Abstract

The Electric Insertion Transfer Experiment (ELITE) is an Air Force Advanced Technology Transition Demonstration which is being executed as a Cooperative Research and Development Agreement between the Phillips Laboratory and TRW. The objective is to build, test and fly a solar-electric orbit transfer and orbit maneuver spacecraft, as a precursor to an operational electric orbit transfer vehicle (EOTV). As one of the first programs to partner the Air Force with private industry under a CRDA, ELITE is on the brink of breakthrough technology at a cost savings.

The payoff from the ELITE mission is the development and demonstration of the integrated systems that reliably deliver greatly increased performance in orbit transfer and on-orbit maneuvering. This increased performance translates into combinations of (1) increased non-power/propulsion system (mission payload) mass, (2) decreased launch cost by using a smaller launch vehicle, (3) increased total spacecraft impulse available for on-orbit maneuvering (stationkeeping, repositioning, drag makeup), and (4) greatly increased on-orbit power for the payload.

The ELITE flight experiment will cost effectively demonstrate the key technologies by sharing development expense and risk between government and industry. An integrated team, consisting of TRW, Phillips Lab, and Aerospace Corporation personnel has conducted EOTV mission analyses in order to bound operational EOTV requirements so that a meaningful ELITE flight demonstration can be developed. Significant interaction with spacecraft program offices and other members of the user community has taken place. The combined ELITE team is currently performing system trades to baseline the flight experiment requirements and flow them down to specific mission requirements and spacecraft technical requirements. The program is moving toward a System Requirements Review in April and the System Design Review in August of this year.

Introduction

A successful launch is only the beginning of a successful mission in space. Insertion into higher orbit from low earth orbit is the next critical step in achieving mission success. For some years conventional upper stages such as the Centaur and the IUS have been used to reach higher orbits. These chemical fueled boosters bring with them higher propellant mass fractions which can mean reductions in available payload mass. This forces the use of a heavier launch vehicle to avoid diminishing payload capability. Higher launch costs are unavoidable if mission integrity is to be maintained. Once injected into low earth orbit, the chemical upper stage booster expends

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most of the spacecraft's fuel in reaching higher earth orbit or geosynchronous orbit. Final orbit is reached by expending more propellant to perform the orbit adjustments needed for accurate insertion. The space based asset thus settles into its mission orbit. Only a small amount of propellant remains on board for minor on-orbit maneuvers such as slewing, attitude control, and stationkeeping. An additional mission would be required to change the spacecraft's orbit.

Among the many lessons learned in Operation Desert Storm was the need for dynamic range on orbit for future space based assets. Future space missions will require low cost access to higher orbits, reduced propellant mass fraction ratios, and increased on-orbit dynamic range. The orbit transfer solution that meets these needs is the Electric Orbit Transfer Vehicle or EOTV.

Electric propulsion coupled with advanced solar array technology is far more fuel efficient than chemical propulsion methods. Even though electric propulsion is more fuel efficient than chemical systems, the thrust is on the order of fractions of a pound, and will depend upon the amount of power available. Therefore the orbit transfer from low earth orbit, to geosynchronous orbit may take several hundred orbits and will last several months. However, other factors may reduce the difference in time between the spiral transfer and chemical impulsive transfer. The low acceleration of the spiral transfer may allow system checkout during orbit transfer. The continuous low thrust will also allow more accurate insertion into final orbit thus eliminating the time needed for orbit adjustments. Also by using an Atlas class vehicle instead of a Titan IV, significant launch processing time may be saved, thus reducing the time difference between the low thrust spiral and the impulsive orbit transfer.

EOTV will provide orbit transfer with a much smaller propellant mass fraction than traditional systems, thus producing increased payload mass fractions. This allows the use of a medium class launch vehicle such as the Atlas II to boost spacecraft that up until now could only be launched on a heavy booster such as a Titan IV. This alone represents a savings of 75 M to 100 M dollars per launch. Additionally, the decreased propellant mass fraction enables the spacecraft to operate longer, thus reducing the added cost of replacement.

EOTV employs arcjet thrusters to produce thrust. Electric arcjets propel the spacecraft by heating pressurized gaseous hydrogen or ammonia with a high voltage electric arc. These gases are then expelled through a nozzle thus producing thrust. Critical EOTV technologies are currently being demonstrated. Recent testing at JPL verified arcjet performance levels. Advanced solar array technology provides the power required for electric propulsion. Several array technologies are currently under development that do not degrade with radiation as conventional solar power systems do.

In addition to significant mission cost savings, electric propulsion coupled with advanced solar arrays, can provide mission capabilities that chemical systems do not provide. Operation Desert Storm showed that increased on-orbit maneuverability of space assets is critical to operations planners. EOTV with its fuel efficient thrusting capability allows a space asset to change its ground coverage area. Also EOTV equipped spacecraft can alter their inclination and altitude thus
providing greatly enhanced mission performance. EOTV provides these capabilities without sacrificing lifetime of expensive space based assets. Additionally, EOTV's advanced solar arrays provide high on-orbit power previously unavailable to spacecraft. This increases the capabilities of many power hungry payloads. Provided there is an Air Force requirement, the EOTV can return the asset to shuttle orbit for servicing should a malfunction be detected during orbit transfer. This is not feasible with conventional chemical systems.

To prove the EOTV concept, TRW and the Phillips Lab are bringing innovations to business and technology under a single program, ELITE. ELITE, the Electric Insertion Transfer Experiment, will demonstrate EOTV systems, technologies and operations. This flight experiment will validate key system and subsystem designs of an electric propulsion spacecraft. As one of the largest programs to partner the Air Force with private industry, under a Cooperative Research and Development Agreement, or CRDA, the flight experiment will cost effectively demonstrate key technologies by sharing development expense and risk between government and industry.

**Space Launch Alternatives**

The National Space Launch Strategy calls for long-term improvements in national space launch capabilities. The joint DoD/NASA NLS program has the goal of providing new medium and heavy lift launch vehicles with improved reliability, responsiveness and mission performance at reduced cost, replacing the current Delta, Atlas, and Titan vehicles after the turn of the century. Options for the orbit transfer upper stage are also being investigated. The advanced upper stage is planned to be a cryogenic fuel chemical stage. However, there are several low-thrust, high performance technologies that offer alternatives. These technologies include: solar-electric, nuclear-electric, and solar-thermal power/propulsion systems. Nuclear-thermal propulsion is not in the low-thrust category, but is another class of system under consideration. Selection of the best complementary mix of these upper stage concepts for further development can only be made when the technologies have gained acceptance from the user community based on demonstrations traceable to operational systems.

The selection of how to proceed with upper stage development may be influenced by the changing world political structure. As the hostile threat to on-orbit space assets decreases, more attention should be given to reducing launch costs by using the Launch on Schedule scenario which is currently the normal NLS operational mode. The requirements for the contingency modes of Launch on Need and Surge for a few types of military satellites may even be re-examined. World political changes could also increase the requirements for satellite repositioning capability to provide worldwide coverage.

Solar-electric orbit transfer and orbit maneuvering vehicles made integral with mission payloads offer the longer on-orbit lifetime and repositioning capability while greatly reducing launch costs. The long deployment time of a EOTV is consistent with the Launch on Schedule requirements of NLS, and analysis has shown little impact from additional Van Allen radiation to current natural radiation hardened designs.
The ELITE mission will gather data and demonstrate functions, hardware, and software that are needed for any of the low-thrust technologies to evolve into an operational vehicle. Specifically they all require:

1) the management of low thrust trajectories
2) the implementation of some level of autonomy in both guidance navigation and control (GN&C) and system health and maintenance to reduce the need for ground control operations
3) radiation hardened spacecraft bus and payload protection schemes
4) high power management and distribution systems
5) propellant storage and feed management

Simple and reliable operation of these hardware and software components is part of the mission success criteria for the ELITE program.

ELITE Program Goals and Responsibilities

ELITE is both an experiment and a demonstration. On one hand, the mission is to collect the scientific and engineering data required to answer critical technical questions that address the feasibility of solar-electric orbit transfer and on-orbit maneuvering (SEOTOM). On the other hand, ELITE will demonstrate critical SEOTOM functions for the first time. Essential mission demonstrations include: adequate altitude and inclination changes to establish LEO to GEO capability, autonomous GN&C, on-orbit repositioning, and system/payload reliable operation following prolonged exposure to the radiation belts, as well as to the electric propulsion system.

ELITE must show method/design traceability and performance scaleability to an operational vehicle, to be a meaningful demonstration. ELITE is, however, a design-to-cost experiment, thus the affordable level of flight demonstration must be traded against acceptable ground testing. The operational requirements for an EOTV have been under study, however, no formal requirements have been issued by DoD, NASA, or any commercial user. This absence of formal requirements, has, of course, complicated the experiment design process.

The experiment design team has presented the user community with a list of critical technical questions that should be addressed in ground test or in the flight experiment to adequately transition this technology to the state of maturity required for operational implementation. This interaction with the user community has helped define the proper trade space for the experiment designers to evaluate cost effective experiment concepts suitable for the ELITE mission. At this time, top-level requirements for the flight experiment, are being analyzed, and subsystem trade studies performed to arrive at baselines for the System Requirements Review.

The basic segments of the total ELITE system and the major subsystems of the space segment have been identified, and responsibility for each assigned. It is planned to use a refurbished Titan IIG to launch ELITE. Space Division/Space Transportation & Test and the Titan SPO are working on budgeting the launch costs, and allocating the vehicle to the ELITE.
program. The facilities of the Air Force Satellite Control Network (AFSCN) will provide the ground segment of the ELITE mission, with possible interaction with a planned ground station at the Phillips Lab in Albuquerque, New Mexico.

The CRDA delineates the responsibilities for providing the spacecraft subsystems. The Phillips Lab will provide under separate procurements an arcjet propulsion subsystem, a solar array subsystem and experiment diagnostics. TRW will provide, through their IR&D program, the systems design engineering, autonomous GN&C hardware and software, propellant storage and feed subsystem, spacecraft bus, (including the high power distribution system), spacecraft integration and test, and launch vehicle/spacecraft integration support. The Air Force will provide the launch vehicle, launch services and post launch operations/data reduction.

Organization, Funding and Schedule

The management interrelationships (technical and programmatic) as well as the integrated program office manpower and organization form a management approach that will demonstrate for the first time the execution of a large dollar-value CRDA. The Space Experiments Directorate is the PL organization responsible for managing this program with the Advanced Systems Division of the Space and Technology Group of TRW.

The organization of the ELITE Program Office is shown in Figure 1. The PL program manager and most of his program office team will come from the Space Experiments Directorate. Some government personnel may be used as matrix support to the program office from other PL directorates. For each of the AF procurements, there will be a project officer who will be responsible for integrating his schedule with the overall program schedule through the program manager. Technical management and interface with the TRW supplied spacecraft bus will be done through the AF systems manager for the three PL supplied subsystems. He will coordinate the mission planning and satellite control and data down link planning efforts. The AF ground equipment and launch interface manager will interface with the launch vehicle program office and the Space Test and Transportation organization at SD and their contractors, to provide the launch vehicle, launch integration support, and launch services. Aerospace Corporation personnel provide a valuable resource for system engineering tasking as they have been analyzing EOTV and Elite performance characteristics for over two years.

The PL and TRW Systems engineering teams have formed a spacecraft interface working group. The group is chaired by the TRW systems engineer, since TRW has overall spacecraft systems engineering responsibility per the CRDA. The PL leads a working group with TRW and Mission Control Center participation to develop mission planning including flight timeline, command and data plans, operations plans and procedures, and training requirements. The PL also leads a working group with TRW, Launch Vehicle SPO/contractor and ST&T participation to develop booster interface requirements and plan for launch services.

Funding for ELITE comes from two different Air Force Program Elements. Advanced Spacecraft Technology Integration, (PE63401f), provides about
half of the Air Force funding, and the other half comes out of Space and Missile Rocket Propulsion, (63302f). TRW funding, through their IRAD program, is at the same level as the total AF funding.

ELITE is being planned for a calendar year 1996 launch, with PDR in May of 1993, and CDR in May of 1994. It is planned to have the Air Force subsystem suppliers on contract by the end of this fiscal year. There is a TRW funding decision gate at the end of this year. The decision will be based on user support and funding outlook for an Engineering Manufacturing and Development (EMD) phase for EOTV, technology development status, and budgetary constraints (both TRW and AF).

**EOTV Mission Analyses**

Last year, preliminary mission analyses was performed to identify the most promising EOTV mission characteristics, and provide a baseline against which the ELITE demonstration requirements could be further developed. These analyses considered ranges of: electric propulsion (EP) and solar array characteristics; spacecraft mass and drag properties; initial and final orbits and transfer times; and various thrusting policies.

These trades have shown that the benefits of EP are greatest using an EOTV integral with mission payload, and launched off a medium launch vehicle. Specifically, there is the potential for delivering 5000 to 7000 lbs of net satellite mission payload (not including EOTV components: solar array, ACS, Comm, Propulsion) to GEO using an Atlas IIAS which has undergone a structural upgrade. The Atlas II AS with Centaur IIA alone can only deliver about 2300 lbs to GEO with an apogee kick motor it can deliver about 4000 lbs. Both of these numbers must have the weight of comparable common bus/propulsion components subtracted before comparing to the 5000 to 7000 lb potential capability of hydrogen EOTV. The potential 7000 lb capability of an integral EOTV launched from an MLV is based on an 180 day transfer time, using hydrogen arcjets and advanced solar arrays. Concern over the effect of the slow spiral through the radiation belts was alleviated when analysis showed little impact to current natural radiation hardened designs.

Trade Studies, performed by the Aerospace Corporation, McDonnell Douglas have also shown that an operational vehicle will have the best performance using hydrogen arcjets. Operational designs using this technology will become very attractive once hydrogen arcjets are available with 2000 hours lifetime that operate at 1100 to 1400 seconds specific impulse and roughly 40% efficiency. The Phillips Laboratory is conducting an in-house ground development and test program to demonstrate the performance required for an operational hydrogen arcjet system. NASA is currently conducting a ground test program at Lewis Research Center which is expected to provide data necessary to design a LH2 storage and feed system for a H2 arcjet. NASA LeRC also has a ground development program for H2 arcjets.

**ELITE Baseline Mission**

Flight qualified hydrogen arcjets and a flight qualified storage and feed systems require further development at this time. Neither can be currently funded by the ELITE program.
However, the ELITE flight experiment can achieve most of its objectives using ammonia arcjet technology that is currently being flight qualified. Further, the flight performance of hydrogen arcjets can be accurately predicted using the results of an ammonia based ELITE flight, and a validated ground model. This ground modeling is presently being planned as an in-house PL effort. ELITE is therefore baselining an ammonia arcjet with high confidence of meeting the CY96 launch date and providing the necessary information to support (along with the ground development efforts) a technology freeze date of 1997 for any of the prospective EOTV transition opportunities.

The ELITE is being designed to mirror an EOTV in three areas: flight operations; system demonstration of applicable technologies; and operational environment. In the area of flight operations, ELITE will simulate a LEO to GEO flight and undergo the same types of maneuvers. EOTV trades favored an initial orbit around 200 to 250 nm. The Titan IIG will launch ELITE into an initial park orbit of 200 nm. The integral EOTV wet weight is on the order of 11000 lbs to deliver the 5000 to 7000 lb mission specific payload to an operational orbit of 19323 nm (GEO). ELITE will weigh about 4000 lbs and deliver roughly 2000 lbs to its mission orbit, not including the solar array weight. The demonstration vehicle is sized to reach an altitude of about 2150 nm, demonstrating adequate orbit raising and inclination change, while reaching a radiation environment where the vehicle can accumulate the same total dose the EOTV would experience.

The technology traceability area is more difficult. The plan for showing traceability to a hydrogen EOTV has already been discussed. An EOTV will have to have a solar array system that has both high specific power, (say > 55 watts/kg), and low cost per watt, (in the neighborhood of $500/watt), to be viable competition for chemical upper stages. This will make the array choice for ELITE difficult, because the technologies that have the potential to meet these requirements are either not available in time for ELITE, or may not be affordable. An alternative is to fly an untraceable technology along with samples of more promising technologies. This question will be answered through the procurement process over the remainder of this fiscal year.

ELITE will perform in a very similar environment to an EOTV. It will experience approximately 700 eclipses, requiring it to cycle on and off. The experiment design team is investigating the need to demonstrate simultaneous thruster operation to investigate plume-plume interaction for multiple thruster EOTVs. The spacecraft will see roughly the same total radiation dose as a LEO to GEO transfer, and a very similar dynamic environment produced by the low-thrust/low-acceleration transfer.

A preliminary mission requirements document (MRD) has been written for the ELITE demonstration. Numerous detailed test objectives have been proposed. The ELITE team is in the process of reviewing these test objectives considering: impact on spacecraft design and cost; the most recent user community input; and measurements required versus affordability and availability of diagnostic instrumentation.

The MRD categorizes the detailed test objectives into six groups. The first
group demonstrate EOTV operational maneuvers and capabilities, including payload delivery, orbital maneuvering, durability, and restart following long-term storage on orbit. The second group characterize the electric propulsion subsystem performance, and any contamination of, or electromagnetic interference with the spacecraft. The characterization of the solar array subsystem performance and degradation forms the third group. Key to ELITE mission success, is the evaluation of the complex autonomous guidance, navigation and control needed in an operational system. Included in this fourth group of test objectives is the evaluation of system health and fault management algorithms. The demonstration of low-thrust control technology includes not only thrust vector pointing and solar array pointing, but also, the control of the high power required to operate the thruster. This fifth group of test objectives is technology dependent and will become better defined as the system definition proceeds. The unique mission orbit of the ELITE spacecraft offers the opportunity to collect environmental data beyond that which is needed to verify EOTV feasibility. The sixth group of proposed test objectives offers this additional scientific data.

The baseline mission parameters for ELITE will be established at SRR. The experiment design team is working toward the following nominal mission. The launch off of a Titan I1G in 1996 will be from Vandenburg AFB. The ELITE spacecraft will be put into a 63.5 degree inclination at 200 nm to perform approximately two weeks of initialization and checkout. Many of the test objectives will be performed during the subsequent first month of spiral transfer. The total spiral time will, of course, depend on the amount of power used, but will be on the order of two months for a nominal 10 kw power delivered to the Arcjet Power Conditioning Unit. Once the nominal mission altitude of 2150 nm is reached, the spacecraft will enter a durability phase. Only essential health and status functions will be powered for a period of from three to six months. At the end of this period, ELITE will be checked out, and the arcjet restarted to demonstrate reusability for orbital maneuvering. Other scenarios are being considered for a lower powered ELITE spacecraft in the event sufficient solar array power for the nominal mission can not be afforded.

The ELITE spacecraft will be based on a TRW standardized low cost spacecraft design approach. The production of the spacecraft for the ATTD will therefore be a demonstration of the producibility of a low-cost standardized solar-electric spacecraft bus for operational missions. ELITE will carry two arcjets; the baseline plan is to fire one arcjet for the majority of the mission, because of limitations on affordable power level. The second arcjet is there for redundancy and possible tests of simultaneous arcjet firing. Using autonomous navigation and thrust vector control software, the ELITE spacecraft will demonstrate reduced ground mission support requirements. The operation of the autonomous GN&C functions will be monitored from the Mission Control Center which will have override capability to perform standard navigation update and to interrupt spiral transfer to simulate payload operations during transfer.

Transition Opportunities

Many opportunities exist for increasing mission payload mass, decreasing
launch costs, and increasing total spacecraft impulse by applying high power electric propulsion technology to DoD, NASA, SDIO, and commercial spacecraft missions. More opportunities will evolve as mission planners take advantage of the large power source available to mission payloads delivered with an integral solar-electric orbit transfer and orbit maneuver spacecraft. The growth in system weight for missions in the planning stages now can be handled without going to a larger launch vehicle by taking the integral SEOTOM approach. Modification of existing spacecraft designs must be evaluated case by case.

Arcjet propulsion technology could have significant impact on the cost and life of communications satellites. This could benefit military, NASA, SDIO, and commercial programs. The next block change beyond Milstar II may be the appropriate technology insertion opportunity (approximately FY 05) for the military application. NASA's TDRS II program requires a satellite in the three to four thousand pound range to be placed in a geo-synchronous orbit. The higher specific impulse obtainable from an arcjet propulsion system can significantly reduce the weight of propellant required for satellite stationkeeping over a fifteen year mission life. Additionally, it results in a significant cost saving by allowing the use of a smaller, lower cost launch vehicle for this size of payload. The benefit to commercial communication satellites is more transponders to geosynchronous orbit off the same launch vehicle and the efficient high power solar arrays to drive them, which are already part of the solar-electric propulsion subsystem.

COMSAT Laboratories is interested in arcjet propulsion for orbit transfer of commercial communications satellites. COMSAT feels it is critically important to understand the power requirements and spacecraft structural impact and that the ELITE mission offers an opportunity to get real answers.

The GPS SPO has indicated interest in electric propulsion for Block IIF with a 1998 technology freeze date for launches in 2003. The Brilliant Eyes SPO is currently investigating use of solar-electric propulsion to deliver the BE constellation. Electric propulsion is also of interest for low-thrust interplanetary cargo transfer missions.

Other specific targets will emerge as block changes to existing assets are identified or new program starts are generated. Operation Desert Storm highlighted the need for maneuverable, long-life spacecraft. The NASA Strategic Plan for transportation technology calls for the development of both nuclear-electric and solar-electric propulsion for interplanetary transfers. COMSAT Laboratories has agreed that \( H_2 \) arcjet technology for orbit transfer is the next major step in arcjet propulsion for commercial communications satellites. There is a growing consensus at the national level that electric propulsion technology should be further developed.

**Conclusion**

The basic needs of the spacecraft program office and user communities are very general: mission success; new payload options at reduced life cycle costs; and easy integration, flexible operation, and producibility. Implicit in these needs are lower cost access to mission orbits, higher payload mass...
fraction, increased spacecraft maneuverability without sacrificing spacecraft lifetime, and (for some missions) higher power on orbit. The joint Phillips Lab/TRW ELITE program represents a big step towards satisfying these needs using a standard interface solar-electric spacecraft bus that integrates easily with mission payloads, and has flexible mission operations.

There is little doubt that the arcjet, solar array, and spacecraft bus technologies to be demonstrated on ELITE could have significant impact on the cost and life of future satellites. The problem in technology transfer is the long time required to develop new concepts to the state of maturity required for their implementation into the very expensive satellites now starting their development cycle.

Facing today’s economic realities, TRW and the Air Force will shape the technology and build the vehicle to meet demands for increased capability and flexibility in space. ELITE will spearhead the evolution of a multimission family of low cost integrated payload propulsion designs. For the partners, TRW and the Air Force, the return on investment for ELITE is the promising future of the Electric Orbit Transfer Vehicle.
Figure 1 Organization

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