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FLIGHT TEST RESULTS FOR THE SRALT RRF AND TARGET INTERCEPT MISSIONS

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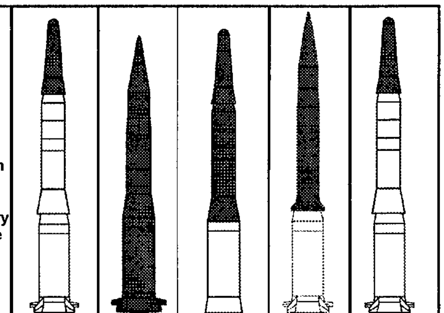
Abstract

This paper presents flight test results for the Short Range Air Launch Target (SRALT) risk reduction flight (RRF) and the four target intercept missions achieved during 1999, and compares them to simulation performance predictions. Lessons learned include ground and airdrop testing, target flight performance, instrumentation, and test range interfaces. The flight test targets were developed for the United States Army Space and Missile Defense Command (USASMDC) in support of Theater Missile Defense (TMD) interceptor flight testing. Successful execution of the SRALT RFF ended the total dependence on ground launch testing and associated test range constraints. The five targets used threat representative reentry vehicle (RV) front ends and common delivery vehicle subsystems to achieve realistic test scenarios covering a range of TMD threats. The extensive on-board instrumentation suite provided real-time telemetry data to confirm accomplishment of mission flight test objectives and a basis for comparison to simulation predictions. Successful completion of the target missions required a disciplined mission requirements analysis, design, fabrication, and test process. Extensive ground integration testing was conducted for every missile, with additional airdrop tests for SRALT.

1.0 Introduction

The success of four tactical ballistic missile (TBM) target intercept missions and the first successful air launch of a TBM target made 1999 an historic year for the USASMDC and the Ballistic Missile Defense Organization (BMDO) (Figure 1.0-1). Coleman Aerospace Company (CAC) provided the Hera TBM target vehicle and the SRALT vehicle for these five successful missions, two of which were Theater High Altitude Area Defense (THAAD) intercepts and two were Patriot Advanced Capability-3 (PAC-3) intercepts. Flight test result comparisons to pre-flight simulation predictions confirmed that the target met the mission objectives in each of the flight tests.



Flight Configuration ■ = Reentry Vehicle					
Mission Name	PAC-3 SCF-2	SRALT	FT-10 (2)	FT-11	PAC-3 DT-9
Launch Date	3/15/99	3/30/99	6/10/99	8/2/99	9/16/99
Launch Site	Ft. Wingate LC96	PMRF	WSMR LC94	WSMR LC94	Ft. Wingate LC96
Objective	Intercept by PAC-3	Demo air launch	Intercept by THAAD	Intercept by THAAD	Intercept by PAC-3
Trajectory Type	Shaped	Ballistic	Ballistic	Ballistic	Shaped
Payload Configuration	Separating RV	Unitary	Unitary	Unitary	Separating RV

CAC 00-062 01

Figure 1.0-1. The success of the Hera target and the PAC-3 and THAAD interceptors, as well as the successful air launch of the SRALT, made 1999 an historic year for the USASMDC.

The four TBM target intercepts were significant milestones that advanced the development of the interceptor programs, allowing them to enter the next phase of development.

The successful development and execution of the air-launched target ended the total dependence on ground-launch testing and the associated test range constraints, thus expanding available test scenarios for the TMD community. The success of SRALT is reflected in the initiation of two other air launch target programs under BMDO: the Long Range Air Launch Target (LRALT) program by the US Air Force Space and Missile Systems Center (SMC); and the Consolidated Theater Target Services (CTTS) Linebacker program by USASMDC.

To ensure that all objectives for a threat-representative target flight test are met for the primary user, CAC employs a mission planning process (Figure 1.0-2) that encompasses a number of iterative steps. This includes deriving the mission requirements, identifying the target configuration, coordinating between the primary user and range safety, documenting via a Mission Requirements Letter (MRL), and providing performance prediction data including trajectory and signature to the primary and other users.

Analytical techniques used to predict flight performance include six-degree-of-freedom (6DOF) simulation, computer-in-the-loop, and hardware-in-the-loop runs. Data from these missions were provided to the user community and range safety for evaluation. The simulations were updated with actual flight data after each flight. Flight test results showed that flight performance prediction techniques were highly accurate when compared with actual flight data.

2.0 Flight Test Results for PAC-3 SCF-2

The first successful PAC-3 mission in which the Hera target vehicle was successfully intercepted was performed March 15, 1999 from Fort Wingate. The launch vehicle flew a shaped trajectory with a separating, RV payload configuration (Figure 1.0-1).

2.1 Test Objectives

The test objectives of the PAC-3 SCF-2 mission were as follows:

1) Provide a short-medium range, separating target for PAC-3
2) Provide PAC-3 ground radar opportunity to track and collect data
3) Verify performance simulations.

All PAC-3 SCF-2 mission test objectives were met.

2.2 Trajectory Analysis

The differences between the achieved trajectory and the pre-flight prediction fell well within the tolerances. Velocity and altitude at each stage burnout were near nominal. Figure 2.2-1 compares the achieved trajectory, as instrumented by the on-board inertial system, with the pre-flight simulation prediction.

A summary comparison of the achieved trajectory, as instrumented by the onboard inertial system and pre-flight trajectory predictions from 6DOF simulation is presented in Table 2.2-1. All trajectory conditions match expected simulation results within predicted tolerances.

Table 2.2-1. Trajectory at Significant Flight Events

Event	Achieved	Predicted	Variation
1st Stage Burnout			
Time (s)	64.4	64.6	-0.2σ
Velocity (m/s)	1140	1128	0.6σ
Altitude (km)	29.9	30.2	-0.8σ
2nd Stage Burnout			
Time (s)	212.3	121.4	0.4σ
Velocity (m/s)	1349	1356	-0.7σ
Altitude (km)	85.2	84.2	0.4σ
Apogee			
Altitude (km)	93.9	92.5	0.6σ

2.3 Accuracy Analysis

A summary of the RV delivery accuracy is shown in Table 2.3-1.

Table 2.3-1. RV Delivery Accuracy at Aimpoint

Position Error	Perf Rel to Reqmt	3σ Dispersion from Sim	Perf Rel to Expected Dispersion	Perf Rel to MRL Reqmt
North	-167m	1161m	-0.1σ	11% of max
East	-233m	570m	-0.4σ	16% of max
Radial	287m			

Figure 2.3-1 shows the RV location from a variety of sources as it passes through the aimpoint altitude. Based on White Sands Missile Range (WSMR) radar best estimated trajectory (BET), the RV passed 167 meters south and 233 meters west of the designated aimpoint. These values are within expected tolerances and far exceed mission requirements.

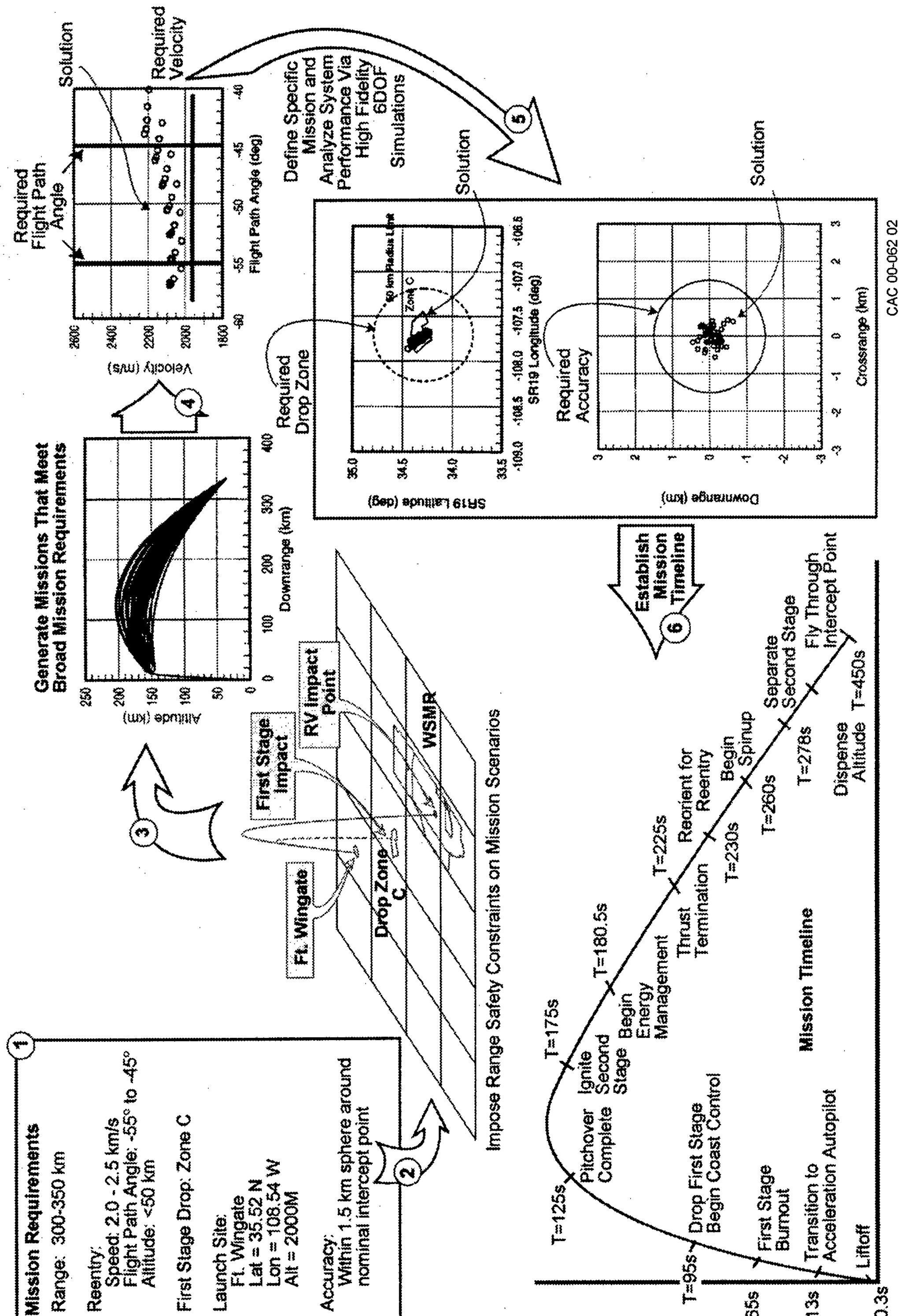


Figure 1.0-2. Mission Planning Process

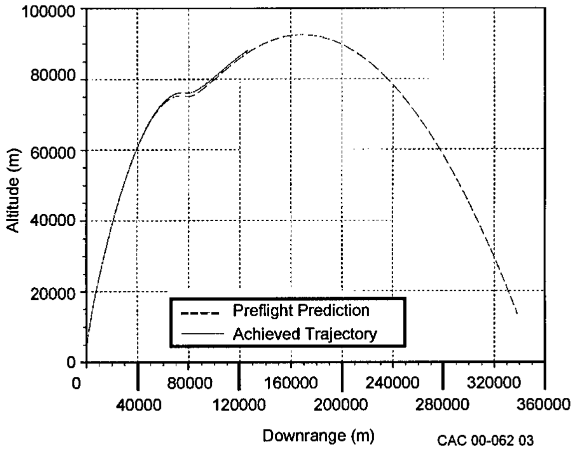


Figure 2.2-1. Comparison of Achieved Trajectory With Pre-flight Simulation Prediction

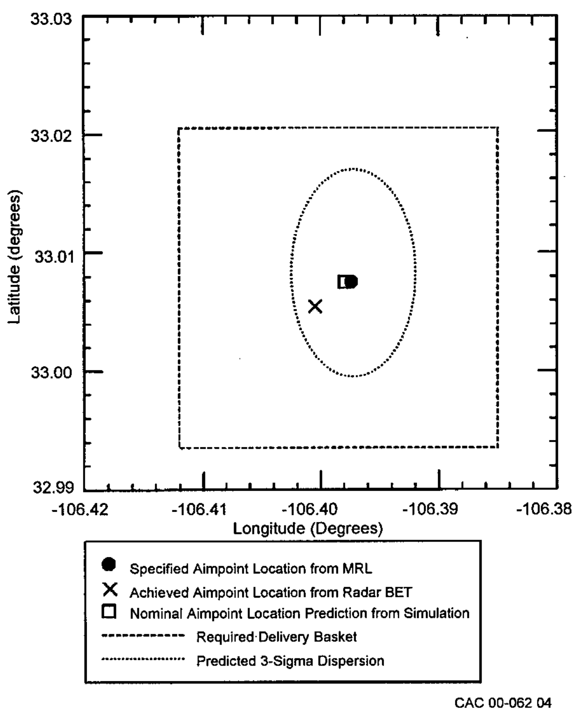


Figure 2.3-1. RV Location at the Aimpoint Altitude

3.0 Flight Test Results for THAAD FT-10

The first successful THAAD mission in which the Hera target vehicle was successfully intercepted was performed June 10, 1999 from WSMR. The launch vehicle flew a ballistic trajectory with a RV and booster in a unitary payload configuration (Figure 1.0-1).

3.1 Test Objectives

The test objectives of the THAAD FT-10 mission were as follows:

1) Provide a short-medium range, unitary target for THAAD
2) Provide THAAD radar opportunity to track and collect data
3) Verify performance simulations.

All THAAD FT-10 mission test objectives were met.

3.2 Trajectory Analysis

The differences between the achieved trajectory and the pre-flight prediction fell well within the expected tolerances. Velocity and altitude at second-stage burnout were nominal. Figure 3.2-1 compares the achieved trajectory, as instrumented by the on-board inertial system, with the pre-flight simulation prediction.

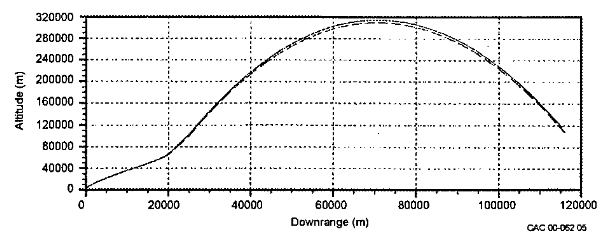


Figure 3.2-1. Comparison of Achieved Trajectory with Pre-flight Simulation

A summary comparison of the achieved trajectory, as instrumented by the onboard inertial system and pre-flight trajectory predictions from 6DOF simulation is presented in Table 3.2-1. All trajectory conditions match expected simulation results within predicted tolerances.

Table 3.2-1. Trajectory at Significant Flight Events

Event	Achieved	Predicted	Variation
1st Stage Burnout			
Time (s)	63.9	64.6	-0.7σ
Velocity (m/s)	1102	1107	-0.3σ
Altitude (km)	30.7	31.6	-2.1σ
2nd Stage Burnout			
Time (s)	122.5	124.0	-0.9σ
Velocity (m/s)	1909	1913	-0.2σ
Altitude (km)	113.1	116.9	-2.1σ
Apogee			
Altitude (km)	310.0	314.9	-0.8σ

4.0 Flight Test Results for THAAD FT-11

The second THAAD mission in which the Hera target vehicle was successfully intercepted was performed August 2, 1999 from WSMR. The target launch vehicle flew a ballistic trajectory with an RV and a booster in a unitary payload configuration (Figure 1.0-1).

4.1 Test Objectives

The test objectives of the THAAD FT-11 mission were as follows:

1) Provide a short-medium range, separating target for THAAD
2) Provide THAAD radar opportunity to track and collect data
3) Verify performance simulations.

All THAAD FT-11 mission test objectives were met.

4.2 Trajectory Analysis

The differences between the achieved trajectory and the pre-flight prediction fell well within the expected tolerances. Velocity at second-stage burnout was slightly below normal. Second-stage burnout altitude (6 km low) and apogee (12 km low) were not anomalous given measured mass and air density when combined with normal drag and motor tolerances. Table 4.2-1 summarizes the contributing factors and tolerances. Figure 4.2-1 compares the achieved trajectory, as instrumented by the on-board inertial system, with the pre-flight simulation prediction.

Table 4.2-1. THAAD FT-11 Second Stage Burnout Altitude and Apogee Tolerance Analysis

Contributing Factors:	3σ Tolerances:
– Mass	± 100 lb
– Atmospheric properties	± 15% dens
– Motor impulse (FS, SS)	± 1.0%, 1.5%
– Drag	± 15%
Effects of 3σ Tolerance on 2nd Stage Burnout Altitude:	**Delta:**
– Mass	± 6 km
– Air Density	± 1 km
– Motor impulse	± 3 km
– Drag	± 6 km
Effects of 3σ Tolerance on Apogee:	**Delta:**
– Mass	± 24 km
– Air Density	± 4 km
– Motor impulse	± 14 km
– Drag	± 21 km

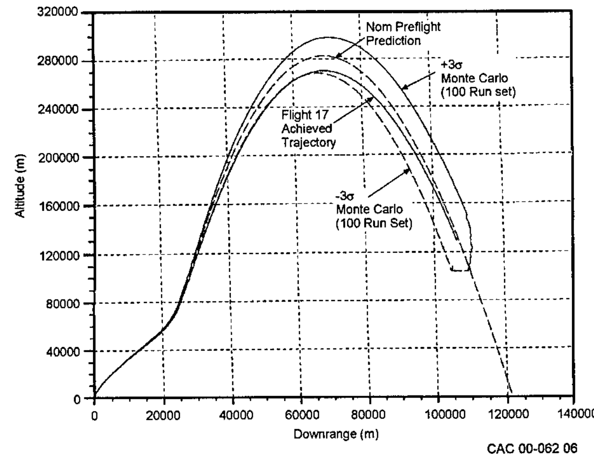


Figure 4.2-1. Comparison of Achieved Trajectory with Pre-flight Simulation Prediction

A summary comparison of the achieved trajectory, as instrumented by the on-board inertial system, and pre-flight trajectory predictions from 6DOF simulation is presented in Table 4.2-2. All trajectory conditions match expected simulation results within predicted tolerances.

Table 4.2-2. Trajectory at Significant Flight Events

Event	Achieved	Predicted	Variation
1st Stage Burnout			
Time (s)	64.7	64.6	0.1σ
Velocity (m/s)	1056	1077	-0.2σ
Altitude (km)	29.5	30.7	-0.4σ
2nd Stage Burnout			
Time (s)	123.2	124.1	-0.5σ
Velocity (m/s)	1752	1786	-0.3σ
Altitude (km)	105.7	111.3	-0.6σ
Apogee			
Altitude (km)	270.0	282.6	-0.3σ

5.0 Flight Test Results for PAC-3 DT-3

The second consecutive PAC-3 mission in which the Hera target vehicle was successfully intercepted was performed September 16, 1999 from Fort Wingate. The launch vehicle flew a shaped trajectory with a separating RV payload configuration (Figure 1.0-1).

5.1 Test Objectives

The test objectives of the PAC-3 DT-3 mission were as follows:

1) Provide a short-medium range, separating target for PAC-3
2) Provide PAC-3 radar opportunity to track and collect data

3) Verify performance simulations
4) Intercept of the RV by PAC-3 missile.

All PAC-3 DT-3 mission test objectives were met.

5.2 Trajectory Analysis

The differences between the achieved trajectory and the pre-flight prediction fell well within the expected tolerances. Velocity and altitude at second-stage burnout were nominal. Figure 5.2-1 compares the achieved trajectory, as instrumented by the on-board inertial system, with the pre-flight simulation prediction.

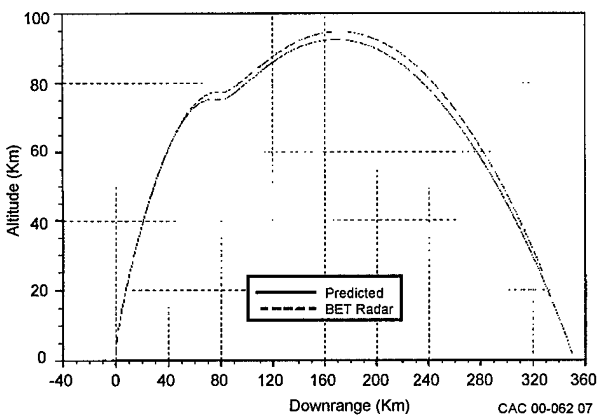


Figure 5.2-1. Comparison of Achieved Trajectory with Pre-flight Simulation Prediction

A summary comparison of the achieved trajectory, as instrumented by the on-board inertial system, and pre-flight trajectory predictions from 6DOF simulation is presented in Table 5.2-1. All trajectory conditions match expected simulation results within predicted tolerances.

Table 5.2-1. Trajectory at Significant Flight Events

Event	Achieved	Predicted	Variation
1st Stage Burnout			
Time (s)	63.0	64.6	-1.6σ
Velocity (m/s)	1151.5	1128	1.2σ
Altitude (km)	30.0	30.2	-0.5σ
2nd Stage Burnout			
Time (s)	210.2	211.4	0.5σ
Velocity (m/s)	1344	1356	-1.2σ
Altitude (km)	86.8	84.2	1.0σ
Apogee			
Altitude (km)	94.8	92.5	1.0σ

5.3 Accuracy Analysis

A summary of the miss distance between the RV radar BET track and the required aimpoint is presented in Table 5.3-1.

Table 5.3-1. RV Delivery Accuracy at Aimpoint

Position Error	Perf Rel to Reqmt	3σ Dispersion from Sim	Perf Rel to Expected Dispersion
North	-100m	1161m	-0.3σ
East	-48m	570m	-0.3σ
Radial	111m		

Note: Aimpoint performance based on range radar BET

6.0 Flight Test Results for SRALT

The SRALT mission was successfully performed March 30, 1999 from the Pacific Missile Range Facility. SRALT was a single-stage, unitary configuration with an RV and booster (Figure 1.0-1). SRALT demonstrated the operational feasibility of air-launching a live target missile from a C-130 aircraft and flying down range to a planned impact point.

The following objectives were met by the SRALT mission:

1) Successful extraction, descent, and release of the SRALT and subsequent ignition of the SRALT (Figure 6.0-1)
2) Global positioning system (GPS)-guided flight of the target along the prescribed trajectory
3) GPS and telemetry reception by the test range and remote area safety aircraft (RASA)
4) Accuracy verification and trajectory track by test range assets
5) Photographic documentation
6) Reentry signature measurement and correlation by ground and air sensors.

At the same time as these critical objectives were met, the SRALT program illustrated a number of important benefits of the air-launch approach in general, including:

1) Reduced reliance on, and costs associated with, land launch range resources
2) Capability to use standard, common cargo aircraft
3) Capability to use standard, certified air-drop techniques and equipment
4) Ability to maintain launch vehicles and payloads in flight-ready status for quick reaction launches

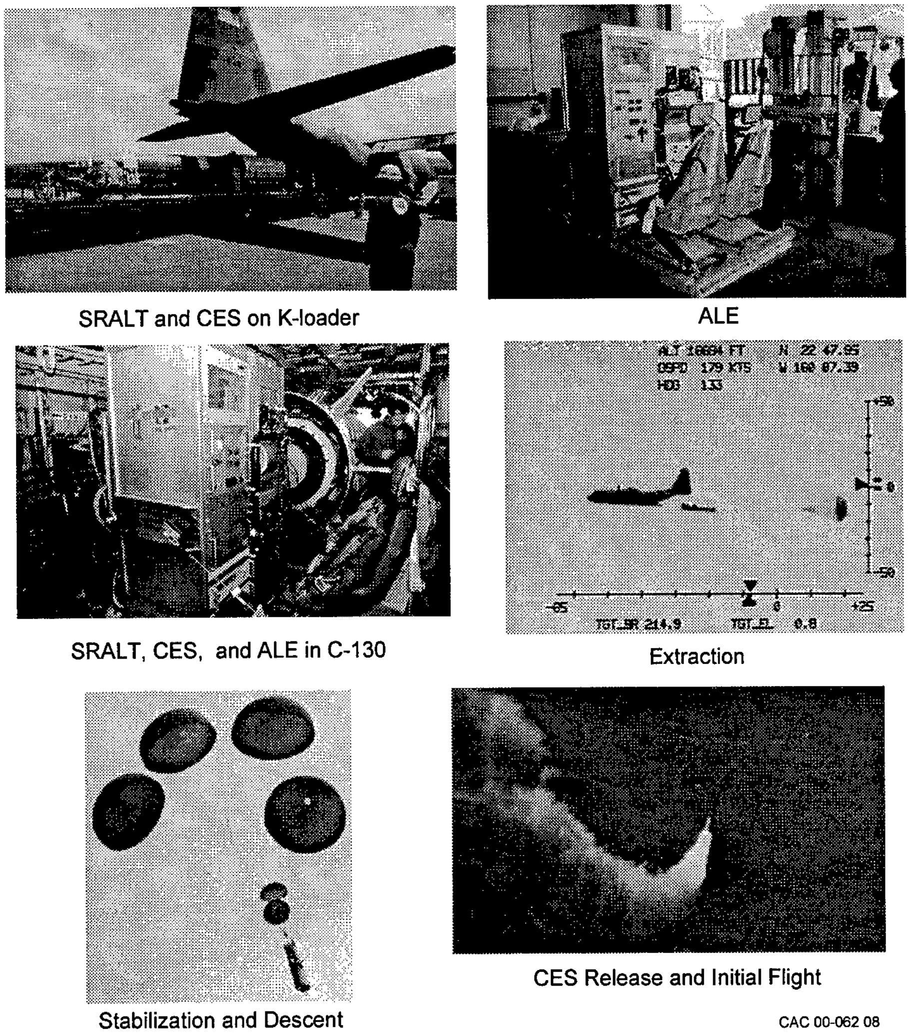


Figure 6.0-1. CRC achieved successful extraction, descent, release, and flight of the SRALT.

5) Multiple, simultaneous engagements with different target flight azimuths.

6.1 Trajectory

The SRALT met the mission flight profile to fly a ballistic trajectory with a 299-km. range and a 99-km. apogee. The flight's actual 282-km range was within the allowed ±25 km down-range aimpoint dispersion, and the apogee altitude of 98,560.7 meters was within expected dispersions as defined in the MRL. The SRALT's velocity was within the ±10% requirement at the aimpoint as specified in the MRL.

The achieved flight path of -58.1 degrees at the aimpoint altitude was steeper than that of the reference threat trajectory and violated the ±10% requirement specified in the MRL. The RRF trajectory was changed as a result of a workaround to the flight path algorithm error and resulted in a nominal flight path of -52.4 ±5.24 degrees at a simulated intercept altitude (Table 6.1-1). The actual

flight path deviation is attributed to aerodynamic modeling errors associated with the effects of 'cold' motor performance, higher than expected drag, and lower than expected stability. Aerodynamic models have been updated to provide more predictable flight dynamics for future missions.

The SRALT impacted within the specified flight target impact area and met the MRL's requirement. The aimpoint dispersion requirements were also achieved.

Table 6.1-1. Achieved Performance versus Pre-flight Simulation Predictions Based on Trajectory Revision

	Pre-flight Simulation (Rev FA)		Actual Perf (TLM)	
	Mean	1 σ Value	Value	Actual Deviation (σ)
Booster Ignition				
Time since extraction (s)	180.3	17.1	188.1	+0.5
Latitude (deg)	22.682	0.009	22.688	+0.7
Longitude (deg)	-160.195	0.013	-160.214	-1.5
Downrange (km)	-0.8	1.2	1.3	+1.8
Cross range (km)	0.2	1.1	0.8	+0.5
Altitude (m)	1544	50	1585	+0.8
Start No-TT Guidance				
Time since Ignition (s)	58.5	1.1	60.4	+1.7
Booster Burnout				
Time since Ignition (s)	64.2	0.9	65.0	+0.9
Down range (km)	22.0	1.5	23.5	+1.0
Cross range (km)	-0.1	1.1	0.3	+0.4
Altitude (m)	35.38	0.46	34.50	-1.9
Velocity (m/s)	1576	8	1561	-1.9
Flight Path (deg)	45.4	1.0	47.0	+1.6
Apogee				
Altitude (km)	99.1	2.5	98.6	-0.2
At Simulated Intercept				
Time since Ignition (s)	317.9	4.9	318.1	0.0
Latitude (deg)	24.200	0.024	24.136	-2.7
Longitude (deg)	-162.514	0.034	-162.411	+3.0
Downrange (km)	290.0	4.4	277.4	-2.9
Cross range (km)	-4.7	0.4	-4.7	0.0
Velocity (m/s)	1419	18	1404	-0.8
Flight Path (deg)	-52.4	0.8	-58.1	-7.1
At Impact				
Time since Ignition (s)	328.8	4.8	327.5	-0.3
Latitude (deg)	24.232	0.026	24.161	-2.7
Longitude (deg)	-162.574	0.035	-162.442	+3.8
Downrange (km)	297.0	4.6	281.5	-3.4
Cross range (km)	-4.2	0.7	-5.2	-1.4
Velocity (m/s)	764	41	810	+1.1
Flight Path (deg)	-57.8	1.4	-72.3	-10.4

6.2 Technical Evolution of SRALT

Use of Operational Aircraft and Crews – Execution of the SRALT program required that a complete system (target, extraction system, airborne support equipment, and crew) meet specific requirements. An Interim Hazard Classification (IHC) was established for the target system. The IHC, progressive successful test results, and the structural analysis and safety data provided in the test plan served as the basis for the USAF Aeronautical Systems Center to issue both Air Drop and Air Cargo Certificates. The USAF Air Mobility Command approved the SRALT for air drop as a standard payload. Therefore, any USAF C-130H aircraft and crew qualified for High Altitude Low Opening (HALO) parachute extraction drops can be used for SRALT operations.

Use of GPS – Application of GPS data was used during flight for guidance. SRALT had a full GPS capability that is essential in the demonstration of remote area range safety capability. The inherent nature of air launched targets implies that the target launch will occur outside line-of-sight for range radar support. To provide two sources of trajectory information for range safety in the absence of radar tracking, the use of GPS data is essential. The SRALT launch demonstrated excellent correlation of GPS/target control system/range radar position information. In addition, if the launch is out of sight of radar, it is out of sight of land-based telemetry reception stations. To fully demonstrate and exploit SRALT concepts, a P-3 RASA was employed during the captive carry and flight operations to demonstrate full over-the-horizon operation from the supporting range. The RASA served to receive, record, and relay to the range, two telemetry streams from the target as well transmitting range-generated arming tones to the target. It is important to note that the GPS antenna required a filter so that the aircraft radio transmissions did not interfere with the GPS satellite signal reception.

Establishment of a Temporary Aircraft Modification – The operational nature of the SRALT final objective also dictated that the SRALT system and launch crew be capable of operating without support from test and evaluation assets. A minor modification package was developed that adapts the SRALT airborne launch equipment and crew support systems to any H model C-130 aircraft. This temporary modification can be installed and removed within a few hours, and provides electrical interface, crew communication, GPS and target transmitter antennas, and crew breathing oxygen. The modification was approved by the USAF Air Logistics Center for operational use.

6.3 Lessons Learned

Reduced Loads during Parachute Deceleration – SRALT program requirements reflected the recognition that RV surfaces and payloads were exposed to physical contact and deployment loads. As a result, the SRALT carriage extraction system

(CES) received extensive attention to minimize deployment loads and to protect the RV surface and contents from physical contact with any of the extraction components. Figure 6.3-1 shows the complex of two extraction parachutes, two stabilization parachutes, and four main parachutes used to decelerate the SRALT from 140 knots horizontal velocity at 17,000 feet to 57 feet per second near-vertical orientation at 5,000 feet altitude.

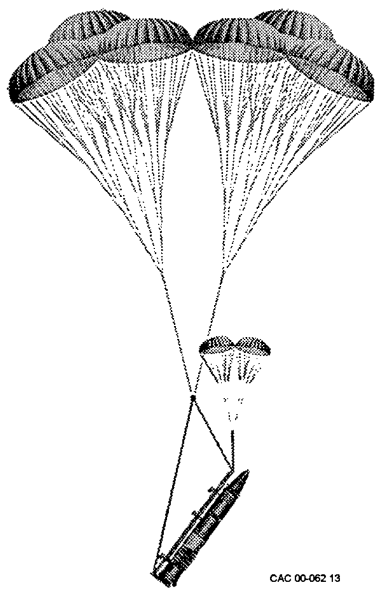


Figure 6.3-1 SRALT Decelerator System

The four main parachutes are reefed in three stages to provide load mitigation. The acceleration loads imposed on SRALT during the extraction and deceleration process in the RRF are depicted in Figure 6.3-2. As shown in the chart, the rather sophisticated configuration maintained the deployment loads to a maximum of 2.5g, considerably below the axial loads experienced during normal flight.

Elimination of Tension Loads – Other approaches to air launching missiles attached the parachutes directly to the missile. Suspension loads were passed directly to the missile as a tension load immediately aft of the RV mounting joint. When parachutes are attached in this manner, all of the loads forward of this point result in the structure being in compression. However, all loads from this point aft put the structure in tension, a structure that is designed primarily for compression loads (axial acceleration). Modifying a missile for tension loads causes structural complexity and adds weight. The SRALT system eliminated most of the tension loads. This was accomplished by relocation of the deceleration parachute attachment directly to the CES. SRALT attached the parachutes to the CES with three blankets and a large retention pin. Although the portion of the structure behind the pin is also in tension, versus preferred compression, it constitutes a much smaller fraction of the structure in a far less critical area. The blankets also provide an alternate load path during virtually all of the deployment sequence, mitigating the tension loads. SRALT also provided protection of the RV from mechanical contact by the use of a parachute guide tray.

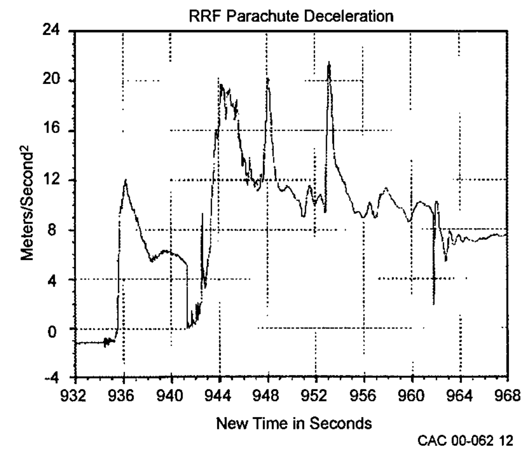


Figure 6.3-2. Parachute Deceleration

Off Vertical Release – To avoid SRALT re-contact with the CES, a repositioning system reorients the target to approximately 40 degrees elevation prior to release and ignition. Repositioning loads are limited to less than 2g by an energy absorption bridle system. The loads can be seen in Figure 6.3-3.

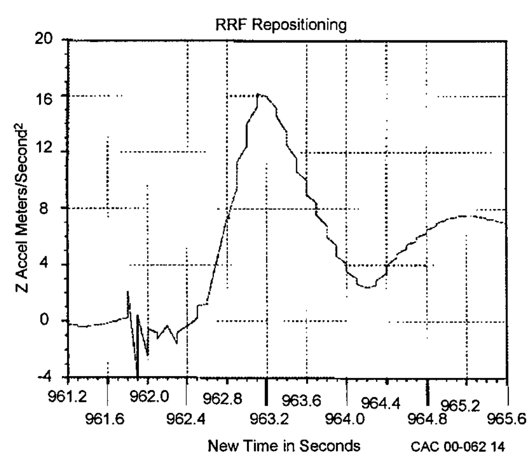


Figure 6.3-3. RRF Repositioning

Enhanced Accuracy – The SRALT mission met the program accuracy requirements. Specifically, the SRALT RRF achieved down-range accuracy for a

300-km. trajectory of 17.9-km using CAC's non-thrust-terminating guidance. However, it was recognized that future interceptor programs would require greater accuracy. To provide solutions for enhanced accuracy in air launched targets programs, CAC initiated a series of programs that resulted in a substantial improvement in accuracy (Figure 6.3-4). As part of an independent research and development (IRAD) project, as well as a task order under the CTTS contract, CAC was able to improve accuracy to 10 km through modifying guidance equations, going from an open-loop approach to a closed-loop approach. An even more significant improvement in accuracy was achieved later during the CTTS Linebacker proposal process when CAC developed a closed-loop instantaneous impact prediction guidance approach that allows accuracy to be improved to 4.2 km. This approach requires no new hardware or hardware development, making it low cost and low risk. CAC achieved a real breakthrough in accuracy improvement when it developed an innovative approach to attitude control using GFP hardware. Using existing GFP hardware to obtain pitch and roll control, as well as modifications to software logic, CAC was able to improve accuracy by a factor of 6 relative to the SRALT RRF. This approach results in accuracy of 2 km. from aimpoint. Accuracy can be improved still farther through use of a velocity correction motor (VCM), shown in Figure 6.2-5. A VCM, which is installed in the single-stage adapter section (SSAS) of the missile, delivers a total axial impulse of 72,259 lbf-s, and axial thrust of 2937 lbf, and burn duration of 24.6 seconds. This simple, reliable solution, developed with Thiokol, improves accuracy to 1.3 km.

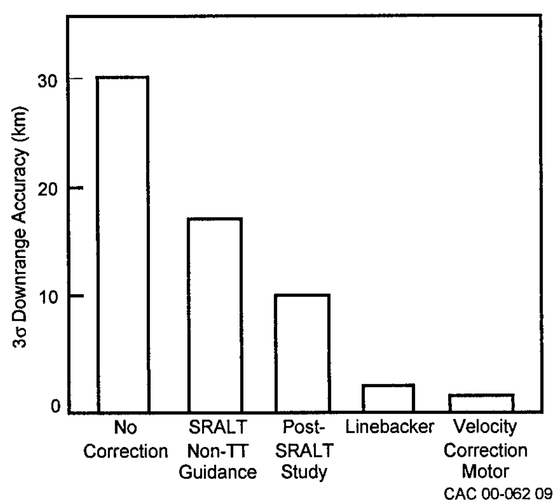


Figure 6.3-4. Through a series of continual improvement actions, CAC developed solutions to improve single stage accuracy from approximately 17 km to 1.3 km.

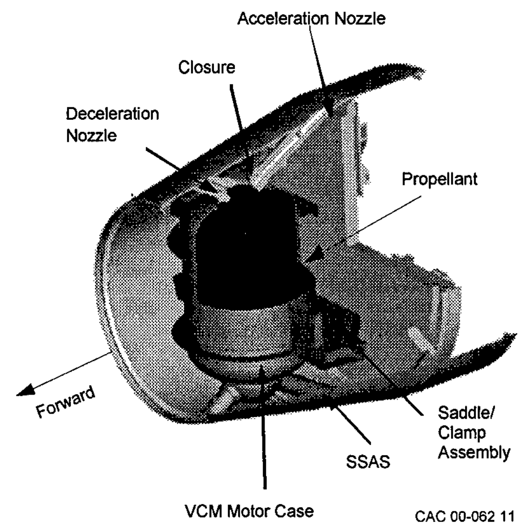


Figure 6.3-5. CAC's solid propellant VCM mounts in the SSAS, provides forward and aft velocity correction, and meets stringent trajectory and accuracy requirements.

7.0 Conclusions

1) THAAD and PAC-3 flight test result comparisons to pre-flight simulation predictions confirmed that the Hera target met the mission objectives in each of the flight tests.
1) Hera is a highly threat representative target for use in development testing of advanced intercept systems
3) Air launch targets have been demonstrated to be operationally feasible, and to provide trajectory and engagement flexibility. They continue to mature as a result of programs like LRALT and CTTS Linebacker.
4) Advancements in missile extraction and deceleration provide substantially increased confidence in the condition of the missile at the launch epoch.
5) GPS provides a source of position information for target guidance and for range safety and flight termination system (FTS) function.
6) The SRALT design for total integration of GPS into the drop point and guidance solution provides greater flexibility in the preparation of air launched targets for multiple, simultaneous engagements.
7) Single-stage accuracy enhancements such as the VCM provide the capability to meet the accuracy and time of arrival requirements of the targets community, resulting in high-fidelity threat replication.