

MINIATURIZATION METHODS FOR DEEP SPACE MICROSPACECRAFT

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Abstract

Due to the shrinking NASA budget, future scientific spacecraft programs will be driven by their "life-cycle" cost. This cost figure, which includes development, integration, launch, and operation, can be reduced by making spacecraft smaller and more autonomous. Such miniature spacecraft allow the launch of several microspacecraft on a single launch vehicle or the launch of a single microspacecraft as a "piggy-back" rider on top a primary payload. Although each of these small spacecraft will not be capable of conducting the diversified science that is accomplished by such grand vehicles as Voyager and Cassini, a group of microspacecraft can conduct a composite of many different kinds of valuable science missions as well as enhance overall mission reliability.

The methodology used in the design of microspacecraft is different than that which is used for traditional planetary spacecraft. This design approach involves the incorporation of advanced miniaturizing technologies as well as the modification of the system architecture so that it can support the desired small mass and size. The progress in miniaturization is evolutionary: size can be reduced from one design to the next by further modifying the system architecture and incorporating even more advanced technologies. This paper will cover the specific approaches used in the evolutionary miniaturization process as well as the advanced technologies needed to build a miniature spacecraft designed to accomplish an asteroid flyby mission. A concept for a 3kg microspacecraft and an associated launch strategy are presented.

Introduction

Today's planetary spacecraft (Voyager, Galileo, Cassini) carry many instruments on-board and conduct many scientific experiments at their destination. Because of this, they are considered today as heavy, power-demanding, and complex. Qualification tests for their parts and subsystems were long and expensive, adding to an already long development time and high costs. The recent loss of the Mars Observer brought to attention (yet again) the risk of placing large resources into a single, complex spacecraft. This

unfortunate setback has increased the support for smaller, more focused missions. With the shrinking NASA budget, scientists and engineers are looking at ways of conducting valuable planetary science for less. Smaller spacecraft are expected to do just that. The vision is that of micro scale vehicles that will weigh orders of magnitude less than current spacecraft, consume far less power, evolve from concept to launch in less time and for less money, and still support focused world-class science investigations.

The main rationale for designing and building smaller spacecraft is the need to lower total project costs. Smaller spacecraft can be launched on smaller launch vehicles (LVs) which cost much less than heavy ones. Even smaller spacecraft can be launched as "piggy-back" riders on LVs for other missions when mass margins are available, or as multiple spacecraft launched on a single LV, thus reaching more than a single target or conducting science that can only be accomplished by multiple views of a single object. In addition, smaller spacecraft allow for greater upper stages within a given launch vehicle envelope, thus allowing higher launch energies and enabling shorter cruise phases for missions to far targets.

There are several other factors that make smaller spacecraft less expensive. Compact spacecraft require smaller integration and test facilities. Smaller spacecraft generally support simpler missions and allow for simpler system architectures which may lead to lower operations costs. On the other hand, these vehicles require advanced technologies which incur high development costs. Many would require more expensive manufacturing and qualification techniques. However, as the use of and demand for these technologies increase, these costs can be amortized over multiple uses.

Background and Approach

In the late 1980s, the Pegasus launch vehicle was introduced. Although it did not fly until 1990, it brought about an interest in smaller spacecraft that could be launched for lower cost. In 1990, a JPL study called the Pegasus-launched Near Earth Asteroid Flyby (PNEAF) [1] introduced a design for a spacecraft that could conduct deep

space science investigation after launch from this small and cheap launch vehicle. Near earth asteroids (NEAs) were chosen since the launch energy and post-launch ΔV required to reach them is rather modest, yet their exploration provides significant scientific contributions to the study of the solar system. The PNEAF concept is a spinning spacecraft weighing 77.5kg wet. Taking the NEA exploration a step further, the Asteroid Investigation with Microspacecraft (AIM), a study conducted in 1991 [2], explored the concept of flying three spacecraft on a single Pegasus, each headed towards a different asteroid. Each of the three spacecraft weighs 35.7kg wet. The next effort to miniaturize took place in the summer of 1993. This "second generation" microspacecraft as applied to asteroid flybys weighs 5.5kg wet [3,4]. The concept developed for this study using the approaches described below builds on this second generation design.

The goals of the study described in this paper were to identify an approach to the miniaturization of microspacecraft and to identify a set of technologies that would enable the realization of such vehicles. An additional goal was to use the identified approach and technologies to develop a fourth concept in the series of shrinking spacecraft designed to accommodate an asteroid flyby mission.

Figure 1 shows key properties that were targeted in the miniaturization process and their relation to each other. Reduction in power consumption reduces battery and solar array requirements as well as reduces heat dissipation and therefore the overall component size. A reduction in the number of individual components and their sizes reduces the overall volume which reduces the required support structure and overall system mass. Finally, a reduction in the number and size of apertures reduces the required surface area of the vehicle which in turn allows for a reduction in volume and thus in mass. The sections below will address the methods used to achieve a reduction in these properties.

Hardware Integration

The individual hardware elements are a prime focus for the miniaturization process. Each hardware unit occupies a certain volume and is supported by structure, most use power-consuming electronic devices for their operation, and several require access to the environment outside the spacecraft (using an aperture). Each of these three properties contributes to the mass and size of the overall system. Therefore, reducing the number of units as well as reducing their size may significantly miniaturize the system. This requires that either certain functions be eliminated or that each hardware element perform additional functions.

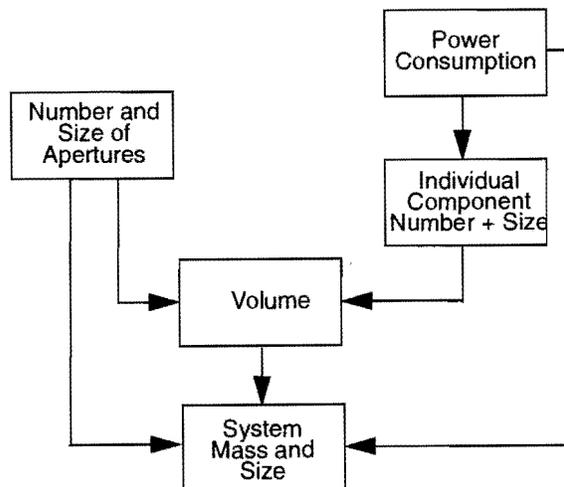


Figure 1: Relationship of key properties that affect the size and mass of space systems.

One approach to the integration of hardware units is to integrate such common resources as apertures, electronics, and supporting structure. Figure 2 shows the integration of these parameters as a two-step process.

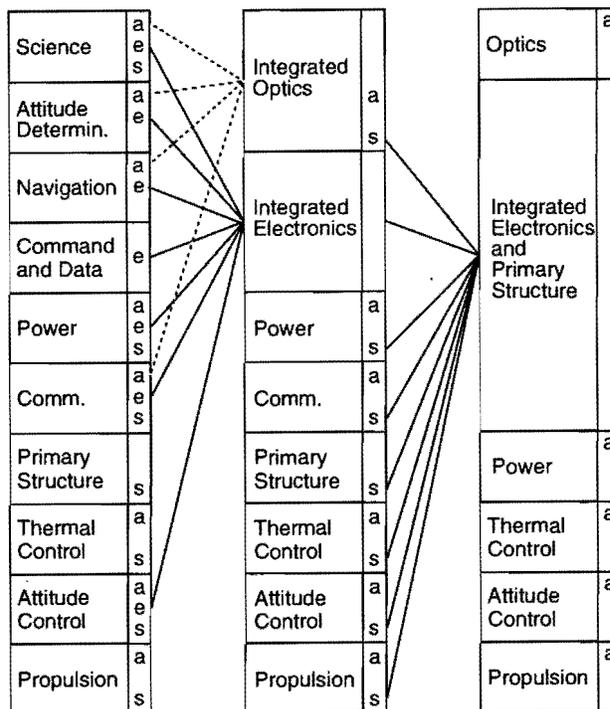


Figure 2: Integration of apertures ('a'), electronics ('e'), and structure ('s') among the hardware used to perform primary functions on-board.

In the first step all optical apertures and all electronics are combined. A single telescope (with a single set of optics) is used both as a scientific camera and as a star and target tracker. Optical communication exploits this optical system as well. Three co-located packages contain all electronics: computation and memory electronics, attitude and health acquisition electronics (including an IRU, engineering multiplexer, A/D converter, and optical communication electronics), and power electronics (including distribution and regulation circuitry, switches, and valve drivers).

The second step involves the integration of all hardware used for structural support and integration. The electronics packages provide the primary structural and thermal support (they *are* the spacecraft bus) and their edges are the thermal radiators. The attitude control thrusters are small enough to be mounted directly on these packages. The composite propellant tank is integrated with these packages by extending several of its fibers [5]. These composite strips hold the optics, electronics, and the tank together. The resulting architecture includes a single integrated unit of optics, electronics, and propulsion with five fields-of-view, or apertures: camera, solar array, radiators, attitude control thrusters, and main propulsion.

Volume Reduction

As evident in nature, smaller things are inherently stronger. For example, bones in small animals are much more slender than in large animals. This is so because the reduction in size of structures is an elastic scaling problem. In geometric scaling, mass is proportional to the cube of the length, or the volume. However, structural downscaling preserves constant resistance to buckling and bending as well as reduces stress levels under equal loads. This causes the structural mass to decrease more proportionally to l^4 , as opposed to l^3 [6]. Thus it is particularly important to also try and minimize the volume that the system occupies so structural support mass can be significantly reduced.

The majority of the volume occupied by the optical bench is empty. This is because distances between optical elements are fixed by the required optical performance of the telescope. This “dead” volume can be reduced only by changing the telescope configuration, a design change that can require additional components. If the volume reduction is significant, however, the mass of support structure saved by reducing volume can be greater than the mass required for the additional components. Figure 3 shows how a change from a simple Cassegrain configuration to a Schmidt (which requires a tertiary mirror) can make the telescope more compact.

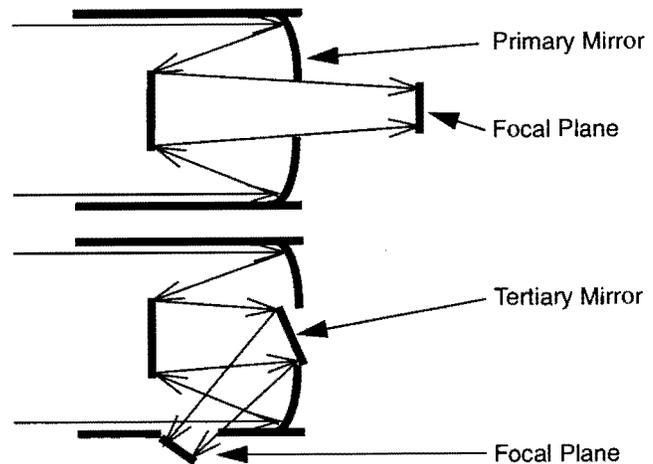


Figure 3: Reduction in volume occupied by optical bench using a different telescope configuration: Cassegrain (top) versus Schmidt (bottom).

The co-location of the electronics reduces the total structural and thermal support hardware. In addition, advanced electronic packaging techniques allow even further reduction in support mass. This new technique is a result of the microelectronics revolution that took place during the 1980s and is now sweeping the portable electronics industry. It opens the door for a new level of hardware integration where integrated circuit (IC) die as well as micro-mechanical components can be directly supported by a single compact module that carries all structural and thermal loads.

Propulsion systems for traditional small satellites include a spherical tank containing a monopropellant (usually Hydrazine), a single main thruster, and attitude control thrusters that feed from the tank. In the miniaturization of this system two issues were addressed: volume and plumbing. Reduction in plumbing is accomplished by making the reaction control thrusters solid-state. This decouples the reaction control system from the primary propulsion and eliminates all related plumbing. Reduction in total spacecraft volume is achieved by modifying the tank shape and by using an array of microthrusters instead of the main engine. The diameter of the tank is changed so that it matches the diameter of the spacecraft bus making the whole system more compact. To maintain a constant volume, the tank is “flattened” into an ellipsoidal container which can be manufactured just as easily as spherical tanks with fiber winding. A thin (0.5cm) substrate, containing many microthrusters, attached to the bottom of the tank replaces the long and narrow thruster, which is a rather awkward extension. This microthruster array is a new concept developed in this study.

In order to realize the microthruster concept, a microfluid flow control system is required. This area also benefits from the micromachining technology developed for microelectronics and is currently of particular interest to biotechnologists who would like to build tiny machines that can be injected into the blood stream and release controlled quantities of drugs at the proper time and location. The development of microvalves for these applications brought about this idea of an array of microthrusters. In addition to its compactness and low mass, this concept allows for graceful degradation; the failure of one or several of the thrusters does not disable the entire propulsion system. Figure 4 shows a schematic of this concept. A substrate 10cm in diameter can support 100 or more thrusters, each providing less than 10mN of thrust. The thruster chambers are oriented horizontally to reduce the substrate thickness, thus reducing mass. This should not affect performance, although the behavior of fluids in such narrow channels might. This topic is currently being researched. The chamber length is set to 13mm, the length required for the full decomposition of Hydrazine. Pressure-balanced microvalves [7] can be actuated independently allowing propellant to flow from the always-full plenum to each thruster. The ceramic substrate itself is capable of supporting launch and thermal loads; its estimated mass is 75g.

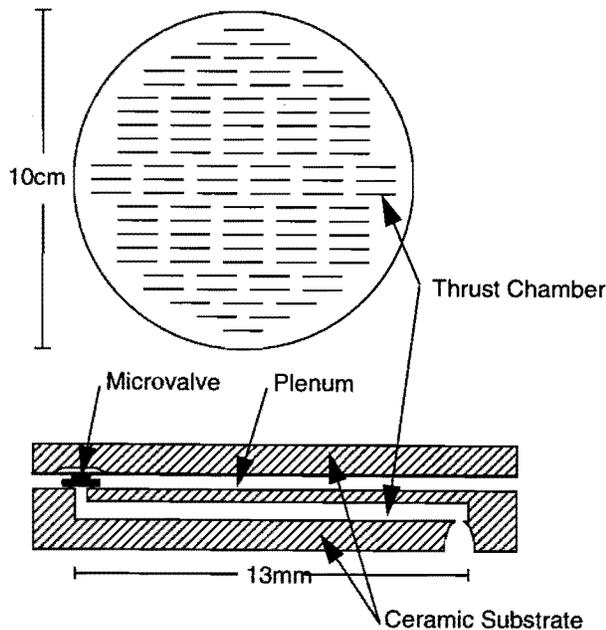


Figure 4: Top and cross-sectional views of a microthruster array.

The optically-based communication subsystem is not one of the main architectural building blocks of the spacecraft (*i.e.*, optics, electronics, propulsion) since it is embedded

within them. A laser and a microlens array are added to the optics subsystem (placed behind the tertiary mirror) and the driving circuitry is added to the electronics subsystem. This system is capable of transmitting a high data rate (1kb/s at 1.6AU) relative to an equivalently-sized RF system, although it is not as mature and the supporting ground infrastructure for signal reception does not yet exist. The use of the laser does not degrade the image quality of the optical system since little, if any, of the energy radiated from the laser reaches the focal plane. The only required modification to the telescope is the replacement of the tertiary reflective element with a dichroic that enables a narrow frequency band laser light to pass through while reflecting all other radiation. No beam-scanning mirrors are necessary since the focal plane can be used to track the earth. In addition, tighter pointing is not required since the laser beam can address each pixel in the array individually. The beam can therefore be directed toward the exact point within the telescope's field-of-view where the detector determines the earth to be, thus increasing accuracy beyond what is provided by the spacecraft [8]. This architecture eliminates the need for a separate aperture (antenna) and volume dedicated for communication.

Power Reduction

Reducing the power consumption of various on-board components affects, both directly and indirectly, the mass and size of the spacecraft. Fewer power-consuming components produce less heat, which in turn requires less thermal control hardware to transfer it to where it can be radiated. High power requirements put a greater demand on the power-supply resources of the spacecraft. Whether bigger batteries or a greater area of solar array are needed, a higher power requirement increases both the mass and size of the power subsystem.

The portable electronics industry produced many new technologies in recent years that reduce power consumption in electrical devices. These advances can be used in space applications, though the higher radiation environment in space requires that additional care be taken. There are two primary methods to reduce power consumption. The first is to increase the efficiency of the device, thus reducing the amount of energy being wasted; and the second is to reduce the voltage applied to ICs. While these methods are being applied today to such products as cellular phones and laptop computers, the specific technologies have yet to be space-qualified. Even though the space industry lags the state-of-the-art technology in this field by several years, it may be safe to assume that these technologies will eventually be qualified to be used in space applications.

The effective design of logic and memory devices, as well as of the electrical systems they make up, can considerably increase efficiency, thus reducing the amount of power that turns into heat as well as reducing overall power consumption. There are several ways to increase this efficiency. The first is to use static components wherever possible. A static CMOS chip consumes very little or no power at all when not in use. If dynamic devices such as dynamic random access memory (DRAM) are necessary, there are still ways to make the “refresh” process less power-taxing. Advances in processes such as staggered- or slow-refreshing will soon approach static RAM power consumption levels [9].

Another method to increase the efficiency of electrical components is to actively control the frequency at which they are operated. This can be applied at both the device and the system levels. Since power scales linearly with clock frequency rates, the ability to control the frequency could allow the system to prioritize and vary the speed in which it performs its various tasks. For computations or functions that are not very time-critical, a slower clock rate can reduce the power necessary to drive the device. Active power management, which varies processing speed according to needed response rate may, over time, reduce energy consumption.

Since power scales as voltage squared, another effective way to reduce power consumption is to reduce the operating voltage. Table 1 shows the percentage reduction in power as the operating voltage is reduced. These figures are relative to the 5V standard currently being used in space designs which is currently being replaced by 3.3V in commercial applications. It is projected that logic voltage will decrease to 2.5V by 1996 and 1.5V by the year 2000 [10]. While these have been demonstrated, 0.3V logic is still in the research stage.

Table 1: Effects of Voltage Reduction on Power Consumption

Operating Voltage [V]	Reduction in Power ^a
3.3	56.4%
2.5	75.0%
1.5	91.0%
0.3	99.6%

a. Relative to 5V.

Example Concept

The principles described above were used to develop an example microspacecraft designed for an asteroid flyby mission [11]. A schematic of this concept representing a design for a microspacecraft weighing less than 3kg and a flight configuration are shown in Figures 5 and 6, respectively. Note that during launch the solar array panels are wrapped around the body of the spacecraft.

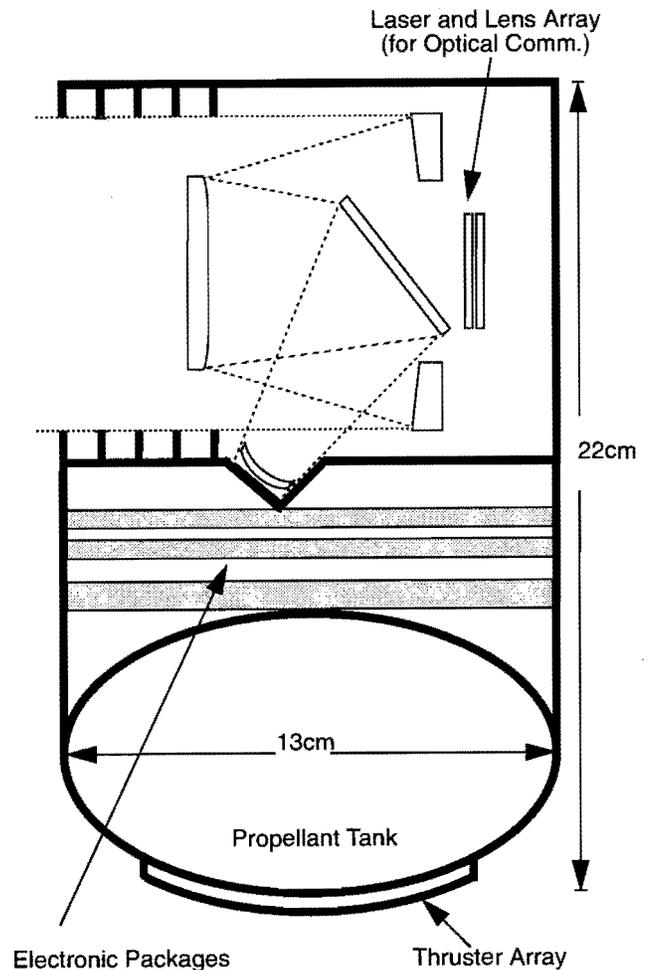


Figure 5: Schematic of microspacecraft physical architecture.

The primary advanced technologies required to realize this particular concept are:

- Microchip laser and microlens arrays
- Microthruster and microvalve array
- Low voltage devices
- Advanced electronic packaging techniques (including ultra-high density integration and die stacking)

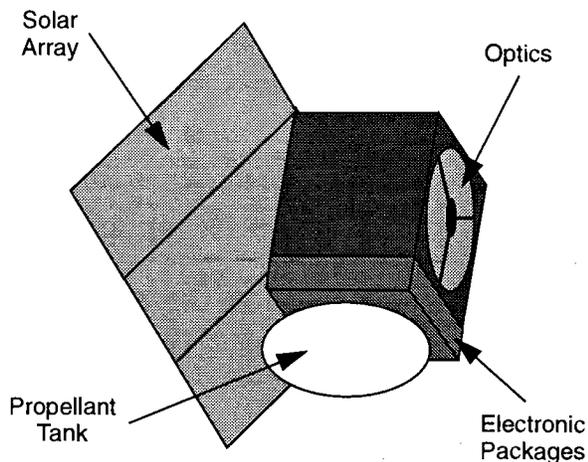


Figure 6: Flight configuration of microspacecraft concept.

There is a risk involved with relying on such technologies. This is due to physical limitations which might become apparent later on in the development process and which may result in the technology not being realized. In addition, political limitations which govern the amount of funding allocated for technology development may inhibit progress. The concept presented here incorporates technologies which are of interest to industries outside aerospace, thus ensuring that their development does not solely rely on NASA or DOD funding. By the same token, although some technologies might not be realized tomorrow, others, which cannot be predicted today, will. Therefore, the risk associated with the advanced technologies used in this example microspacecraft is offset by the possibility that other technologies will emerge in the future which may be able to replace those failed.

In addition to technology readiness concerns, launch vehicle architecture was also addressed. A dedicated upper stage providing a launch energy (C_3) of $4\text{km}^2/\text{s}^2$ † will require a rather large stage which will overshadow the advantages of the diminutive spacecraft. This problem can be solved by providing a single upper stage for each four-microspacecraft cluster. Such a group of vehicles can target a particular asteroid and observe it from different angles. This trajectory flexibility is allowed by the 200m/s ΔV capability provided on-board each spacecraft. Seven such clusters can fit side-by-side across the Pegasus payload shroud for a total of 28 microspacecraft. This launch configuration is presented in Figure 7.

†. Typical high-end launch energy for near Earth asteroids at 0.8-1.2AU.

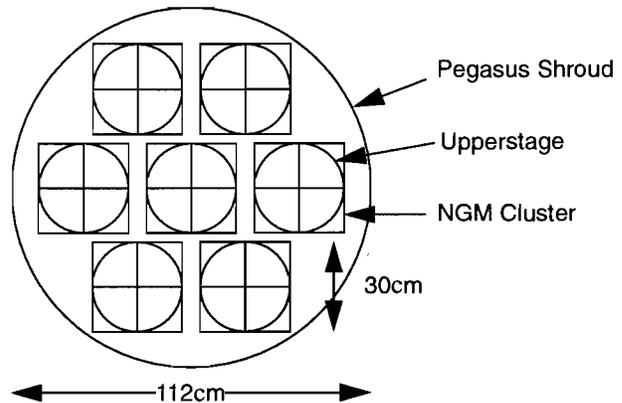


Figure 7: Cross-sectional schematic of the microspacecraft integrated on the Pegasus launch vehicle.

Conclusions

Due to NASA's shrinking budget, it is clear that future deep-space spacecraft will need to be smaller and cheaper while still providing valuable scientific insight, much as their larger predecessors did. Developing a set of core technologies through an evolutionary process will allow the design and construction of a new class of spacecraft.

Increased awareness of the potential of small-scale spacecraft demands greater research into the advanced architectures and technologies that enable the miniaturization process. This demand will increase with time and interest. The development of other feasible concepts, both for asteroid flybys and beyond, should heighten this interest. Also, since there is great demand for miniature technologies in such commercial fields as the portable electronics and cellular communications industries, many of these can be "converted" for space application with a cost which is far less than that required for development of these technologies from the ground up. The resulting technology base should provide the proper environment for building miniature spacecraft.

Finally, this concept (as well as its predecessors) proved that the physical limit of miniaturization has not yet been reached. As new technologies and techniques are introduced (as they are on what seems to be a daily basis) concepts for even smaller spacecraft may be developed.

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