Electromagnetically Launched Microspacecraft for Space Science Missions

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This paper presents the concept of using very small spacecraft launched by an electromagnetic launcher located in low Earth orbit to perform space science missions. A discussion of flight time vs distance performance, potential missions, electromagnetic launchers, microspacecraft concepts, and a conceptual launcher design are included. It is suggested that the present is an especially good time to investigate the subject concept due to the current launch vehicle crisis for space science, and due to the large amounts of resources that the Strategic Defense Initiative Organization (SDIO) has spent on the development of the technology for electromagnetic launchers and projectiles.

Introduction

THE purpose of this paper is to present the concept of using very small spacecraft launched by an electromagnetic launcher located in low Earth orbit to perform space science missions. This paper will discuss the following topics: 1) flight time vs distance performance, 2) potential missions, 3) electromagnetic launchers, 4) microspacecraft design, and 5) a conceptual launcher design.

Small (~1-10 kg) scientific spacecraft can conceivably be launched by an electromagnetic launcher located in low Earth orbit. Exit velocities (impulsive delta V) on the order of 10 km/s can be achieved. Exit velocities of 10 km/s will give the spacecraft enough energy to travel to a distance of 10 a.u. from the sun in about 2 yr.

The electromagnetically (EM) launched spacecraft would be small relative to present planetary spacecraft, i.e., 1-10 kg. This size of spacecraft would call for an entirely different approach to space science compared to current practice, but not so different from what was practiced at the beginning of the "space age." Instead of one large, expensive spacecraft launched every few years, projects could launch many, perhaps 10-50 identical, small, relatively inexpensive spacecraft per year. Whereas failure of current planetary spacecraft would be catastrophic, failure of small EM-launched spacecraft would not be critical to the mission due to the redundancy provided by multiple spacecraft. EM launchers exist.[1] They are called railguns. Railguns have accelerated small masses (0.3 kg) to several km/s. Other types of EM launchers have been proposed,[2,3] most notably the "mass driver."

The key question for this concept is whether there are enough valid space science missions whose science objectives could be met by electromagnetically launched microspacecraft (EMLMSC) to warrant the development of the technology to enable such missions. A key technology for this concept is miniature, high-g insensitive spacecraft components and science instruments.

The present is an especially good time to investigate the subject concept due to two items. First, due to the recent launch vehicle problems, flight activity in space science has been significantly curtailed, which forces and allows new ideas to be created and considered. Second, the Strategic Defense Initiative Organization (SDIO) has spent large amounts of resources on the development of the technology for EM launchers and projectiles.

Potential Performance

Figure 1 presents the calculated trip time vs distance performance for EM-launched payloads. The assumptions for Fig. 1 include 1) impulsive delta V of 10-50 km/s, 2) the payload is launched from a 500-km circular Earth orbit, 3) the payload is launched at the right time and in the right direction in order to take advantage of its orbital energy relative to both the Earth and the sun, and 4) the payload is launched on a heliocentric, hyperbolic escape trajectory. Figure 1 shows that a payload launched at 10 km/s with the preceding assumptions reaches 10, 100, and 1000 a.u. from the sun in 2.2, 34, and 390 yr, respectively. Launched at 50 km/s, the payload would reach the same distances in 0.6, 6.2, and 62.8 yr.

Potential Missions

References 4, 5, and 6 contain material related to the topic of missions for EMLMSC. Missions for EMLMSC will be both similar and different when compared to past and present space science missions. Missions should take advantage of the speed and potential low cost offered by EMLMSC. Missions using EMLMSC wil be able to address questions about both

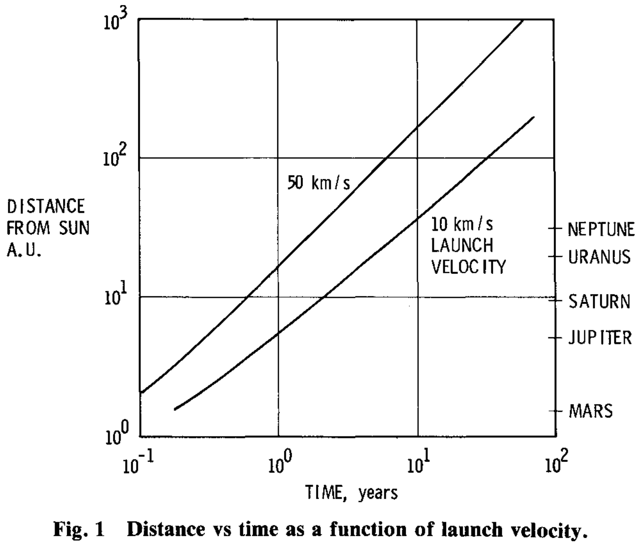

Fig. 1 Distance vs time as a function of launch velocity.

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the bodies in space and the interplanetary medium. Conceptually, EMLMSC could perform both impact missions (like Ranger) and flyby missions (like Voyager). Missions using EMLMSC will probably need to dedicate the spacecraft to a small number (one to three) of experiments due to mass and size constraints.Although limited to only a few experiments per spacecraft, EMLMSC missions will be able to fly several spacecraft to the same target relatively quickly compared to current missions. The ability to perform many experiments quickly will be a key feature of EMLMSC missions for space scientists.

Keeping in mind the unique attributes and the limitations of EMLMSC, the following are possible science objectives for interplanetary-medium EMLMSC missions: 1) gravitational-wave investigations, 2) the study of the infrared background in the 1- to 30-μ region, 3) the study of the zodiacal light, 4) the characterization of solar system dust, 5) the characterization of the particle and field environment of the heliopause, 6) the study of low-energy cosmic rays, and 7) the study of the morphology of the solar system magnetic field. Science objectives for planetary bodies include: 1) imaging of the surfaces, 2) in situ geochemical studies of surfaces, 3) studying trajectories of bodies, and 4) characterizing the particle and field environment close into the sun.

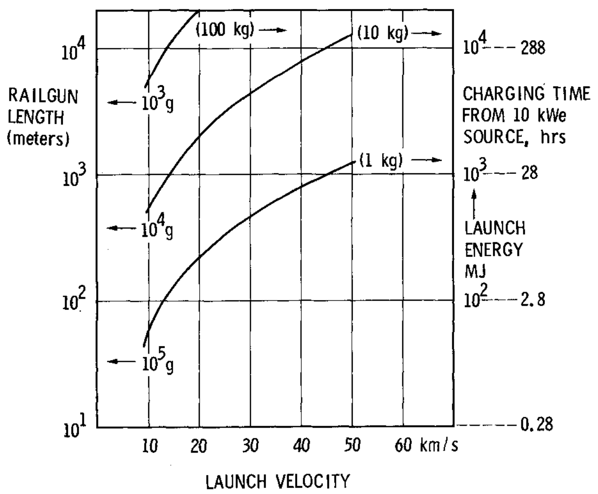

Fig. 2 Railgun parameters of length and energy vs launch velocity.

Table 1 Demonstrated railgun performance

Mass, grams	Velocity, km/s	Circa	Reference
2.8	11 +/− 1	1981	1
2.5	8.5	1984	9
600	1	1985–86	1
100	3.1	1985	1
318	4.2	1984	10
566	0.5	1983	11

Potential instruments for EMLMSC missions include imaging devices; cosmic ray, dust, and energetic particle detectors; magnetometer; gamma ray spectrometer; and neutral and ion particle detectors. Science instruments can also be made small. Conceptual penetrator designs contain small versions of most types of instruments that are used for planetary science.[7] Reference 8 describes a concept for a 400-g magnetometer and a 400-g alpha particle/proton backscatter and X-ray fluorescence instrument for a planetary penetrator. The proposed penetrator for the Comet Rendezvous and Asteroid Flyby mission includes a 1.2-kg gamma ray spectrometer. The proposed wide angle "camera" for the Mars Observer mission is a charge coupled device (CCD) that has a mass of about 2 kg. Although small, these instruments are still about a factor of 10 larger than what could be easily accommodated by an EMLMSC.

With the foregoing discussion of science objectives and instruments as a background, the following is a list of missions that could conceptually be supported by EMLMSC. A thorough mapping of the Earth's magnetosphere using many spacecraft taking simultaneous data at various locations could be performed. Particle and field packages could be "dropped" into the sun. Particle and field spacecraft could be sent far out of the ecliptic plane. Microspacecraft could be sent to sample many asteroids on "Ranger-like" missions. A search for a tenth planet could be mounted by tracking a formation of microspacecraft. A search for gravity waves could be carried out by many microspacecraft all coherently linked.

Electromagnetic Launchers

Figure 2 presents a summary of some of the basic parameters of interest when considering EM-launched payloads. Using the left-hand scale, Fig. 2 shows that for a launch velocity of 10 km/s and a constant launch acceleration of 50,000 g (line not shown), the launcher length wll be about 100 m. The right-hand scale of Fig. 2 shows that a 1-kg payload launched at 10 km/s will have a kinetic energy of 50 MJ. Assuming no inefficiencies throughout the system, the launcher could be recharged from a 10-kW power source in about 83 min. However, using realistic efficiencies, the charging time could be three times longer. Nonetheless, the point to be made is that microspacecraft can be electromagnetically launched as often as about one every day with a small (2–10 kW) power supply. The concept of EMLMSC for space science does not require a large steady-state, space power system.

References 1 and 3 present a summary of the types of electromagnetic launchers and the status of some devices. The railgun is receiving the most attention from researchers. Railguns have also demonstrated performance that implies that they have the most near-term potential for being able to achieve the mass and velocity requirements of space science missions. Railguns exist and have accelerated several grams close to 10 km/s, 0.32 kg to 4.2 km/s, and 0.6 kg to 1 km/s (see Table 1). Near-term goals for railgun performance are to accelerate kilogram masses to velocities of several kilometers per second. Reference 12 has a velocity goal as high as 50 km/s.

Table 2 Demonstrated high-g projectile technology

Item	Acceleration	Launcher	Circa	Comments	Reference
40-mm projectile	50,000 g 100,000	Artillery cannon	1984	Microelectronic package controlled solid prop. "charges" to enable postlaunch maneuvering	13
U.S. Air Force projectile	60,000	Gas gun	1985	RF transmitter and batteries	14 15
Copperhead projectile	20,000	Artillery	1980	RF T/R subsystem	7
CCD imager	20,000	Gas gun	1977	Prototype imager for planetary penetrators	16

Table 3 Conceptual railgun-launched spacecraft

Diameter, cm	Mass, kg	Power, W	Guidance approach	Sensor	Avionics
10–15	3–5	N/A	Optical semi-active homing	Si detector	FOG[a] roll ref., spin rate 100 rpm
10	1	20	Optical homing	IR seeker	FOG roll ref., spin rate 32 rpm
10	0.9	N/A	Semi-active	mm wave	Earth sensor spin rate 20 rpm
12	1.4–2.1	25	Passive seeker	Laser beam rider & IR seeker	FOG spin & 3 axis
10	1.1	5	Semi-active	mm wave & UV homing	20 rpm spin rate

[a]Fiber optics gyroscope.

Technology Base

The SDIO is studying EM launchers and projectiles for defense missions. Although the pace and extent of SDIO's effort in EM launchers and projectiles has slowed over the past years, it has, nonetheless, produced a large body of technical information and technology that can be used for space science missions. The SDIO has sponsored several programs studying the use of EM launchers and small projectiles. Both ground- and space-based launchers have been studied. The most recent program has a long-term goal to produce EM-launched projectiles with a 2-kg mass that are qualified for space.

To achieve the velocities of interest for space science missions, in a launcher of reasonable length (less than 100 m), average launch acceleration levels of 50,000–200,000 *g* or more are required. High-*g* insensitive spacecraft subsystems and instruments are a key ingredient in the EMLMSC concept. High-*g* technology has also been extensively developed. First, the military is developing the technology for "intelligent" projectiles and munitions that can be fired out of ordinary artillery cannons. Artillery cannons accelerate projectiles by about 5000–10,000 *g* and achieve exit velocities of about 1 km/s. Table 2 presents the characteristics of several functioning packages that survived high accelerations. Table 2 also includes a CCD imager that was tested to 20,000 *g* as a prototype imager for a NASA planetary penetrator.

As mentioned previously, the SDIO has been supporting R&D in the area of space-based railgun platforms. As part of this SDIO research, the projectiles (spacecraft) to be launched by these platforms have been conceptually designed, and typical components have been subjected to simulated acceleration and magnetic-field environments. Some of the components that have been tested include batteries, hybrid circuits, IR detectors, lenses, microprocessors, monolithic accelerometers, piezoelectric stacks, monopropellant catalysts, and thrusters. Although not all of the tests were successful, the general trend clearly shows that common components can survive very high acceleration levels (100,000 *g*) when suitably packaged. Components specifically designed for electromagnetic launch should be able to survive higher acceleration levels.

Railgun launchers will also expose the spacecraft and its components to high-magnetic fields and, more importantly, very high time-varying magnetic fields. Typical requirements are for railgun-launched spacecraft to survive a B field of 10 T and B-dot of 10,000–100,000 T/s. SDIO contractors have also subjected many of the same components discussed previously to high-B and B-dot tests. Again, although not all of the tests were successful, the general trend indicates compatibility with the requirements.

The concept presented in this paper could take advantage of the work performed by the SDIO on EM launchers and projectiles to limit the amount of new resources required to bring about a successful EM launcher and spacecraft for space science.

Concepts for Electromagnetically Launched Microspacecraft

As previously mentioned, the SDIO is developing the technology for EM-launched intelligent projectiles. References 17–19 describe projectile (spacecraft) concepts that include power, propulsion, guidance, structure, telecommunications, and command and control subsystems. These spacecraft have remote-sensing instruments that enable them to carry out their mission. These concepts were developed under the requirement to operate after being electromagnetically launched with 200,000–500,000 *g* of acceleration. The mass of these spacecraft ranged from 1–5 kg. Table 3 presents a summary of the key characteristics of several SDIO concepts for railgun-launched microspacecraft.[19]

Figure 3 presents a concept for a railgun-launched microspacecraft using projected technology. The spacecraft has a mass of about 1.5 kg and is accelerated to 10 km/s at 500,000 *g* and has a large postlaunch delta V capability. Reference 18 describes a propulsion subsystem for 1-kg railgun-launched spacecraft that could produce 1300 m/s of delta V using standard bipropellants. The spacecraft shown in Fig. 3 spins about the sensor axis and has the capability to search for, acquire (with an IR seeker), and maneuver to the target. Concepts for attitude-control sensors exist. Accelerometers[20] have been and fiber optic gyros can conceivably be made on a single wafer of silicon.

For space science missions, EMLMSC concepts developed for SDIO missions will need to be modified to include a long-duration power source and the ability to return data over interplanetary distances. Conceptually, one can extend the design shown in Fig. 3 to a planetary spacecraft. Power can be obtained from one or more radioisotope heater units (RHU) that produce 1 thermal W from 2 g of radioisotope fuel. RHU's are currently used on interplanetary spacecraft. Thermoelectric conversion can produce 40 mW per RHU. Batteries could provide peak power.

Data can be returned using radio or optical frequencies. With a medium-gain antenna at Ka band and 1 W of radio power, 10 bps could be returned to a 70-m antenna over 4 a.u. From 2.5 a.u., 25 bps could be received. Using a Nd:YAG optical link, 200 bps could be sent from 10 a.u. using a 10-cm aperture, 0.1-W laser power, and a 10-m receiver in orbit around the Earth. The optical link could support 800 bps and 5000 bps over 50 and 20 a.u., respectively.

Conceptual Launcher Design

For the purposes of this section, a railgun was selected as the launcher. The reasons for selecting the railgun include: 1) the significant amounts of resources spent by the military for railgun technology, 2) the relatively advanced state of railgun technology (see Table 1), 3) NASA has already studied the use of railguns as EM launchers,[21,22] and 4) conceptual railgun design is straight forward. The selection of the railgun for the

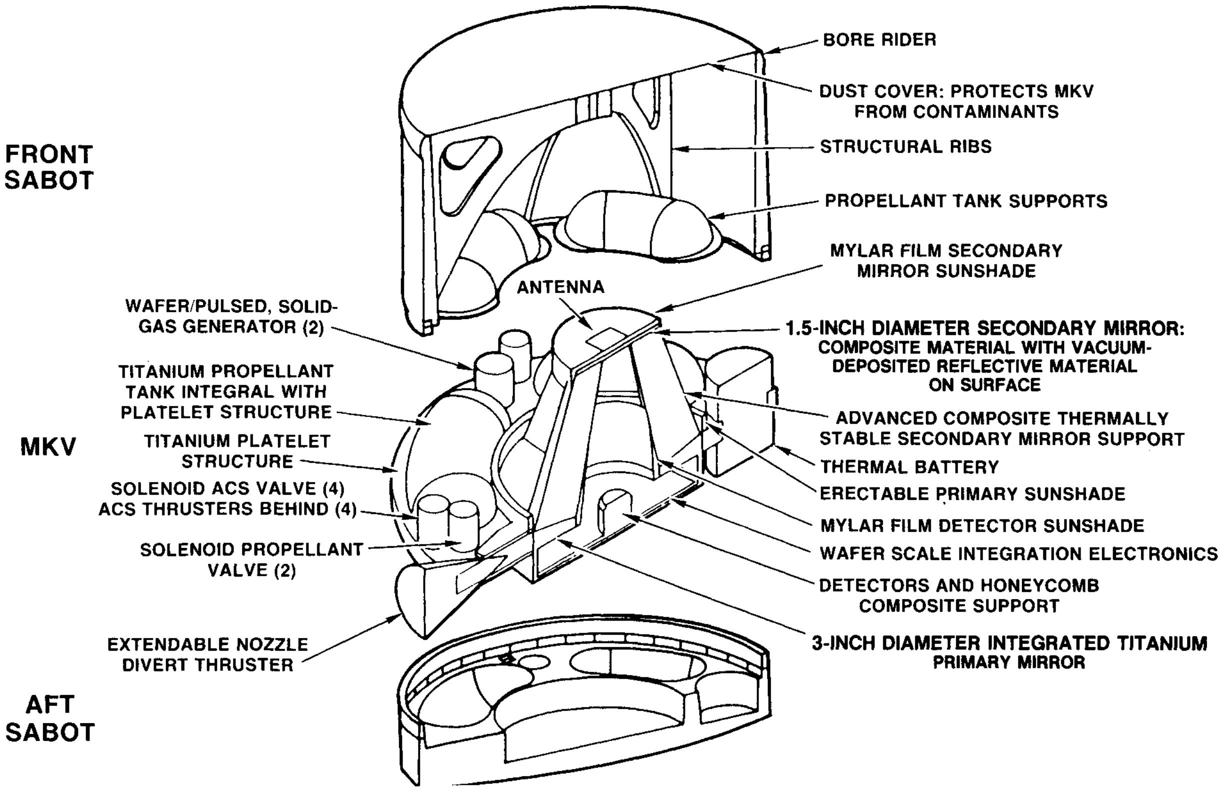

Fig. 3 Railgun-launched microspacecraft concept using advanced technology for an SDI mission.

Table 4 Railgun platform conceptual design 100-m-long railgun: 1 kg accelerated to 10 km/s

Item	Mass, kg	Cost, K$
Amzirc rails	2,900	750
Insulator	800	750
Kevlar	1,700	750
AL tube	900	750
HPG's (23 devices)	28,880	2,300
Inductor (23 devices)	34,500	700
Structure & cabling	2,000	5,000
Preboost gas gun	100	200
Switches	200	1,000
Spacecraft subsystems		
Power	100	2,500
Resisto-jet	100	500
CDS/telecom	50	4,000
AACS (thrusters & wheels)	100	4,000
Sun shade (100X1X2M)	100	200
Reserve (25%)	18,100	5,900
Total	90,450 kg	$29,300 K

purposes of this section is not meant to imply that other types of EM launchers might not be superior for use as a launcher for space science payloads.

The example point design is 1 kg accelerated to 10 km/s. The approach in Ref. 21 was used to provide the following railgun conceptual design. The required kinetic energy is 50 MJ. It is assumed that only 50% of the stored energy will be transferred to the spacecraft, and that 10% of the stored energy will not be able to be transferred to the railgun. A launcher length of 100 m was selected as a reasonable value. Accelerating 1 kg to 10 km/s in a 100-m launcher takes an average (assumed constant) acceleration of 51,000 *g*. The force applied to the projectile will be 500,000 N. The acceleration process will take 0.02 s.

As was done in Ref. 21, a distributed-energy-source railgun was selected for this conceptual design. The railgun will be powered by homopolar generator/inductor (HPG/I) power units. References 23 and 24 describe HPG/I units that have been built. Five mJ is a convenient size for HPG/I power units. Twenty-three 5-MJ HPG/I power units will be required. References 23–25 contain the mass and cost per unit energy parameters for HPG/I power units for railguns. Superconducting equipment was not assumed for this example, although the HPG/I's were assumed to operate at liquid nitrogen temperatures.

The railgun itself will be built in 23 modules, each 4.35 m in length. For sizing and costing purposes, it is assumed that the railgun will be a free flyer at an altitutde of 500 km. The railgun could be attached to the space station and would certainly need men for assembly. As a free flyer, the railgun would require the normal spacecraft subsystems, i. e., power, propulsion, command and control, telecomunications, attitude control, temperature control, and structure. Small electric resisto-jets will be used to provide the impulse required to reboost the platform after each launching. A 1.5-kW solar array and batteries will be used in the power sybsystem. The resisto-jets will have to operate at 1 kW for about 14 h to provide the reboost impulse. The resisto-jets will consume about 2 kg of propellant per reboost maneuver.

Table 4 presents a mass and cost summary of the conceptual railgun platform. Although the total mass exceeds the capability of the Space Shuttle, a dedicated shuttle launch would not be necessary due to the modular design of the railgun. The railgun modules (4.35 m and about 4000 kg) could be flown to the space station for assembly on a "space-available basis" in regularly scheduled shuttle resupply trips.

Although the preceding concept was presented in a space-station context, the space station is not critical to the concept. The conceptual design shown in Table 4 was designed as a free-flying platform. In fact, a feasibility test could be performed using only the shuttle and three of the conceptual railgun modules. A three-module railgun has the potential to send a 1-kg spacecraft to the moon. The railgun would not need to leave the shuttle payload bay. On a subsequent mission, the railgun platform could be released as a shuttle-tended free flyer. The total 100-m-long railgun could be built up over several shuttle missions.

Summary

This paper has presented the concept of using very small spacecraft launched by an electromagnetic launcher located in low Earth orbit to perform space science missions. The electromagnetically launched microspacecraft would have a mass of 1–10 kg. Instead of one large, expensive spacecraft launched every few years (in the best of times), projects could launch many, perhaps 10–50 identical, small, relatively inexpensive spacecraft per year. The ability to perform many experiments quickly will be a key feature of EMLMSC missions for space scientists. If the concept is shown to be feasible and ultimately applied, it will open an entirely new avenue for the achievement of space science objectives.

The paper discussed the potential performance of electromagnetic launchers for space science missions. Launched on a heliocentric, hyperbolic escape trajectory at 10 km/s, a spacecraft reaches 10, 100, and 1000 a.u. from the sun in 2.2., 34, and 390 yr, respectively. Launched at 50 km/s, the payload would reach the same distances in 0.6, 6.2, and 62.8 yr. Electromagnetic launchers called railguns exist and have accelerated several grams close to 10 km/s and 0.32 kg to 4.2 km/s. Railgun programs around the nation have goals to accelerate kilogram-size objects to several kilometers per second.

Electromagnetically launched microspacecraft will have to withstand accelerations of about 100,000 *g*. Testing performed by the SDIO has shown that components can survive such acceleration. Electromagnetically launched microspacecraft concepts have been created for the SDIO. These conceptual spacecraft have most of the functions of current interplanetary spacecraft and a mass of 1–5 kg. It was noted that the SDIO has been supporting R&D in the area of electromagnetic launchers and projectiles for several years and has invested many millions of dollars for studies and technology that can be directly used for space science purposes.

A conceptual railgun platform design was presented that could launch a 1-kg spacecraft to 10 km/s. The platform would be a free flyer near the space station and have a mass of nearly 90,000 kg and a cost of about $30 million.

The present is an especially good time to investigate the subject concept for two reasons. First, due to the recent launch vehicle problems, flight activity in space science has been significantly curtailed, which forces and allows new ideas to be created and considered. Second, the SDIO has spent large amounts of resources on the development of the technology for EM launchers and projectiles.

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