INCREASING SPACE ACCESS AVAILABILITY FOR SMALL PAYLOADS: THE PACASTRO LAUNCH VEHICLE

Dr. Rick Fleeter[*], Dr. Frank McLoughlin[**], Dr. Ray Mills[†]
PacAstro
520 Huntmar Park Drive, Herndon, VA 22070
703-709-2240 (phone); 703-709-0790 (fax)

Abstract

This paper familiarizes the Small Satellite community with the capabilities and advantages offered by the PacAstro launch vehicle and its applications to low-cost launch needs. At a projected cost of $5M per launch, the 2-stage, pressure-fed liquid fueled vehicle is designed to transport 225 kg (500 lbm) to a 750 km (405 nm) altitude circular polar orbit, or to a 1200 km (650 nm) altitude circular equatorial orbit. The smooth burning engine provides a gentle vibration environment and can be throttled, shut-down, and restarted to accommodate accurate orbit insertion. The large 1.5 m ID and 2.4 m long payload volume allows multiple payloads to be launched side-by-side.

The vehicle exploits over 30 years of U.S. booster technology and requires no technology development. The PacAstro vehicle uses proven components for all major elements including engines, supplied by TRW, fairing, and stage separation. The PacAstro team, which includes TRW and Swedish Space Corporation, has considerable hardware and launch experience. PacAstro is combining the application of well proven, low cost launch vehicle technologies with the techniques of small, low cost satellite development to create a launch vehicle with costs comparable to or below those of the satellites it will carry.

Introduction

The same technologies which created a revolution in personal computers have enabled development of Scout / Pegasus class satellites with many of the capabilities of multi-ton spacecraft of a decade ago. Their lower complexity and part count, compared with their predecessors, has lowered their development cost, while their decreased mass and smaller volume allow use of smaller, less expensive launch vehicles. This technology enables cost-effective, quick-response technology demonstrations and cluster or constellation missions comprised of large numbers of small satellites.

But without a similarly low cost, responsive launch system, the great potential of these smaller, cost efficient payloads cannot be realized. PacAstro was created in 1990 to address this need in the emerging small satellite industry. Without bias toward any particular technology, we optimized a Scout class vehicle design for minimum overall mission cost, including reliability, satellite design and test (reflecting launch loads, interface and manifesting requirements), environmental impact and development cost (including the effects of development program risks). While the expenses of air launching and solid motors are justified for some defense missions, PacAstro's pressure-fed liquid, ground launched vehicle lowers launch cost significantly to $5M per launch while meeting all requirements for most development, research, and operational missions.

The PacAstro vehicle uses proven components for all major elements including engines, supplied by TRW, fairing, and stage separation. The PacAstro team, which includes TRW and Swedish Space Corporation, has considerable hardware and launch experience.

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[*] President
[**] Senior Engineer, Member AIAA
[†] Senior Engineer, Senior Member AIAA

Part I: Recognizing Requirements

The decade of the 1950's saw humanity's first steps into space. The 1960's were characterized by the success of many satellite applications (defense, telecommunications, earth observation, scientific research) and the landing of people on the moon. The 1970's saw the start of the space shuttle with airliner-like round trips to low earth orbit. Miniaturization, in part, characterized space in the 1980's, as the US and other nations made important progress in space using small, low-cost satellites. The existence of highly capable small satellites with costs as low as a few million dollars is proof of the progress we have made in lowering satellite costs.

What is the challenge of the 1990's? We believe it is the transition from a launch technology development strategy to a focus on reliable, low-cost transportation to orbit. Such common-sense launch service will enable technology development resources to be focused on the space missions themselves rather than the access to space. This is nowhere more true than for small payloads, where launch cost is the major portion of total mission cost and the technology potential for both defense and commercial applications is significantly under-realized.

To successfully market any technology, whether it is aircraft, computers, telecommunications or spacecraft, many factors must be considered. Finance-ability, simplicity, reliability, accessibility, and customer service replace technology development as the focus of engineering effort. Technology is not forgotten, but neither is it an end in itself - technology is driven by market forces. This differs from contemporary aerospace projects which are technology driven. That is, they are justified by their technological advances rather than on their immediate utility in the market.

The three major cost elements in all commercial space programs, whether they are in telecommunications, remote sensing, manufacturing or science, in descending order of portion of total mission resources are:

1. Transportation
2. Spacecraft
3. Insurance

The increasing attention being paid to small, simple, low cost satellites is now focusing on launch services. Manufacturers around the world are striving to provide valuable orbital services at lower cost for smaller satellites. The existence of highly capable small satellites with costs of only a few million dollars are proof of the progress we have made in lowering satellite costs.

Progress in reducing space transportation costs has been much less dramatic than progress in reducing small satellite costs. In fact, the shuttle and the Pegasus air launched rocket are among the most expensive means (on a unit mass basis) yet developed to place payloads in orbit. Launch vehicle key technologies, particularly rocket propulsion, simply have not experienced the revolution which occurred in electronics and thus cost reductions have not occurred in this industry. Pegasus, while acknowledging the desirability of low cost, was justified because of the flexibility an air launch offers to some operational defense missions. Similarly while the early shuttle advocates used cost as a justification, the real mission of the shuttle was to advance launch vehicle technology, particularly in reusable vehicles which can return significant payloads, and their own airframes, from orbit.

While the shuttle and expendable vehicles such as Delta II can launch small payloads for low cost, the availability and mission responsiveness of piggyback launches are almost always unacceptable and thus stifle the very advantages of small payloads. Also, the guidance and propulsion systems needed to transfer to the necessary orbit significantly increase the cost, size and complexity of the small spacecraft.

The shuttle history illustrates a vital factor in a prudent launch strategy: independence from a single launch vehicle or technology. The Challenger tragedy virtually paralyzed US large payload launch capability for several years. However, today the air launched, solid propellant Pegasus is the only dedicated small payload launcher as Scout is phased out, and its manifest is already crowded and delayed. Even a shorter grounding than that of the shuttle in 1986-1987 would critically impact small payload applications just as the important defense and commercial potential of these payloads should increasingly be realized. Most proposed Pegasus alternatives use similar solid rocket technology.

The PacAstro vehicle's pressure-fed liquid propellant, two-stage to orbit design was determined by and focused upon two conditions: need for a viable low-cost, reliable transportation service; and experience and hardware developed in over 30 years of successful launch vehicle developments.

Part II: The Path to Lower Cost Transportation

While launch services can be procured to meet the needs of the small satellite project, the costs are often high compared with low cost satellite project resources. Table 1 lists the currently available launch options for small satellites.

Table 1. Current Launch Options for Small Satellites

Dedicated Small Satellite Launchers

Rocket	Manufacturer	Payload Diameter and Length	Payload Mass	Orbit	Cost ($M)	Remarks
-	**PacAstro**	1.5m (D) x 2.4m (L)	225 kg	750 km polar	5	
Pegasus w/ HAPS	OSC	1.16m (D) x 1.8m (L)	195 kg	750 km polar	12	3 solid; optional liquid stage 4
Scout	LTV	.97m (D) x 1.5m (L)	145 kg	750 km polar	14	
Conestoga	EER	0.9m (D) x 1.8m (L)	225 kg	750 km polar	15	
Orbital Express	Microsat	0.76m (D) x 1m (L)	100 kg	750 km polar	13	concept proposed
Aquila	AmRoc	2.34m (D)	500 kg	750 km polar	13	4 stage hybrid proposed
Shavit	IAI	1.25m (D) †	500 kg	750 km polar	10	3 solid+1 biprop stage proposed

Small Payload Accommodations on Large Launchers

Rocket	Manufacturer	Payload Diameter (typical)	Payload Mass	Orbit	Cost ($M)	Remarks
Ariane	ESA	0.4m x 04m x 0.6m	65 kg	*	0.2	ASAP
Delta	MacDonnel Douglas	1.2 m	150 kg †	*	2.5 †	
Titan	Martin Marietta	1.2 m	150 kg †	*	2.5 †	
STS	NASA	0.5m (D) x 0.74m (L)	70 kg	175 km, 28°	0.15	GAS can

* depends on primary payload
† approximate

The PacAstro vehicle was optimized exclusively to minimize the total cost of inserting a small payload into its desired orbit. Our cost analysis included not only the cost of the vehicle engineering, production and operation, but also secondary costs such as program risk and insurance, building the payload to withstand launch loads, and the cost of trimming the achieved orbit to the payload needs. This system level overview of the PacAstro vehicle is limited to the principal features of the design to emphasize its feasibility.

The philosophy to minimize mission cost molded the PacAstro vehicle and operations in the following significant ways:

Propellant:
Table 2 compares a few of the major types of propellants in existence today. The traditional advantages of solid propellants are not applicable to many small payload defense missions. Instantaneous mission readiness, quite valuable for some operational applications, is not an important requirement for technology demonstrations. The high density of heavily aluminized solid fuels affords a small vehicle diameter which is important for drag reduction of air-borne missiles. However, drag reduction is not as critical a criterion for orbit insertion. Manufacturing and handling of solid propellants require particular attention and are a constant safety hazard.

Table 2. Comparison of Propellant Alternatives

Fuel	relative cost	I_{sp}* (sec)	specific gravity	exhaust	safety/ storage
LOX / kerosene	low/ low	300	1.14 / 0.81	CO_2, H_2O (safe)	cryogen (90 K), safe
LOX/RP-1	low/ low	300	1.14 / 0.81	CO_2, H_2O (safe)	cryogen (90 K), safe
LOX / LH_2	low/ med	389	1.14 / 0.07	H_2O	cryogen (20 K), large vol.
LF_2 / LH_2	high/ med	411	1.5 / 0.07	F, HF	cryogen, toxic, corrosive, reactive, explosive
H_2O_2 / N_2H_4 (or MMH)	low/ med	285	1.38 / 1.0	H_20, O_2	unstable, toxic, ignitable
NTO / MMH	low/ med	288	1.44 / 1.0	NH_3, N_2H_2	toxic, corrosive, ignitable
N_2H_4 (hydrazine)	med	240	1.0	NH_3, N_2H_2	toxic, ignitable, stable
ammonium nitrate / Al	high	192	1.5 g/cc	little toxic	toxic, explosive, corrosive
ammonium perchlorate / Al	high	262	1.7 g/cc	HCl, Al	toxic, explosive, corrosive

* I_{sp} referenced to 1000 psia chamber pressure and 14.7 psia nozzle exit pressure

Liquid propellant systems cost less than solid propellant systems. Once engineering is amortized, non-recurring expenses for liquid engines are lower than for solid motors. Secondary costs associated with transportation to the launch site and on-site safety are greatly reduced with liquids. Risk is reduced because fuel and oxidizer are kept separate until launch.

There are several key operational advantages of liquid propellants. A benign vibration environment, in comparison to solids, accommodates more sensitive payloads and also reduces payload structural mass, interface design complication, and vibration induced component failures. More accurate orbit insertion can be accommodated by liquid engines which can be throttled or shut-down, without costly, uncertain propellant shaving and tight payload mass control characteristic of solids. The shut-down feature has the additional benefits of increased safety during pre-flight engine testing. Another important advantage of allowing for an engine restart is that Earth gravitational effects can be exploited for assistance in high altitude orbit insertion. The ability to restart reduces the number of stages required, since the restart can be performed without an additional engine. Further, solid propellants are less energetic (enthalpy per mass) than liquid propellants.

Liquid oxygen (LOX) and kerosene (or RP-1) is the most cost effective and environmentally benign liquid propellant alternative. Both oxidizer and fuel are readily available and much less expensive than solids. Further, the handling and the testing of these liquids is straightforward, safe, and routinely performed. No costly constraints need be placed on the tankage design. LOX/RP-1 performance (I_{sp}) is quite comparable to many other liquid propellants, without the safety, storage, and/or cost concerns of other higher performance propellants. For example, Hydrogen peroxide (H_2O_2) is a readily available oxidizer and can be used for medium performance results with hydrazine (N_2H_4) or monomethylhydrazine (MMH). However, H_2O_2 is difficult to store, as it decomposes even under favorable conditions. Further it can produce severe burns to human skin and it readily ignites with common materials. Both hydrazine and MMH are themselves quite costly, hazardous to human health, and costly to handle and store. Liquid Fluorine (LF_2) is highly toxic, corrosive, spontaneously reactive to common materials and metals, and it evaporates readily, making it difficult to store for long periods. The environmentally benign exhaust of LOX/RP-1 engines contains only water vapor and carbon dioxide, naturally occurring, harmless, atmospheric gases.

Pump vs. Pressure Injection:
Table 3 summarizes the tradeoff between pressure and pump fed systems. While pump technology has advanced, it constitutes a steep non-recurring cost barrier both to develop the pump and to test it with the engine. While these costs are recovered via mass efficiency in large vehicles (e.g. Titan IV), the mass tradeoff is not so significant for small vehicles.

Table 3. Pressure vs. Pump Fed Liquid Engines

Pressure fed	Pump fed
• lower complexity and risk • less mass despite stressed and heavy tanks • higher reliability	• less mass for high thrust long duration engines • higher development costs • potentially high recurring cost • costly, fragile, lightweight tanks

Staging:
Each stage of a rocket is a distinct system. Minimizing the number of stages reduces costs when all other factors are equal. Liquid fuel allows development of a highly capable vehicle using only two stages. This lowers manufacturing cost as well as risk, since only two stages need to work to achieve a successful launch. In case of any malfunction at launch start, the first stage can be shut down after ignition and the launch aborted without loss of the vehicle. For this reason insurers count only one "critical" stage ignition in a two-stage liquid design versus four critical ignitions for typical small solid propellant vehicles. The engine shut-down feature also simplifies pre-flight performance testing.

Fewer stages also means fewer interstage separation mechanisms, often the culprit in launch vehicle failures. The PacAstro vehicle requires only one interstage separation mechanism, compared to two or three for other vehicles with similar performance. Thus, assuming a 99 percent interstage separation mechanism success rate, the risk of a stage separation failure is up to 50 percent worse with other launch vehicles than with PacAstro.

Launch Site:
Among air, sea, land vehicle and fixed land-based sites, launching from an existing, fixed land site is the least expensive. Air launch requires man-rating of all flight components plus a mechanism to transition from horizontal to vertical flight. Very high lateral loads are imposed on the spacecraft payload during this transition. The aircraft used to launch the rocket contributes high fixed and recurring expenses for its purchase, modification and maintenance, for its crew and for each flight. Sea launches have many of the same disadvantages. A dry, clean, stable platform must be built at sea to prepare and test the vehicle and its satellite payload before launch. Open ocean environments are very deleterious for spacecraft structural, electronics and sensor components and many of the man-rating problems remain. Mobile land launchers require all the services of fixed sites, except they must be developed for mobility, increasing their cost. The mobility of these three competing methods also makes them subject to regulations stemming from arms treaty ratification which augments the uncertainty of their development and launch costs and from regulations on the transport of hazardous materials.

Fixed launch sites, in contrast, allow establishment of cleared, reusable launch trajectories. At any of these sites, satellite developers can access their payloads until minutes before launch, increasing mission success probability and lowering payload development costs compared with mobile launch platforms.

Vehicle Subsystems and Components:
Development of a launch vehicle at reduced costs while achieving good performance and minimizing program and flight risks lead us to incorporate proven flight hardware already developed for other applications. The engines, valves, guidance system and stage separation system are all selected from the existing US inventory of proven components.

Table 4 summarizes the major components of the PacAstro vehicle. All components are readily available, as is indicated by the identified vendors for the various components, or quite easily developed. The four large tanks are built by an industrial manufacturer already providing tanks in large numbers for a range of industrial applications. The graphite composite pressurant tanks are also off the shelf products manufactured in volume and hence are available at low cost.

Many major vehicle components are supplied by PacAstro team members AeroAstro, TRW, and SSC (Swedish Space Corporation), significantly reducing program risk. AeroAstro is providing much of the avionics including the computer processor. TRW is providing the engine for both stages. SSC, which has extensive sounding rocket experience, may provide the payload fairing. The long and impressive space experience of both TRW and SSC is available to PacAstro for component specification and procurement assistance.

Table 4. Major Components of PacAstro Vehicle

Avionics & Control

Name/Description	*Quantity*	*Vendor #1*	*Vendor #2*
Computer Components			
80286 MP2 Processor PMM 3225/xxx	*1*	AeroAstro	AlTech
48 Bit Out/4 Ch Analog Out	*1*	AeroAstro	AlTech
(8 Channel ADC)	*4*	AeroAstro	AlTech
Ser Comm PMM 3058/000	*2*	AeroAstro	AlTech
Sensors			
Inertial Measurement Unit (3-axis)	*1*	Northrop	Litton
GPS receiver	*1*	Northrop	Trimble
Telemetry Components			
Xmit/Receive Diplexor	*1*	AeroAstro	Watkins
Antenna Components	*1*	AeroAstro	Watkins
Dual Command Destruct Components	*1*	Loral	Aydin Vector

Name/Description	*Quantity*	*Vendor #1*	*Vendor #2*
Ordnance Components			
Explosive Bolts, Hold-Down	*4*	Explosive Technology	
Tank Destruct Charge, Stg 1	*1*	Explosive Technology	
Tank Destruct Charge, Stg 2	*1*	Explosive Technology	
Safe & Arm CD	*1*	Quantic	
Safe & Arm Standard Ordnance	*1*	Quantic	
TLX	*1*	Explosive Technology	
Miscellaneous support			
Cabling, Connectors	*1*	Deutsch	
Mounting Hardware	*1*	PacAstro	
Batteries	*4*	Catalyst	
Plumbing	*1*		
Electronics	*1*		

First Stage Tank & Engine

Name/Description	*Quantity*	*Vendor #1*	*Vendor #2*
Tank			
Fuel / Ox Tanks	*2*	Brown Tank	numerous
High Pressure Storage	*12*	SCI	numerous
Engine			
Chamber	*1*	TRW	PacAstro
Injector	*1*	TRW	PacAstro
Ablative Liner	*1*	TRW	Marquardt
Actuators & Servo Valves	*2*	Dyvalve	Parker
Thrust Chamber Gimbal Hardware			
Valves			
Main Propellant	*2*	Flodyne	
Gas Regulator Subsystem	*2*	PacAstro	
Venturies	*2*	Fox	
Fill and Drain	*2*	Flodyne	
Vent	*2*	Flodyne	
Misc.	*1*		
Sensors			
Pressure	*5*	Sensometrics	
Temperature	*3*		
Accelerometers	*3*		
Misc.	*1*		
Fairing	*1*	SSC	PacAstro
Propellants	*1*		

Second Stage Tank & Engine

Name/Description	*Quantity*	*Vendor #1*	*Vendor #2*
Tank			
Fuel / Ox Tanks	*2*	Brown Tank	numerous
High Pressure Storage	*12*	SCI	numerous
Engine			
Chamber	*1*	TRW	PacAstro
Injector	*1*	TRW	PacAstro
Ablative Liner	*1*	TRW	Marquardt
Actuators & Servo Valves	*2*	Dyvalve	Parker
Thrust Chamber Gimbal Hardware			
Valves			
Main Propellant	*2*	Flodyne	
Gas Regulator Subsystem	*2*	PacAstro	
Venturies	*2*	Fox	
Fill and Drain	*2*	Flodyne	
Vent	*2*	Flodyne	
Misc.	*1*		
Sensors			
Pressure	*5*	Sensometrics	
Temperature	*3*		
Accelerometers	*3*		
Misc.	*1*		
Fairing	*1*	SSC	PacAstro
Propellants	*1*		

Figure 1 shows a test configuration of the TRW engine which will be thrust-scaled to the PacAstro engines. This engine has already been successfully thrust-scaled and tested over wide ranges, 8.9 kN, 73 kN, 220 kN, and 1100 kN, bounding the PacAstro thrust levels of 310 kN and 38 kN. The TRW engines are derived from the Apollo Lunar Module Descent Engine (LMDE) which achieved a 100 percent flight success rate in descent, soft landing and ascent from the lunar surface, and returned the Apollo 13 crew to Earth when the main on board propulsion system failed. The coaxial pintle injection of these engines makes them inherently stable. They have been subjected to extensive combustion stability tests including bomb tests and have never exhibited combustion instability with either LOX/RP-1 or LOX/LH$_2$ propellant. They have exhibited soft starts and shut-downs in hundreds of firings. In off-nominal tests the engines have operated stably at 60 percent flow rates and oxidizer/fuel ratios from 25 percent below to 79 percent above nominal. The successful ablative cooling of these engines, made possible by low chamber pressures, has been demonstrated repeatedly. For example, one ablative cooled pintle tip successfully withstood 31 starts. The engines have consistently demonstrated characteristic velocity efficiencies ($\eta_c{}^*$) of greater than 95 percent, with measurements as high as 100 percent.

Payload Envelope and Vehicle Profile:

Sharing flights among two or three payloads is a highly effective way to lower launch costs. A major obstacle to shared flights on existing small vehicles is their small diameter. This forces stacking of the satellites, imposing stringent structural requirements on them, or necessitating a carrier which decreases available payload mass and volume capability. The liquid propellant vehicle naturally tends to be of larger diameter and a PacAstro outer diameter of 1.6 meters, over 50% wider than other small vehicles, was selected to enable two, three, four or more payloads to be launched from a common interface plate, as shown in Figure 2. This packaging philosophy has been proven simple and reliable on the Ariane secondary payload accommodation.

Vehicle Description and Performance:

The PacAstro vehicle principle design data are listed in Table 5 and the vehicle is shown in Figure 2. The available payload volume is 3.25 m^3.

Table 5. Vehicle Description and Performance

parameter	stage 1	stage 2	total
inside diameter (meters)	1.5	1.5	
height (meters)	12.6 (includes inter-stage)	9.5 (includes 2.4 m payload height)	22.1
delta-V (m/sec)	2670	7040	9710
I_{sp} (sec)	sea-level: 247 vacuum: 279	vacuum: 323	
fuel	LOX / RP-1	LOX / RP-1	
chamber pressure(Pa)	$1.7x10^6$	$8.8x10^5$	
burn time (sec)	126	428	
thrust/weight	1.31	0.67	
exit velocity (m/sec)	2420	3040	
throat area (m^2)	0.132	0.023	
exit area (m^2)	0.407	0.924	
mass flow rate (kg/sec)	129	12.0	

The first stage uses a single, gimbaled 310 kN thrust engine and the second stage uses a single 38 kN engine. Both stages use some of the pressurant helium for roll control. The propellant tanks are welded aluminum. Using the first stage for example, their wall thickness is 10 mm which allows the tank to be easily manufactured, to carry the design pressure load of 2.7 MPa with large margin, and to transmit structural loads through the vehicle. There are no major structure elements in the vehicle besides the four propellant tanks and cylindrical skirts. This reduces both the number of parts and the labor of vehicle assembly and integration.

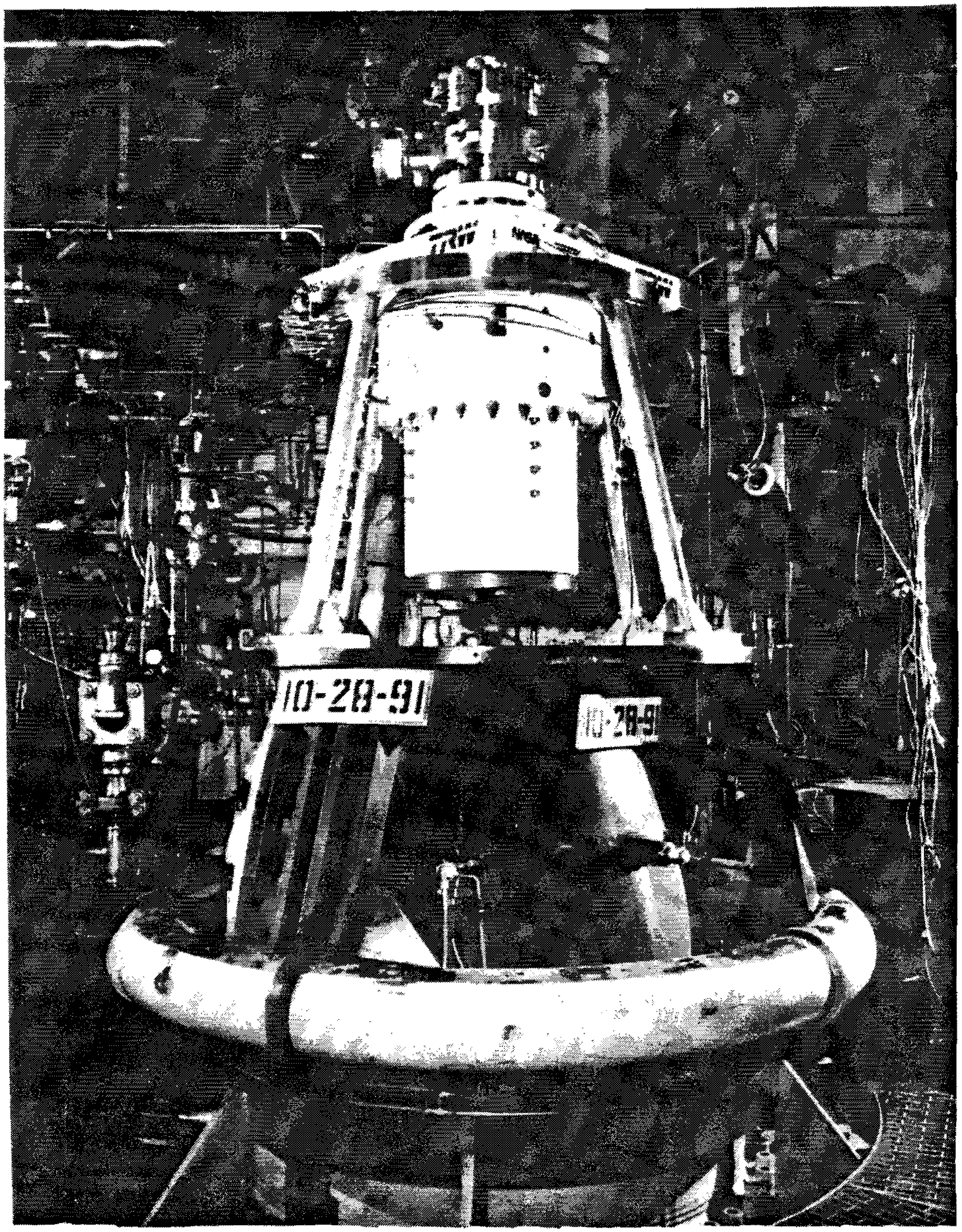


Figure 1. TRW Liquid Propellant Engine in Test Fixture
The TRW engines used by PacAstro have flight-proven heritage with inherently stable axial injection. TRW also brings its unsurpassed technical skills to the PacAstro team.

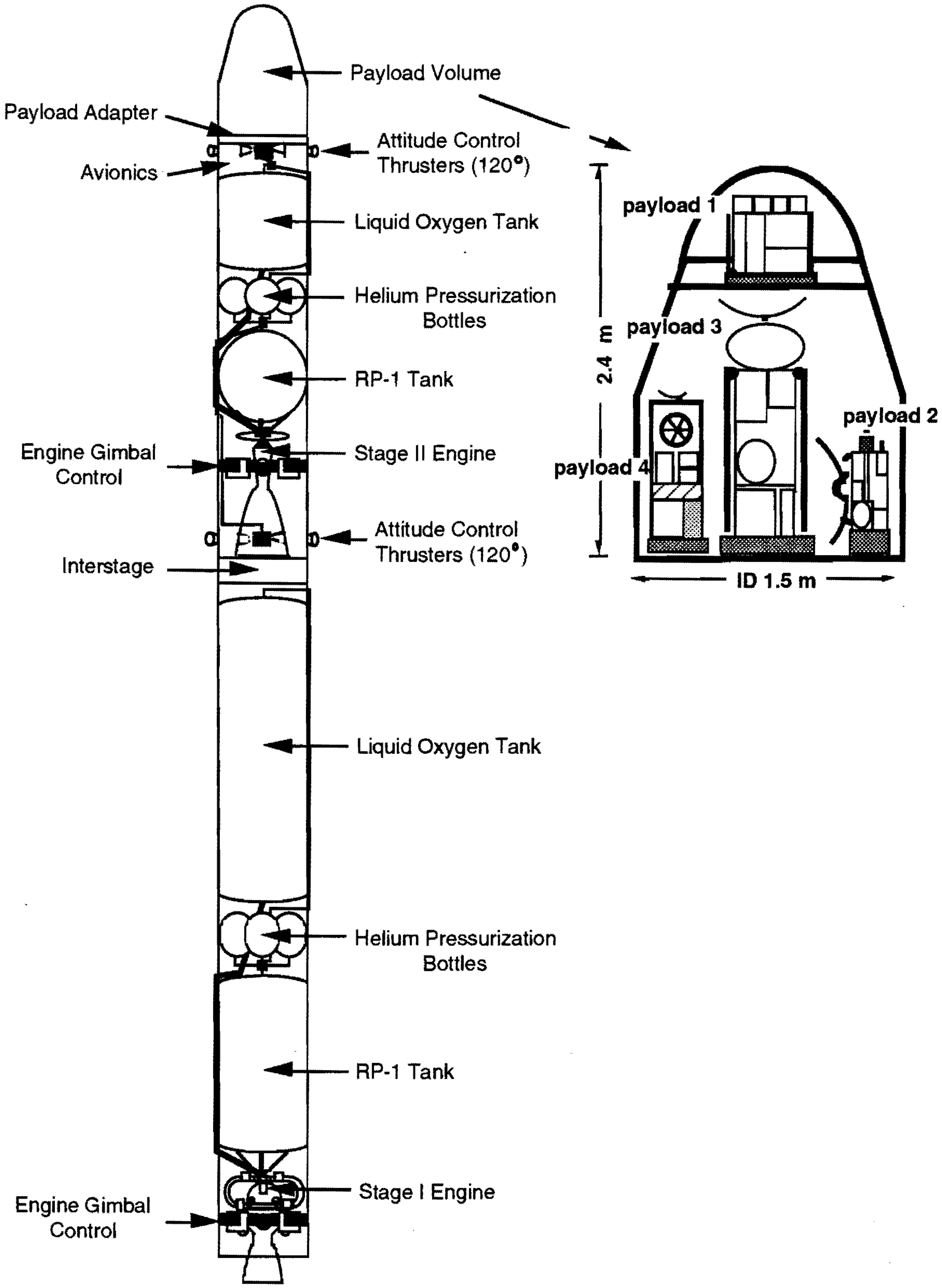


Figure 2. PacAstro Launch Vehicle

Figure 3 illustrates the performance of the vehicle. Using a first stage of 18,570 kg that includes 16,250 kg of propellant, and a second stage (including payload) of 5740 kg that includes 5120 kg of propellant, the vehicle will carry a payload of 227 kg to a 1200 km circular orbit from a low-latitude launch site with due-east launch or to a circular polar 750 km altitude orbit from a 69° latitude launch site.

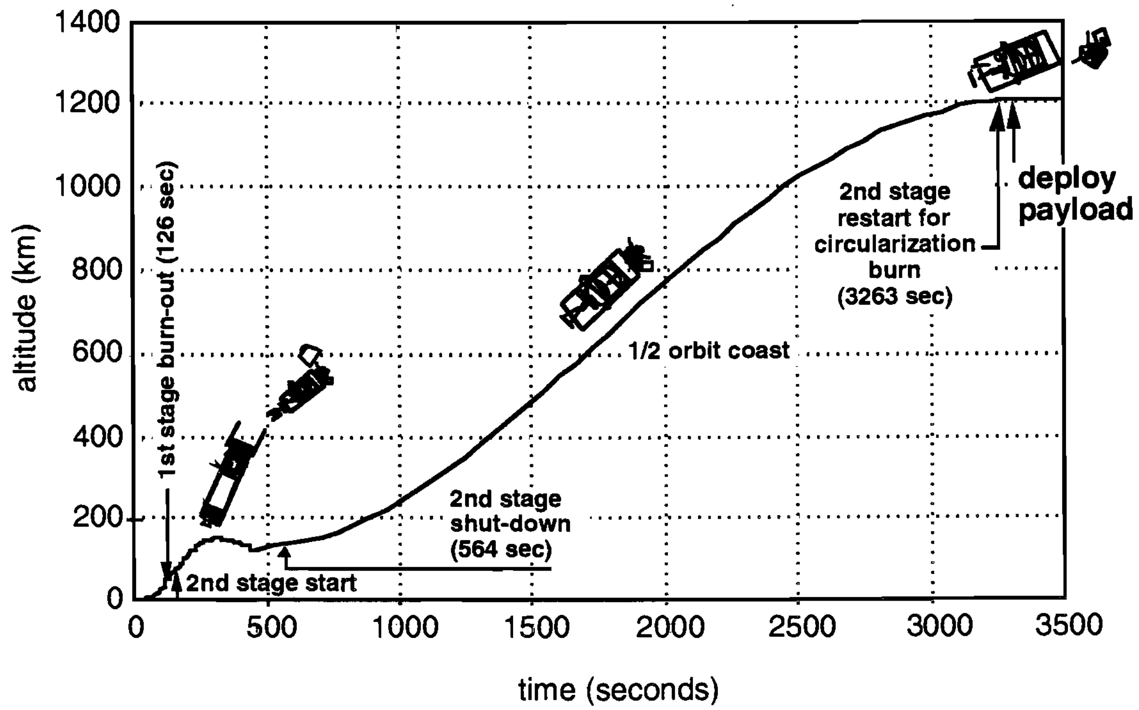


Figure 3. PacAstro Due-East Orbit Delivery Capability for 227 kg Payload from Low-Latitude Launch Site

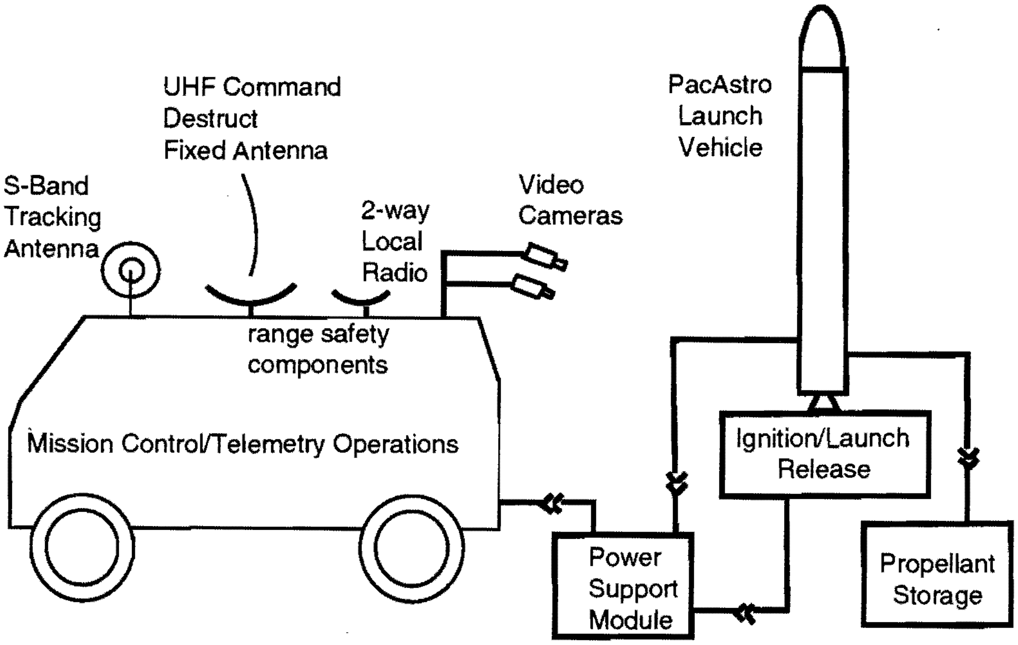
The PacAstro vehicle can use two burns of the second stage to achieve a 1200 km circular orbit launching from a low-latitude site, or a 750 km circular polar orbit from a 69° latitude site.

The trajectory and timing strategy exploits the ability of liquid propellant engines to shut-down and restart. This feature allows the vehicle to fly to the perigee of an elliptic 125 km x 1200 km orbit, then shut down and coast half an orbit to apogee, then restart to perform a short burn to circularize at 1200 km. This highly efficient orbit transfer uses a simple Hohmann transfer to low earth orbit using the Earth's gravity to assist orbit raising, rather than fighting Earth's gravity as is common in high angle of attack trajectories used in vehicles without restart capability (e.g. solids). This technique has been used successfully for many years, and was most recently employed by the Russian SL-14 Cyclone's third stage to deliver the Meteor-3 satellite to a 1200 km altitude circular orbit. The reliability of the second stage restart is much higher than the complication of an additional stage. Restart does not present substantial additional risk or complexity, however an additional stage would require additional hardware, development and complexity. Further, the restart maneuver is managed in software so that it can be tailored or removed depending on mission payload and orbit requirements. A dedicated additional stage does not have this flexibility and therefore is a burden which must be carried in every mission.

While PacAstro engineers are responsible for vehicle systems engineering and performance analysis, the extensive experience in these areas of both TRW and SSC is benefiting the PacAstro vehicle in several ways. First, these team members are supplying design and analysis tools to supplement and verify those already developed by PacAstro for vehicle optimization, performance evaluation, and orbit insertion. Second, TRW and SSC personnel are available to PacAstro for specific technical assistance when needed. Finally, the space flight experience of TRW and SSC is valuable for internal monitoring of systems engineering tasks.

Telemetry and Control Systems:

The telemetry and control system uses flight-proven components. We take advantage of the power and storage capability of modern digital systems to minimize the number of discrete components and provide some vehicle autonomy. This allows the flight path to be controlled from a single ground terminal located at the launch site (Figure 4).



All required telemetry systems can be supplied to the launch site in a single mobile van. Other required services are readily available at all existing launch sites.

Figure 4 PacAstro Ground Operations Components

Achieving circular orbit and other maneuvers executed out of range of the ground station are managed without ground interaction. In fact the only ground control operations required during launch and ascent are monitoring for range safety and data recording for post launch vehicle performance analysis. Like many small satellites, the vehicle carries a digital store and forward system to relay its performance data back to the launch site from orbit during the subsequent passes.

PacAstro team members AeroAstro and SSC have extensive and complimentary ground station experience. AeroAstro designs and supplies ground stations for small satellites. SSC operates several ground stations at its Esrange Space Operations Center for range safety, vehicle tracking, and satellite tracking (Figure 5). While procedures at Esrange are not identical to those at US launch sites, there are many hardware and procedural similarities which benefit PacAstro.

The guidance and control strategy exploits simple, robust, proven, and readily available components. Guidance information for each stage is provided by three orthogonal inertial measurement units (IMUs)/gyroscopes, for attitude information. A GPS receiver, such as those developed by Trimble Navigation and successfully used in launch, supplies ephemeris information.

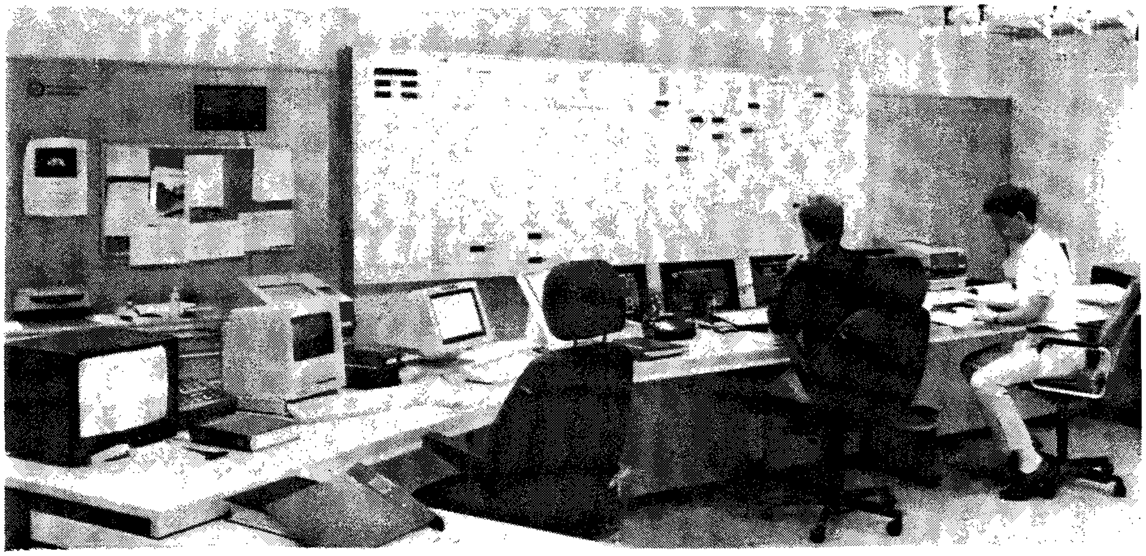


Figure 5. SSC Telemetry Station

Control torques about the pitch and yaw axes of each stage are provided by gimbaling the main thrust nozzle. This reliable actuation strategy does not significantly reduce thrust or specific impulse, is weight competitive with other mechanical methods, and does not impart large side-forces to the vehicle structure. The gimbaling is implemented using simple, reliable flex hinges and translational hydraulic actuators in a cross configuration. The cross structure also provides transverse support for the engine assembly. Roll control for both stages is provided by bleeding the helium pressurant.

Helium thrusters also provide yaw and pitch control during the coast phase of the elliptic transfer orbit. These thrusters are used to rotate the vehicle 180° about a transverse axis during coast so the second stage engine can circularize to the final orbit upon restart. The equilateral-triangle thruster placement shown in Figure 2 is the minimum-thruster design that effects pure moments even with any single thruster failure.

An essential part of any guidance and control strategy is dynamic environment and disturbance characterization. For example, wind disturbances on launch can be catastrophic if not properly considered in designing the guidance and control logic, especially winds aloft which are less-easily characterized, difficult to measure, and more severe than low altitude winds. PacAstro benefits from SSC technical monitoring and disturbance characterization based on decades of successful sounding rocket launch experience (Figure 6). SSC launches resemble PacAstro's in that a 225 kg class payload is carried to altitudes as high as 900 km.

Integration and Test:

PacAstro minimizes development testing by using proven components for all major vehicle systems and many subsystems. Use of only two stages and stage similarity also lowers development cost considerably. Lower development cost means significantly lower per-launch cost since recovery of development cost is typically a significant percentage of per-launch cost for commercial launch vehicles. PacAstro launch costs are computed conservatively assuming a very low launch rate (1 per year). They do not assume nor depend upon achievement of very high launch rates.

The design simplicity and modularity of the PacAstro vehicle minimizes recurring integration costs. For example, structural components are minimized by placing the propellant tanks in the critical load path and using them as the vehicle wall (with spray-on aluminized or pyrex ablative external insulation). While this necessitates heavier tanks, the overall vehicle cost is lowered while maintaining the performance goal of placing a 225 kg class payload in a 750 km circular polar orbit. The two-stage to orbit design, enabled by the restart capability of liquid propellant engines, lowers integration costs by tens of percent from a three or four stage vehicle.

PacAstro can draw on the comprehensive capabilities and experience of SSC and TRW for remaining development tests, qualification tests, and integration. TRW has relevant experience in all vehicle subsystems, including payload integration and, most importantly, liquid propulsion systems. Much of the testing of the TRW engines, which have flight-proven heritage, is already complete. A successful test sequence using LOX/LH_2 propellant is shown in Figure 7. The same engines have been tested and proven stable using LOX/RP-1.

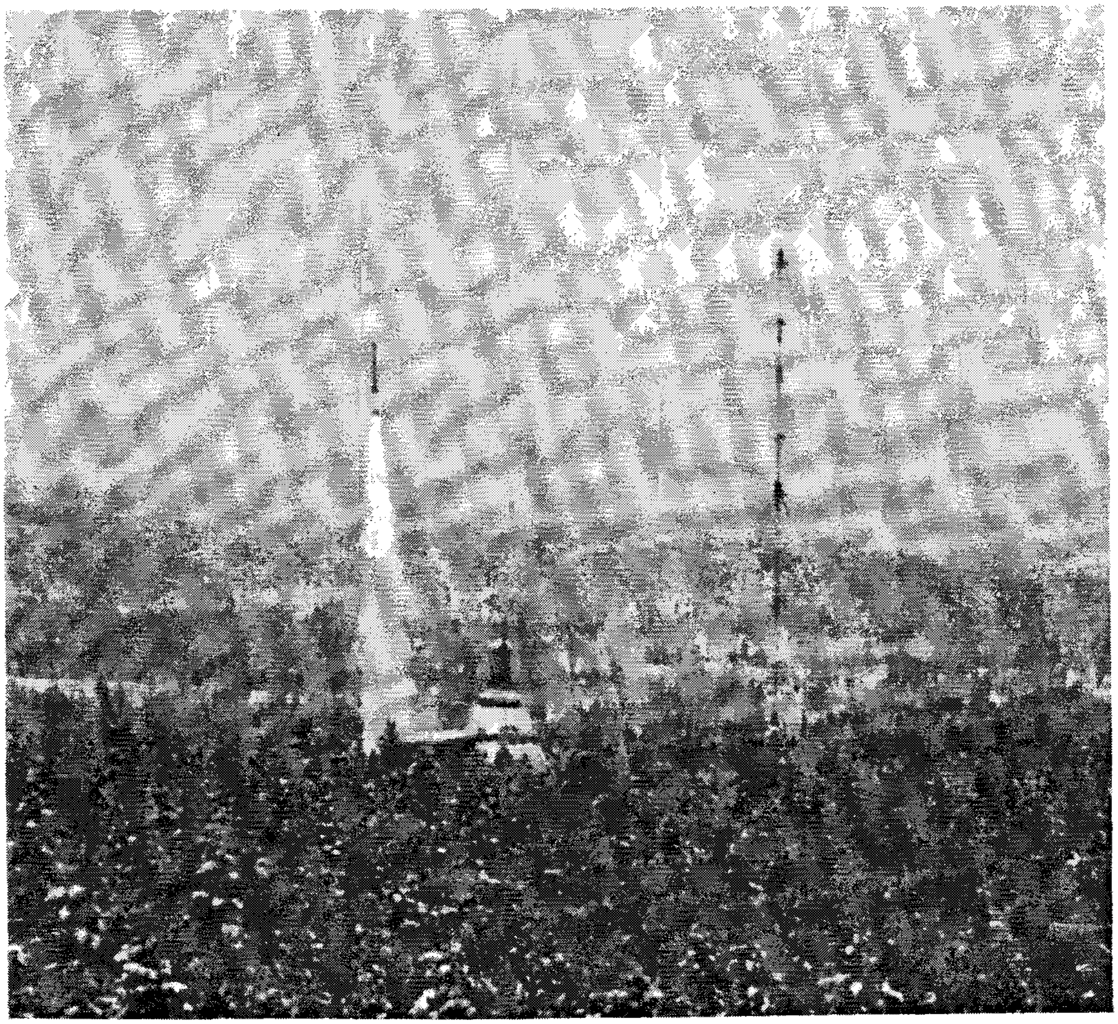
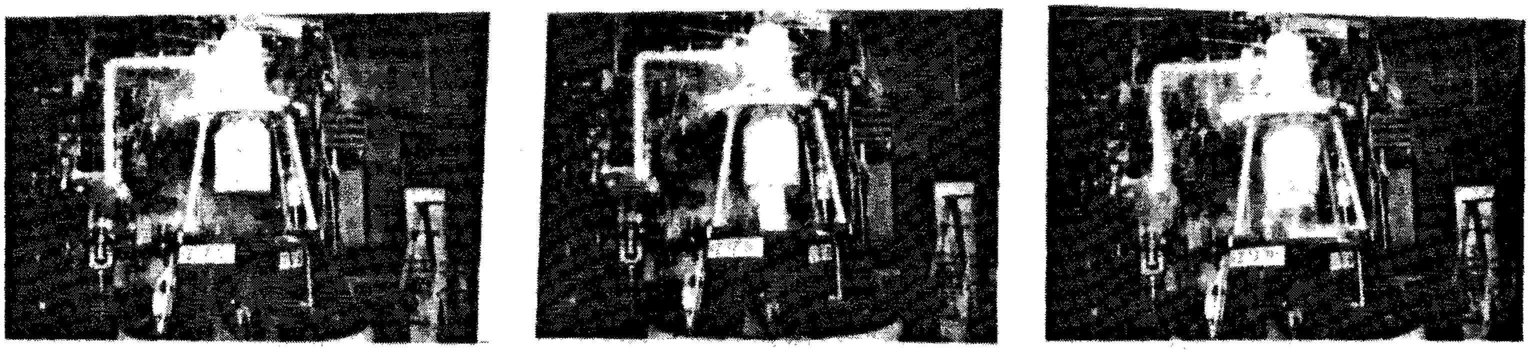
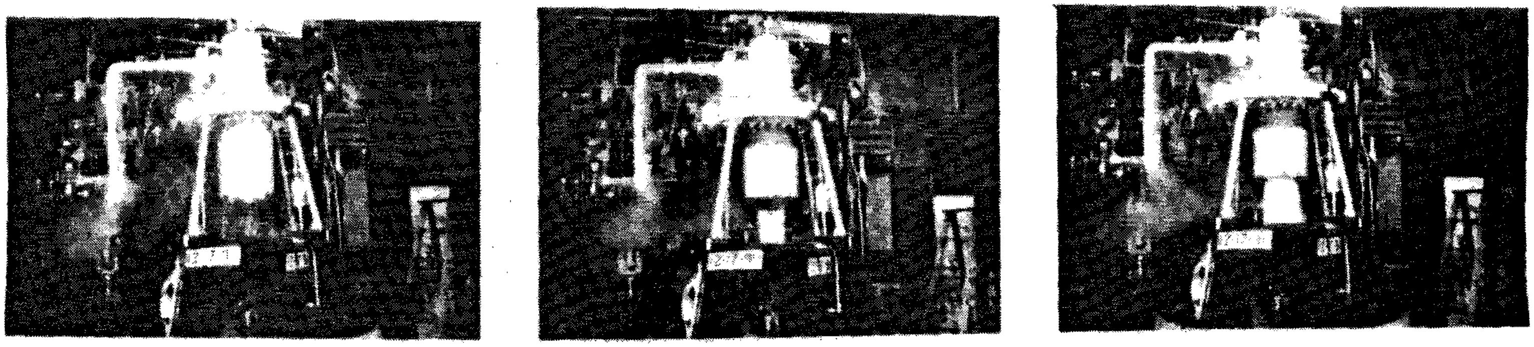


Figure 6. SSC Sounding Rocket Launch from Esrange Space Operations Center

Swedish Space Corporation brings extensive launch and ground operations experience to the PacAstro team



Pretest **Start-up** **100% Thrust**



100% Thrust **Shut-down** **GH_e Purge**

Figure 7. TRW Engine Test Sequence using LOX/LH_2
The same engines have been tested successfully
and proven stable using LOX/RP-1

SSC also has relevant subsystem capabilities and extensive experience integrating payloads and integrating and testing launch vehicles approaching the
size of the PacAstro vehicle. SSC test and integration activities are shown in Figure 8 for the MASER, a medium-sized SSC sounding rocket.

Use of existing TRW and SSC integration and test equipment and procedures enables PacAstro to reduce cost. PacAstro plans to further reduce test and integration costs by using government furnished equipment and government furnished facilities whenever possible.

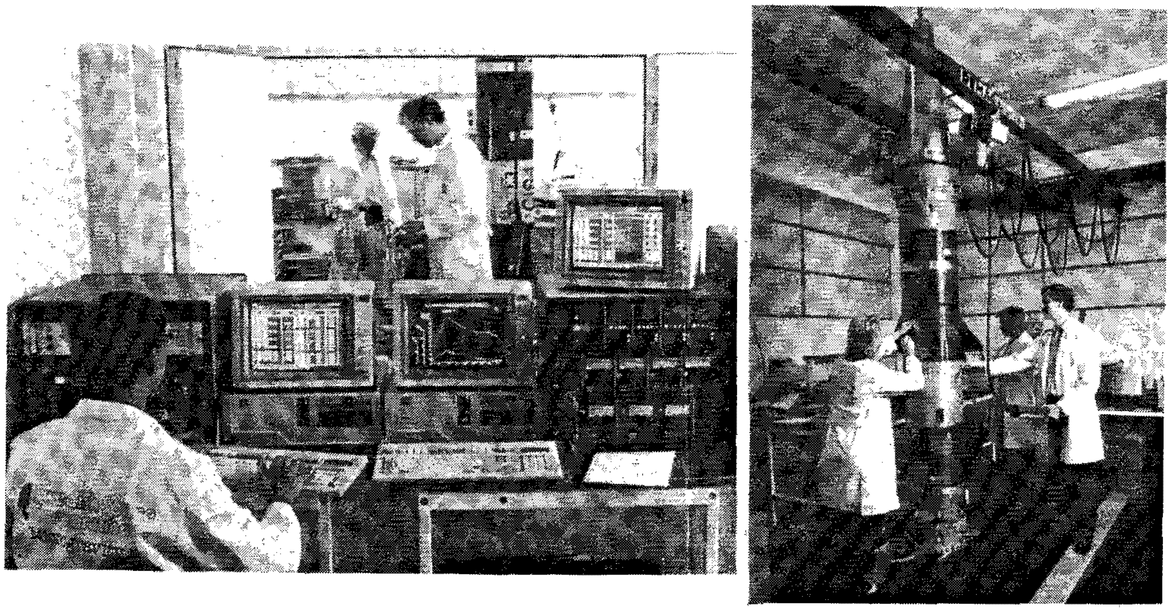


Figure 8. SSC Sounding Rocket Integration and Test

Ground and Launch Site Operations:
PacAstro's liquid propellant design enables the vehicle to be launched from almost any existing or proposed site, including Wallops Island, ETR, WTR, Hawaii, SSC's Esrange launch center in northern Sweden, and the Norwegian Space Center's Andøya launch site. The advantages of liquid propellants in lowering cost and reducing risk for transport, handling, and procurement have been discussed in the section on propellant (see above). The PacAstro vehicle is small and safe enough to be transported in two semi-trailers, in an Air Force C-141 or larger transport, or by ship.

The PacAstro team has the advantage of SSC's experience in carrying out all phases of launch vehicle ground operations, starting in the early 1960s. This experience includes design, manufacturing, and procurement of test, facilities, and launch equipment, transportation, range integration, safety, and support, media support and equipment, and launch operations. SSC's extensive capabilities in these areas are partially indicated by the overview of the Esrange Space Operations Center shown in Figure 9. While not all Esrange operations are common to US launch sites, there is considerable overlap and SSC support will be available regardless of launch site. TRW's significant ground and launch operations experience will also benefit PacAstro.

Figure 9. SSC Esrange Space Operations Center

Management Approach:
The PacAstro team has the dedication, low overhead, and responsiveness of a smaller, innovative company backed up by the resources and experience of larger organizations.

PacAstro achieves high performance with low cost by operating in a "skunk-works" atmosphere. The success of this approach is evidenced by many celebrated examples including the early Saturn booster program, the SR-71 aircraft, and the Apollo guidance and control system. More recently PacAstro's sister company, AeroAstro, has achieved recognized success with this approach, and PacAstro enjoys the same management and systems engineering personnel as AeroAstro.

Concurrently, PacAstro has the extensive technical knowledge, material resources, and experience of TRW and SSC to draw upon whenever necessary. TRW and SSC also provide internal technical oversight of the PacAstro vehicle, support equipment, and ground, launch, and flight operations.

Cost Estimation:
Estimates of the project development costs were developed together with a project milestone schedule. The schedule was used to identify critical milestones that must be met in order to launch within three years of program start. Project staffing, hardware and infrastructure requirements were then developed to meet these milestones. These costs were developed from research on similar systems and with vendors of all principle and many lower tier components (Table 6). Component and subsystem manufacturing are included in the material costs using commercially available components. A staff of 17 engineers and technicians were assumed in developing the recurring costs as summarized in Table 7. The resulting cost per launch is $5 M in 1992 dollars.

Table 6. Principal Material Component Costs

Propulsion and Structure			Avionics and Ground Support	
	1st Stage	2nd Stage		
Tanks	$162,000	$80,400	Computer	$37,300
Engine	$117,000	$93,500	IMU	$80,000
Valves	$83,000	$78,000	Telemetry	$44,000
Sensors	$9,000	$9,000	Ordnance	$17,800
Fairing	$20,000	$20,000	Gnd. Sup. & Misc.	$75,800
Fuel	$20,000	$10,000		
Total	$411,000	$290,900	Total	$254,900

Table 7. Recurring Costs

Direct Labor	16%
Materials	38%
Contingency	22%
Overhead Support	24%
Total	100%

Part III: Development Plan

Beginning with a small amount of seed money, PacAstro developed the technical approach, the cost models and the market strategy which were assembled into a business plan (Figure 10). PacAstro then concentrated its efforts on introducing the project and the business plan to various investors and investment groups. During this phase several investors agreed to provide the funds required to complete the first design phase and undertake the major marketing effort required to sign on new customers. During the present phase, key customers are being approached, progress continues with subsystem definition, and we are seeking the next round of financing to build and launch the first three rockets.

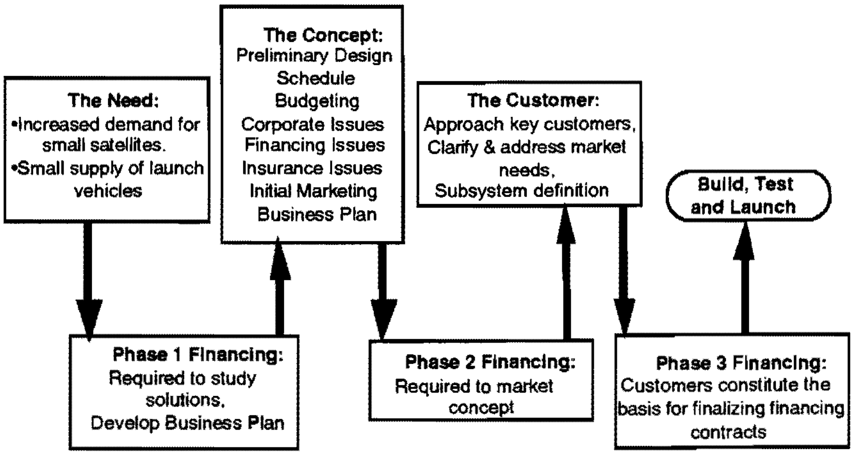


Figure 10. PacAstro Project Phasing

Summary and Conclusions

Table 8 summarizes the principal advantages provided by the PacAstro vehicle for launch of small satellites.

Table 8. PacAstro Launch System Key Advantages

Advantage	Description
Low Cost	$5M: 225 kg to 750 km polar circular
Strong Experienced Team	AeroAstro, TRW, Swedish Space Corp.
Available, Proven Components	All major components of-the-shelf; Tested TRW engines: robust, excellent performance
Proven Technology	Exploits 30-year old liquid engine heritage; Near-term realizable; low risk
Only Two Stages	Reduces system complexity, and testing, insurance, and integration costs
Prudent Alternative	Ground launched, liquid fueled launch option for national security
Wide Payload Volume	Accommodates multiple side-by-side payloads
Precise Orbit Insertion	Engines can be throttled or shut-down
Soft Ride	Less severe vibration/acoustic environment than solids eases satellite load requirements
Engine Shut Down Capability	Safe: for testing and for stage 1 lift-off
Engine Restart Capability	Affords efficient Hohmann transfer insertion
Pressure-Fed Engines	Less complex and more reliable than pump-fed; No development required
Ground Launch	Easily accessed, low risk
Environmentally Safe	Exhaust is water and CO2

Conclusions: PacAstro's goal is to increase space access availability for small payloads by using proven components in a launch vehicle optimized for low-cost and reliability. To this end PacAstro is producing a two-stage, pressure-fed liquid propellant vehicle capable of transporting a 225 kg (500 lbm) class payload to 750 km (400 nm) circular polar orbit for $5 M per launch. The PacAstro team, including AeroAstro, TRW and Swedish Space Corporation, has considerable hardware and launch experience and the vehicle uses proven components for all major elements. The PacAstro vehicle is an important alternative to existing and proposed air and ground launched solid propellant vehicles in this class, which are more costly and hold greater risk due to man rating, more stages, and the inherent hazards and mission inflexibilities of solid propellants. PacAstro's liquid propellants offer a softer ride, more precise orbit insertion, shut-down capability for safer testing and launch operations, and restart capability which allows only one critical stage.