# Mini Literature Review on Aquilla Launch

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# Flight Breakdown [1]

**Breakdown of flight**

- pre-programmed pitch-yaw angle phase to minimize aerodynamic loads.
- maximum dynamic pressure condition of 990 psf occurs at 55 seconds into the flight.
- end of first stage burn, first stage separation occurs new pre-programmed pitch profile is initiated.
- third stage burn during which the payload fairing is jettisoned from the vehicle
- a coast phase is initiated
- fourth stage burn, closed-loop guidance and control system guides to intermediate transfer orbit of 100 x 270 nm
- On attaining the 100 X270 intermediate transfer orbit, the fourth stage is shutdown At apogee. The fourth stage is restarted and circularizes the orbit into a 270 nmi circular orbii.
- Guidance, Navigation and Control (GNC) system is able to guarantee three-sigma inclination angle accuracy to 0.20" with a commercial Inertial Navigation Unit (INU)

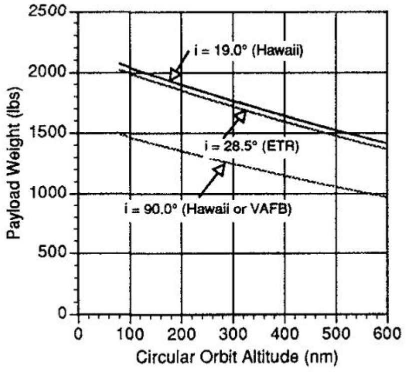
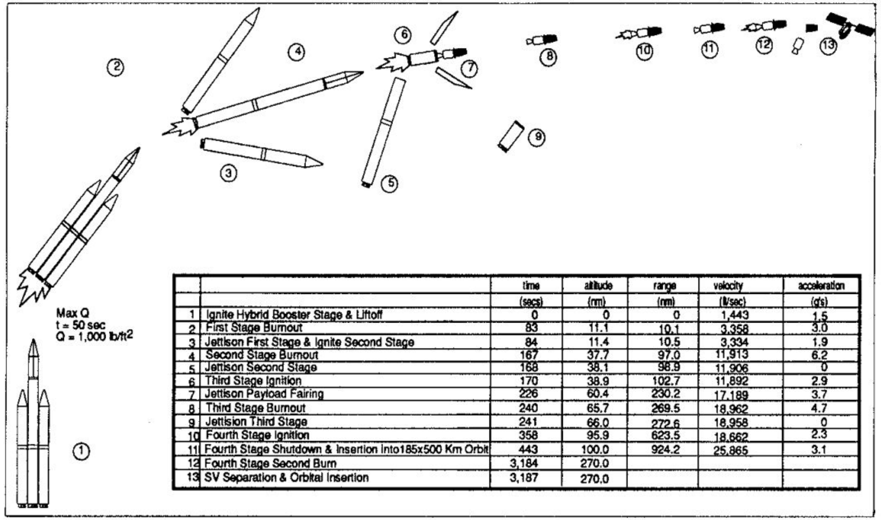



Figure 4 - Parking Orbit Ascent Performance




| | | time (secs) | altitude (nm) | range (nm) | velocity (ft/sec) | acceleration (g's) |
|---|---|---|---|---|---|---|
| 1 | Ignite Hybrid Booster Stage & Liftoff | 0 | 0 | 0 | 1,443 | 1.5 |
| 2 | First Stage Burnout | 83 | 11.1 | 10.1 | 3,358 | 3.0 |
| 3 | Jettison First Stage & Ignite Second Stage | 84 | 11.4 | 10.5 | 3,334 | 1.9 |
| 4 | Second Stage Burnout | 167 | 37.7 | 97.0 | 11,913 | 6.2 |
| 5 | Jettison Second Stage | 168 | 38.1 | 98.9 | 11,906 | 0 |
| 6 | Third Stage Ignition | 170 | 38.9 | 102.7 | 11,892 | 2.9 |
| 7 | Jettison Payload Fairing | 226 | 60.4 | 230.2 | 17,189 | 3.7 |
| 8 | Third Stage Burnout | 240 | 65.7 | 269.5 | 18,962 | 4.7 |
| 9 | Jettision Third Stage | 241 | 66.0 | 272.6 | 18,958 | 0 |
| 10 | Fourth Stage Ignition | 358 | 95.9 | 623.5 | 18,662 | 2.3 |
| 11 | Fourth Stage Shutdown & Insertion Into185x500 Km Orbit | 443 | 100.0 | 924.2 | 25,865 | 3.1 |
| 12 | Fourth Stage Second Burn | 3,184 | 270.0 | | | |
| 13 | SV Separation & Orbital Insertion | 3,187 | 270.0 | | | |

Figure 5 - Aquila Nominal Mission Profile

# Key Ideas [1]

- American Rocket Company's (AMROC)  low-cost hybrid propulsion to deliver **2,000 pound payloads** into low Earth orbit
- **inert solid polybutadiene fuel** and either **liquid oxygen** or **nitrous oxide** as **oxidizer**
- The **hybrid has several advantages** over conventional solid and liquid systems: (1) **non-explosive** and non-toxic propellants; (2) **clean exhaust** products which do not include hydrogen chlorides; (3) **controllable staWstop and full throttling capability;** (4) **lower development and production costs**; and (5) **enhanced manufacturing, ground and flight safety.** The hybrid rocket propulsion system combines the advantages of conventional solid and liquid propulsion, but at a lower cost than either propulsion system.
- The **rate of combustion** of a hybrid is **limited by the flowrate of the oxidizer over the fuel surface**. Thus by throttling the flow the **thrust is modulated**
- **liquid rocket injectors are complex** injectors that require hydraulic matching between the two fluids thereby complicating the injector development, particularly for throttling applications.

# Key ideas [1] cont.

The Aquila launch system

- (1)  **dedicated space launcher** as opposed to riding as a secondary payload on a large expendable launcher
- (2) non-explosive and non-toxic rocket **safe**
- (3) **restartable upper stage** for trajectory shaping, precise orbital placement, and mission flexibility;
- (4) **late payload access** a few hours prior to launch;
- (5) a benign payload environment; **extra safe**
- (6) **on-pad launch abort capability** in the event of a launch malfunction:
- (7) on-demand, high flight rate launch services.

# Design [1]

**First stage** - Two H-1500 turbopump-fed LOxlHTPB hybrid propulsion systems ( 832 kN)

**Second stage** H-1500 ( 832 kN) vacuum thrust

**Third stage**- U-250 pressure-fed N,O/HTPB hybrid

**Fourth stage**: U-75 pressure-fed N,O/HTPB hybrid propulsion system

**Payload** ( 907 Kg) LEO

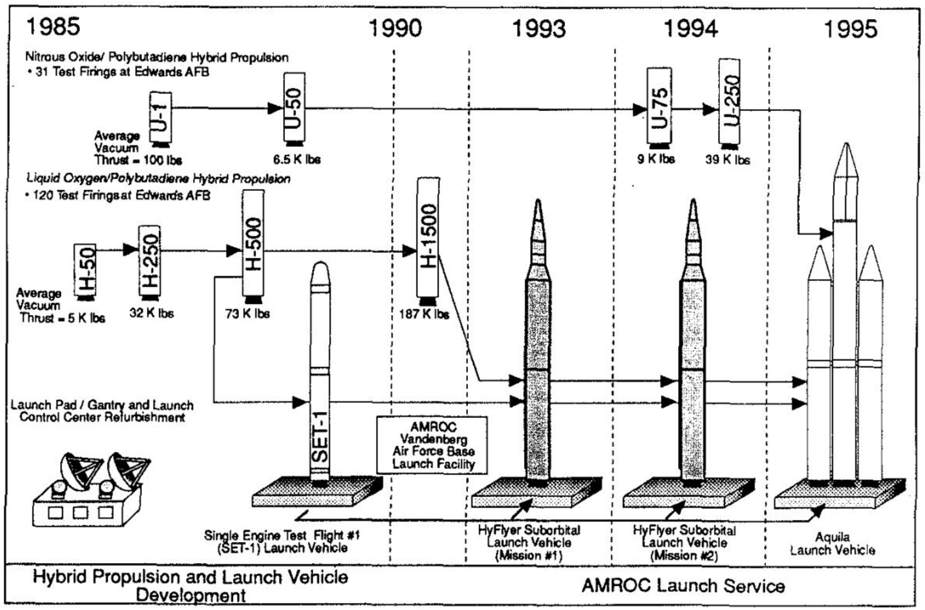



**Figure 1 - AMROC's Experience and Development Plans**

# Performance [1]

- 907 Kg payload to a 100 nautical mile(nmi) circular orbit at a 28.5 degree orbit inclination

- And ( 635Kg ) to a 100 nmi circular orbit at a 90.0 deg orbit inclination.

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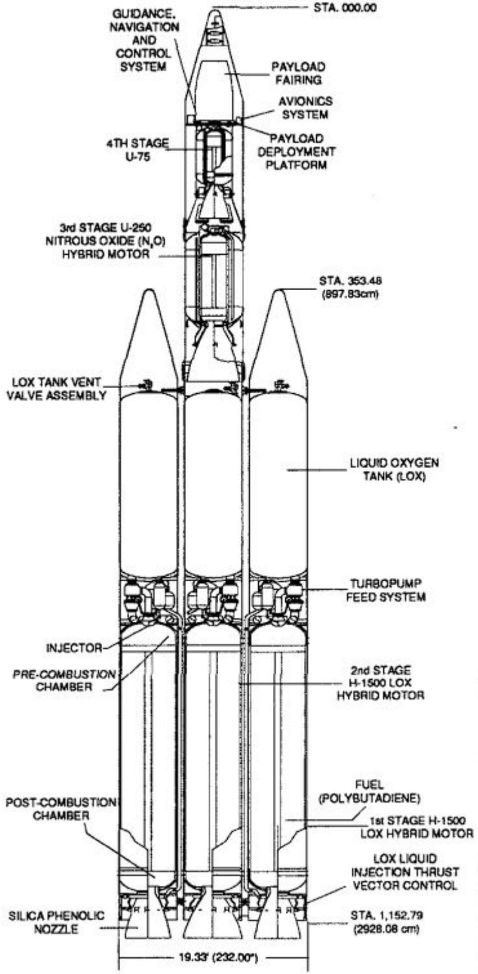


Figure 2 - Aquila Launch Vehicle

# Nozzle

H-1500 nozzle is a one-piece tape-wrapped silica phenolic and glass/phenolic with a diameter of 72 inches, and a motor length of 343 ablative nozzle.

Silica phenolic produces a char layer when exposed to the combustion gases

Glass/Phenolic portion = outer shell of the nozzle which provides the structural support for the nozzle and the Liquid Injection Thrust Vector Control (LITVC) valves

# Internals breakdown [1]

Injector

- H-1500 even distribution of atomized liquid oxygen to the motor integral venturi, shower head-type injector LOX cone shaped spray

Ignition system

- utilizes a pyrophoric liquid, Triethylaluminum (TEAL), which is injected coaxially with the liquid oxygen through the motor injector at motorignition. The TEAL reacts with the LOx causing it to vaporize a layer of fuel on the fuel grain surface.

Oxidizer tank

- H-1500 oxidizer tank is the storage vessel for the LOX

Lox feed/turbopump systems

- feeds and throttles the LOX into the motor injector. 500 Ibm/sec at 750 psia

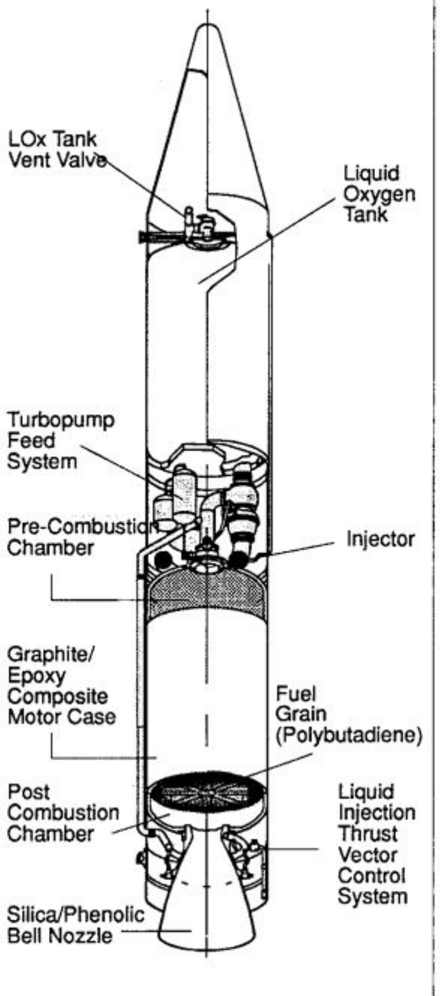


Figure 6 - H-1500 Hybrid Propulsion System

# Upper stage [1]

Throttleable, restartable hybrid propulsion, hybrid upper stages can be used to remove orbital targeting errors from booster ascent and dependably insert payloads into precise orbits.

**Thrust vectoring**
Thrust axis a maximum of 2 degrees using four redundant, digitally controlled valves.

- Six cold gas thrusters fed from the vapor section of the nitrous oxide tank control Roll during upper stage operation and three-axis attitude control during the coast phase prior to fourth stage ignition

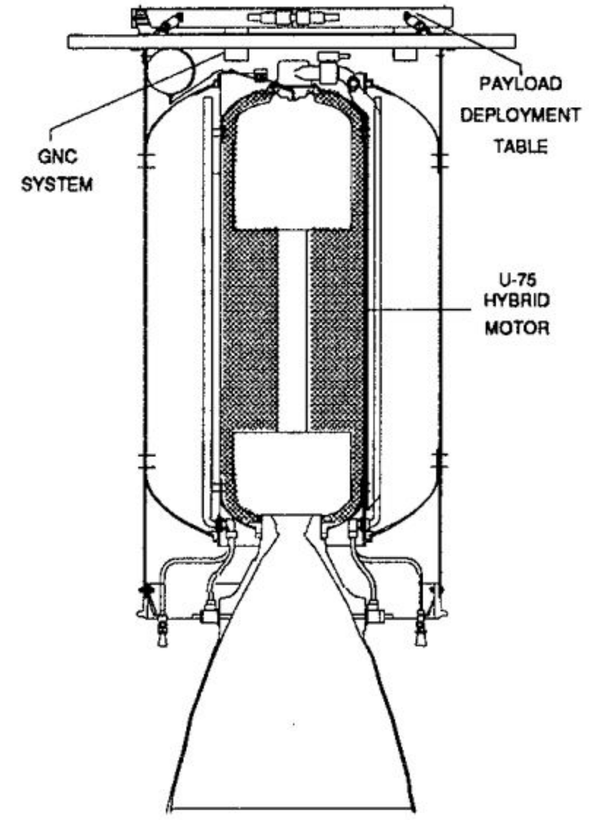



Figure 7 - U-75 Hybrid Upper Stage Propulsion System

# Thrust Vectoring

Liquid Injection Thrust Vector Control (LITVC) or cold gas attitude control during each phase of the flight trajectory.

As well as motor propellant, LOX is used as LITVC injectant fluid.

**LOX** is drawn via turbo pump, fed **into the LITVC** manifold surrounding the nozzle, and distributed to **eight high resolution digital electric LITVC valves** equally spaced around the nozzle. During operation, the **liquid oxygen** is **injected** into the nozzle **approximately 1/3** of the distance **between** the **nozzle throat** and the **nozzle exit plane**. The **injected fluid expands** upon entering the nozzle, creating a **shock wave** in the nozzle, and **imparting a side force** on the nozzle.

Up to 6 degrees at discrete nozzle azimuths for pitch, yaw and roll control

# Block diagram

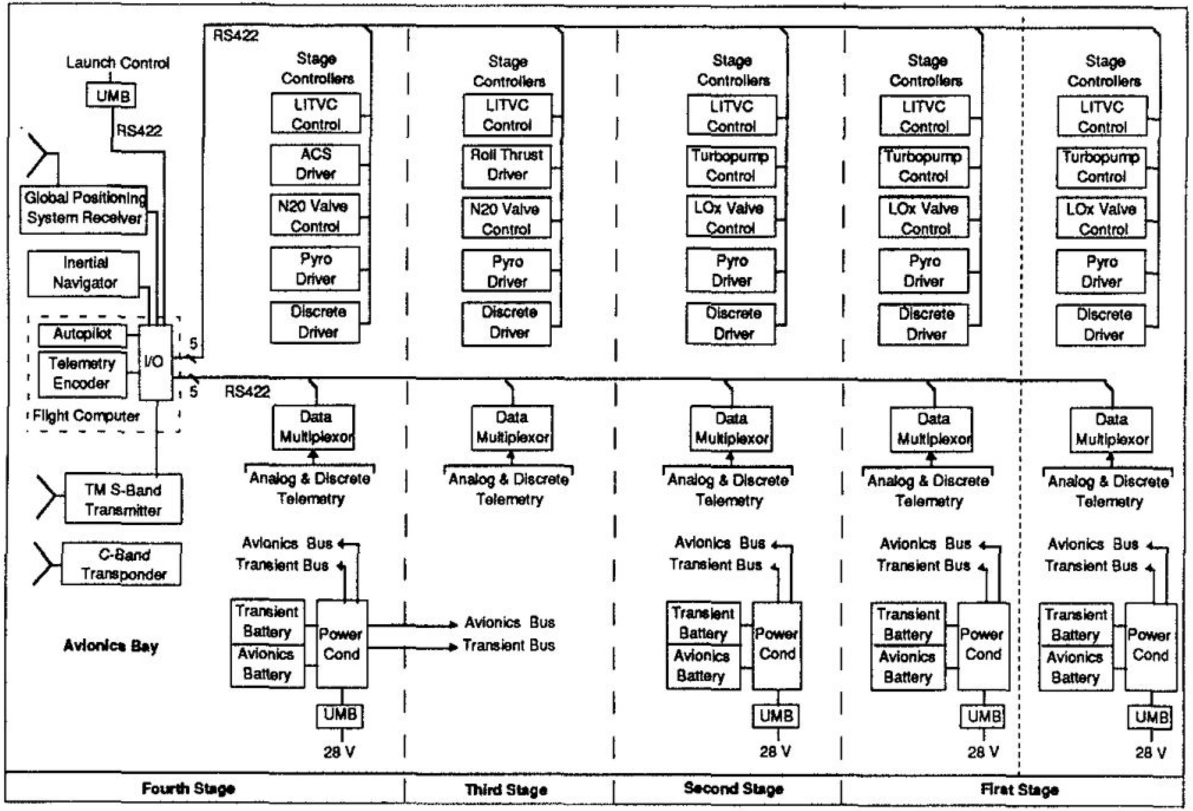



Figure 8 - Aquila Avionics Block Diagram

Other discussed systems

- Guidance, Navigation, Control (GNC)Svstem
- Data acquisition and telemetry (DAT)
- Flight termination (FTS
- Electrical power, conditioning and distribution systems (PCD
- Payload fairing environment.

# Hybrid propulsion system [2]

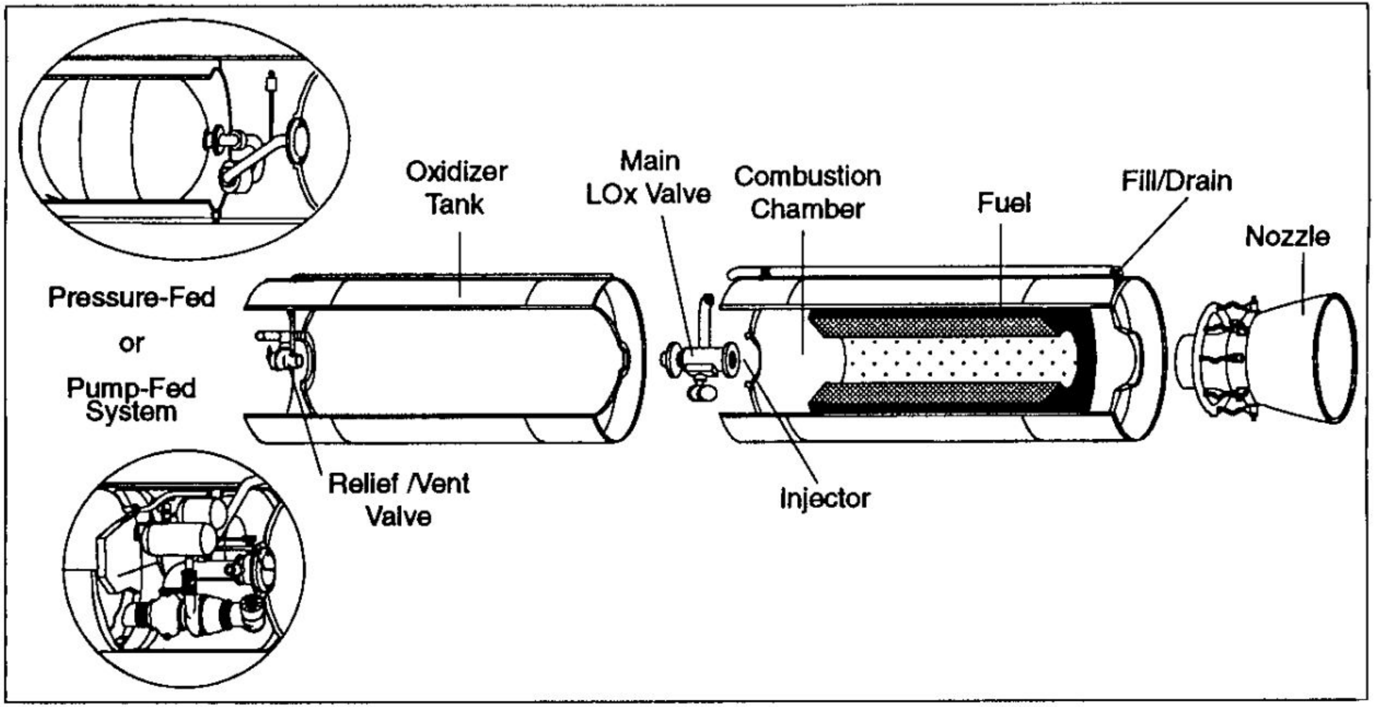
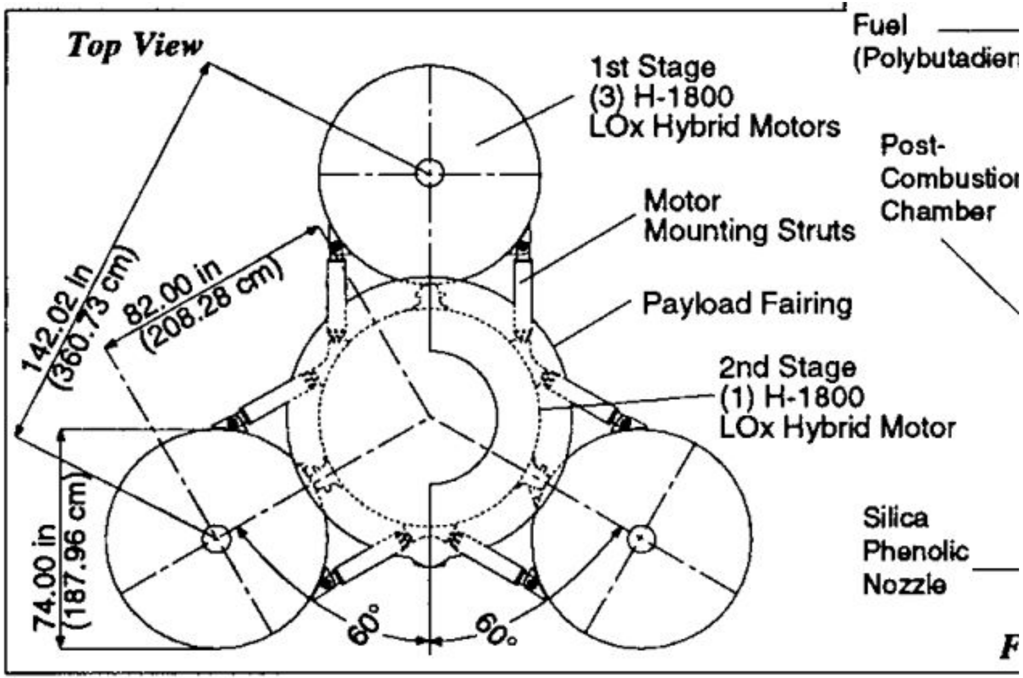



*Figure 2. Hybrid Propulsion System*

The hybrid combustion process is **insensitive** to **minor grain de-bonds and cracks** because the hybrid combustion actually **occurs** in a **flame zone near** the surface. If a crack exists, the **oxidizer and fuel mixture ratio** will be such that it is fuel rich thus the **rate of combustion is very slow reducing** the **potential** of a **burn through** to **the motor case**

# Launch vehicle

Four-stage - hybrid-propulsion-based launch vehicle capable of delivering up to 3,200 lb, (1,450 kg) payloads into a 100 nmi (185 km) circular orbit at a 90 degree inclination



# Hybrid system

H-1800 motor

- graphite/epoxy composite case
- Polybutadiene fuel Grain

| Item | 1st Stage | 2nd Stage |
|---|---|---|
| Vacuum Total Impulse (lb-sec) | 54,890,000 | 19,080,000 |
| Average Vacuum Thrust (lb) | 722,298 | 264,951 |
| Vacuum Specific Impulse (sec) | 282.3 | 288.7 |
| Burn Time (sec) | 76 | 72 |
| Average Chamber Pressure (psia) | 373.5 | 400.5 |
| Motor Diameter | 74 | 74 |
| Motor Length w/o Nozzle (in) | 385.5 | 385.5 |
| Nozzle Expansion Ratio | 9:1 | 12.7:1 |
| Weight | | |
| Propellant Weights | | |
| Polybutadiene Fuel (lb) | 70,363 | 23,914 |
| Liquid Oxygen (lb) | 133,089 | 45,232 |
| Nitrous Oxide (lb) | | |
| HTPB/AP/Al Fuel (lb) | | |
| Stage Weight | 243,801 | 83,047 |
| Control System | | |
| Liquid Injection Thrust Vector Control | Pitch, Yaw, Roll | Pitch, Yaw |
| Hydrogen Peroxide Roll Control | - | Roll |
| Hydrogen Peroxide Attitude Control | - | - |
| Nitrous Oxide Cold Gas Attitude Control | - | - |

*Table 1. H-1800 Propulsion System Specifications*

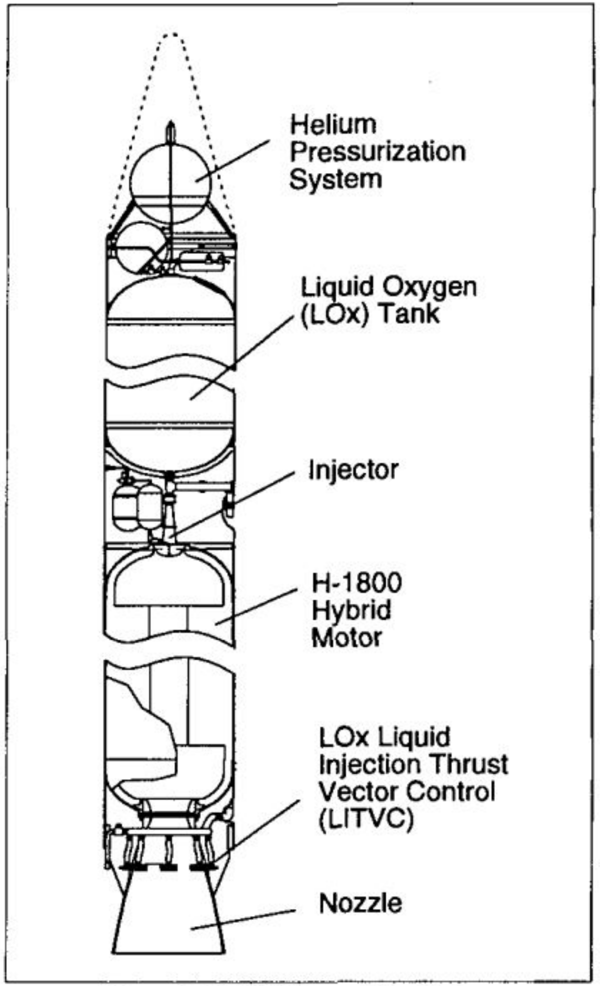



*Figure 4. H-1800 Propulsion System*

# Third stage system

- ORBUS 21s solid rocket motor
- Kevlar/epoxy motor case
- carbon-phenolic exit cone
- Pitch, yaw, and roll control are provided by hydrogen peroxide Atti- tude Control System (ACS)

| Item | 1st Stage | 2nd Stage |
|---|---|---|
| Vacuum Total Impulse (lb-sec) | 54,890,000 | 19,080,000 |
| Average Vacuum Thrust (lb) | 722,298 | 264,951 |
| Vacuum Specific Impulse (sec) | 282.3 | 288.7 |
| Burn Time (sec) | 76 | 72 |
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| Motor Diameter | 74 | 74 |
| Motor Length w/o Nozzle (in) | 385.5 | 385.5 |
| Nozzle Expension Ratio | 9:1 | 12.7:1 |
| **Weight** | | |
| Propellant Weights | | |
| Polybutadiene Fuel (lb) | 70,363 | 23,914 |
| Liquid Oxygen (lb) | 133,089 | 45,232 |
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| HTPB/AP/Al Fuel (lb) | | |
| Stage Weight | 243,801 | 83,047 |
| **Control System** | | |
| Liquid Injection Thrust Vector Control | Pitch, Yaw, Roll | Pitch, Yaw |
| Hydrogen Peroxide Roll Control | - | Roll |
| Hydrogen Peroxide Attitude Control | - | - |
| Nitrous Oxide Cold Gas Attitude Control | - | - |

*Table 2. Upper Stages Propulsion System Specifications*

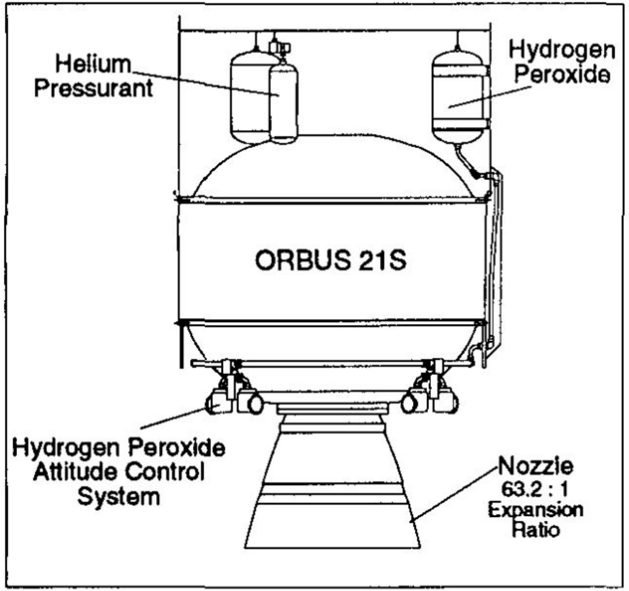



*Figure 5. Third Stage ORBUS®21S SRM*

# Fourth stage system

- Aquila fourth stage motor is an AMROC pressure-fed U-75 Nitrous Oxide ($N_2O$)/HTPB hybrid motor.

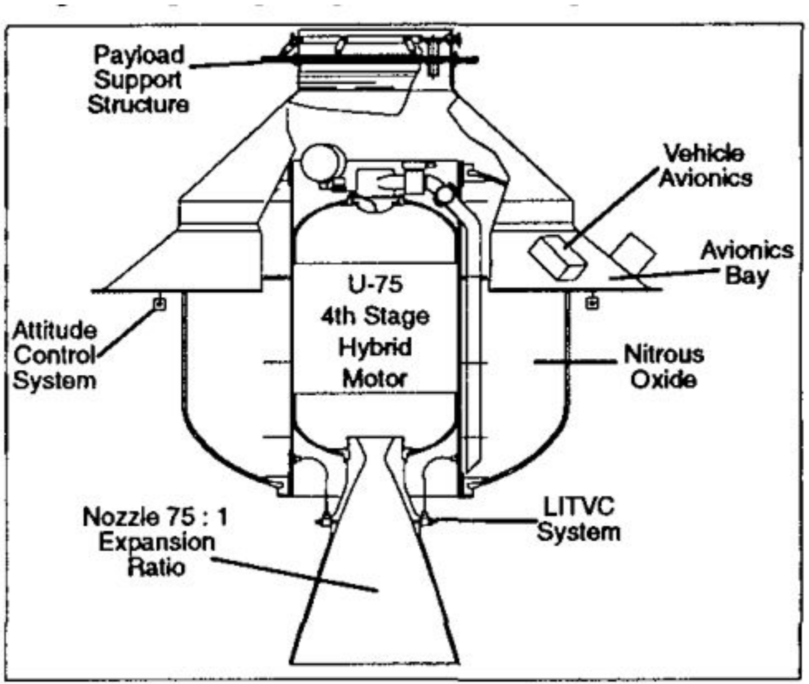
- Nitrous oxide

- oxidizer tank and the motor case are manufactured from graphite/epoxy composites.

- stage uses a light-weight high expansion carbon-phenolic nozzle

- nozzle is equipped with an LITVC system

- Same motor as in [1]



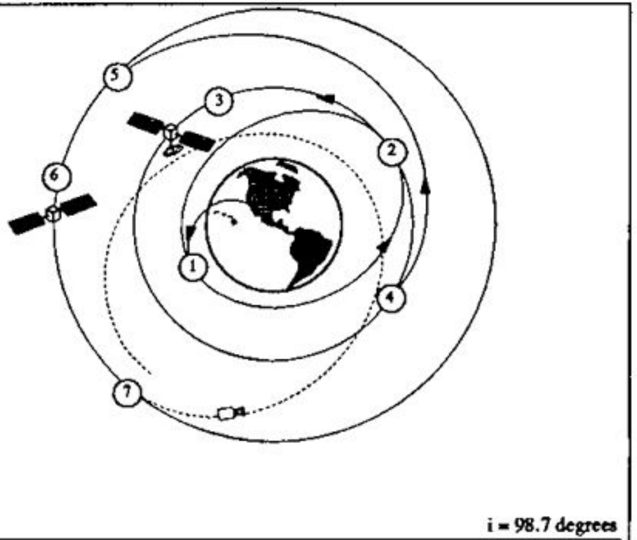
# Orbit accuracy

Stages of orbit maneuvers seen on right.

<u>Orbit Injection Accuracy</u>

Based on an Aquila launch from VAFB, Aquila will insert a payload into a 100 nmi. (185 km) circular parking orbit with three-sigma accuracies of:

- Perigee/Apogee Altitude = ± 13.2 nmi (24.5 km)
- Orbit Inclination Angle = ± 0.046 degrees
- RAAN Angle = ± 0.042 degrees



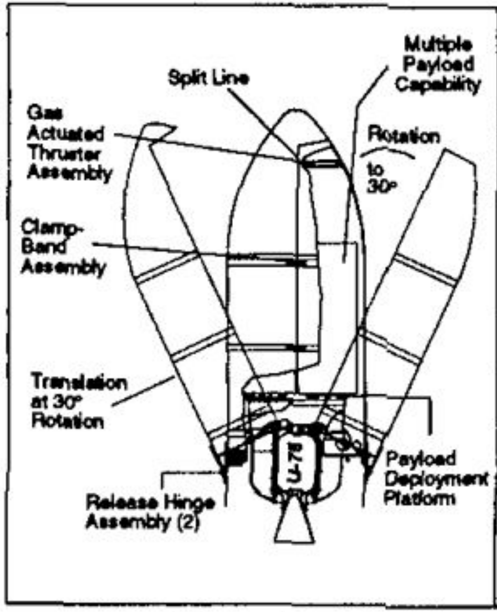

| | |
|---|---|
| 1 | Insert into 100 x 250 nm (185 x 462 km) Transfer Orbit |
| 2 | U-75 Second Burn to Circularize at 250 nm, Trims Burn if Necessary |
| 3 | Orient to Attitude and Deploy First Payload |
| 4 | U-75 Third Burn to 250 x 450 nm Transfer Orbit |
| 5 | U-75 Fourth Burn to Circularize at 450 nm, Trims Burn if Necessary |
| 6 | Orient to Attitude and Deploy Second Payload |
| 7 | U-75 Fifth Burn to a High Drag Orbit |

***Figure 11. Candidate On-Orbit Maneuvers***

# Payload

## Payload Accommodations

Aquila's payload accommodations have been designed to offer users several different mounting options as well as present more usable payload volume than any other launch vehicle in its class. Aquila's payload compartment is enclosed by a large 94 inch (2.38 m) diameter payload fairing, which has over 450 $ft^3$ ( 12.7 $m^3$) volume which is sufficient for multiple payloads in either a side by side or stacked configuration.




| Features | |
|---|---|
| Usable Volume ........ | 450 cu. ft. (12.7 $m^3$) |
| Diameter ........................ | 94 in. (2.38 m) |
| Length ........................ | 235 in. (5.96 m) |
| Payload Fairing Mass ... | 1,446 lbm. (657 kg) |
| Body Material ............ | Graphite/Epoxy & Fiberglass/Epoxy –RF Transparent |
| Fairing Separation System ............ | •4 Redundant Explosive Bolts<br>•3 Two Piece Clamp Bands with 6 Explosive Actuators<br>•Gas Actuated Thruster Assembly |
| *Payload and Launch Vehicle Contact Avoided Because:* ........ | •Sections Rotate 30°<br>•Translation Aided by Angular Motion and Acceleration of Launch Vehicle |
| Payload Separation System ............... | •2 Piece Clamp Band<br>•2 Dual Charge Explosive Bolts<br>•4 or 6 Separation Springs for Payload Release |

***Figure 12. Aquila Payload Fairing***

# Payload continued

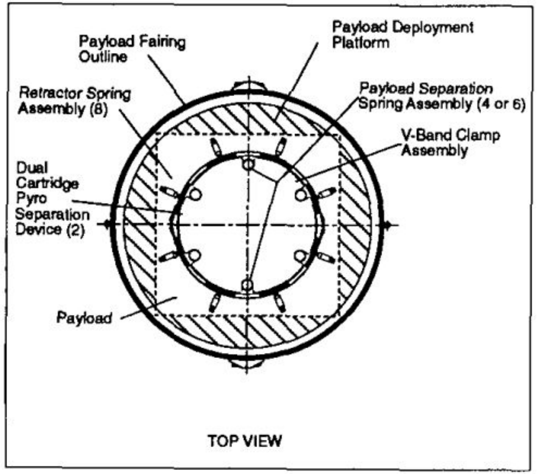



*Figure 14. Payload Deployment Platform*

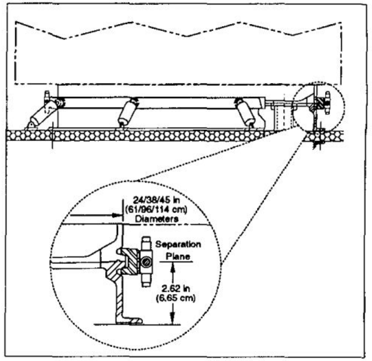



*Figure 15. Typical Spacecraft Attachment*

- In-flight acoustic levels
- maximum dynamic pressure are minimized statistically lower than other same class vehicles.
- Acoustic levels on lift-off are minimized by a flame trench design
- Pyro shock loads reduced by the choice of a clamp-band separation system.

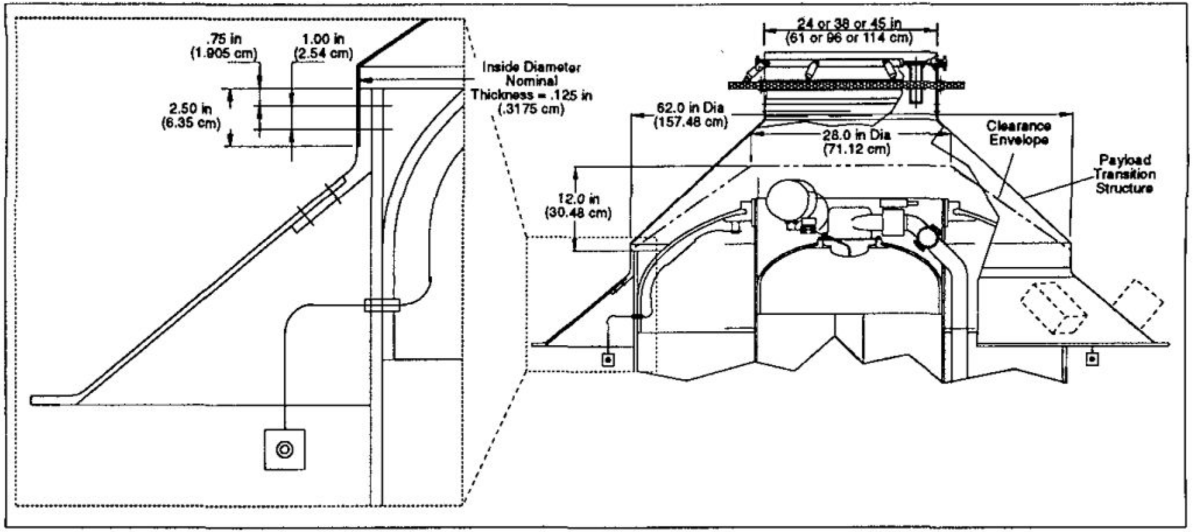



*Figure 16. 4th Stage Payload Deployment Platform Interface Ring*

# Flight data

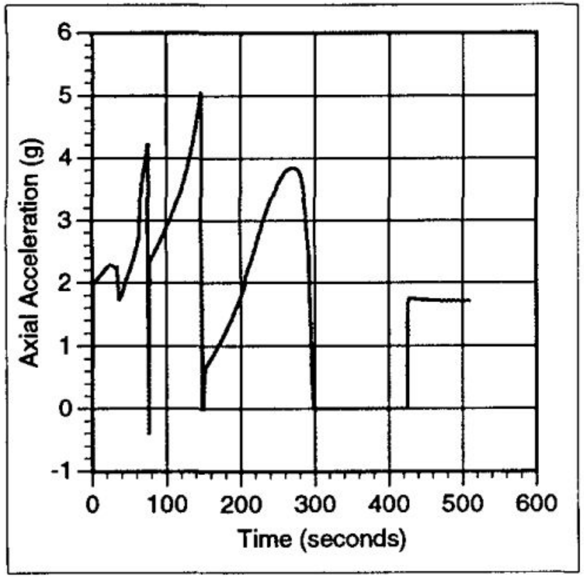



*Figure 17. Acceleration vs Time*

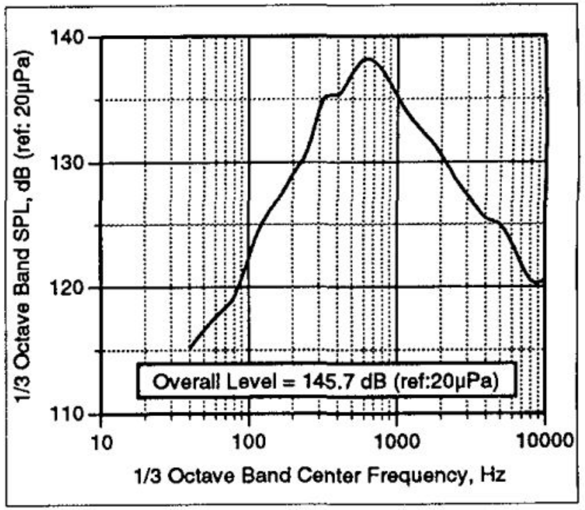



*Figure 18. Payload Acoustic Levels*

Issues discussed

- Random vibration
- Acoustics
- Shock
- Payload processing and launch
- Launch site arrival and checkout
- Thermal
- Payload to launch integration
- Launch operations

# Launch operations

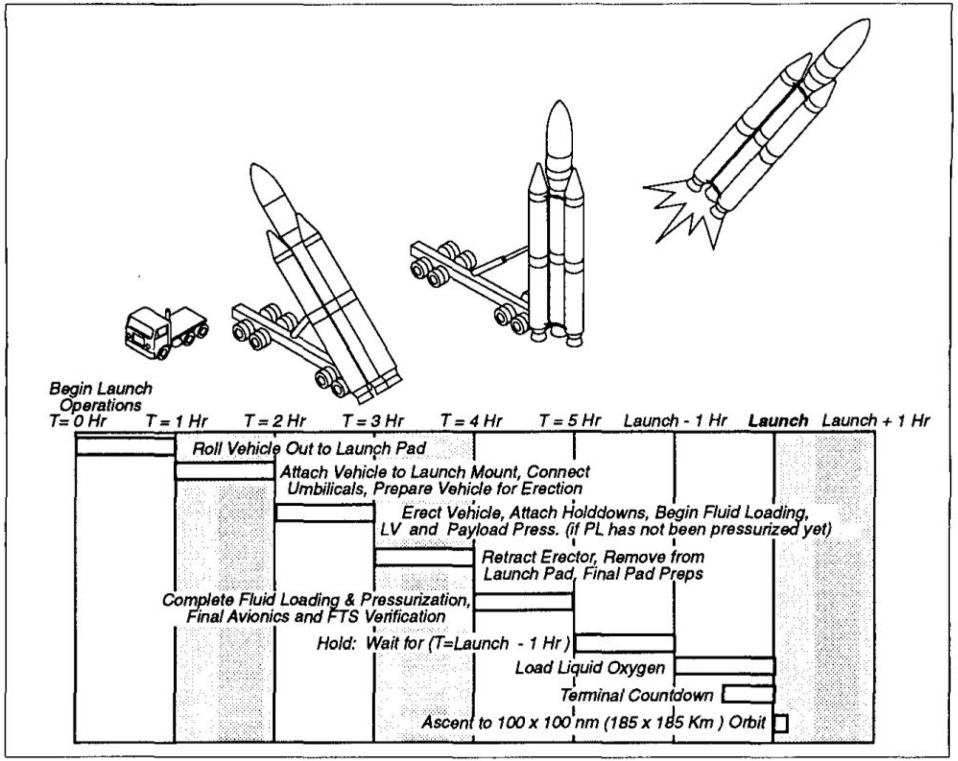



*Figure 23. Aquila Launch Operations*

The **final launch procedures** are:

- perform final payload
- propulsion and avionics system Preparations
- load liquid oxygen
- verify launch vehicle
- payload RF links
- arm the range safety command and destruct system
- terminal countdown
- LAUNCH!

# Sources

[1] K. J. Flittie and J. S. McFarlane, "The Commercial Aquila Launch Vehicle," presented at the AIAA/SAE/ASME 27th Joint Propulsion Conference, June 24-26, 1991, Sacramento, CA, Paper AIAA-91-2046.

And

[2] G. R. Whittinghill and B. C. McKinney, "The Aquila Launch Service for Small Satellites," presented at the AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference and Exhibit, July 6-8, 1992, Nashville, TN, Paper AIAA-92-3588.