UCRL- 101292
PREPRINT

BRILLIANT PEBBLES

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Prepared For Presentation As An Invited Paper At
The Strategic Defense Initiative Technical Achievements Symposium
National Academy of Sciences
Washington, D.C.
29-30 June 1989

June 1989

Lawrence Livermore National Laboratory

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Abstract

A strategic defense system is sketched which consists of nothing more than a set of identical, highly capable, small spacecraft deployed in low Earth orbit and tasked with interdicting via hypervelocity collision ballistic missiles and their components in flight under human command and control. The member spacecraft of such a defensive constellation may each be equipped with the functional analogs of eyes, ears, mouths, brains and legs capable of detecting and hunting down advanced ballistic missiles over distances of thousands of kilometers without external aid or guidance, yet may have a size and weight comparable to that of a pubescent child. Interestingly enough, these Brilliant Pebbles — highly intelligent but sharply scaled-down Smart Rocks — can be implemented with contemporary American technology for a deployed cost of much less than a million dollars each, and less than 10,000 of them appear likely to offer a robust, stand-alone strategic defense capability, including the possibility of adaptive preferential defense. Supporting Government test and evaluation of this concept through realistic but Treaty-compliant in-space exercises is the principal focus of the program for the next two years. Other major national security-supporting applications of the Brilliant Pebbles technology, such as Brilliant Eyes, are briefly surveyed.

* *Research performed under the auspices of the U.S. Department of Energy under Contract W-7405-eng-48 with the University of California, with support from the Strategic Defense Initiative Organization of the Office of the Secretary of Defense.*

Introduction. The challenge posed to anyone designing a defense of the West from attack with nuclear warhead-tipped ballistic missiles is a formidable one: the near-term Soviet order-of-battle for strategic war will consist of roughly 10,000 thermonuclear reentry vehicles mounted on more than a thousand land- and sea-launched ballistic missiles, aggregating to more than 5,000 tons of hydrogen bombs. Most of this will be targeted to burst upon American and Allied territory within an interval of a single hour after the commencement of a Soviet attack.

The rational designer will note that such an attack becomes ever more difficult to avert as it moves from the Soviet missile silos, mobile launchers and submarines toward the territory to be devastated. Bombs atop ballistic missiles are little more threatening than stones perched on flying fuel tanks: they are safed against accidental detonation by their owners — simply because they're so close to home — and their means of conveyance are remarkably fragile, slow-moving and brightly self-illuminated. Upon completion of boost phase and entry into the space environment, the individual bombs appear only in tough jacketing, moreover likely cloaked in a variety of exotic means which may render them effectively invisible to defensive actions. On the other hand, when descending back into the Earth's atmosphere after 10 to 20 minutes of flight in space, the thermonuclear reentry vehicles again become exposed to defensive viewing by the inevitable action of the Earth's atmosphere but now have become relatively very implacable: they can be destroyed and their explosions averted only by quite heroic means, means which are often difficult to invoke just where they are needed, in the fraction of a minute during which they may be effective.

The rational strategic defensive system designer, if not masochistic, will therefore attempt to do as much of his job as possible while the attack is in its initial phases, when the offensive objects which he must avert or negate are most visible, most vulnerable and most sluggish. However, since at such early times they are most distant from his home base and since this window of extraordinary defensive opportunity is time-wise narrow, he must act swiftly and at great remove from his own base. These basic considerations strongly impel him to pre-position his defensive assets within useful range of the attacker's territory — the more slowly they can be brought to bear, the closer to the ballistic missiles' so-called "fly-out corridors" they must be when the attack commences.

Now, for speed-of-light defensive weaponry, whose beams fly at speeds a hundred thousand times that of average booster speeds, the pre-positioning distance can easily be tens of thousands of kilometers. For interception means composed of ordinary matter, which can feasibly be propelled to speeds which are only small multiples of the peak speeds of boosters, the characteristic pre-positioning distance must be not greatly in excess of the distances which boosters fly from their launching sites prior to releasing their reentry vehicles. If the attacker is the Soviet Union, then geography compels the conclusion that material interception means must be positioned close to the Soviet borders or else over the Soviet missile fields themselves, in low Earth orbit.

Now the effective destruction of a booster or a post-boost vehicle is a remarkably straightforward thing to accomplish, when the speeds characteristic of space-flight are considered. Objects in low Earth orbit travel nearly an order-of-magnitude faster than do tank cannon shells with muzzle velocity. As an inescapable result, they carry energy-of-motion — kinetic energy — nearly *two* orders-of-magnitude greater than a cannon shell of comparable mass: a one-pound mass in low Earth orbit carries the kinetic energy of a several dozen pound shell leaping out of tank cannon barrel. *Any* one-pound spacecraft colliding with a booster or post-boost vehicle can thus be expected to leave them looking like they had taken a hit at point-blank range with a 6-inch cannon shell. Actually, the destruction which results is considerably more severe, as the colliding spacecraft turns into density-of-lead, sun-hot vapor *inside* the booster or post-boost vehicle, so great is the collisional energy density. Any ballistic missile object so struck dissolves into literally millions of tiny fragments centered on an expanding fireball — as was demonstrated so vividly in the Homing Overlay and Delta 180 Experiments.

In the space environment, then, essentially any hit kills — and kills *very* robustly. In particular, very small spacecraft can kill very large ones, simply by colliding with them. Pertinent scales are indicated in Figure 1.

What's Required For The Job? The central thesis of the Brilliant Pebbles thrust is that each interceptor can be endowed with enough capability that it can perform its military mission with no assistance from the outside world, moreover can be so endowed at a sufficiently low cost as to make it entirely feasible to do so, and finally that this can all be done with contemporary, late 1980s American technology, the kind that's available for sale now. Stated simply, this thesis amounts to an assertion that the analogs of eyes for locating and pursuing targets, the analogs of ears and mouth for communication with central command and control (and possibly with other spacecraft), the analogs of legs for carrying everything else around and a gut to provide the required operating energy to everything else and, of course, the analog of a brain to receive input from the eyes and ears (and kinesthetic organs) and to command the legs and gut can be provided to each Brilliant Pebble with adequately high functionality and for adequately low cost. A typical layout is indicated in Figure 2.

Since the military task of space-based strategic defense is by now reasonably well-specified and the cost of the required defensive technology is well-defined, if the components of these systems are indeed marketplace-accessible, it should be possible to determine — at least to within reasonable bounds — whether or not such capability endowment is feasible. Indeed, the Government has adopted the intuitively reasonable cost-effectiveness-at-the-margin criterion proposed by Paul Nitze for determining whether any strategic defense system is practical. The here-and-now aspect of the Brilliant Pebbles central thesis permits this Nitze criterion to be applied to Brilliant Pebbles now, rather than a half-decade or more into the future, when the cost of defense and its value in terms of the offense which must be negated both are less clearly discerned. The military job to be done is indicated in Figures 3 and 4.

The Pertinent Technology Base. But what is it about the contemporary technology base which makes a Brilliant Pebbles-based defense feasible now, and what has changed so drastically relative to, say, a half-decade ago, when one of us (LLW) was so skeptical about the utility, even the survivability, of strategic defensive assets of any kind which were pre-deployed in space?

The first part of the answer is quickly, if not pleasantly, disposed of. One of us (LLW) had a frankly Aristotlean attitude toward the survivability of military assets pre-deployed in space, centered on the difficulties-in-principle of ensuring the survivability and effectiveness of space assets against the efforts of a capable-and-determined adversary. (Aristotle, you'll recall, was the fellow who was married over three intervals during his long life to three young women, yet asserted to his dying day that adult men had four more teeth in their mouths than did adult women, an expression of a male's unquestionable biological superiority.)

I have Greg Canavan, Edward Teller and my wife Yuki to thank for opening my eyes in this matter: Greg patiently insisted that I consider quantitatively the details — and the synergisms — of the opportunities presented to the defense and its in-space assets by small size, low cost, proliferation, decoying, maneuver and evasion. Edward and Yuki took turns refereeing my debates with Greg to make sure that there were no factors of 2 or π slipped in the clinches by either side, with Yuki finally giving me the ten-count at the conclusion of a long and memorable breakfast debate with Greg three years ago.

Jack Hammond — who was probably widely considered to be the Benedict Arnold of the kinetic energy world when he became SDI's directed energy chieftain a few years back — then graciously exposed me to the technology base underlying much of kinetic energy systems, technology whose development he had funded during his time as KE technology czar. This tutorial constituted the *coup d'grace* to most of my objections, and my own, now-unblinking review of the recent exponentially swift advances of the pertinent sensor and computing technology bases did the rest. Figure 5 indicates one aspect of these advances.

It became clear very rapidly that it was indeed practical to create the fist-size kinetic kill seeker packages whose feasibility Greg and Jack had asserted, and to do so with technology that could be bought off-the-shelf, much of it only a little advanced over mass-produced consumer and technical professional electronics: video camcorders, scientific work stations and the like. Though this result was striking enough, it was even more astonishing to total up the likely costs: it seemed likely that a simple, small kinetic kill vehicle seeker package composed of such elements could be mass-produced for a few tens of thousands of dollars, moreover in the here-and-now.

However, the question of the size and weight of the associated propulsion plant which would carry around the eyes-and-brain of the vehicle, its seeker package, was still a relatively open one. Naively, the answer is given simply by choosing a propellant (which has an intrinsic specific impulsive, or propulsive performance) and then cranking through the rocket equation on your hand-calculator for a few seconds. Unfortunately, such naive crank-turning ignores the empty or dry weight of the propulsion plant, tacitly assuming that it's negligible compared to that of the payload. This isn't a terribly bad assumption for modern large liquid-fuelled rockets, for which the wet-to-dry mass ratio may actually exceed 10:1, but it turns out to be completely uncharacteristic of even modern small rockets, both liquid- and solid-fuelled, which have full-to-empty mass ratios which are more typically 2:1 and seem to top out at about 3:1. Now a mass ratio this small can ruin your whole day: it dooms you either to having a large number of stages in order to get a decent Δv — which likely ruins both your total system mass and your total dollar budgets — or else it cripples your vehicle performance, thereby requiring you to have a huge vehicle population in place in order to get the defensive job accomplished, somewhat like having a hockey team whose goalies are all hobbled, so that you have to have five of them to do one unfettered goalie's job.

Now it's completely clear, from first principles, that small rockets should be every bit as capable as are big ones: the applicable laws of physics command this, and the pertinent rules of mechanical engineering support this dictum. While we were still brooding on why such performance couldn't be realized in practice in the 1980s, John Whitehead came up with the key set of ideas for making it so — and then convinced seasoned propulsion system engineers to successfully collaborate with him on realizing such propulsion systems. This success has made feasible a drastic reduction in the overall mass budget for a contemporary kinetic-kill vehicle, turning a potentially "brilliant rock" into a "brilliant pebble."

With the advent of such propulsion systems, the set of technologies needed to realize Brilliant Pebbles became complete.

Ways And Means. Now our modern world is filled with many more interesting widget-related ideas than it is with interesting widgets, and the basic reason is that it's much easier to have a good technical idea — and even to flesh it out and to polish it considerably — than it is to get it realized in working hardware. Part of the reason for this is that working with high technology, by definition, involves using the very best that the human race is capable of creating at any given time, of straining against the longest levers that presently exist. Doing so in a productive fashion requires the coordinated effort of the most capable and motivated people, but it also needs resources, and needs them rather abundantly. As a practical matter, such resource levels originate in relatively few locales, foremost of which is the Government.

The little-discussed but widely known fact is that there is *nothing* which a large, well-established Federal R&D shop finds more offensive than a suggestion — let alone a serious proposal — to the effect that its declared mission can be accomplished quickly and cheaply. Such a suggestion challenges the basis thesis of its existence, namely, that much time and money must be spent — and many empires built and extended, careers advanced, and so on — before this problem can be solved, or at least be recognized as no longer interesting. For this reason alone, most really interesting widget ideas die in their infancy, of simple starvation.

Fortunately, General Jim Abrahamson was much more focused on solving the strategic defense problem than he was on building a mighty R&D empire, and in Jack Hammond he had a Office Director who would dig even into a shrinking pocket to find resources with which to pursue approaches which he and General Abrahamson found promising — even though they were only peripherally related to directed energy, Jack's primary area of administrative responsibility. Finding seed money for the Brilliant Pebbles initiative thus earned Jack his second "Benedict Arnold" citation, this time from the directed energy community. A measure of the shame which he must have felt is given by the fact that the obscure little Brilliant Pebbles budget line still bore a directed energy technology base label when Jack turned over his directed energy management responsibilities to Tom Meyer and become General Abrahamson's Special Assistant, late last year.

By the time Jack and General Abrahamson left SDIO early this year, the tech base work out of which Brilliant Pebbles had largely grown had received SDIO support for 3 years, and work explicitly aimed at Brilliant Pebbles creation was in its second year. Brief though it might be by contemporary DoD RDT&E standards, this interval's results were enough to elicit the now well-known remarks in General Abrahamson's *End of Tour Report.*

Where Things Stand. But what's past is prolog, and this has been a lengthy one. What's been accomplished, and where do things stand?

Basically, all the component technologies required to assemble what we consider to be a "first generation" Brilliant Pebble have been gathered in from their sources in the American tech base and performance-qualified in laboratory test chamber and test stand operation. Every individual sub-system which we need performs at least at the level which is required, though not always in as small or as light-weight package as we would like to have in the ultimate "first generation" Pebble.

In addition, various assemblies of Brilliant Pebble sub-systems have been integrated for early test-and-evaluation purposes, and have been successfully flown in the lab, in aircraft and in spacecraft. We have been very pleased at how quickly and how successfully these early field testing activities have been carried out, and we are deeply indebted both to our many industrial partners for their essential contributions and to SDIO for Mike Rendine's streamlined management of these efforts which made them possible.

What's Coming Up? R&D for the "first generation" Pebble is early in its second half, as we see it. What remains to be done is systematic grinding away on presently over-size or over-weight sub-systems, as we execute the main-line task of integrating all Pebble sub-systems into a coherent whole, making them play together well, first in the laboratory and then in field test-and-evaluation exercising.

In the course of this work, which this year involves less than 1% of the total SDIO budget, we will rely ever more heavily on a continually expanding set of industrial partners. One very tangible expression of this is the fact that, while we presently spend about $1 of every $4 which we receive from SDIO on Lab-internal manpower and minor procurement, this ratio will increase nearly as rapidly as does total SDIO funding during the next two years of test-and-evaluation-intensive effort.

The Brilliant Pebbles thrust is fundamentally different from Phase I efforts in that it is a technology-driven, from-the-bottom-up alternative to most all of the Phase I architecture, rather than a requirements-driven, from-the-top-down element of this architecture. The Brilliant Pebbles charter from SDIO has been to develop and demonstrate the quickest, cheapest, most effective means of doing the SDS Phase I tasking along KKV lines without performance-critical reliance on any other SDS Phase I element and, since we can never be certain that we've chosen the best set of building blocks from which to do this, we always must be prepared to swap in technology which represents a better way to solve the basic problem. As a consequence, our set of industrial partners in 1989 may be markedly different from that of 1990, and significant changes might even occur as late as 1991.

The field work to be largely completed during the next two years consists of a series of ever-more challenging exercises in which Brilliant Pebbles at varying degrees of sophistication are called upon to detect, track, seek, home on and collide with rockets in flight, over ever greater ranges, at ever higher closing speeds and under ever more demanding environmental conditions, as indicated in Figure 6. A companion set of tests will evaluate the durability and all-systems functionality of lifejacketed Brilliant Pebbles in orbit for multi-month periods. Still other tests will be conducted in special underground laboratory environments. All Brilliant Pebble tests are designed and Government-reviewed to ensure their compliance with a strict interpretation of the ABM Treaty — no tricks, surprises or quibbling. We believe that these tests, if successful, will constitute a logically nearly compelling case for the technical feasibility of defending against strategic nuclear attacks conducted with ballistic missiles, as specified by the Nitze Criteria.

One of the most crucial — and certainly the least technical — gauntlet to be run is the one coming up soonest, the great 1989 Cost-Estimating Exercise. SDIO has warmed up for this by gathering up a half-dozen cost estimates for Brilliant Pebbles during the past half-year, and presently has 8 additional studies known to us underway, including big Air Force and SDIO-internal ones. Since we lack the extensive Talmudic backgrounding to estimate costs up to DoD standards, our support of this mighty theological undertaking — over and above inputting a detailed vehicle specification document — is necessarily confined to asking folks in the industrial sector who actually build and sell similar items what they would charge the Government to supply a few thousand units per year for a few years. It seems likely, however, that their responses will put first generation Brilliant Pebbles unit costs between $200 K and $500 K.

Looking over the shoulders of the cost-estimators as they practice their esoteric rites, seemingly all you need to know is the weight of the major pieces, so here they are: less than 2.5 lbs. of seeker package, including all optics, electrooptics and computer on the Brilliant Pebble interceptor itself; less than 10 lbs. of dry propulsion system mass for the entire Brilliant Pebble spacecraft and less than 20 lbs. of assorted spacecraft components in the Brilliant Pebble's lifejacket, such as solar array, rechargeable batteries, low-rate attitude control, thermal management, survivability features, and so forth. Add hydrazine — which costs about as much as good whiskey, ounce-for-ounce — to your taste, to top off the mass budget of the full-up Brilliant Pebble; we favor somewhere between 5 and 9 gallons per Pebble.

If you're the Big Picture type, you're probably wondering how many Pebbles comprise what sort of strategic defense system. The basic answer is that there is no basic answer — different, more-or-less reasonable assumptions about the nature of the offensive threat, the form and thus defensive efficiency of the battlemanagement strategy and tactics to be used, the time- and space-sequencing of the attack, the fraction of the attack to be negated, the effectiveness of offensive suppression of the defense, etc. can push the required constellation size all over the field, from below 3000 to over 10,000. However, 7000 is a reasonable median number which fully satisfies the JCS tasking for Phase I strategic defense all by itself, against an advanced, responsive turn-of-the-century Soviet threat, featuring a variety of fast-burn boosters. If a total of 10,000 Brilliant Pebbles were to be deployed over a constellation service life of a decade for an average cost of $0.5 M each, the in-space system hardware cost would then be about $5 B.

Brilliant Pebbles Spin-Offs: Brilliant Eyes, Et Al. The Brilliant Pebbles thrust is oriented exclusively through the present time to the strategic defense problem. However, a number of only distantly related roles and applications have been noted for Pebbles or Pebble derivatives.

Obviously, any spacecraft with reasonably high spatial and temporal resolution, multispectral cameras which also carries a husky amount of digital data processing and recording capability, further potentiated with moderate to high bandwidth communications, is likely to be called upon to carry space and Earth surveillance tasks, as indicated in Figure 7. When there are so many such vehicles that dozens of them can see the same location on Earth or in space at any one time and no Earthly location can escape such monitoring, their surveillance utility is likely to be seen to be even greater. When the on-board capacity exists to search raw imagery for certain objects of great interest and to relay back the locations of such objects, alerting its wingmen to their positions in the process, surveillance interest is heightened further. The high framing rates of Pebble cameras may even be useful in locating and categorizing transient events, such as artillery muzzle and gravity bomb flashes. It may be of interest to note that Chairman Les Aspin of the House Armed Services Committee recently stated publicly that the U.S. spending on Earth surveillance activities had averaged $6 B annually over the past decade. Figure 8 suggests related possibilities, all of which come under the rubric of "Brilliant Eyes".

Space defense is a quite obvious role for any space vehicle with sensors, computing and propulsive capacities — if it's cheap enough. A Pebble has legs so long that it can stride from low Earth orbit to anywhere in the Earth-Moon system — or even leave it, for that matter — and it's so inexpensive that it could be used to body-block any intruder threatening a high-value U.S. space asset, such as MILSTAR, with high economic efficiency. Such defensive actions could either be ground-commanded or, in emergencies, highly automatic.

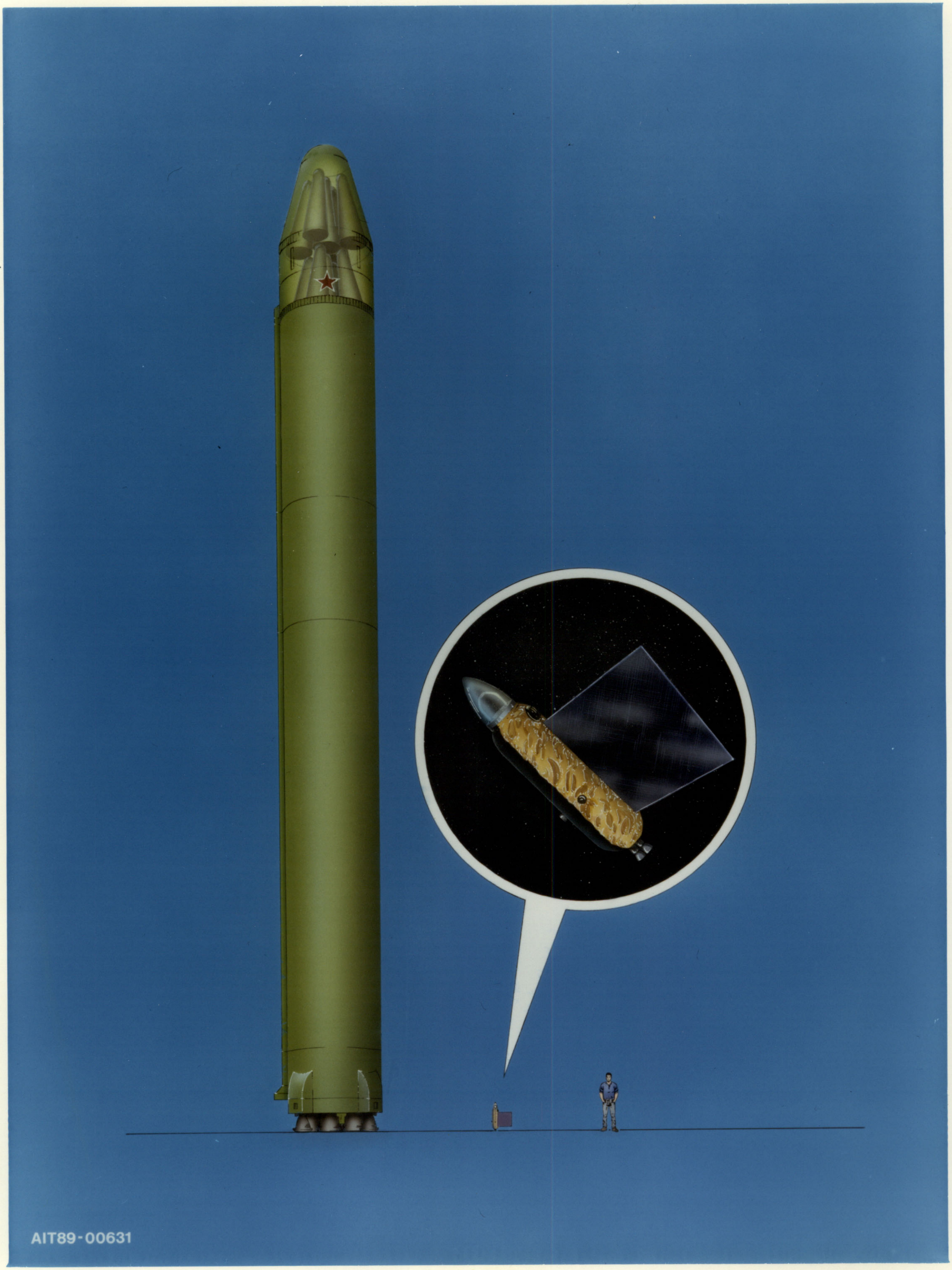
This list could go on for some time. We'll conclude it for now by noting that Pebbles may not be confined to the space environment with respect to defensive activities. Slightly augmented Pebbles may reenter the upper atmosphere and brake to a halt at several dozen kilometers altitude, following powered flight from great distances during emergencies. Slowly sinking under gravity and looking up and to the north, Pebbles could then engage in preferential or even adaptive preferential defense of American or Allied targets under strategic attack, by body-blocking atmospherically unmasked reentry vehicles as they drift down through the stratosphere toward their targets. A Brilliant Pebble constellation of typical size might defeat a thousand additional warheads by such high-endo atmospheric, robustly discriminating defensive action. Obviously, Brilliant Pebbles could also be employed to promptly shut down a "war of the cities" in the Third World among any of the 30 nations now acquiring IRBM capability — a type of conflict that might otherwise ensnare the U.S. and the U.S.S.R. — as well as protecting the U.S. and its Allies from nuclear and chemical attacks mounted with IRBM capabilities.

Summary. Brilliant Pebbles represent a straightforward — albeit rigorous — expression of the American technology base of the late 1980s in the military space context. The enormous strides made during the past decade in silicon-based digital microelectronics have made available supercomputing capacity on a pair of chips, enough memory on a single RAM chip to store the largest novels several times over and single chip-based ability to seize and store an image with better-than-normal-photographic resolution on time scales of millionths of a second. When added to the long-latent but newly expressed ability of *small* liquid-fuelled propulsion systems to perform with the payload-to-initial mass ratios of modern *large* liquid-fuelled rockets, the resulting set of eyes, brain and leg analogs is capable of truly marvelous feats. Those sketched in the foregoing are but a few examples in the context of national security operations in space.

One of the wryly amusing aspects of the human condition is that technology, particularly high technology, flourishes most strikingly under the patronage of the military, whether in our age or in the time of da Vinci. A lightly modified Brilliant Pebble could fly to Mars or Venus, or low-orbit the Moon, but the likelihood of one doing so anytime soon is admittedly not large. Instead, we seemingly must keep before us John Kennedy's solemn warning of a quarter century ago, "The nation that controls space will come to control the Earth", and then act accordingly.

Acknowledgments. Very many people have made signal contributions to the Brilliant Pebbles thrust in advancing it to where it is today. While we cannot thank them all individually here, we wish to express our special gratitude to those who continue to lead the technical efforts at LLNL: Richard Bionta, Nick Colella, Rod Hyde, Muriel Ishikawa, Arno Ledebuhr, Lyn Pleasance and John Whitehead.

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.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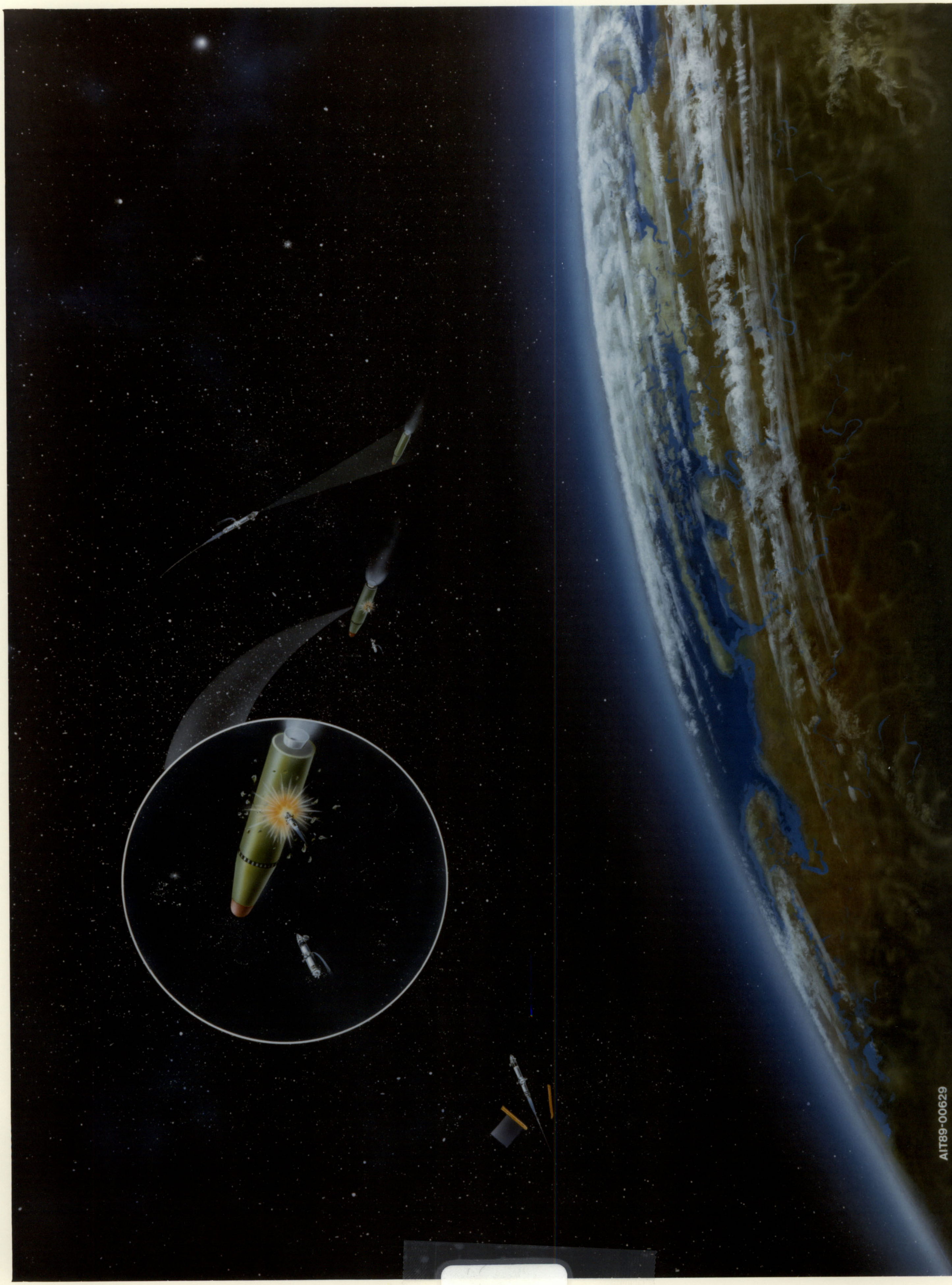


Figure 2

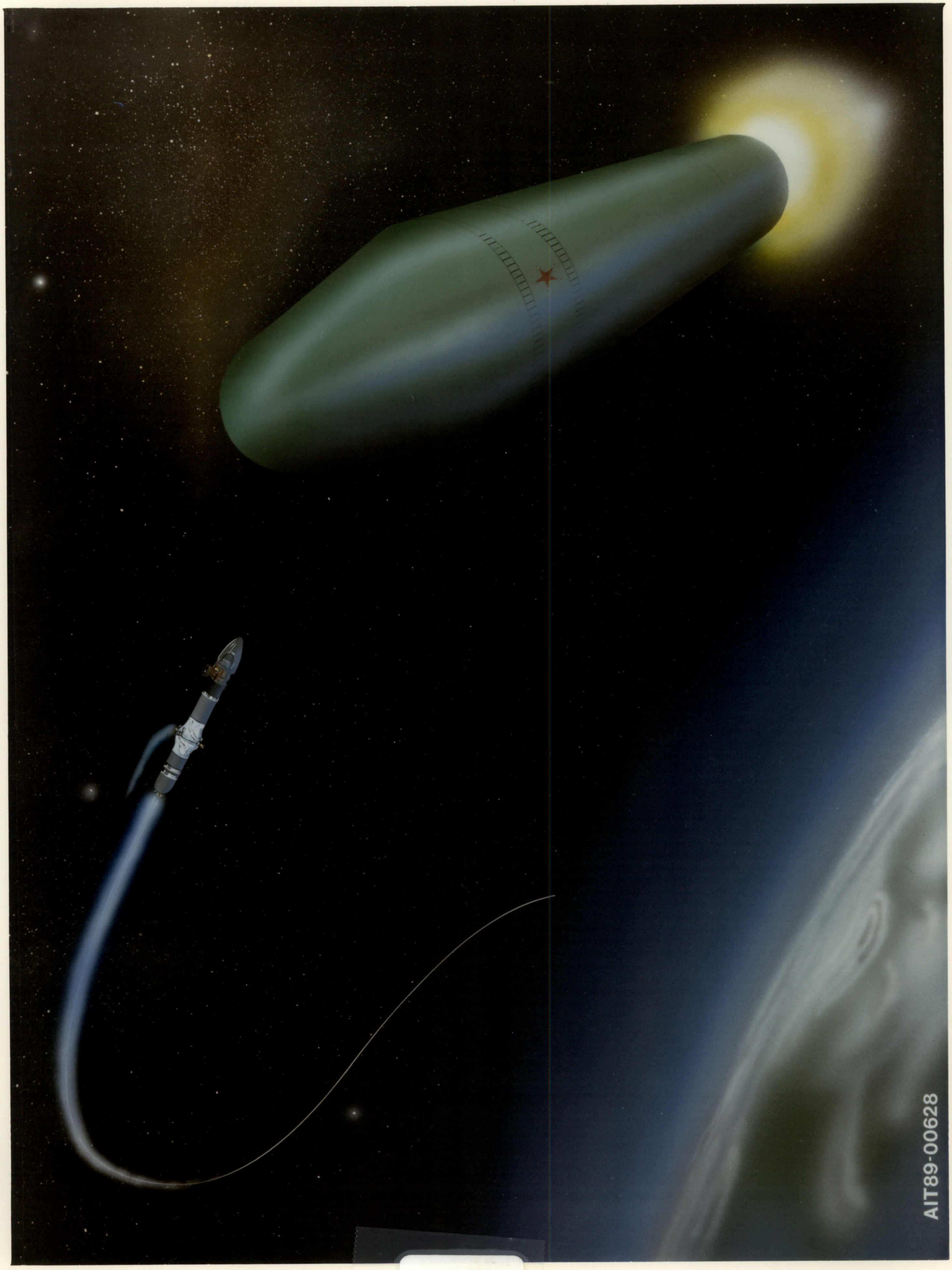
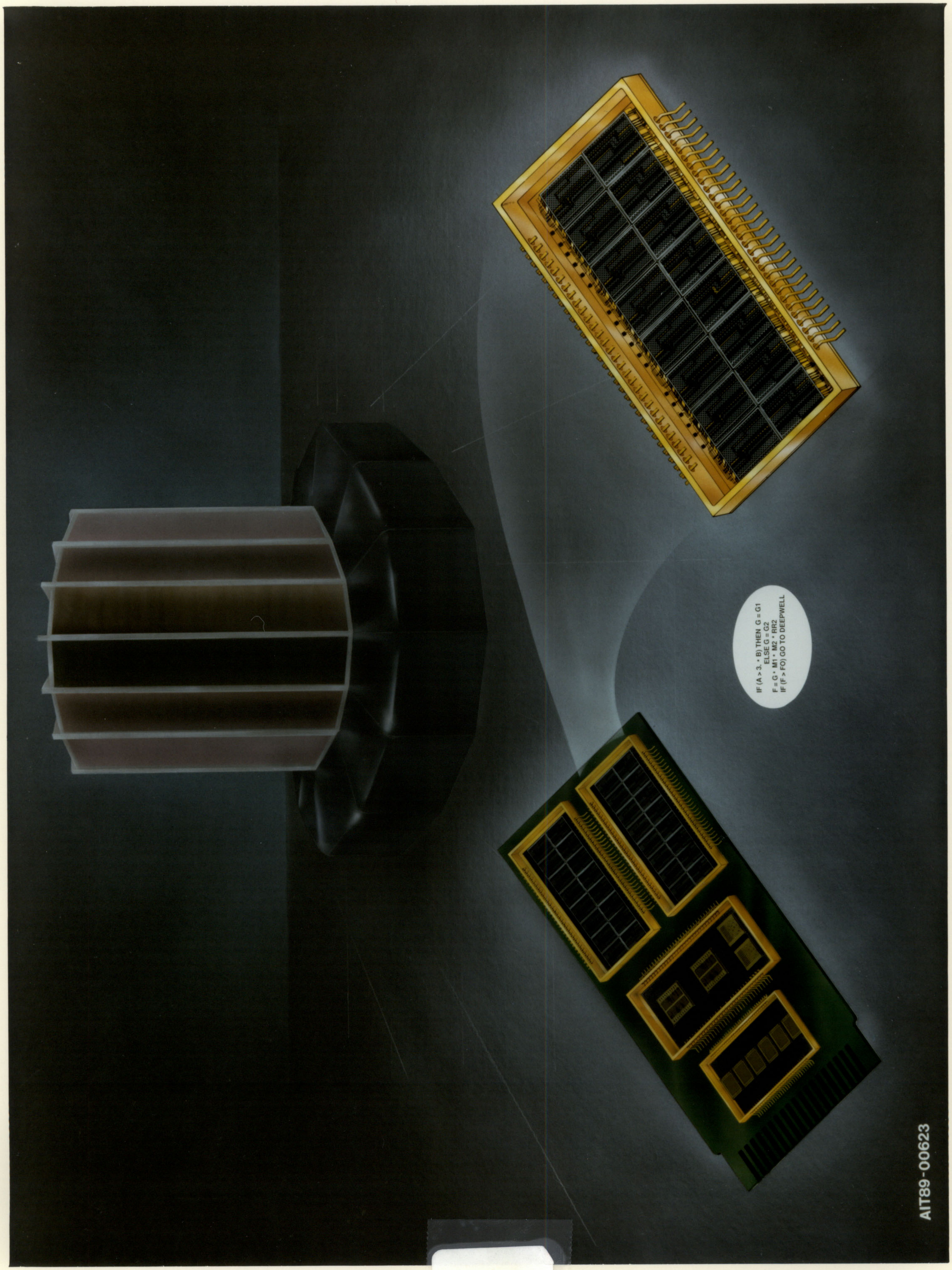


Figure 3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ELSE G = G2
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IF (F > FO) GO TO DEEPWELL
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Figure 5

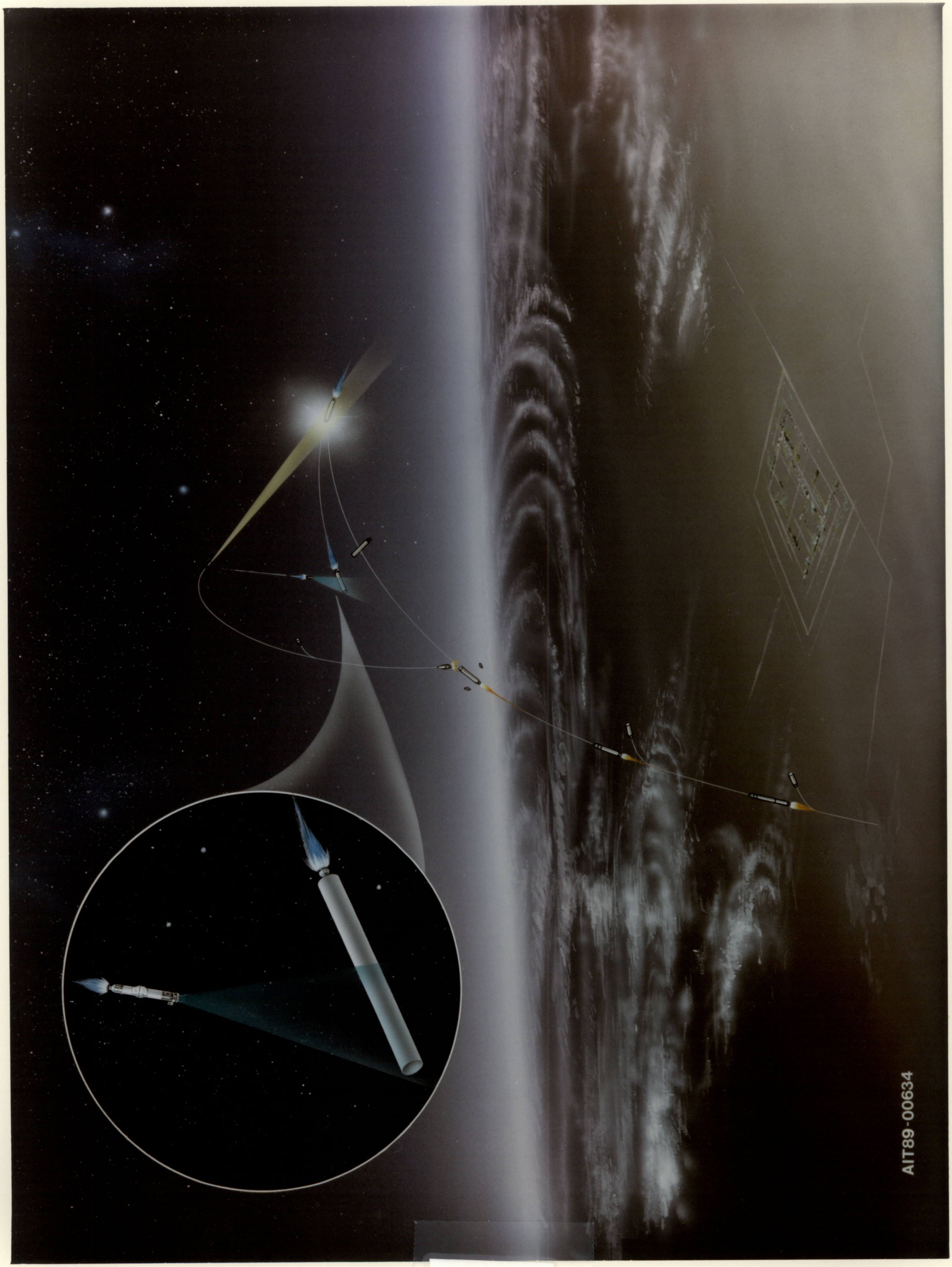

Figure 6

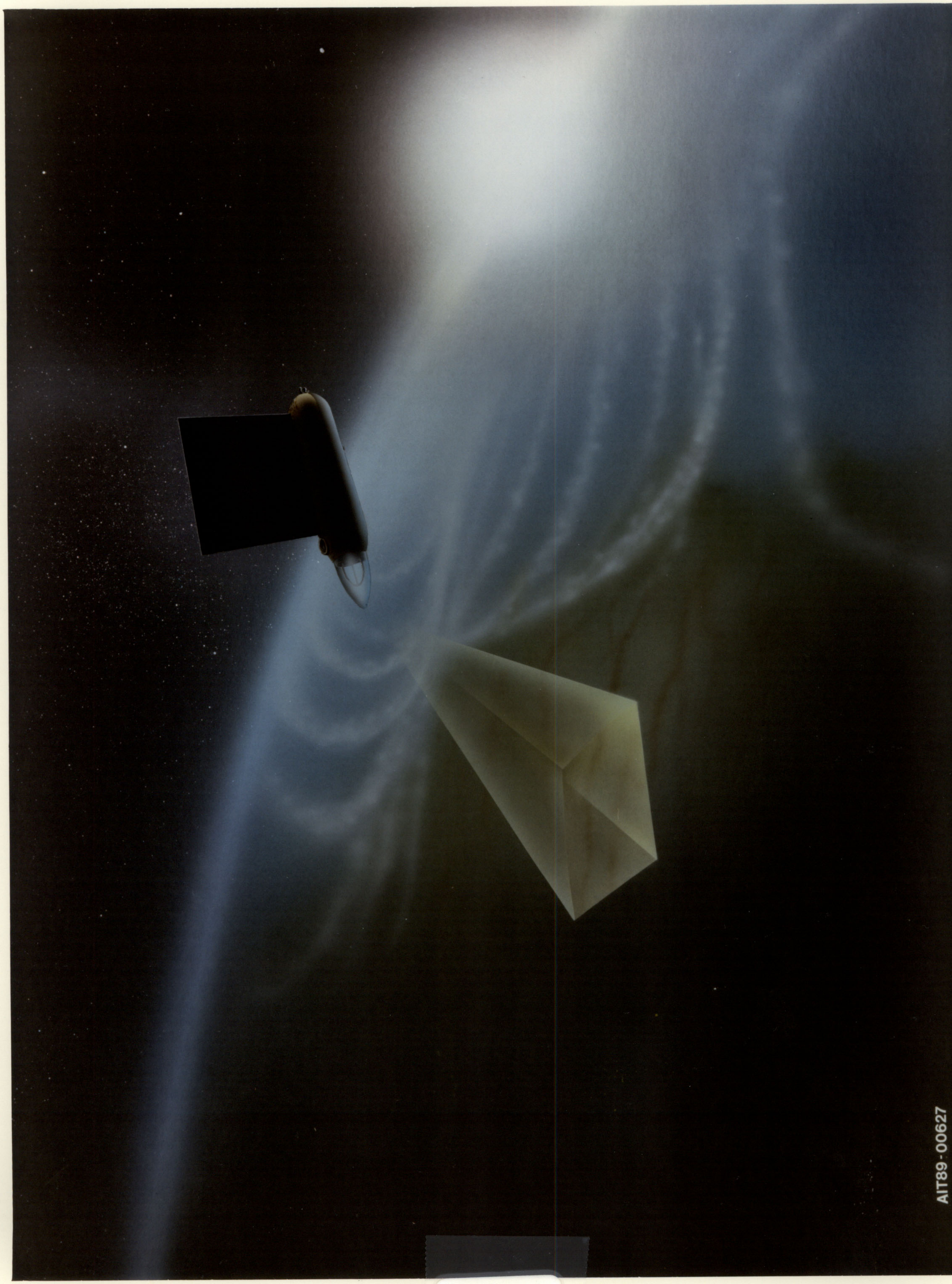

Figure 7

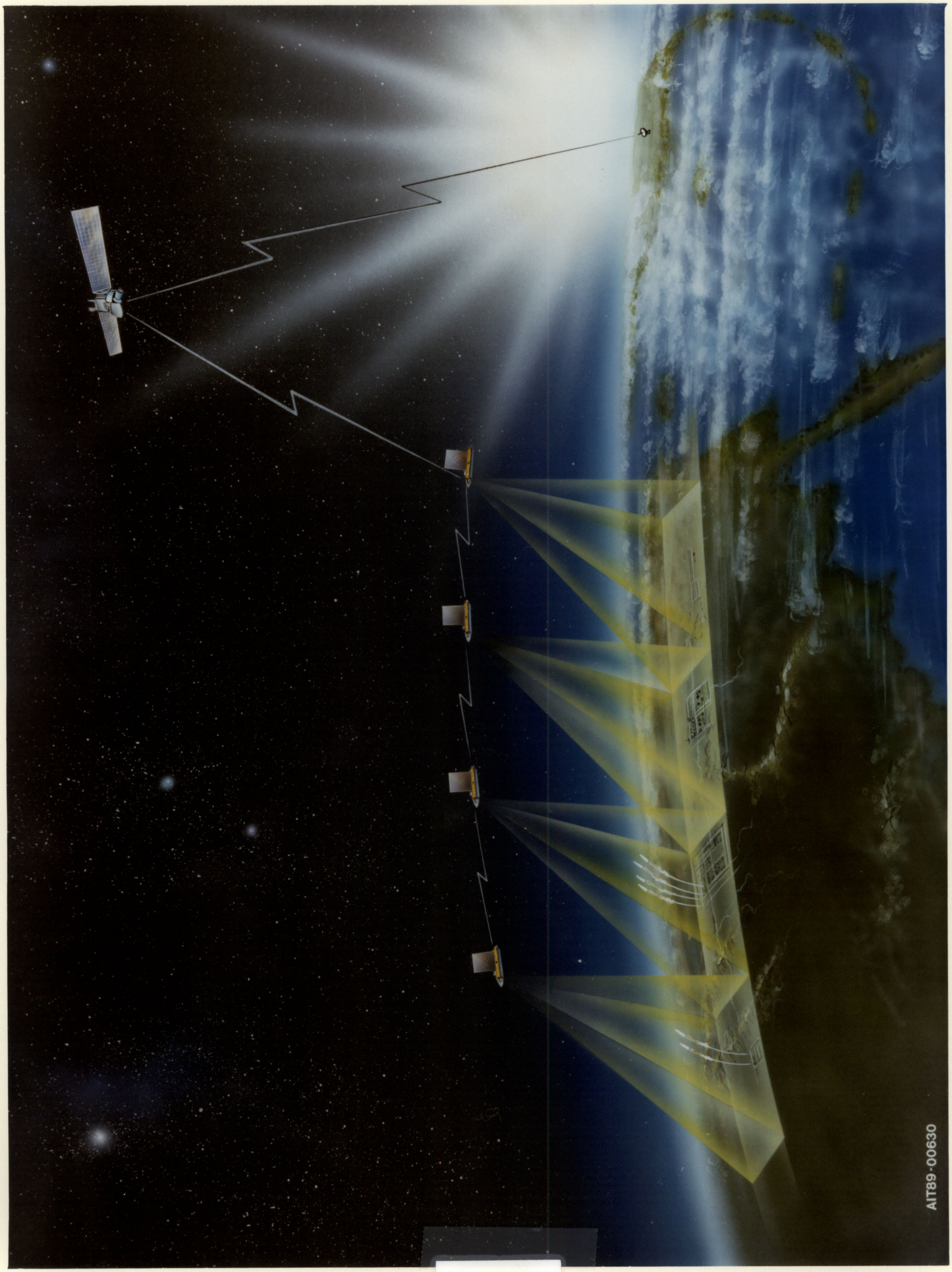

Figure 8