pressure which results in mild brain edema) that do seem to worsen with cumulative time in weightlessness. This is a function of compliance of the vasculature (i.e., stiffness of the vessels and their ability to stretch and change with an increased fluid load). The ‘attack rate’ (how many astronauts will get SANS) is a function of time due to compliance. Presently, attack rates are close to 30%. But that should be explained as 30% in a six-month period. At 16-18 months the attack rate would most likely be 100% of all individuals. Some people’s vessels can hold the fluid in better than others.

Although crewmembers remain functional despite correctable shifts in visual acuity, some of these effects endure for months to years following flight. Neither the mechanism nor the long-term implications of SANS are well understood, but it is reasonable to consider this an adverse consequence of prolonged exposure to weightlessness. As understanding progresses, countermeasures to this entity are likely. This eye issue could be something that drives us back to artificial gravity.

Despite the nearly global adaptive changes that occur, crew remain in an acceptable operating band for performing missions of 6 months on the ISS, with high levels of functional performance expected throughout this time. Most all these weightless-associated adaptations are expected to be mitigated by even a partial gravity field, to a currently unknown extent.

The major risk for which we have no current viable countermeasures is ionizing radiation, associated with an increased risk of cancers correlated with cumulative dose, acute radiation syndromes in solar particle events, and less well quantified risks of radiation induced vascular disease and central nervous system effects. This is the main limiter to human presence in space, with risk outside of Earth's geomagnetic fields much higher due to full exposure to solar particles and galactic cosmic rays.

Missions lasting for more than 200 days remain unchartered territory. Experiences learned during the year-long twin study suggest that far more data is needed. A normal mission to the International Space Station lasts five to six months, so scientists have a good deal of data about what happens to the human body in space for that length of time. But very little is known about what occurs after month six.

ISS experiences represent the vast part of our experience base in Long Duration Flight. Bone / muscle can be preserved with current countermeasures. SANS remains an issue, as does radiation. Both of these are gender weighted, albeit in opposite directions. Countermeasures do not exist for neurosensory decrements, radiation, and SANS. Radiation really remains the long pole in the tent. Both radiation and micro g adversely affect the immune system, in deep space with full GCR the combinational immune system impacts are presumably greater.

C. Costs/ Income/ ‘profit” – the “business case for commercial space. Simplistically, this requires a demand to supply a product or service that sells enough above cost to create a profit. Overall, many of the frontier technologies such as reusable rockets, miniaturization, AI/Robotics, printing, knowledgeability, reusability writ large, reliability engineering etc. are reducing costs.

D. Energetics – Historically, chemical fuels have been used, for they are far less energy dense than nuclear or anti-matter (positron) energetics, and the techs to affordably and safely operationalize nuclear systems and positrons are advancing. Solar is becoming an increasingly useful energy source for on planet, in space and propulsion. Solar can be “heavy” and works far less well out beyond Mars. Chemical fuels can be produced via ISRU, transported, and stored in fuel depots. Nuclear enables huge increases in specific impulse (Isp) up to 6,000 seconds when powering VASIMR, and the use of mass drivers will be beneficial, which can use any mass including regolith for propulsion (vice using fuels) which provides both energy and propulsive mass.

E. “Bugs” in space – experience indicates that due to effects of microgravity and radiation, bugs put in space become more virulent. Since humans carry some 15,000 or so bugs in their gut a spacecraft carrying humans will have “bugs” aboard also. Whether these, during longer trips, could morph into pathogens or corrosion catalysts (or some other negative effect) is unknown. So far so good.

F. Markets/ Competition:

One area of deep space business interest is mining asteroids for platinum and transporting material to earth. There are some 300,000 tons of platinum in seawater, and the major cost reductions for renewable energy, including wind and solar in some markets that are 2 cents per KWH now with costs still dropping, could provide the energy to extract the mineral. Also, there is ongoing research to replace platinum with respect to some uses including catalysis. Then there are the potential impacts on market price of large supply increases.

He3 from the moon for Fusion – He3 as a fusion fuel utilizes an aneutronic energy cycle, as does p-B 11 and certain other fuels. We have much P-B11. Aneutronic fusion has large losses, and is not the current fusion frontrunner approach. He3 found on Earth is almost entirely from the decay of tritium produced in reactors. If more was needed, we could produce more here. The issue would be relative cost.

Mining rare earth materials from moon, asteroids – In actuality, on Earth rare Earths are not rare, most are produced in China now because of cost. Much more could be mined, produced if needed at somewhat larger cost. Again, there is research to reduce their utilization via substitute processes and materials, and the bottom line is cost differentials between space mining and increased earth production.

Mineral Mining in space, moon, asteroids, for use on Earth – There are some 47 minerals present in seawater, many of which are extracted from seawater now. As noted previously, the reducing costs of terrestrial renewable energy would aid the affordability of mineral extraction from seawater, and yet again the bottom line is the cost differential of space mining vs. additional production here.

Space-based solar power (SBSP) – There has long standing serious interest in space solar power. As a base load, it provides much greater efficiency than terrestrial PV (no clouds, 24/7/365 Sun etc.) green energy with massive capacity. The major issue with this has always been cost, primarily the cost of space access. Cheap space will greatly reduce this cost problem. Whether it will be enough to be competitive with renewables such as solar and wind now selling for some 2 cents per KWH with costs still dropping is to be determined. The potential SSSP applicability to moon, mars, in space, and asteroids, is obvious. It is likely part of an infrastructure suitable for the colonization stage of development or for in-space processing of water into fuel, space manufacturing, in space transit, onboard and propulsion, as well as powering satellites etc.

G. Legalities – Thus far only a small number of countries, notably including the U.S., have legislated the private extraction and sale of space resources. There is a sizable international attitude, based upon the space treaties' supposed intent, that considers space resources common wealth and to be used for the overall good of the planet writ large. The legalities associated with cleaning up space debris are more clean-cut since space debris is owned by whomever put it there. Future cleanup activities will need the owners' permission and whatever else required to touch, collect and possible reuse the stuff. Along with the costs this has stymied cleaning up space debris.

H. Dust, Moon and Mars dust are a major health and operational problem for on body activities. Mitigating and controlling dust is a first order issue which needs to be researched with mitigation approaches designed into the mission. The dust is abrasive, electrostatic, magnetic, oxidative, chemically reactive, contains silicates, gypsum. On Mars, it contains perchlorates, which affects the thyroid and arsenic, cadmium and beryllium. There is concern that the dust could become much more corrosive, a greater problem once inside habitats at their higher pressure, temperature and oxygen content.

I. Space Debris – since the late 50s, we have put up the order of 6,600 satellites, some 1,130 of which are still operational. However, many of the non-operational ones are still up there. There have been some 240 explosions in space and many collisions, 2 of them serious major events. And all of this has contributed to the current space debris population.

The amount of this space debris is daunting. Estimates indicate that there are about 6,000 tons, with some 5,000 pieces greater than 1 meter in size, 22,000 greater than 10 cm, 700,000 greater than 1 cm, and 150,000,000 bits greater than 1 mm. Even the smaller pieces, given the closure speeds, can create worrisome effects upon impact. As an example, an impact speed of 12 km/sec has approximately 10 times the energy density of dynamite. A quote from a 2011 National Research Council report entitled *Limiting Future Collision Risk to Spacecraft* summarizes that year's outlook, which is becoming ever more serious. "When a handful of reasonable assumptions are used in NASA's Micrometeoroids and Orbital Debris (MMOD) models, scenarios are uncovered that conclude that the current orbital debris environment has already reached a ‘tipping point,’ meaning the amount of debris currently in orbit–in terms of the population of large debris objects, as well as overall mass of debris in orbit–has reached a threshold where it will continually collide with itself, further increasing the population of orbital debris.

This increase will lead to corresponding increases in spacecraft failures, which will only result in more debris in orbit. The increase thus far has been most rapid in low Earth orbit (LEO), with geosynchronous Earth orbits (GEOs) potentially suffering the same fate, although over a much longer time period. The exact timing and pace of this exponential growth are uncertain, but the serious implications of such a scenario require careful attention because of the strategic and commercial importance of US space operations**.** In the literature, this cascading of collisions producing ever more debris until the space region is essentially unusable is termed the “Kessler Effect.” Given the major and increasing worldwide reliance upon space assets–our “positional earth utilities”–has made space debris an increasingly serious problem

Overall current solution spaces include:

- Detect, track and maneuver/navigate around debris.
- Protect from impact. For example, Whipple shields for small debris, detect debris and maneuver, install critical/sensitive portions in the interior of the spacecraft, or “harden” the design so it can “take the hit.” This may not work for larger debris, or may be too expensive. Some external critical parts such as solar panels and antennas are obvious issues when considering protection under this solution.
- Self remove. Designing objects that deorbit at the end of their life, extend drag-producing devices, move to parking orbits, or utilize the higher drag during solar maximum.

J. Resource Data, While by various means the existence of a wide variety of deep space resources has been detected, Their exploitation, especially ‘moon Water”, requires extensive further data acquisition, to determine chemical state, amounts, depths, locations etc. to enable crafting plans and estimating costs for resource extraction and processing.

K. Surface Mobility, It has been noted that the typography of Mars is mostly sufficiently rugged that flying vice driving is probably required for other than very local environs. Such off-surface mobility capability has long been studied, including helos, aircraft, balloons, rockets, Given the sizable amount of Magnesium in the Mars Regolith, Magnesium-CO2 rockets may be efficacious.

Synopsis – Prospective Impacts of Frontier Technologies Upon Commercial Space Activities Going Forward [refs. 17, 25, 26, 42]

1. Reusable Rockets:
   - For humans, enables affordable radiation protection reusable "overcoats", artificial gravity, propulsive EDL, and the requisite cost reductions to enhance and afford health and safety through redundancy and reliability enhancements
   - For space manufacturing, provides the requisite low-cost access.
   - For all space activities, greatly reduced costs, including possibly enabling for such as SSP, Mining, "Tourism", satellites writ large etc.

2. Miniaturization of nearly everything except humans and their equipage that scales with their size
   - Alters $/lb to value/lb
   - Enables many vs. few payloads per launch, reducing costs still further
   - Enables co-operative constellations of satellites
   - Reduces launch costs for a given capability in orbit/space.

3. NTAC/ Kilopower/Positrons, etc.
   - Enables fast transits (200 days round trip to Mars)
   - Major reductions in fuel weight via VASIMR, high thrust MHD propulsion, 6,000 seconds of Isp

  - Applicable to in space habitats, propulsion, on planet power/ habitats, mining/ transportation on body
  - Enables large scale operations at lower cost
4. Electrical Propulsion
   - Higher Isp, greater fuel efficiency
   - High Thrust MHD
   - Mass Drivers, utilizing any mass as propulsive mass vice refining fuel that combines propulsive mass and energy
   - Electric tethers to enable affordable space debris cleanup
   - Slingatron, 10 to 50 Kg projectiles, many per minute
5. "Sails" (solar, magnetic, laser, particle)
   - Propulsion for SLO boat freighters, cyclers, for supplies
6. Tethers
   - Electric tethers for orbit raising etc.
   - Momentum tethers to/ from orbit, bodies
7. AI, Autonomous Robotics
   - ISRU, on Mars especially, but on any applicable planetary body etc. autonomous robotics could make pre-human arrival via printing etc., much to most of the requisite human equipage etc. writ large, fuels, food, life support, hardware / using plastics initially of all stripes.
   - As AI develops, going forward human level and beyond operations sans the costs of onsite humans.
8. Printing Manufacture/ materials
   - Nano scale printing for superb microstructures, 5X to possibly 10X materials
   - Up to 10X nano tube composites
   - Utilization by autonomous robotics everywhere, on body, in space manufacture
   - Resultant reductions in dry weight would increase payload fraction and reduce payload weight resulting in factors reductions in space access cost
9. Radiation Protection

- The “all up” approach, BCMs, arrange equipage to interdict/protect, crew selection, flight during solar max, for chemical-Mars are not sufficient
- Fast transits, 200-day round trip to Mars,
- Reusable, left in orbit between missions, mass “overcoat, low Z materials, order of 3 plus meters of polyethylene

10. Space/ Martian Resources
    - Discovery of ever-increasing quantities of useful resources on planets, moons, asteroids, etc. Essential, via ISRU, for significant in space operations and colonization. Earth per se utilization requires consideration of competitive approaches, sources.
    - Provides the rational and specifics for utilization of autonomous robotics, much of planning for deep space industrialization and colonization.
    - Greatly reduces the lofting, transport from earth of supplies for sustainability
    - ISRU can provide habitation, fuel, life support, radiation protection, hardware/ equipage, manufactures and supplies for commerce

Anticipated Space Commercialization Opportunities [refs. 20-24, 42-48]

Commercial Space Utilities beyond GEO (communications, energy/fuel/ transportation, maintenance/ repair, life support, etc.) – These in various forms and flavors will be needed for both government and commercial deep space activities, and especially for colonization. Development has already begun in several of these.

Space Mining - The asteroid water is particularly interesting, especially if the quantity proves to be significantly less and extraction costs of moon water prove significantly more than anticipated. Given the extant competitive ocean/ other earth resources, space mining may be more applicable to deep space utilization(s).

Space Beach Combing/ cleaning up space debris – Given the current situation with respect to space debris and the plans to loft far more satellites, factors more, we will probably going forward have to move on from avoidance to removal. The legal issues and costs have held that in abeyance. The costs could be addressed via use of E-M tethers powered by NTAC or solar, fuel-less transportation to collect for space manufacture repurposing/ remanufacturing.

Space Manufacturing – With the space access cost reduction in the offing from reusable rockets and 5X to 10X materials/ dry weight reduction the major impediment to space manufacturing is greatly mitigated. This capability would enable in-space manufacture of equipage not suitable, such as too large or too fragile for launch, even in piece parts.

Space Tourism – When the human health/ safety issues including reliability, radiation, microgravity are addressed, which are major mission design issues, the "cheap Space" emergence from reusable rockets etc. should greatly accelerate this.

Quantum Computing/ Technologies in space – This is a new-bee, with viability, realism still yet to be determined. However, delaying decoherence, maintaining quantum conditions, temperature, vacuum, and "quiet" conditions appear to be the space conditions of interest.

Earth Positional Utilities – This is the current, very successful, Commercial Space. Cheap space will make it even more so and several additional niche areas will be enabled.

The "Hard Problems" For Deep Commercial Space Going Forward

- ROI, Closed Business case
- Competition writ large
- In some cases legalities
- The "unknowns", long term effects of space on humans, detailed nature, location and extent of space resources

- Rapidly changing technologies, altering what is needed with respect to products, how to supply such and the competition writ large.
- Time Frames for Deep Space commercialization nominally longer than the usual 3 to 5 year business planning
- Changing nature of governmental activities, what of such can be relied on, where and when

The “Frontiers” of Deep Space Commercialization

- Colonization of Moon(s), Mars, Titan, poles of mercury, upper atmosphere of Venus
- Space hardened humans, from genomics, BCMs, Crisper, “evolution”, etc.
- Synthetic Biology Contributions, potentially huge going forward
- Mars with all those resources the “Product Store” for the inner solar system
- Terraforming (Mars, Titan, etc.)

Concluding Remarks

Frontier technologies and technical approaches are reducing costs and enabling major development in commercial space, both below and above GEO, the latter termed “Deep Space”. There are at least the order of some 15 putative commercial space activities which many refer to as “New Space”. These will be greatly and favorably affected by the plummeting costs of space access due to the switch to reusable rockets and updated manufacturing, design, and operational methods. In some cases, less costly space access enables economic competition to planned deep space activities/ markets.

To the extent that commercial deep space is executed by robotics, the actualization future is optimistic – AI, Robotics, Printing Manufacture, Energetics Advances, etc. are all supportive and on a strong upward trend. However, experience in laboratories and on station, in near earth space indicates that long term space presence for humans is currently problematic, requiring extensive mitigation approaches for reduced g and radiation and systems reliability issues.

What is apparently clear is that:

- The costs of space access are reducing
- Nearly everything except humans and their equipage that scales with their size is miniaturizing and acquiring better functionality.
- Revolutionary energetics and propulsion approaches are being worked.
- Frontier applicable technologies include AI, Robotics, Autonomy, Printing, Etc.
- Far more detailed data are required regarding on-body resources, including locations, chemical state, quantity, etc. to develop robust business cases

Particularly strong commercial space arenas going forward include commercial utilities writ large beyond GEO, space mining for use in deep space, space debris cleanup, space manufacturing, augmented "positional" earth utilities at GEO and below (domain of historic commercial space) and possibly quantum computing/ quantum technologies in space, to delay decoherence.

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14. ABSTRACT

A plethora of converging frontier technologies are reducing the costs of space access and utilization, enabling major growth going forward in commercial space , both Geo and below and in “Deep Space”, beyond GEO. Paper reviews these frontier technologies and enabling technological approaches, the landscape of enabled emerging commercial applications, their issues and in some cases their competition and outlook, along with the attendant “hard problems”. Major issues include mitigation of the in space human health issues, reliability and safety, details regarding on body space resources and a closed competitive and timely business case.

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