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Paper Session I-A - Creating Space Mobility: A Vision for Our Twenty-first Century Spacelift Architecture

Fred Kennedy
US Air Force Phillips Laboratory, Kirtland AFB, NM, USAF

Martin France
Headquarters, US Air Force Space Command, Peterson AFB, CO, USAF

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CREATING SPACE MOBILITY: A VISION FOR
OUR TWENTY-FIRST CENTURY SPACELIFT ARCHITECTURE

Capt Fred Kennedy
US Air Force Phillips Laboratory
Kirtland AFB, NM

Maj Martin France
Headquarters, US Air Force Space Command
Peterson AFB, CO

ABSTRACT

The current national spacelift architecture remains largely unchanged from the 60's, consisting mainly of expendable boosters, a small number of operating ranges populated with vehicle specific launch complexes, and ground-based tracking, telemetry and command (lT&C) -- one more akin to the experimental than the operational world. Today, however, we stand at a turning point in space-related technologies that will enable a whole new class of systems promising to dramatically lower the cost of space access, while increasing operability, responsiveness and reliability to levels approaching those of air and sealift. The key components of this future architecture -- an Evolved Expendable Launch Vehicle (EELV); Single-Stage-to-Orbit (SSTO) Reusable Launch Vehicles (RLV); an Orbital Transfer Vehicle; and a Space Based Range -- will offer synergistic benefits over our current architecture that finally lead to the true aircraft-like access envisioned since before Sputnik. Only when such a system is in place, either nationally or internationally, can we truly consider ourselves to be spacefaring, fully exploiting the opportunities that occupying the high ground entails.

This paper outlines this future vision for a fully functional space architecture, reviewing the current state of development and key technologies necessary to field the key components. It will outline how their operational interaction maximizes spacelift capability for minimum cost, thus expanding the space transportation market and providing new capabilities for the civil, commercial and military sectors. The resulting document serves as an important concept of operations definition, usable by planning, RD&A and operations communities during this period of transition.

NOMENCLATURE

AFMC	Air Force Materiel Command
DoD	Department of Defense
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
IOTV	Integrated Orbital Transfer Vehicle
ISUS	Integrated Solar Upper Stage
kW	kilowatt
LDEF	Long Duration Exposure Facility
LEO	Low Earth Orbit
m_{pl}	payload mass, kg
mT	metric ton, 1000 kg (2200 lbs)
NASA	National Aeronautics and Space Administration
nm	nanometer
OAS	Office of Aerospace Studies
OECS	Space Propulsion and Power Operational Effectiveness and Comparison Study
OTV	Orbital Transfer Vehicle
RLV	Reusable Launch Vehicle
SSTO	Single Stage To Orbit
ROTV	Reusable Orbital Transfer Vehicle
TAV	Transatmospheric Vehicle
USSPACECOM	US Space Command

INTRODUCTION

Foreword

Space exploitation is expensive, an undertaking currently beyond the reach of all but a few nations on Earth in 1996. The United States, the Former Soviet Union, France, Japan, and China all maintain space access via one or more expendable launch vehicles. The U.S. relies primarily on a fleet of Delta, Atlas, and Titan boosters to perform its current military missions. Civil (scientific) missions are flown from the partially-reusable Space Shuttle. Commercial missions, comprised almost exclusively of geostationary communications satellites, are flown aboard whatever launch vehicle is available for a reasonable cost.

Space exploitation is in its infancy. Those satellite assets in orbit today are there primarily for Earth observation and communications. Conventional missions can be easily grouped along the electromagnetic spectrum: optical imaging (visual bands between 4000 and 7000 rim), radar imaging (centimeter and millimeter bands), data relay, transmission, and reception, including navigation (radio wavelengths between 0.1 cm and 100 km), weather forecasting, nuclear detonation detection, and aircraft/launch vehicle boost detection and tracking (infrared bands, chiefly between .75 mm and 100 mm). Current military missions are concerned with signaling and reconnaissance, and as such are reminiscent not of World War I era aircraft (in which the battle for the air was beginning to take on clear significance to European commanders) but of the American Civil War, in which unwieldy balloons provided data on troop movements that would otherwise have been impossible to obtain.

The hydrogen-gas *Union,* which flew in August of 1861, permitted Thaddeus Lowe to assist northern artillery in their assaults on southern positions in Virginia. Later, a total of seven balloons were constructed and added to the North's inventory. Lowe "made 3,000 ascents, spending several hundred hours aloft observing enemy operations." Balloon reconnaissance was attempted again, in Puerto Rico during the Spanish-American War in 1898. The hydrogen used for lift was flammable and expensive to produce, and the balloonist and his vehicle remained at the mercy of the prevailing winds throughout his mission. Such issues--which translate into lack of maneuverability (responsiveness) and affordability--are mirrored in today's space architecture [Anderson, pp. 10-14].

Current Architecture and Trends

Assets employed by the space-faring nations are generally placed in a few basic orbits and left there for the life of the asset's mission. Station-keeping is performed to hold satellites in place, and maneuvers are occasionally performed to move satellites (i.e. GEO latitude changes), but the latter are usually contingency moves responding to crises. Such maneuvers use precious on-orbit propellant, reducing station-keeping life, and therefore mission life. Satellite operators do not risk propellant on whims. Thus, today's satellites are, for the most part, immobile.

Low-Earth orbit satellites (under 1000 km altitude) are primarily divided into: (1) high-inclination missions for imaging applications, in which proximity to the planet is an important factor in resolution (optical imaging, such as France's SPOT) or power (radar imaging); and (2) various-inclination communications missions. Polar missions, often in sun-synchronous orbits in order to achieve repeatable ground tracks, cannot be easily moved. This is regrettable because these satellites can be clearly detected with ground-based telescopes and their orbits determined precisely. Potential adversaries can thus mitigate these systems' efficacy by judiciously selecting times for the performance of crucial activities such as tests and troop movements, getting under cover during a known overflight. A "no sparrow may fall" network, in which observational gaps are completely closed, would be prohibitively expensive given today's satellite and launch vehicle costs.

Low-altitude communications missions began with simple store-and-forward systems in the 1960s [Wertz, p. 505]. These have a signitificant disadvantage in their long delays between data reception and transmission (which can be hours, waiting for specific ground stations to come into view). Larger constellations of low- and medium-orbit communications satellites are planned for introduction in the late 1990s, supplying the growing demand for mobile telecommunications. Crosslinking among numerous satellites provides both a robust, survivable constellation and minimized delay times. The Global Positioning System (GPS), a 24-satellite constellation in six 55° inclined planes at 20,000 km altitude, is a medium-orbit solution to full Earth coverage. Teledesic, Iridium, and Globalstar are commercial constellations proposed during the past several years, which would provide global

mobile communications capability. They range in size horn a few tens of satellites to more than 800. Inexpensive, small satellites and low-cost launch systems will be critical to the success of these ventures.

Geosynchronous orbit (35,786 km, circular) is an important resource for communications and remote sensing payloads. Constant viewing over a specific Earth location confers a major advantage, permitting fixed ground antennas for communications applications. This advantage is offset by the scarcity of "slots" (parceled out in 2° increments to prevent interference), lack of coverage above 70° latitude, significant station-keeping requirements, and the high delta-V required to achieve this orbit (4300 m/s LEO-GEO for conventional high-thrust upper stages). Nevertheless, near-global coverage can be obtained at this altitude with three satellites. Numerous military, civil and commercial assets occupy slots in GEO. Due to the finite number of slots, high launch costs, and relatively small number of satellites needed for substantial Earth coverage, the trend in GEO will be to larger systems, in fact, as large as can be launched. The most current example of this trend is Hughes' HS702 satellite bus, intended to service 12-15 kW communications satellites [Aviation Week, p. 27]. Methods for reducing the cost and complexity of launch systems are essential for improving access to high orbits such as GEO.

Molniya orbits, highly-inclined (63.4°) and highly elliptical (e = 0.75, with apogees of 40,000 km) provide long dwell times over high-latitude regions. Twelve-hour Molniya systems dwell over one hemisphere for up to ten hours out of each day, and are particularly useful for communications relay and remote sensing (chiefly IR) applications. The relatively low cost of access (delta-V= 2500 m/s, LEO-GEO) and high-latitude coverage of Molniya-based assets provide some distinct advantages over GEO systems. Since two Molniya systems provide essentially full coverage, the trend in these orbits will probably be similar to GEO--larger, more capable satellites.

American satellites in any of these orbits are launched aboard one of the domestic expendable launch vehicles, all of which are descended from 1950s ballistic missile programs. Delta, Atlas, and Titan provide services ranging from 5 mT to 22.5 mT in LEO. The Space Shuttle can place nearly 30 mT in a circular 300 km orbit. All of these boosters are expensive and require extensive processing prior to launch. The Titan IV/Centaur, which launches heavy military payloads to GEO, costs between $286M and $400M [payer], or as much as $75,000/kg. This vehicle requires 211 days from call-up to launch, but one recent payload sat on the pad for more than 1,000 days. Delta and Atlas can meet 60- and 90-day call-ups, respectively. Smaller U.S. boosters, including Pegasus, Taurus, and LMLV, are intended to fill the perceived need for smaller payloads, below 5 mT to LEO.

Commercial satellites also have the option of launching aboard one of several foreign boosters, including France's Ariane, China's Long March, and Russia's Proton, Zenit, and Cosmos vehicles. These systems tend to be cheaper alternatives to American boosters, and have already seriously undercut the commercial launch industry in this country over the past fifteen years.

The lack of affordability and responsiveness of the domestic fleet led to a comprehensive look at the nation's approach to space launch during 1993-94. NASA's Access to Space Study in 1993 concluded that low-cost, reusable single-stage-to-orbit boosters had become feasible and should be pursued. Lt Gen Moorman's Space Launch Modernization Study examined several options to reduce costs and improve the operations of launch systems. A dual-track plan was suggested, in which: (1) the DoD would "evolve" the current fleet of expendable launchers with the goal of reducing costs by 25% and, eventually, 50% over current values; and (2) NASA would embark on technology development culminating in an experimental reusable launch vehicle. Such systems might permit order-of-magnitude cost reductions and rapid turnaround on the order of days, approaching "aircraft-like" operations. These studies virtually ignored a third, critical system--the launch vehicle upper stage or a future cousin, the "orbital transfer vehicle" (OTV).

A recent Aerospace Corporation analysis [Chivington] concluded that over 60% of payloads in the 2000-2020 timeframe will be placed in orbits other than LEO. These include primarily GEO and medium orbits. Improving the performance of the upper stage can drastically increase a booster's payload capacity to high orbits, permitting large payloads to be launched from smaller, less expensive boosters. This realignment of payloads, or "stepdown," can be significant: Moving from a Titan IV/Centaur ($400M) to an Atlas IIAS ($110-13OM) could potentially save hundreds of millions of dollars per launch. AFMC'S Office of Aerospace Studies (OAS) recently conducted the *Space Propulsion and Power Operational Effectiveness and Cost Comparison Study* (OECS), with the assistance of Air Force Space Command, the Space and Missiles Systems Center, and the Phillips Laboratory. OAS concluded that two OTV types, solar thermal and solar electric, could reduce constellation costs by as much as 5 0°/0, without modifications to the current fleet of boosters. These systems could be expendable ('jettisoned

once final orbit is reached) or integrated (remaining with the space asset and providing additional functionality, including maneuvering and power). OAS is now examining reusable OTVS, or "Space Tugs," their utility in a next-generation space architecture and applicable technologies.

A FUTURE SPACELIFT ARCHITECTURE

Remote sensing and communications will not become obsolete as space missions; they will remain critical sources of information. However, the architecture of the next century needs to mature substantially in order to become both active and competitive. The current architecture is primarily passive; consisting of a set of spacecraft that remain in stable orbits, collecting information and transmitting it Earthside. There is virtually no consideration given to spacecraft defense, maneuvering, recovery, repair, and refueling, space-to-space surveillance, or denial. These "missions" have obvious analogs in the aircraft community but have been consistently been viewed as both futuristic and unnecessary by the space community. They will be implemented in the future space architecture through the use of both OTVs and RLVs.

The current architecture is non-competitive: witness the consternation caused by foreign competition in the space launch industry. U.S. vehicles, derivatives of ICBMs, are too expensive and difficult to process. Satellite builders also share the blame for building one-of-a-kind packages and maintaining an R&D paradigm that prevents "operationalization" of space. While the DOD-sponsored EELV Program moves to reduce launch costs by as much as 50%, it is the NASA-led RLV effort that promises real changes in how we put vehicles in space. If successful, the RLV will provide very low launch costs and rapid call-ups. Such a robust Earth-to-orbit element allows "last-minute" satellite launches, re-manifesting without penalty, and expanded space access to users who were formerly priced out of the market.

Defense will become increasingly important as more nations acquire the ability to place objects in orbit. Military platforms in any orbit could become targets in future conflicts where the U. S.' adversaries have ballistic missile or launch vehicle capabilities. Military systems provide critical data during peace and wartime, and, if blinded, they could significantly impair American communications and intelligence. The example of GPS is instructive. GPS navigation is becoming increasingly accepted in military and commercial circles. Near-term satellites in LEO may use GPS for attitude control. Trucking concerns will use GPS signals to track their deliveries. Military commanders will rely on GPS to guide battlefield engagements. Deliberate incapacitation of one (or, perhaps, a plane of four) GPS spacecraft could seriously degrade navigational capabilities across a variety of using communities. The threat could take various shapes, including kinetic impact, explosive devices, or overloading various sensors. An adversary's vehicle could simply rendezvous with the satellite and obscure its photovoltaic arrays, draining its batteries during a critical ground action, then withdrawing when the action is complete--not "killing" the satellite but disabling it temporarily. Clearly, some form of evasive or defensive capability is needed. Greater and greater reliance upon spaceborne assets, without consideration given to protection, is an extremely risky strategy. It presumes an indefinite continuation of the status quo--a thesis not borne out by history.

Recovering an asset potentially permits repair and/or refueling, as well as assessment of satellite failure. Air Force Space Command lists recovery as one of its top ten priorities for spacelift [AFSPC/XPX]. Yet recovery is currently not practiced except in special cases. NASA's Space Shuttle returned the Long Duration Exposure Facility (LDEF) to Earth and made repairs to the Hubble Observatory. However, the Shuttle is limited to LEO. A malfunctioning GEO or Molniya platform is currently out of reach, both monetarily and operationally. For instance, retrieving an 1100-kg DSCS III military communications platform from GEO cannot be done even with the largest U.S. vehicle, the Titan IV/Centaur. Note:

$$m_{pl} = m_{propellant} = 5220 \text{ kg}; \; m_{Centaur} = 3200 \text{ kg}$$

Titan IV/Centaur can place up to 5.22 mT of payload in GEO. It is a LO_2/LH_2 chemical engine with a rated specific impulse of 443 s and is capable of multiple restarts, which potentially would allow it to fly "empty" to GEO, dock with an errant satellite (given appropriate structures and guidance), and perform a two-burn return to LEO. Yet, even if the payload mass were entirely devoted to propellant, it would be insufficient to return the stage itself

$$m_{return} = (m_{pl} + m_{Centaur}) \; e^{(-dV/c)}$$

$$m_{return} = m_{Centaur}$$

Solving for $m_{propellant}$ (the required propellant mass) gives:

$$m_{propellant} = 5416 \text{ kg}$$

Only 5220 kg of propellant are available; recovery is clearly not an option, even with advanced chemical propulsion. Making recovery a standard operational mission will require high-spectilc impulse propulsion. Solar electric and solar thermal OTVS are the systems that enable these missions.

Denial of hostile space assets is the reverse of satellite "defense." The case of Rimsat lends credence to long-unheeded concerns involving "rogue" satellites. Rimsat leased two Russian Gorizont satellites in GEO in order to provide Asia-Pacific customers with television broadcast support. However, Rimsat failed to make payments to the Russian operators, who threatened to interrupt service. The ensuing crisis was further exacerbated by a confusion involving the assignment of GEO slots for these satellites (owned by the Kingdom of Tonga). There is currently no capability in US or foreign inventories for enforcing international regulations concerning satellite operation--were a company to "take over" a slot owned by a foreign nation and begin broadcasting, there would be little the international community (or the offended nation) could do. Simply destroying the satellite is possible, but such a course is often considered tantamount to war. A "graduated response" is clearly needed; a LEO satellite could be "turned off" by shielding its antennas or solar arrays. An RLV or OTV could rendezvous with the offending satellite and simply take a few high-resolution photographs, which could be discreetly provided to the user, a warning of more extreme actions that could be taken. Clearly, these capabilities also extend into the realm of warfare.

EXPENDABLE LAUNCH VEHICLES BRIDGE THE GAP

The fleet of current launch vehicles is largely expendable -- with the obvious exception being the partially reusable Space Transportation System (shuttle). Within the United States, all medium to heavy lift boosters (Delta, Atlas and Titan families) are derived from early IRBM and ICBM systems developed in the 1950s and 60s. Each has seen several upgrades and additions, but the core vehicle technologies remain largely the same. They are operated individually, from unique launch facilities, requiring many a large 'standing army' to support any launch. Several recent studies have examined these and other short-comings (The Augustine Report of 1990, the Aldridge Study of 1992, NASA's Access to Space Study, the 1993 DOD Bottom-Up Review and the 1994 Moorman Report), and made recommendations for near and long term improvements. Only one of these studies, NASA's Access to Space Study, had the development of a reusable launch system as its primary recommendation. All others recommended either continuation of the status quo, development of new expendable (either evolved or 'clean sheet') or some mix of new expendable and reusables. Each study, though, is clear in stating that the current cost of expendable spacelift is high -- from $5K to more than $15K per pound to LEO depending on the reference and system -- and that a viable spacelift architecture is vital to the US's standing as a world leader.

Expendable vehicles will continue to be part of the spacelift landscape well into the future. The current National Space Transportation Policy calls for NASA to take the lead in RLV development, while the DOD heads development of expendable vehicles. With the recent the DOD commitment to the EELV program, targeting 25%. to 50%. reduction in launch costs for medium and heavy lift missions and first flights expected in 2000 (Medium) and 2003 (Heavy), a viable, economical fleet of expendable vehicles should be online well before a comparable reusable fleet is available. If the projected savings are achieved -- through a streamlined acquisition strategy, the use of mature technologies, highly reliable, low-cost systems and a common launch infrastructure -- the resulting vehicle family will provide access to space at costs at or below that of state-subsidized foreign competitors such as China's Long March, the Russian Proton or ESA'S Ariane 5.

RLVS will be developed in an incremental fashion, starting with the X-33 program and progressing to more capable vehicles as technology and operational capabilities are proven. The commercial RLV envisioned to follow the X-33 tech demonstration program probably demonstrates small and medium lift on a responsive and inexpensive basis relatively soon after completion and initial operational capability (IOC), as envisioned by marketing assessments of each of the current X-33 contractors. This development will cause the medium lift

EELV to be a transitional system, or cost-saving 'stop gap' in our lift architecture, phasing out of the picture when and if the economics of dependable SSTO Reusable Launch Vehicles prove too attractive to ignore.

The ability to perform certain heavy lift missions (Shuttle or Titan IV-class) will continue to be largely performed by the expendable fleet at least until a reusable vehicle is operating as a shuttle replacement. Reusable launch vehicles cannot easily perform these high-weight, high-orbit (Molniya, GPS, and GEO) missions without the inclusion of an upper stage or orbital transfer vehicle.

Currently, the number of heavy lift launches per year is projected to average about three per year for Titan IV over the next 25 years, with eight Shuttle flights per year through at least 2008. In comparison, the medium lift market (<20,000 lbs to LEO) expects nearly 30 launches per year based upon the Air Force Space Command National Mission Model, with many more possible flights in the international market. The cost of developing a special, heavy lift RLV for this small portion of the mission model available may not, in fact, be justifiable. Many of these and other large payloads are also volumetrically large, requiring unique payload fairings and payload integration considerations that may not be compatible with a standardized RLV payload bay, optimized for repeatable operations. Additionally, the responsiveness that an SSTO system might provide may not be of any advantage to missions that require long lead times for satellite construction.

Another important class of missions well-suited to expendable vehicles is space exploration -- particularly interplanetary missions. Again, these are long lead-time missions with very specific volume and weight requirements relative to the payload.   Such 'one time' shots certainly do not justify major modification to an operating RLV system.

A functional, inexpensive (relative to today's costs), reliable and expendable heavy lift capability that can adequately respond to special missions as described above will complement a largely reusable spacelift architecture by eliminating the need for RLVS to cover every niche in the spacelift market. Such a strategy would allow RLVS to do what they do best -- multiple standard profile missions with common payload interfaces on a responsive, low-cost basis.

REUSABLE LAUNCH VEHICLES AS WORKHORSES

The Space Shuttle, developed in the 1970s, was the world's first reusable launch vehicle. While it is the most reliable launch system in the inventory, with only a single failure to date, it is both extremely expensive and difficult to maintain. At $300-500M per flight [Bayer], it has not permitted the order-of-magnitude reduction in per-kilogram cost to orbit that helped sell the program to Congress. Still, the Shuttle does demonstrate the technological feasibility of RLVS. Next century's launch infrastructure will require the advent of low-cost reusable systems to bring about true space mobility; our current launch capability will be viewed as incredibly primitive by our descendants in 2025 or 2050.

NASA's Access to Space Study, conducted in 1993, examined three potential options for the future launch vehicle architecture: (1) "retain and upgrade the Space Shuttle and expendable launch vehicles," (2) develop new expendable vehicles using conventional technologies and transition from current vehicles beginning in 2005," and (3) develop new reusable vehicles using advanced technology, and transition from current technology beginning in 2008." NASA's analysts concluded that a fleet of single-stage-to-orbit RLVS would eventually reduce launch costs by up to 80%, although the development of these vehicles would require a significant up-front investment. The current cost of placing a pound of payload in LEO would be reduced from Shuttle's current capability of $7,488/lb to $1,500/lb. NASA's SSTO will permit reduced operations costs in the Space Station era, where numerous deployment and resupply flights have raised dire predictions about Station's feasibility. Furthermore, SSTO would "leapfrog the US into a next-generation launch capability," garnering the domestic launch industry an extremely favorable position in the international spacelift market. A medium-lift RLV would be capable of handling the vast majority of communication platforms placed on-orbit.

SSTO will require advanced technology to perform its mission. The margins afforded by multistaging are not available here; a single-stage-to-orbit vehicle must ascend to orbit and return to an Earthside landing site for maintenance and turnaround. Until recently, the technology to produce a viable SSTO was not in hand. The required propellant mass fraction of such a vehicle is approximately .88; that is, 88% of the vehicle's gross lift-off weight is propellant -- liquid hydrogen and liquid oxygen. The remainder is tied up in structure, engines, avionics,

and support equipment. The figure of. 88 represents current propulsive performance with LOX/LH$_2$ or tripropellant engines. The attainable mass fraction, given current technological capabilities in structures, is currently between .88 and .91 [Sponable]. Advances in lightweight thermal protection, aluminum-lithium LO$_2$ tanks, and graphite composite hydrogen tanks make SSTO an achievable system [Bekey].

The Ballistic Missile Defense Organization, in concert with McDonnell-Douglas, developed a technology demonstration vehicle, the Delta Clipper, during 1991-93. DC-X was procured on a fast-track schedule for under $70M and demonstrated several key SSTO capabilities. The first, and most important, was the ability to emulate aircraft operations. For a reusable launcher to fly cheaply, call-up, turnaround time, simplified procedures and processes, and a small crew are essential. DC-X also demonstrated adverse weather flight capability, a flight abort capability (following damage to the vehicle), and selected technologies, including autonomous vertical takeoff/vertical landing ability.

The follow-on NASA-led effort in reusable launchers will culminate in 1999 with a series of test flights of the newest experimental spaceplane, the X-33. Three contractors -- McDonnell-Douglas, Rockwell, and Lockheed-Martin -- are vying for the rights to build and test the SSTO suborbital demonstrator vehicle. Some of the key technologies that will have to be in hand in order to successfully show a single-stage orbit capability are lightweight composite tankage and structure, robust thermal protection systems, advanced, highly operable cryogenic propulsion, vehicle health management, and advanced avionics.

In the hands of the military, such a vehicle's potential moves beyond mere issues of life-cycle cost savings. A reusable spaceplane, prepared to move from an initial call-up to launch in times measured in hours rather than months, can be an effective platform for numerous military missions. The spaceplane fulfills the US Air Force's requirement for "global reach," bringing any location on the globe within striking distance in only 40 minutes. Potential applications include "many mission areas.. reconnaissance, surveillance, and precision employment of weapons." Streamlined maintenance and operations will permit blue-suit crews, not a cadre of engineers and scientists, the ability to launch space vehicles in the same manner aircraft are flown today.

Expendable launch vehicles will remain as gap-fillers for some time, but they are not the key to the 21st century's space paradigm. Achieving space mobility rests on the development of two systems: A highly-reliable earth-to-orbit vehicle that can operate like current aircraft, performing multiple missions (spacelift, force enhancement, space control, and force application), and space-to-space transfer systems, or orbital transfer vehicles, which extend the area of potential exploitation--and control--from low earth orbit across the entire Earth-Moon system.

INTEGRATED AND REUSABLE TRANSFER VEHICLES

The current method for reaching high orbits, such as geosynchronous, is to include an expendable solid motor or liquid propellant engine with the mission payload inside a launch vehicle's payload fairing. Solid motor stages, such as McDonnell-Douglas' Payload Assist Module (PAM), produce high thrust-to-weight but low specific impulse capability (<300 s). Liquid systems, based on monopropellant and bipropellant hydrazine, or, at the top of the performance spectrum, LOX/LH$_2$, also permit high thrust-to-weight at increased I$_{SP}$ (<460 s). Both solid and chemical upper stages have been used aboard US and foreign launchers to place payloads in high earth orbit. A typical geosynchronous communications satellite aboard an Atlas IIAS is lofted to a suborbital trajectory, whereupon the high-thrust chemical stage performs a series of burns that raises orbital apogee to GEO altitude. Inclination changes and circularization burns are performed. Transfer between LEO and GEO requires approximately five hours. Upon reaching orbit, they are inactivated and often jettisoned from the space asset.

Over the past several decades, novel approaches to delivering payloads to high orbits have been suggested and developed. The most common, and best investigated, are the multiple approaches that rely on electrical propulsion, the power source being either solar photovoltaics or, downstream, nuclear reactors. Electrothermal propulsion (resistojets and arcjets) offers specific impulses of up to 1400 s. Electrostatic propulsion (ion thrusters and stationary plasma thrusters) offer even higher performance, in the thousands of seconds of I$_{SP}$. This very high level of performance permits electrically-propelled vehicles to dramatically reduce the propellant mass required to achieve high orbit, but this capability comes at a cost: Long transfer times. These systems are limited by available power input, and typically provide thrust levels in the millinewton to several newton thrust range. A LEO-GEO transfer of a standard HS 601 communications satellite by electric propulsion might require six months to several years. Such long transfer times often conflict with user desires to achieve orbit as quickly as possible,

in order to either generate revenue (in the case of commercial communications satellite builders) or to satisfy military requirements. Nevertheless, the large performance gains allowed by electrically-propelled orbital transfer vehicles could potentially shift large payloads to smaller, less expensive boosters. Placing Titan IV payloads on Atlas or medium-lift ELVs could substantially reduce our dependence on the heaviest launchers in the domestic fleet, easing the transition to a fully reusable architecture.

An alternative to electrically-propelled OTVs is a direct thermal propulsion system. Such a vehicle would provide an intermediate performance capability between existing chemical propulsion and electric propulsion. Specific impulses of between 600 and 1000 s are achievable, while thrust levels of tens to hundreds of newtons would allow relatively rapid transfer between low and high orbits (one week to one month). Like electric propulsion systems, direct thermal systems can be powered by solar or nuclear energy. Thermal systems provide a useful compromise between the low performance and rapid response of existing systems, and the extremely high performance and poor responsiveness of electric systems. Thermal systems, unlike electric propulsion, can access highly elliptical orbits (such as the highly-inclined Molniya orbit, used for long dwell over one hemisphere).

Both solar electric and solar thermal systems are potentially demonstrable within the next several years. Ion thrusters have been baselined aboard Hughes' HS 702 satellites to provide greater payload capability to high orbit (these systems would make up part of the delta-V requirement, the majority of the transfer being performed by chemical systems). One variant of a solar thermal system, the Integrated Solar Upper Stage (ISUS), will be ground-demonstrated in a joint Air Force/NASA test in early 1997 [Kennedy]. The ISUS system is "bimodal," transferring a satellite from low orbit to high, and then remaining with the satellite to provide electrical power to the payload. This dual-mode operation potentially saves significant additional weight, as on-orbit power systems typically make up between 20 and 30% of a spacecraft's dry weight.

Either electric or thermal propulsion potentially enables one of two types of advanced orbital transfer vehicle --an integrated orbital transfer vehicle (or IOTV, **such** as the ISUS system described above), which remains with the satellite after achieving orbit; and a reusable orbital transfer vehicle (ROTV), which is based on-orbit, is refueled after each transfer mission, and which must rendezvous and dock with payload packages in LEO and transfer these payloads to their ultimate destination orbits. ROTVs, paired with RLVs, access all of near-earth space. A rapid-response RLV capability, which can launch prespecified payloads into low orbit, permits the creation of an aircraft-like architecture between the ground and LEO. ROTVs, which remain in orbit, will link LEO with high energy orbits. Molniya, GEO, GPS (half-GEO), and lunar orbits are potential destinations that an RLV-ROTV architecture could make commonplace. Thus, this new, mobile architecture provides an opportunity to enhance not only commercial and military missions, but journeys of exploration.

SPACE-BASED RANGE

As the previously described 'transport' components of a future spacelift architecture are fielded, the current range and tracking systems will not be capable of handling a full-scale 'operationalized' space environment. The future scenario is likely to include multiple RLV sorties per day originating from many different sites on the globe, not necessarily landing at their respective liftoff facility. ROTVs will be in constant operation, plying the LEO to GEO milieu with valuable cargo to deploy, return or reposition. Transpace operations will **not** only include traditional lift missions, but also Earth-to-Earth rapid transport, military RLV missions such as training and reconnaissance and surveillance, space tourism and Space Station servicing. Increasingly, the line between air and **space** operations will blur, causing conflicts between those responsible for effective, safe air control and others conducting **space** missions. It is for this reason that steps should be **taken** immediately to break down the barriers between the current world-wide air traffic control system and the **space** (near-Earth) surveillance and control infrastructure operated largely by US Space Command.

Just as the Federal Aviation Administration's Air Traffic Control system has become the accepted model upon which **a** world-wide command and control network for air travel is based, US SPACECOM'S **space** surveillance system would form the basis for **a** civil Space Traffic Control system. Composed of both ground and space-based assets, a future, integrated Aerospace Traffic Control system would support the full gamut of air and **space** operations **to** include:

1. space debris tracking and warning
2. atmospheric and exo-atmospheric weather

3. orbit and flight path allocation
4. satellite control integration and coordination
5. takeoff (launch) and landing coordination

The catalog and current status of all debris and civil space assets on orbit would be provided via direct communications link to all users, thus reducing the chances of an on-orbit collision that could effectively 'poison' an entire orbital belt.

Weather information via direct satellite broadcast from assets in GEO would be provided to all civil users of air and space. The usual tropospheric and stratospheric conditions would be augmented by conditions updates for the ionosphere and magnetosphere to warn trans-atmospheric and space assets of dangerous magnetic storms or solar particle events that might warrant shielding, a change in mission plans or vehicle orientation.

Just as certain airspace is currently is restricted by nations to conduct military training or for national security proposes, orbital 'alleys' -- a specific orbital plane and altitude range could be reserved for particular military assets or training using military RLVs.

Satellite operators at ground stations around the world would be linked into the world-wide traffic control system as the 'pilots' of their vehicles. They would obtain authorization for repositioning, launch or return just as today's pilots do from the air traffic control system.

Launch and return operations from aerospace ports would proceed much as they do from today's large international airports -- with the addition, probably, of a tram-atmospheric concourse from which passengers and freight will be loaded aboard trans-atmospheric vehicles for delivery to space or for very rapid surface-to-surface transportation.

As GPS technology moves into the cockpit, allowing for safer all-weather operation of aircraft, it has also surfaced in satellites, allowing for more autonomous operation -- requiring less ground-based infrastructure and direct control. Systems such as GPS, coupled with future space-based radar systems and the space surveillance network to supplement the current air traffic control system and provide complete coverage of all activity from surface to GEO and beyond require only integration to provide the type of control and range services that the next century's fully operationalized air and space environment will demand.

IMPLEMENTATION STRATEGIES

Obviously, the future spacelift architecture outlined in above will not take shape overnight. Several components are already in development, though, and there is a real chance that the vision contained herein will become reality within the next 25 years. The primary driver for all decisions relevant to this operationalized space environment, or course, is economics -- particularly the economics of Single-Stage-to-Orbit Reusable Launch Vehicles. Reusable orbit transfer will be of secondary importance to RLVS, as it can economically leverage the capabilities of both ELVs and RLVs. It is the success then of NASA's X-33 program and the viability of the commercially-developed follow-on RLV which will dictate the development and timing of

1. ELV transition to heavy-lift only, small mission rate systems and interplanetary exploration,
2. increased utility and cost savings afforded by reusable OTVS;
3. an integrated air and space traffic control system.

Assuming that the X-33 program proceeds on schedule, as does the Air Force-led EELV, then Figure 1 below describes a timeline for implementation culminating in 'full-up' system by the year 2025.
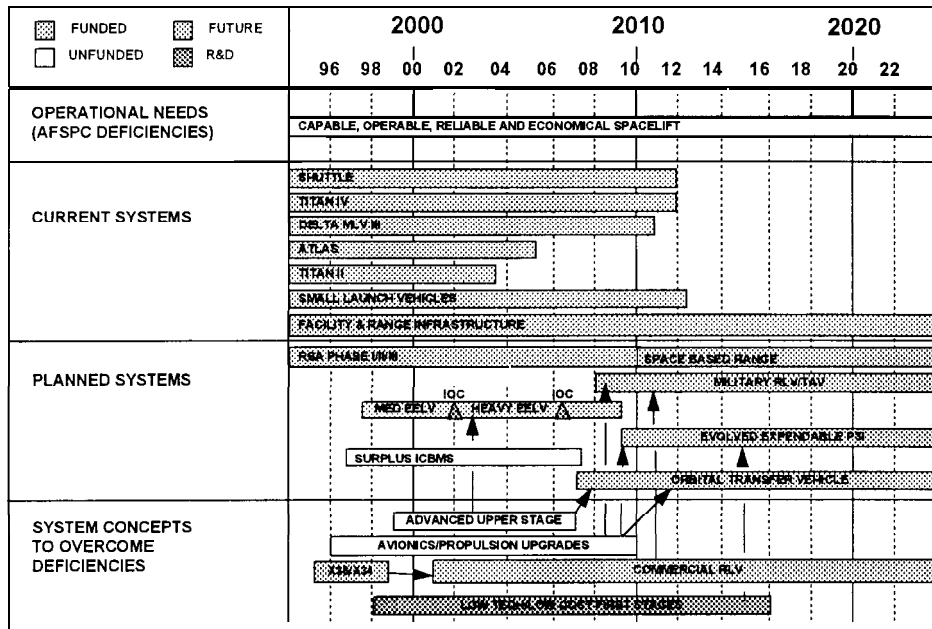
Figure 1 Spacelift Modernization Roadmap

While the ultimate decision criteria for each step along this path will be economic, there are certain key technologies that deserve increased current funding to insure the proper level of maturity when needed. Most of these have been previously identified in the Air Force Space Command 1995 Mission Area Plan for Spacelift, and are described below briefly grouped by the system component most effected by their development.

Reusable Launch Vehicles
    1. Advanced Reusable Liquid Propulsion Engines
    2. Lightweight, Reusable Thermal Protection Systems
    3. Lightweight, Durable Structures and Tanks
    4. Fault Tolerant Avionics

Reusable Orbit Transfer Vehicles
    1. Advanced, Reusable Space Propulsion
    2. Advanced Space Power Systems
    3. Robotic Rendezvous Systems

Expendable Launch Vehicles
    1. Low-Cost Manufacturing Technology
    2. Low-Cost, Light-Weight Structures and Tanks
    3. Low-Cost Expendable Propulsion Engines

Space-Based Range
    1. Space-Based Radar
    2. Full-Coverage Earth and Space Weather Coverage/Sensing
    3. High-Level Integration of Air and Space Traffic Control Architectures
    4. Autonomous Satellite Navigation and Operation

CONCLUSIONS

Over the last decade, innumerable studies have pointed the 'way ahead' for spacelift. Many have generated short-lived development and acquisition programs that began with great fanfare, a few billion dollars and a managing bureaucracy already in place. Today, we see two new programs (EELV and RLV) that make many of the same

claims of cheaper access to space, the chance for 'aircraft-like operations, etc.' One must ask if our chances of success any greater today than in 1986?

For a variety of reasons, the answer to the above question is a resounding "yes." Both NASA and DOD have learned from past management mistakes and are now committed to a more efficient, less suffocating approach. The keys to success for both programs are low-cost, low-cost and low-cost. The market will therefore decide what systems we use to deploy our assets to and through space. Technology, too, has matured. Today, Single-Stage-to-Orbit RLVs seem technically feasible without the great leaps of faith demanded by earlier ventures. The incremental approach to testing and development that served the nation so well during the hey-day of "X" aircraft is taking us 'Back to the Future,' with a sane and sensible route from X-33 to fully commercial RLV.

On the expendable front, the waste of overcapacity, large standing armies required for processing and launch, unique launch facilities and decades old infrastructure has given way to the new low-cost, highly-operable family of vehicles approach embodied in the EELV program.

Technology advances in high efficiency space propulsion have driven ROTVs to the brink of on-orbit demonstration, promising greatly reduced launch costs by decoupling launch and final deployment performing 'tactical' spacelift -- transporting payloads throughout the Near-Earth Theater of Operations.

Space-based radar and full-Earth surveillance will then combine with these advances to finally erase the line between air and space operations, making access to space truly routine. For decades now, this routine access to space has been discussed, planned and in some cases actually claimed, but until each of the components described above is fully operational, we remain like Thaddeus Lowe and his balloon -- merely able to venture forth and observe when the conditions are right, for limited periods at points not providing the full picture we and others require.

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