ELECTROMAGNETIC EARTH-TO-SPACE LAUNCH

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Presented at the
4th Symposium on
Electromagnetic Launch Technology
Austin, Texas
April 12-14, 1988

Publication No. PR-89
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Abstract

American dreams of pursuing the high frontier of commercial ventures in space and space colonization have been deflated by the stagnating high cost of launching material to space and, since the Challenger disaster, by an apparent loss in commitment and boldness. Transportation from the earth's surface to earth orbit is difficult and, in fact, is the energy bottleneck which, in spite of remarkable progress in the last quarter century, continues to inhibit our access to space.

For over 60 years, electromagnetic and electrothermal launchers have been proposed more or less seriously as an alternative means for launching materials into space. In addition to offering a higher degree of control and reliability, they can perhaps reduce the cost of launching material to space by several orders of magnitude. But, ardent enthusiasm on the part of the proponents has tended to surpass the actual state of the supporting technology. A viable electromagnetic earth to space launch system requires the development of several critical component technologies beyond the technology of demonstrating the mere task of accelerating a large object (100-1000 kg) to earth escape or earth orbital velocity.

This paper reviews several of the previous electromagnetic and electrothermal launch concepts and discusses the critical related technologies which are essential for the development of practical earth-to-space launch systems. Selected missions and their requirements will be discussed. Launcher concepts are briefly discussed, and specific examples are given to demonstrate significant recent progress in hypervelocity atmospheric transit and hardening of launch vehicle components to withstand higher launch accelerators by several orders of magnitude. These recent advances have significant impact on the payload which may be placed in orbit and have a major influence on the onboard propulsion requirements for orbit insertion.

Based on technical achievements in all the critical supporting technologies, we believe it is now feasible to demonstrate a credible electromagnetic earth to space launch system.

Introduction

For centuries, man has looked to the heavens and dreamed of visiting or living deep in space. In the 1970s, laboratories and colonies in space were frequent topics for discussion in the popular scientific literature and seemed to be close to realization. But recently, these dreams have evaporated in the turbulent winds of economic and technical realities. To escape from the strong gravitational attraction at the earth's surface and place an object in earth orbit is obviously quite difficult and continues to inhibit our access to space, in spite of remarkable technical progress in chemical rocketry over the past quarter of a century.

Alternative launch techniques have been proposed (more or less seriously) which use electromagnetic energy rather than chemical energy to provide the propulsive launch force. This idea is not particularly new, but what is new are some recent advances in several of the key technologies. We will explore these developments and the spectrum of technologies which are essential to the successful development of electromagnetic techniques for launching material from earth to space.

In the early 1970s, Gerard K. O'Neill led the advocacy for space exploration and colonization, highlighted in his successful book entitled *The High Frontier*. He concluded that the unlimited energy available to space inhabitants from solar radiation and materials which are abundantly available from the surface of the moon and from asteroids could make possible a new and attractive life for thousands, and even millions, of people. As opposed to earlier (and even current) proposals, he envisioned that space habitats would not be metal-walled,

compartmentalized space stations, but large, open-style living environments with soil, an abundance of green plants, and even internal skies with an abundant atmosphere. He believed that the pattern of earth-based space exploration should be replaced by permanent habitation and large-scale manufacturing in space.

American dreams of pursuing the high frontier of commercial ventures in space and space colonization have been deflated primarily by the unyielding, high cost of launching material to space, by the physical limits imposed by nature on the chemical energy contained in chemically propelled rockets, and by an apparent growing technical conservatism in U. S. exploratory zeal and boldness.

The United States is in the process of a re-evaluation of its means of launching material to space. In addition to the shuttle, serious consideration is being given to the development of a heavy lift launch vehicle and we are even considering redeveloping the Saturn V (now thirty-year-old technology) which launched our first astronauts to the moon. It is interesting to note that Skylab, which plummeted to the earth a decade ago, was larger than any of our current spacecraft, including the Soviet Mir space station which currently serves as the only space laboratory in orbit.

One of the major advantages of launching material to space using chemically propelled rockets is the maturity and reliability of the technology. But this may, as well, be a major detriment. Chemical rockets may have approached their ultimate potential, since it is unlikely this technology will yield the major technical improvements required to reduce launch costs enough to open the frontiers of space.¹

Various attempts to determine the actual cost of launching material to space have been disappointing and differ by orders of magnitude. All the estimates indicate the costs are high - from \$1,000 to \$40,000 per pound. All of the launches have been performed by government-owned rockets and it is difficult to assess actual launch costs as opposed to R&D and related launch support costs. Considering U. S. launch systems, John and Ruth Lewis conclude² that we have made no significant progress in reducing launch costs since the Saturn I three decades ago. They contrast this with early projections of dramatic expected savings in launch costs, but as each new system was developed, the actual launch costs refused to budge.

Part of the reason for this stagnation may derive from the fundamental limits associated with the physics and chemistry of chemical rockets. The energy available from chemicals used for rocket propulsion is fundamentally limited and, in spite of intensive research over the past several decades, has not yielded order-of-magnitude increases in propellant performance. Generally, the performance of chemical rocket propellants is characterized by their specific impulse. Figure 1 illustrates the energy of the propellant materials as they have become available through time. The early solid propellants were primarily nitrocellulose. Later, a means was developed for utilizing the more energetic, but extremely hazardous, nitroglycerin propellant formulations. In more recent years, cyclotrimethylene

trinitramine (RDX) and its eight-member ring analog (HMX) began to be used because of their even higher energy density. In spite of an intensive effort over the last several decades to develop energetic molecules superior in performance to HMX, few, if any, materials have been found with the requisite energy density and stability. The elusive nitrocubaines may become available as explosive components in the 1990s, but they are currently of interest only as laboratory materials. Liquid propellant compositions have a similar range of performance as these solid propellants, with hydrogen/oxygen being the most energetic. Additionally, since mass fractions for insertion into even the lowest orbits are as high as 90% for fuel alone, chemical rocket systems are designed and constructed to minimize the structural mass which drives the vehicle cost quite high. This requirement, along with the need for quality control, maintenance, and launch services, dominates the total cost of the chemical launch system.

Figure 1. Evolution of energetic materials as components of propellant compositions

Fiction writers and scientists alike have been suggesting the use of electric power as an alternative means of launching material into space for over sixty years. In the spring of 1929, G. A. Polevoi, at the Moscow Exhibition of Interplanetary Machines, presented a description and plan for an electromagnetic first stage to launch a rocket to 1.6 km/s followed by ignition of the rocket to carry it into space at 11 km/s.³ In addition to offering a higher degree of control and reliability, electromagnetic launchers can perhaps reduce the energy cost of launching material into

space by several orders of magnitude and they are not limited by the energy available in specific explosive chemical materials. But ardent enthusiasm on the part of electromagnetic launch proponents has tended to surpass the actual state of the supporting technology and, more importantly, to neglect critical elements in the total launch system. A viable electromagnetic earth-to-space launch system still awaits formulation of a successful concept and demonstration of vital technologies. In fact, it requires the development of several critical component technologies which may be even more important than the task of accelerating a large object to earth orbital or earth escape velocity.

Potential Electromagnetic Launch Missions

There are numerous potential missions for electromagnetic launchers in space. In the mid 60s, studies evaluated the potential production of oxygen on the surface of the moon as a means of providing fuel for further space development and exploration. The initial concepts employed chemically propelled space vehicles (lunar modules) to transport lunar-produced liquid oxygen from the lunar surface into low lunar orbit. There it would serve as a fuel for space vehicles using hydrogen/oxygen propulsion systems. More economical transport may be provided using a lunar-based electromagnetic launcher. In a series of summer studies supported by the NASA Ames Laboratory, electromagnetic mass drivers⁴ were designed to launch fuel and other material from the lunar surface to lunar orbit. Interest in this mission continues with more detailed studies performed during the past year.^{5,6} In 1988, the President signed a new National Space Policy which sets the course for eventual development of a lunar base and for extending U. S. manned operations beyond earth into the solar system. This action redirects NASA to its original focus on science, technology, and exploration and heightens the interest in missions such as the economical launch of material from the lunar surface to low lunar orbit.⁷

An alternative, quite novel space mission was presented in a paper at the 1980 Conference on Electromagnetic Guns and Launchers by John Barber and his associates.⁸ They proposed to use an electromagnetic railgun accelerator to expel reaction materials as a deep space propulsion system. They concluded that for orbital transfer and deep space propulsion, electrical propulsion appears to offer inherent advantages over chemical propulsion and ion propulsion systems. From their calculations, a railgun propulsion system designed for an orbital transfer vehicle can potentially provide significant reductions in system size and propellant requirements compared to chemical and ion thruster systems.

Recently, Ross Jones has proposed electromagnetically launched microspacecraft for space science missions.⁹ He suggests that a number of scientific instrumentation packages, including imaging devices, cosmic ray detectors, neutral and ion particle detectors, gamma ray spectrometers, and others, may be sufficiently G-hardened to withstand the launch acceleration from an electromagnetic gun. His concept is to launch these simple space experiments from an electromagnetic launcher located in low earth orbit. Incredible progress in

the miniaturization and G-hardening of electronic and electro-optic components has been made in recent years, stimulated by the Department of Defense's interest in developing space-launched hypervelocity guided kinetic energy interceptors. If scientific instrumentation can be developed to withstand the launch environment, space exploration can return to its initial, extremely productive approach of frequent launching of relatively inexpensive and simple spacecraft.

In the opening keynote address to this Symposium,¹⁰ Dr. Mark eloquently summarized the importance of electromagnetic launch technology for all of these applications in space. But I want to turn our attention now to another potential space application of electromagnetic propulsion technology. The goals and potential advantages of this application have been promoted for decades, but a credible technical program and technology demonstration has not yet been realized.

The Reality of Electromagnetic Earth to Space Launch

For decades, electromagnetic (EM) earth-to-space launchers have been described by science fiction writers, designed by scientists and engineers, but built by no one. Numerous potential advantages of electromagnetic launch (EML) have been identified: (1) they are capable of launching almost pure payload (it has been estimated¹¹ that the launching cost could be made to approach the cost of the energy - currently 65 cents per pound - plus capital amortization), while chemical rockets must carry their engine, energy source, and reaction mass with them; (2) since most of the propulsion machinery is not launched, it is not subject to the severe weight and volume constraints of chemical rocket propulsion engines and the exotic (and expensive) rocket structure is greatly simplified; (3) they offer a degree of safety and velocity control not easily achieved with chemically explosive propulsion systems; and (4) numerous other operations, support, and maintenance advantages are derived from a launch system in which most of the propulsive equipment remains on the ground. I want to explore the technical challenges and barriers which have inhibited the implementation of this technology for launch from earth to space.

One of the first U. S. detailed studies¹² of an electromagnetic earth-to-space launcher was a feasibility study sponsored by DARPA and the Air Force. It was performed by an industrial team of Litton and Physics International. They investigated the power and launch requirements, aerodynamics, and orbital mechanics for accelerating large payloads to space using an electromagnetic launcher. The details are still classified, but this effort provided an analysis of the size of the components and the aerothermal/aeroballistic difficulties in transiting the atmosphere at hypervelocity.

A more recent effort¹³ led by the NASA/Lewis Laboratory evaluated the mission of disposing of nuclear radioactive waste by launching it into the solar system. The concept was to process spent fuel rods into a nuclear waste payload and transport these payloads to a remote site for launch from the earth surface into the solar system. The study was funded by NASA and performed by Battelle Columbus Laboratories. The point design from this effort

was a railgun powered by a large number of homopolar generators and inductors distributed along the length of the railgun.

In his keynote address, Dr. Mark indicated the strong advantages of electromagnetic guns in space, but expressed serious reservations about the EM launch of materials from earth. His reluctance is probably fueled by the less than spectacular results to date in attacking this problem. To propose serious investment in this technology, it is not sufficient to demonstrate that we can accelerate a one-gram lexan cube to earth orbit or earth escape velocity. Besides the scaling issue, there are serious mission requirements and significant questions about the survivability of a useful payload, both during Hi-G launch and atmospheric flight.

In order to get a handle on the metrics involved, let us look at an orbital mission launched with some type of electromagnetic launcher. Figure 2 illustrates the basic flight path of an EM launched orbital mission. The basic premise of this mission is that as much energy as possible is derived from ground energy sources. This means we did not consider hybrid concepts where part of the propulsion energy of the first stages are rocket derived. The orbiter is launched from the ground, travels through the atmosphere (about 75 miles), and finally reaches its launch apogee at 200 to 800 miles for Low Earth Orbit (LEO) or even 22,000 miles for Geosynchronous Orbit (GEO), at which point it fires its circularization rocket, inserting the orbiter into earth orbit.

LAUNCH TRAJECTORIES

Figure 2. Launch and flight trajectories

Parameters of interest to the launch system designer are: what is the angle at which we launch, how sensitive is the system to launch angle (do we need to change it for different orbital altitude missions); what is the required speed of the orbiter at the launcher muzzle; what kind of pulse power systems are required; what amount of fuel is required to insert the orbiter into orbit; and what is the effect of launcher altitude?

There are clearly missions in which bulk materials (building materials, water, etc.) could be launched to space, but it is important to recognize that if that is the application driving the development of this technology, it

will be of relatively low priority and certainly will not happen in the near future because that application supports an infrastructure (space station or other space assets) that is not in space now and is a long way from being there.

So, in my view, we must have a launch vehicle that is not just a single monolithic block of material, but it must have components required of any orbiter: an aeroshell which is capable of hypervelocity flight in the atmosphere, a navigation system to determine when to fire its circularization rocket, an attitude control system so it is a stable platform, some telemetry, some instrumentation payload, a rocket, and fuel for putting it into a circular orbit.

The orbital vehicle of this type is shown schematically in Figure 3. The vehicle is encased in a sabot which serves two functions: first, it guides and protects the orbiter in the bore, but more importantly for an orbital mission, it provides the structural support that the amorphous fuel will require while undergoing Hi-G launch accelerations. Since that support is only needed during launch, getting rid of its mass in the sabot means that no fuel is required to circularize that portion of the vehicle once the vehicle is at apogee. We believe it is important to separate the sabot to reduce the structural support requirement and reduce the total launch weight.

PROJECTILE

Figure 3. Components of a transatmospheric vehicle for hypervelocity launch and hypersonic flight

These vehicles do not have to be orbital devices to be useful. In fact, we have looked at some applications where one simply would use them as sounding rockets. That turns out to be a very worthwhile mission and it is something we need to explore as a part of an overall EM launch effort, but I do not want us to forget that if we are going to put these vehicles into a stable orbiting configuration, we need to add circularization energy at the far end.

We have taken as the figure of merit for our mission the specific launch energy - that is, the ratio of the amount of kinetic energy we have to put into the fueled vehicle and

sabot as it leaves the muzzle on the ground to the energy of the vehicle in orbit after insertion. This is graphically illustrated in Figure 4. On the way from the ground, we have discarded the sabot and burned the orbit insertion fuel so the launch mass is considerably different from the orbiting mass. We did some analysis of simple circular orbit missions at various insertion altitudes so that we could check the notional concept, arrive at a rough scale of the system size, and perform simple system tradeoff investigations.

Figure 4. A specific launch energy is defined as the ratio of launch energy to energy of the TAV in orbit

I caution you that this figure of merit should not be taken to represent the cost of operating the electromagnetic launcher. In fact, it is misleading to indicate that the cost of electricity to launch a block of something to space is a few dollars per pound. We must stop using the electric meter as our monitor of what this is going to cost.

Figure 5 describes sea-level launch to various orbital altitudes. If launched at low angles, the orbiter goes through a lot of atmosphere, losing a lot of energy getting through it. That is why the specific energy increases rapidly at the left side of the figure. As we launch at higher angles, the orbiter goes through the atmosphere more quickly, but the fuel it must carry to provide energy for orbit insertion or circularization starts to increase. As you might expect, there is a tradeoff somewhere between these extremes. In this conference, there are several papers that have addressed that issue - one of them by Miles Palmer from SAIC.¹⁴ They give basically the same general result - somewhere between 10 and 20 degrees is a reasonable launch angle, depending on the altitude, for the kind of vehicles we are talking about here. As we launch to higher orbits, like geosynchronous orbit, the launch angle becomes less critical.

Another basic observation is that for higher orbits, the optimal launch angle increases due to increasing air drag at the higher required launch velocities and the criticality of the optimization decreases (curve flattens out) due to the smaller effect of the horizontal launch velocity component at these extremely high altitudes. (It is five earth diameters to geosynchronous orbit.)

Figure 5. Specific launch energy as a function of launch angle at sea level

Numerous authors have commented on the desirability of launching up the side or even from the top of a mountain to reduce the atmospheric drag. It makes a significant difference and has considerable influence on the launch energy requirements. Figure 6 depicts our LEO described earlier, but with the launch site at various altitudes. We save about 12% of the energy if we launch at 5,000 feet, 21% if we go to 10,000 feet, and 29% if we go to 15,000 feet.

Figure 6. Specific launch energy and launch angle as a function of launcher altitude

Can we see EML technology being able to support these missions? We estimate that launching a 100 kg orbital package to LEO would require a 30 GJ supply if the launch system operated at 50% efficiency. These kinds of power sources are not commercially available, but are not outrageous extensions of existing systems.

There is an important fundamental consideration that, in the long term, will drive earth-to-space launch systems to use electromagnetic launchers to supplement or replace chemical rockets. In Figures 5 and 6, the scale on the vertical axis indicates that on the order of a few hundred

megajoules of energy was required to put a kilogram payload into orbit. If we consider the energy required for any of the chemical rocket systems to put similar kinds of vehicles in space, whether it is the shuttle, Saturn, or the Ariane, we will find a number about four times larger. The physics and chemistry, in the long term, will dominate the applications of the technology.

Component Technologies for Electromagnetic Earth to Space Launch

In his invited presentation at this Symposium, Henry Kolm mentioned that we really are expecting a lot of electromagnetic launchers and compared the current state of the technology to that of the Goddard rockets. If we consider the space shuttle, rockets have come a fantastically long way from Goddard's initial experiment, launching material in free flight and watching it go generally upward. The shuttle is not a trivial unguided rocket system. There is an incredible amount of infrastructure that goes with a successful shuttle launch. This community must ensure that we address the entire launch system with all of its associated component technologies and infrastructure if we are going to make a credible attempt to implement electromagnetic earth-to-space launch as a viable supplement or alternative to chemical rocket launchers.

This entire Symposium is devoted to detailed descriptions of electromagnetic launchers, their power sources, and associated control systems. The published Proceedings will provide the most current state of the art of this technology. Most of the recent effort has been devoted to railgun and coilgun launchers and there are excellent reviews of these efforts at the Symposium. But, there are other kinds of launchers that may also support earth-to-space access. One of these is the electrothermal (ET) launchers. The basic idea of ET is to accelerate a projectile using gas expansion, as in a conventional gun, but with an electrically heated plasma as the driver gas - this allows higher temperatures and low molecular weights, and thus, a higher projectile velocity. Experimental devices¹⁵ have been built which are attempting to accelerate projectiles to 10 km/s.

Several presentations at the Symposium address launchers of the appropriate scale for earth-to-space launch. Miles Palmer proposes a breech-fed railgun powered by the large battery source at Eglin AFB. The battery source is coupled to an inductor which requires high current opening switches. This launch system is finishing construction and assembly and may be the least expensive near-term means of testing a full-scale launch. Another interesting concept by Driga, et al, at CEM is a very clever scheme using four compulsators and an induction accelerator.¹⁶ What is most important about this concept is that the compulsators described in this presentation are not significantly different in energy from the compulsator being constructed for the DARPA/Army 9 MJ range gun power source.

Let's turn to the issue of the kinds of objects which are required in space. One example is the NASA/JPL Voyager spacecraft which has all sorts of appendages and weighs about seventeen hundred pounds. The Voyager is by no means the biggest satellite launched. Another example is

the DSP satellite. It is 28 feet long, 9 feet in diameter, and is placed in a geosynchronous orbit. Clearly, electromagnetic launchers are not going to be able to move in and quickly take over the satellite launch business! It is not clear that it makes any sense to use a coilgun or railgun to launch this large an object. We can, however, carefully evaluate the missions and the technical tasks we do need to perform in space and determine whether the recent advances in solid state electronics can miniaturize and harden satellites so that EM launch is practical.

Figure 7 illustrates one of the candidates of the SDI guided projectile program. This is a one kilogram device that senses targets and maneuvers in space and was designed to withstand 500 G-ees of acceleration. It is the sort of thing we can perhaps put into space. DARPA and SDIO have developed G-hardened miniaturized components that can be integrated directly to produce compact satellites. This is perhaps one of the most promising and fastest moving technical activities in the Department of Defense.

RAILGUN LAUNCHED MICRO-SPACECRAFT CONCEPT

Figure 7. General Dynamics design of microspacecraft for hypervelocity launch

But, how do we get an orbiter through the atmosphere at hypervelocities without burning or eroding to the point of destruction or loss of accuracy? Figure 8 shows a configuration designed by Rand several years ago. It uses transpiration cooling, in which gases from combustion are expelled through a nosetip. Advanced materials such as carbon-carbon composites which may be able to withstand the heat input to prevent the vehicle from melting may still not be sufficient to prevent loss of accuracy due to uneven nosetip erosion. We need to investigate alternative ways of getting orbiters or projectiles through the atmosphere.

One exciting approach has come from GT Devices in recent weeks.¹⁷ Derek Tidman has proposed a device which uses a combustible liquid jet to cut through the atmosphere in front of the orbiter. The gas mixes with the air at the shock front and burns. His calculations indicate

Figure 8. Aerojet hypervelocity projectile design with transpiration cooling

that the resulting thermal expansion wave provides the orbiter with a region of space for flight that is about an order of magnitude less dense than it would be otherwise.

What Next?

There is a renewed world-wide interest in space and many people are developing new concepts for obtaining access to space. Orbital Transport Services is a private company, among others, that suggests that you do not need government financing to put up commercial satellites. The Japanese Taisei Corp., which is similar to the U. S. engineering giant Bechtel, has proposed a facility on Christmas Island which combines EM and rocket propulsion in a hybrid scheme to launch a space shuttle. Another focus is the International Space Year (ISY) coming up in 1992 which is designed to promote international cooperation in space.

There are numerous attractive launch missions. What we need to do is to develop a sensible, credible program. The EM launch community represented at this Symposium has worked very hard to establish its technical credibility the hard way - we earned it! We came into a world about a decade ago in which people believed this technology was all fluff. But, now we can witness full-scale electromagnetic guns accelerating kilogram-sized projectiles to hypervelocities at any of a number of laboratories throughout the country. These launchers are real. The power sources are real. Hypervelocity projectiles have been designed and are undergoing testing now. We have picked goals that we felt we could meet and we have met them. They were bold steps, but we achieved them. That has been a very good method for the development of this growing industry.

Our focus¹⁸ in developing the technology was to develop the critical component technologies for practical electromagnetic guns for tactical and strategic applications. If we are going to be serious about developing EM technology as a viable candidate for space applications, we need to apply this same method. It is not clear to me that we know how to do this yet. It is clear that we need to think about it with a clean sheet of paper. Many of us love the idea of Electromagnetic Earth-to-Space Launchers, but it is not obvious that you should simply

take railguns as we know them now and scale them up to get to space. What needs to happen, in my view, is to take a fresh start and think about the whole problem again, this time with ten years of extremely successful history behind us.

We will not be able to demonstrate the feasibility of earth-to-space launch by a simple laboratory experiment. We will have to work on the whole problem, including the related technology issues touched on here. The general launch concepts are important and exciting and they are necessary to get the layman onboard, but we cannot ignore the hard professional design and engineering necessary to ensure their credibility. Finding a unique mission is essential. If our mission is simply to supply material to space, we should understand that this mission will probably not become important until twenty or so years from now when the space station is there. If there is an important near-term mission, we need to focus on it and drive for it with all of our energies.

I think we must be serious about electromagnetic earth-to-space launch. If we consider where we were at our first Symposium at San Diego in 1983, Dick Marshall and a few others had successfully performed isolated experiments with electromagnetic launchers (mainly launching grams of lexan to hypervelocity). What we have managed to accomplish was to provide a focus which created an incredibly talented technical community and pulled together a serious effort to develop electromagnetic launcher and pulsed power technology. This community is at the forefront of being able to apply its resources and energies to the problem of launching material to space. We can make a valuable and unique contribution to truly opening the frontier of space.

As a first step, The University of Texas is planning to host a workshop this fall which will provide a forum for serious discussion of EM earth-to-space launch issues. As this develops, we welcome your participation and are confident that the same high level of technical talent, energy, and enthusiasm will lead to the development of a new, credible program of international importance.

Acknowledgements

We wish to thank Dr. Gerald Sears of the Rand Corporation and Jamie Cuadros of General Dynamics for permission to use several of the figures presented in the paper and Dr. Peter Kemmey of DARPA for constructive criticism and discussion.

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