1 INTRODUCTION

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Man has only had the ability to operate spacecraft successfully since 1957, when the Russian satellite Sputnik I was launched into orbit. At the time of writing (2010) the Space Age is just over half a century old. In that time technology has made great strides, and the Apollo human expedition to the Moon and back is now a rather distant memory. In little more than five decades, unmanned explorer spacecraft have flown past all the major bodies of the Solar System, apart from the 'dwarf planet' Pluto—this exception will soon be remedied, however, by the 'New Horizons' spacecraft that is due to fly through the Pluto-Charon system in 2015. Space vehicles have landed on the Moon and Venus, and in recent years Mars has seen a veritable armada of orbiters, landers and rovers in preparation for a hoped-for future human expedition to the red planet. The Galileo Jupiter orbiter successfully deployed a probe in 1995, which 'landed' on the gaseous 'surface' of Jupiter. The Cassini/Huygens spacecraft has been a stunning success, entering orbit around Saturn in 2004, and executing a perfect landing on Titan of the European built Huygens probe in 2005. Minor bodies in the Solar System have also received the attention of mission planners. The first landing on such a body was executed by the Near Earth Asteroid Rendezvous (NEAR) Shoemaker spacecraft, when it touched down on the Eros asteroid in February 2001. This was succeeded in 2005 by the attempted sampling of material from the Itokawa asteroid by the Japanese Hayabusa spacecraft. Although the sampling operation was unsuccessful, the spacecraft is now on a return journey to Earth in the hope that some remnants of asteroid material may be found in its sealed sampling chamber. Similarly, a prime objective of the ambitious European Rosetta programme is to place a lander on a cometary body in 2014. There is also a growing awareness of the impact threat posed by near-Earth asteroids and comets, which is driving research into effective means of diverting such a body from a collision course with Earth.

Since our brief sojourn to the Moon in 1969–1972, human spaceflight has been confined to Earth orbit, with the current focus on construction and utilization of the International Space Station (ISS). The United States, Europe, Russia and Japan are all involved in this

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ambitious long-term programme. The ISS has been a major step for both the technology and politics of the space industry, and has been a useful exercise in learning to live and work in space—a necessary lesson for future human exploration of the Solar System. The 'work horse' of this activity has been the US Space Shuttle, which has been the United States' principal means of human access to orbit over almost three decades. However, 2011 sees the retirement of the Shuttle. This is a major event in NASA's space operations, and it has forced a radical rethink of the United States' human spaceflight programme. This led to the proposal of a less complex man-rated launch vehicle, Ares 1, which is part of the Constellation Programme. The objective of this programme is to produce a new human spaceflight infrastructure to allow a return of US astronauts to the Moon, and ultimately to Mars. However, the shuttle retirement coincides with a deep global financial recession, and the political commitment to the Constellation Programme appears to be very uncertain. This re-evaluation by the US will perhaps herald the reinvigoration of the drive towards the full commercialization of the space infrastructure.

There is no doubt, however, that the development of unmanned application spacecraft will continue unabated. Many countries now have the capability of putting spacecraft into orbit. Satellites have established a firm foothold as part of the infrastructure that underpins our technological society here on Earth. There is every expectation that they have much more to offer in the future.

Before the twentieth century, space travel was largely a flight of fantasy. Most authors during that time failed to understand the nature of a spacecraft's motion, and this resulted in the idea of 'lighter-than-air' travel for most would-be space-farers [1, 2]. At the turn of the twentieth century, however, a Russian teacher, K. E. Tsiolkovsky, laid the foundation stone for rocketry by providing insight into the nature of propulsive motion. In 1903, he published a paper in the *Moscow Technical Review* deriving what we now term the rocket equation, or Tsiolkovsky's equation (equation 3.20). Owing to the small circulation of this journal, the results of his work were largely unknown in the West prior to the work of Hermann Oberth, which was published in 1923.

These analyses provided an understanding of propulsive requirements, but they did not provide the technology. This eventually came, following work by R. H. Goddard in America and Wernher von Braun in Germany. The Germans demonstrated their achievements with the V-2 rocket, which they used towards the end of World War II. Their rockets were the first reliable propulsive systems, and while they were not capable of placing a vehicle into orbit, they could deliver a warhead of approximately 1000 kg over a range of 300 km. It was largely the work of these same German engineers that led to the first successful flight of Sputnik 1 on 4 October 1957, closely followed by the first American satellite, Explorer 1, on 31 January 1958.

Five decades have seen major advances in space technology. It has not always been smooth, as evidenced by the major impact that the Challenger (1986) and Columbia (2003) disasters had on the American space programme. Technological advances in many areas have, however, been achieved. Particularly notable are the developments in energy-conversion technologies, especially solar photovoltaics, fuel cells and batteries. Developments in heat-pipe technology have also occurred in the space arena, with ground-based application in the oil industry. Perhaps the most notable developments in this period, however, have been in electronic computers and software. Although these have not necessarily been driven by space technology, the new capabilities that they afford have been rapidly assimilated, and they have revolutionized the flexibility of spacecraft. In some cases they have even turned a potential mission failure into a grand success.

But the spacecraft has also presented a challenge to Man's ingenuity and understanding. Even something as fundamental as the unconstrained rotational motion of a body is now better understood as a consequence of placing a spacecraft's dynamics under close scrutiny. Man has been successful in devising designs for spacecraft that will withstand a hostile space environment, and he has found many solutions.

1.1 PAYLOADS AND MISSIONS

Payloads and missions for spacecraft are many and varied. Some have reached the stage of being economically viable, such as satellites for communications, weather and navigation purposes. Others monitor Earth for its resources, the health of its crops and pollution. Determination of the extent and nature of global warming is only possible using the global perspective provided by satellites. Other satellites serve the scientific community of today and perhaps the layman of tomorrow by adding to Man's knowledge of the Earth's environment, the solar system and the universe.

Each of these peaceful applications is paralleled by inevitable military ones. By means of global observations, the old 'superpowers' acquired knowledge of military activities on the surface of the planet and the deployment of aircraft. Communication satellites serve the military user, as do weather satellites. The Global Positioning System (GPS) navigational satellite constellation is now able to provide an infantryman, sailor or fighter pilot with his location to an accuracy of about a metre. These 'high ground' space technologies have become an integral part of military activity in the most recent terrestrial conflicts.

Table 1.1 presents a list of payloads/missions with an attempt at placing them into categories based upon the types of trajectory they may follow. The satellites may be categorized in a number of ways such as by orbit altitude, eccentricity or inclination.

It is important to note that the specific orbit adopted for a mission will have a strong impact on the design of the vehicle, as illustrated in the following paragraphs.

Table 1.1 Payload/mission types

Mission	Trajectory type
Communications	Geostationary for low latitudes, Molniya and Tundra for high latitudes (mainly Russian), Constellations of polar LEO satellites for global coverage
Earth resources	Polar LEO for global coverage
Weather	Polar LEO, or geostationary
Navigation	Inclined MEO for global coverage
Astronomy	LEO, HEO, GEO and 'orbits' around Lagrange points
Space environment	Various, including HEO
Military	Polar LEO for global coverage, but various
Space stations	LEO
Technology demonstration	Various

Note: GEO: Geostationary Earth orbit; HEO: Highly elliptical orbit; LEO: Low Earth Orbit; MEO: Medium height Earth Orbit.

Consider geostationary (GEO) missions; these are characterized by the vehicle having a fixed position relative to the features of the Earth. The propulsive requirement to achieve such an orbit is large, and thus the 'dry mass' (exclusive of propellant) is a modest fraction of the all-up 'wet mass' of the vehicle. With the cost per kilogram-in-orbit being as high as it currently is—of the order of \$30 000 per kilogram in geostationary orbit—it usually becomes necessary to optimize the design to achieve minimum mass, and this leads to a large number of vehicle designs, each suitable only for a narrow range of payloads and missions.

Considering the communication between the vehicle and the ground, it is evident that the large distance involved means that the received power is many orders of magnitude less than the transmitted power. The vehicle is continuously visible at its ground control station, and this enables its health to be monitored continuously and reduces the need for it to be autonomous or to have a complex data handling/storage system.

Low Earth orbit (LEO) missions are altogether different. Communication with such craft is more complex as a result of the intermittent nature of ground station passes. This resulted in the development, in the early 1980s, of a new type of spacecraft—the tracking and data relay satellite system (TDRSS)—operating in GEO to provide a link between craft in LEO and a ground centre. This development was particularly important because the Shuttle in LEO required a continuous link with the ground. More generally, the proximity of LEO satellites to the ground does make them an attractive solution for the provision of mobile communications. The power can be reduced and the time delay caused by the finite speed of electromagnetic radiation does not produce the latency problems encountered using a geostationary satellite.

The power subsystem is also notably different when comparing LEO and GEO satellites. A dominant feature is the relative period spent in sunlight and eclipse in these orbits. LEO is characterized by a high fraction of the orbit being spent in eclipse, and hence a need for substantial oversizing of the solar array to meet battery-charging requirements. In GEO, on the other hand, a long time (up to 72 min) spent in eclipse at certain times of the year leads to deep discharge requirements on the battery, although the eclipse itself is only a small fraction of the total orbit period. Additional differences in the power system are also partly due to the changing solar aspect angle to the orbit plane during the course of the year. This may be offset, however, in the case of the sun-synchronous orbit (see Section 5.4 of Chapter 5), which maintains a near-constant aspect angle—this is not normally done for the benefit of the spacecraft bus designer, but rather because it enables instruments viewing the ground to make measurements at the same local time each day.

It soon becomes clear that changes of mission parameters of almost any type have potentially large effects upon the specifications for the subsystems that comprise and support a spacecraft.

1.2 A SYSTEM VIEW OF SPACECRAFT

This book is concerned with spacecraft systems. The variety of types and shapes of these systems is extremely wide. When considering spacecraft, it is convenient to subdivide them into functional elements or subsystems. But it is also important to recognize that the satellite itself is only an element within a larger system. There must be a supporting ground control system (Figure 1.1) that enables commands to be sent up to the vehicle and status and payload information to be returned to the ground. There must also be a launcher system that sets the vehicle on its way to its final orbit. Each of the elements of the overall system must interact with the other elements, and it is the job of the system designer to achieve an overall optimum in which the mission objectives are realized efficiently. It is, for example, usual for the final orbit of a geostationary satellite to be achieved by a combination of a launch vehicle and the boost motor of the satellite itself.

This starts us towards the overall process of systems engineering, which will be treated in detail in the final chapter of this book. Figure 1.1 shows the breakdown of the elements needed to form a satellite mission. Each of these may be considered to perform functions that will have functional requirements associated with them. We can thus have an overriding set of mission requirements that will arise from the objectives of the mission itself. In the process of systems engineering, we are addressing the way in which these functional requirements can best be met, in a methodical manner.

Chambers Science and Technology Dictionary provides the following very apt definition of the term 'system engineering' as used in the space field:

> 'A logical process of activities that transforms a set of requirements arising from a specific mission objective into a full description of a system which fulfils the objective in an optimum way. It ensures that all aspects of a project have been considered and integrated into a consistent whole.'

The 'system' in question here could comprise all the elements within both the space and the ground segments of a spacecraft project, including the interfaces between the major elements, as illustrated in Figure 1.1. Alternatively, the system approach could be applied on a more limited basis to an assembly within the space segment, such as an instrument within the payload. In the case of an instrument, the system breakdown would include antenna elements or optics and detectors as appropriate, and the instrument's mechanical and electrical subsystems.

The *mission objectives* are imposed on the system by the customer, or user of the data. They are statements of the aims of the mission, are qualitative in nature and should

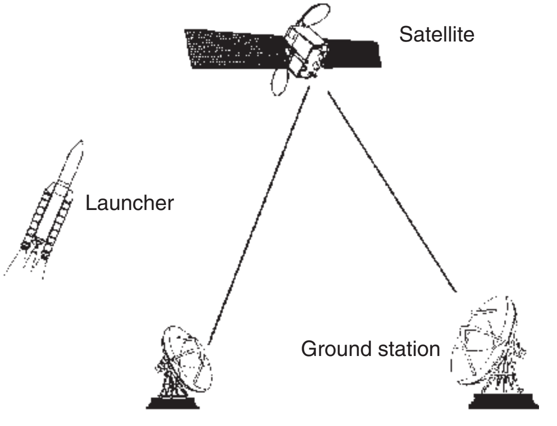

Figure 1.1 The total system — the combined space and ground segments

be general enough to remain virtually unchanged during the design process. It is these fundamental objectives that must be fulfilled as the design evolves.

For example, the mission objectives might be to provide secure and robust three-dimensional position and velocity determination to surface and airborne military users. The *Global Positioning System (GPS)* is a method adopted to meet these objectives.

An illustration of the range of methods and the subsequent requirements that can stem from mission objectives is given by the large number of different concepts that have been proposed to meet the objective of providing a worldwide mobile communication system. They range from an extension of the existing *Inmarsat* spacecraft system to schemes using highly eccentric and tundra orbits (see Chapter 5 for the definitions of these), to a variety of concepts based around a network of LEO satellites, such as The Globalstar or Iridium constellations.

This example demonstrates an underlying principle of system engineering, that is, that there is *never* only one solution to meet the objectives. There will be a diverse range of solutions, some better and some worse, based on an objective discriminating parameter such as cost, mass or some measure of system performance. The problem for the system engineer is to balance all these disparate assessments into a single solution.

The process that the system engineer first undertakes is to define, as a result of the mission objectives, the mission requirements. The subsequent requirements on the system and subsystems evolve from these initial objectives through the design process. This is illustrated in Figure 1.2, which shows how a hierarchy of requirements is established. In Chapter 20 this hierarchy is further explained and illustrated by considering a number

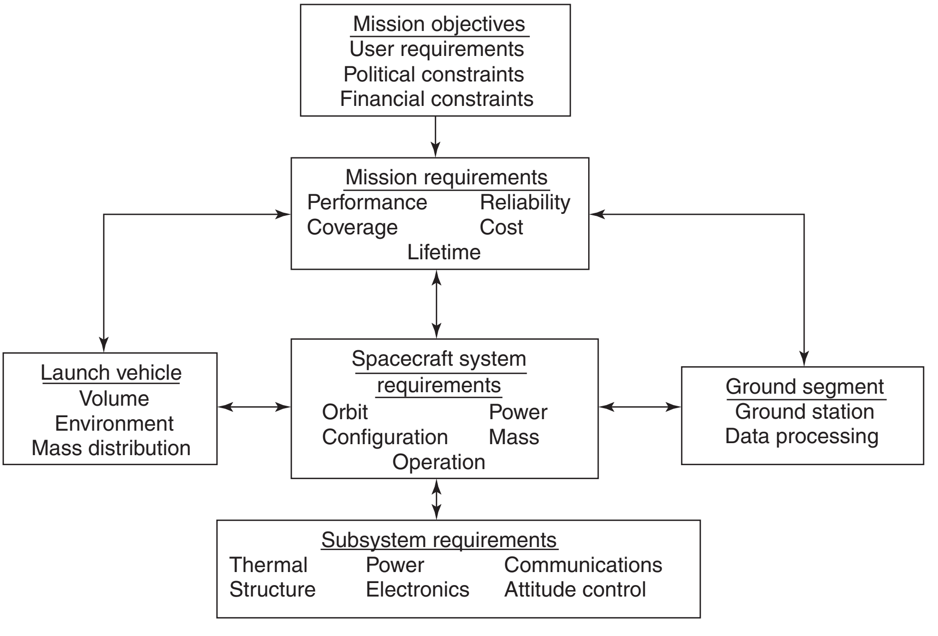

Figure 1.2 Objectives and requirements of a spacecraft mission

of specific spacecraft in detail. At this point, however, it is important to note the double-headed arrows in Figure 1.2. These indicate the feedback and iterative nature of system engineering.

We turn now to the spacecraft system itself. This may be divided conveniently into two principal elements, the payload and the bus (or service module). It is of course the payload that is the motivation for the mission itself. In order that this may function it requires certain resources that will be provided by the bus. In particular, it is possible to identify the functional requirements, which include:

1. The payload must be pointed in the correct direction.
2. The payload must be operable.
3. The data from the payload must be communicated to the ground.
4. The desired orbit for the mission must be maintained.
5. The payload must be held together, and on to the platform on which it is mounted.
6. The payload must operate and be reliable over some specified period.
7. An energy source must be provided to enable the above functions to be performed.

These requirements lead on to the breakdown into subsystems, which is shown in Figure 1.3. Inset in each of these is a number that relates it to the functions above.

The structure of this book recognizes this overall functional breakdown, shown in Figure 1.3. The individual subsystems are covered separately in the chapters. Thus, in Chapter 8 the structural subsystem is considered, and in Chapter 15, mechanism design is outlined. The power subsystem, including the various ways in which power can be raised on a spacecraft, is described in Chapter 10. The main elements of an attitude control subsystem are indicated principally in Chapter 9, although the underlying attitude motion of a free body such as a satellite is covered in Chapter 3. Telemetry and command subsystems may be conveniently considered alongside on-board data handling (OBDH); these

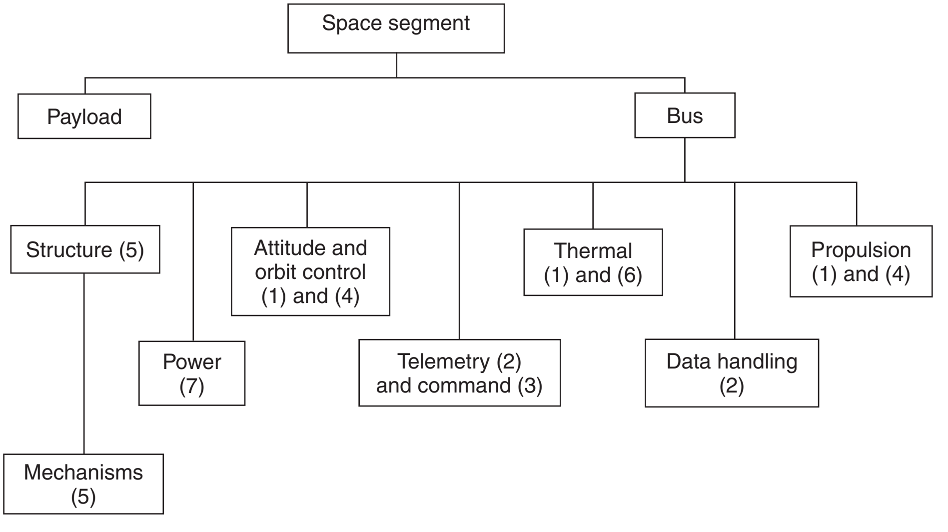

Figure 1.3 Spacecraft subsystems

topics are covered in Chapter 13, with the underlying principles and practice of spacecraft communications in the previous chapter. The thermal control subsystem appears in Chapter 11. Propulsion, as it relates to on-board systems, is described in Chapter 6, while its application to launch systems is described in Chapter 7.

One facet of these subsystems is that the design of any one has impacts and resource implications on the others. A most important feature of spacecraft system design is to identify what aspects of the mission and what elements of the design provide the major influences on the type of satellite that may meet the specific mission requirements. This process is the identification of the *'design drivers'*. In some cases the drivers will affect major features of the spacecraft hardware. The varied mission requirements, coupled with the need to minimize mass and hence power, has thus led to a wide variety of individual design solutions being realized. However, the spacecraft industry is now evolving towards greater standardization—in the shape of the specific buses that may be used to provide the resources for a variety of missions (e.g., the SPOT bus, the Eurostar bus, Mars/Venus Express, etc.—see Chapter 20).

It is not simply the nature of its payload that determines the design that is selected for a given mission, although this will have a considerable influence. Commercial and political influences are strongly felt in spacecraft engineering. Individual companies have specialist expertise; system engineering is dependent on the individual experience within this expertise. This was perhaps most notably demonstrated by the Hughes Company, which advanced the art of the spin-stabilized satellite through a series of *Intelsat* spacecraft. Spacecraft systems engineering is not all science—there is indeed an art to the discipline.

This leads to another major feature of spacecraft system design, namely, the impact of reliability. The majority of terrestrial systems may be maintained, and their reliability, while being important, is not generally critical to their survival. If a major component fails, the maintenance team can be called in. In space, this luxury is not afforded and while the Shuttle did provide in-orbit servicing for a limited number of satellites, this was an extremely expensive option. This requires that the system must be fault-tolerant, and when this tolerance is exceeded the system is no longer operable and the mission has ended.

There are two principal methods used to obtain high reliability. The first is to use a design that is well proven. This is true for both system and component selection.

The requirement to validate the environmental compatibility of components (Chapter 2) leads to relatively old types being used in mature technology, especially in electronic components. This tends to lead to a greater demand for power than the terrestrial 'state-of-the-art' technology. At system level a 'tried and tested' solution will minimize development risk, reducing system cost while also achieving high reliability.

The second method of achieving high reliability is *via* de-rating (Chapter 19). By reducing the power of the many electronic components, for example, a greater life expectancy can be obtained. This leads to an overall increase in mass.

The net effect of designing for high reliability is that spacecraft design is conservative—'if it has been done before then so much the better'. Much of satellite design is thus not state-of-the-art technology. Design teams evolve a particular design solution to meet varied missions—because it is a design they understand—and hence system design is an art as well as a science.

In making the selection of subsystems for the spacecraft, the designer must have a good grasp of the way in which the subsystems work and the complex interactions between them, and they must recognize how the craft fits into the larger system. Further, the designer must be able to trade off advantages in one area with the disadvantages in another and achieve a balance in which the end result will work as a harmonious whole. While each subsystem will have its own performance criterion, its performance must nevertheless be subordinated to that of the system as a whole.

1.3 THE FUTURE

As we enter the second half century of the Space Age, we are approaching a new frontier in space. Up until now, we have been able to gain access to space, and demonstrate a competent exploitation of this environment principally in terms of the use of application satellites—however, our utilization of it is still limited. This limitation is mainly related to the very high cost of access to orbit, and this obstacle needs to be overcome in opening up the new frontier. Beyond the frontier, however, we will require to establish space infrastructure; including the prime elements of communications, and safe and reliable transportation, with a permanent human presence in space—initially on space stations, but then on the Moon and Mars. Over the last 40 years or so, space exploration has had to adapt to changes in world politics. Before that, in the Apollo era, the funding available was motivated by a political end—that of winning the 'space race' and so demonstrating the superiority of one political ideology over another.

Clearly, to set up the infrastructure there must be a space transportation system. The first step—getting off the ground—requires the development of next-generation launchers, which are truly reusable, having aircraft-like operational characteristics. This poses huge technological challenges principally for propulsion engineers and material scientists. However, the rewards for such a breakthrough would be enormous—the resulting reduction in cost to access to orbit would open up the new frontier, not only in terms of space applications and science, but also for human space exploration and space tourism.

The early part of the twenty-first century will see the completion and operation of the ISS. Although this has been a controversial and expensive programme, it will no doubt be superseded by future space stations, which will be used as staging posts, where 'a new team of horses' can be obtained. Surely such orbital staging posts will eventually become assembly and servicing posts as well, so that spacecraft venturing beyond Earth orbit do not have to be designed to withstand the full rigours of launch, when their subsequent stages of travel are relatively stress-free. Manufacturing in space also has significant potential, not only for exotic materials, but also for lightweight structural materials extruded in zero gravity, for use in zero gravity. A communications infrastructure is already in use. There will be a requirement for 'accommodation units' in orbit, fulfilling both scientific and space tourism needs. This will be aided by the store of knowledge being gathered each year of Man's ability to live in space. There is a requirement for a power generating and supply system . . . and so the list goes on.

We are, however, at a crossroad in the way we develop our presence in space. Throughout the past 50 years there has been debate concerning the presence of humans in space: what role should we have and how should this be accomplished. Over the past 30 years there has also been the parallel debate about how space endeavours should be financed—whether by governmental funds or private capital. The philosophies of the past may of course reassert themselves, with the result that we see funding for space programmes once again dominated by tax payers money, but maybe not. This issue is central to the current controversy (of 2009/10) which has been stimulated by the Obama administration and the Augustine Commission, resulting in the cancellation of the Constellation programme.

The issues are drawing together in a way never before witnessed. Up until very recently, the advent of space tourism has only been the province of the dreamer and the science fiction aficionado. This is now changing, stimulated without doubt by the winning of the Ansari X-prize in October 2004 by SpaceShipOne, built by the company Scaled Composites. Their subsequent teaming with Virgin Galactic in 2005 means that it is now possible (in 2010) to reserve a seat online on the first commercial sub-orbital flights. There is, as a result, the potential for the commercial airline industry (which itself was initiated by the not dissimilar Orteig Prize, won by Charles Lindbergh in 1927) to address the issue of access to space. The enabling technologies are gradually emerging alongside the commercial realization that some people can afford to fly into space at a commercial price tag. This is all coming at a time when the prevailing political situation in the USA is pointing to a reassessment of the role NASA should play in future access to space. It seems quite probable that this nexus will indeed further stimulate the progress to the commercial utilization of space. There is a subtle but significant shift. Rather than attempting merely to commercialize the sale of a largely government-funded collection of data products from satellites, typified by the approaches adopted in the 1980s and 90s, a movement can be perceived towards the commercialization of the core process of access to space by individuals.

There is a whole new exciting arena waiting to be explored, occupied and used for the benefit of all mankind.

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