A comparison of altimeters and optical tracking

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Abstract

There are many different methods to determine the altitude of a rocket flight. Some examples include timing a streamer dropped at apogee, triangulating the position using a pair of tracking scopes, measuring changes in barometric pressure or acceleration, and using the Global Positioning System. The objective of this research was to compare several different types of altimeters to optical tracking. To accomplish this, 11 altimeters were placed inside a single payload compartment, and the rocket was launched 13 times. The first flight was also modeled by three different computer simulations and showed excellent agreement with the predicted altitude when a fixed coefficient of drag (C_d) of 0.75 was used. In 10 of the 13 test flights, the altitude reported by optical tracking was either the highest or second highest measurement. The two altimeters with 8-bit analog-to-digital converters (ADCs) performed significantly worse than those with 12-bit resolution or better. This is because the changes in acceleration and pressure are so small for low-altitude flights. Of the altimeters tested with 12-bit resolution or better, the results were all within 3% of average, with a standard deviation of 2%. These results are much better than the maximum allowed error of 10% for optical tracking of contest flights. Calibration differences among the altimeters can lead to one unit consistently reporting higher altitudes than another. Vacuum chamber tests on three altimeters were performed to demonstrate that fact. If altimeters are allowed in all altitude events, contestants will obviously prefer the model that reports a higher altitude. To avoid such calibration problems, altimeters should only be allowed in precision altitude events, in which scores are determined by relative error from a target altitude.

Introduction

One of the first questions the public asks on seeing a rocket is “How high does it go?”. To answer that question, the modeler can use a computer simulation to give an estimate of the altitude, or use one of several different means to measure the actual altitude of a flight. To date, however, there has been no controlled comparison of those different methods. More recently, there were discussions on public mailing lists about the feasibility of using altimeters in place of optical tracking in altitude competition events. There were many opinions expressed, but without any supporting data no decision could be made. The objective of this project is to compare results from several different types of altimeters, optical tracking, and computer simulations.

Methods of Altitude Measurement

The simplest method of measuring altitude is to release a weighted streamer at apogee and time the descent. G. Harry Stine described this method (Stine, 1994) and determined that the streamer reached terminal velocity quickly and then fell at a constant rate of 18 ft/sec. Recently, Estes has released the Max Trax to calculate altitude using this method. The nose cone separates the rocket body at ejection and uses electronics to time from ejection until impact to calculate altitude. The primary sources of error are from the streamer drag coefficient and atmospheric effects. Larger streamers or updrafts will cause slower descent rates and higher reported altitudes. Since this technique is only convenient to measure from ejection, it was not included in this study. All of the other methods report altitude at apogee.

The standard method of measuring altitude in competition is through optical tracking. One or more pairs of tracking scopes are setup along a known baseline and are used to triangulate on the rocket position. Tracking is typically done to ejection so that the tracking powder cloud may be used as a reference point. To ensure accurate results, the baseline must be measured precisely, and the tracking scopes must be leveled and zeroed properly. The baseline should also be sized to match the expected altitude of the flights to be tracked. To illustrate this point, consider a 100 meter flight tracked on baselines of different lengths, with an elevation error of ±1°.

Table 1. Relative error of 100-meter flight with different baselines

Baseline (m)	Elevation (deg)	Relative Error (%)
50	70.5	5.6
100	55.0	3.7
150	43.5	3.5
200	35.5	3.7
400	19.5	5.6

This example assumes a fixed azimuth of 45° on both tracking stations, so the results are identical for the vertical midpoint and geodesic methods of calculating altitude. These results show that the baseline should be 1-2 times the expected altitude. Even with a proper baseline and properly aligned tracking scopes, it is the skill of the scope operators that ultimately determines the quality of the results.

The most common electronic device to measure altitude uses a barometric pressure sensor. Standard atmospheric models have been developed to show how atmospheric pressure decreases with altitude, and a simplified model of pressure versus altitude is shown in Figure 1. At the relatively low altitudes that rockets fly, that function is nearly linear and easy to incorporate in electronics. Note that changes in altitude result in very small changes in pressure.

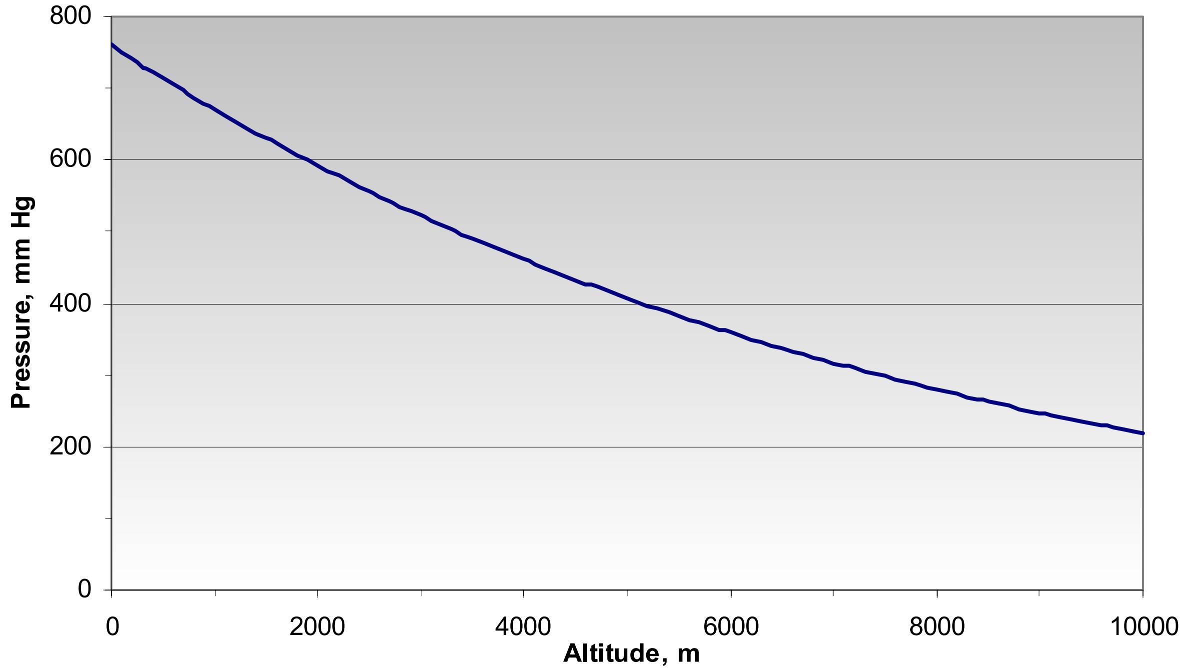

Figure 1. Pressure decreases logarithmically with altitude.

At 300 meters, a 10% increase in altitude corresponds to only a 0.37% decrease in pressure. Pressure sensors output an analog signal, so an analog-to-digital converter with at least 12-bit precision is sufficient to report these small changes. The calibration accuracy of the pressure to altitude calculation is a key factor in determining the overall accuracy of the unit.

Barometric pressure altimeters need to sample the atmospheric pressure outside the rocket, so small vent holes are used to equalize the pressure. The holes need to be sized properly – too small and the pressure will not equalize fast enough, too large and turbulence around the hole will cause unpredictable pressure changes. Additional consideration needs to be taken if the rocket will break the speed of sound, as the passing shock wave will cause erroneous readings. Prior to launch, the altimeter continually samples ground-level pressure. Launch is typically detected by a rapid decrease in pressure, typically corresponding to 100 feet or more in altitude. Apogee is detected at the pressure minimum, and the difference in pressure between ground level and apogee is converted to altitude. Some models support multiple events and may be used to fire a second ejection charge at a pre-determined altitude.

Another electronic device to measure altitude uses an accelerometer instead of pressure sensor. In the simplest case, a single-axis accelerometer is mounted along the vertical axis and periodically measures the vertical acceleration. Prior to launch, the acceleration due to gravity is recorded to use as a starting reference. Launch is detected by a sudden increase in acceleration, so accelerometers tend to work better with high-thrust motors. During flight, acceleration is measured periodically, and those readings are then integrated once to get velocity and again to get altitude. Single-axis accelerometers assume a vertical flight underreport altitude on a non-vertical flight by a factor of the cosine of the degrees from vertical. Using a 3-axis accelerometer can eliminate these errors. The primary benefit to accelerometers over barometric pressure sensors is that no vent hole is required, and there are no issues with supersonic flights.

The most recent development in altitude determination is the use of the Global Positioning System (GPS). To measure altitude, the GPS sensor acquires signals from 4 or more satellites in orbit. Technically, only 3 signals are necessary, but the additional signals are used to correct errors in the clock on the sensor. The sensor then triangulates its position in space by comparing the slight differences in the time it takes each signal to reach the sensor. The vertical accuracy of GPS is about ±30 meters (Hoffmann-Wellenhof and Collins, 1994), which limits the usefulness of GPS for flights less than 1000 meters due to the high relative error.

Computer Models

It is often useful to estimate how high a rocket will go before actually flying it. Several different computer programs have been developed in the past to do these simulations. This section goes through the steps of developing a simple model and compares results of that model to two popular computer programs: RockSim and wRASP. Later, output from these models will be compared to actual flight results. The test rocket used for each of the simulations is 66 mm in diameter, weighs 1352 g, and is launched with a G40-7 motor. Motor data was taken from the NAR Standards & Testing certified motors list and is shown in Figure 2.

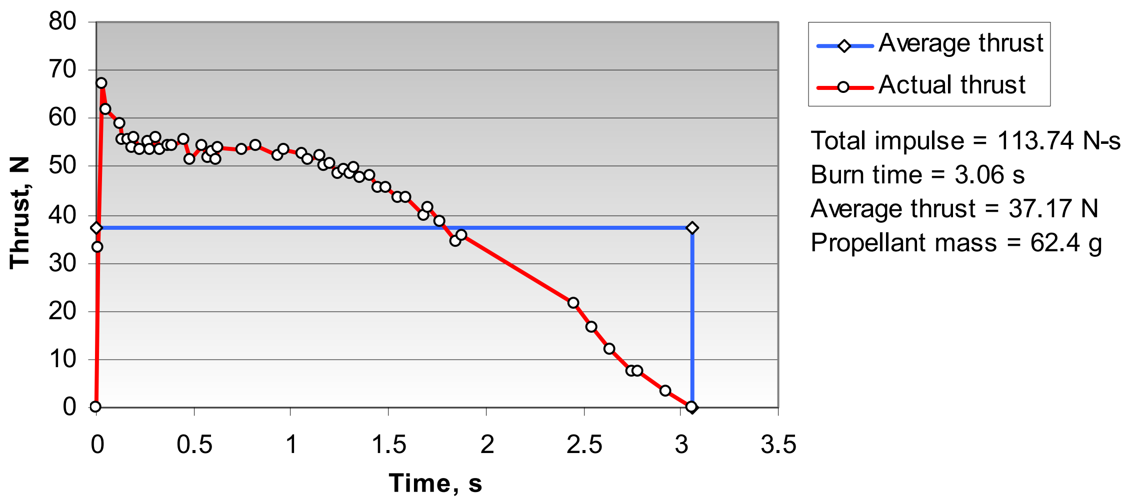

Figure 2. G40 motor thrust curves, average and actual.

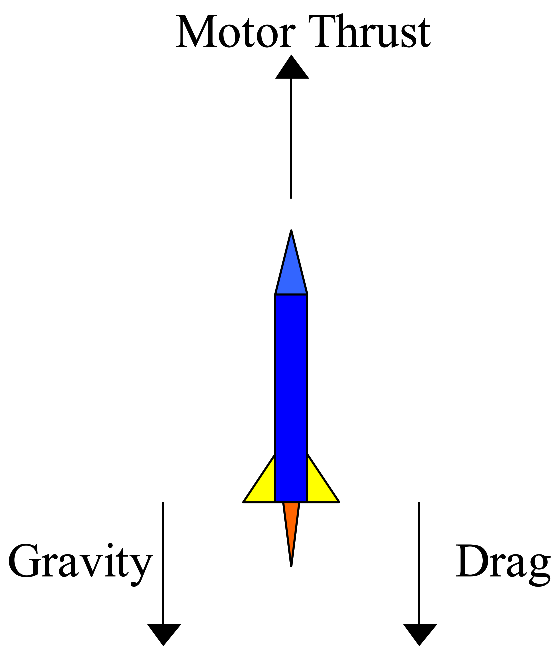

Figure 3. Forces on a rocket in flight.

The first step in developing a model is to examine the forces that act on a rocket in flight as shown in Figure 3. Gravity is always acting downward, and motor thrust is the force that propels the rocket skyward. Aerodynamic drag acts against the motor thrust to reduce altitude.

For the relatively low altitudes model rockets attain, gravity may be assumed to be constant. The simplest model assumes motor thrust is constant over the burn phase and ignores drag entirely. Newton's Second Law of Motion may be used to find the acceleration at any given time using the following equations

$$F_{motor} - F_{gravity} = ma \tag{1}$$

$$F_{motor} - mg = ma \tag{2}$$

$$\frac{F_{motor} - mg}{m} = a \tag{3}$$

where F_{motor} is the motor thrust, $F_{gravity}$ is the force of gravity, m is the mass of the rocket, g is the gravitational constant, and a is the acceleration of the rocket. The values in these equations change throughout the flight, so the model splits the flight into discrete segments in which the forces can be assumed to be constant. At each step, the rocket mass is reduced based on the amount of propellant that has burned, and the acceleration is calculated from equation (3). This acceleration is multiplied by the time interval to get the change in velocity, which is also multiplied by the time interval to get the change in altitude.

Two improvements need to be made to this model to bring it closer to reality: use the actual motor thrust curve and add drag. The equations now become

$$F_{motor} - \left(F_{gravity} + F_{drag}\right) = ma \tag{4}$$

$$F_{motor} - \left(mg + \frac{\pi}{8} \rho d^2 v^2 C_d \right) = ma \qquad (5)$$

$$\frac{F_{motor} - mg + \frac{\pi}{8} \rho d^2 v^2 C_d}{m} = a \qquad (6)$$

where ρ is the density of air, d is the diameter of the rocket, v is the velocity of the rocket, and C_d is the drag coefficient.

The results of the various simulations are shown in Figure 4, along with results calculated by wRASP and RockSim. As one would expect, the flight with no drag was significantly higher than the others. RockSim uses its own internal algorithms to estimate a drag coefficient of 0.55. Numerous test flights have shown this value to be too low. After specifying a more realistic value of 0.75, all three models achieve essentially the same result.

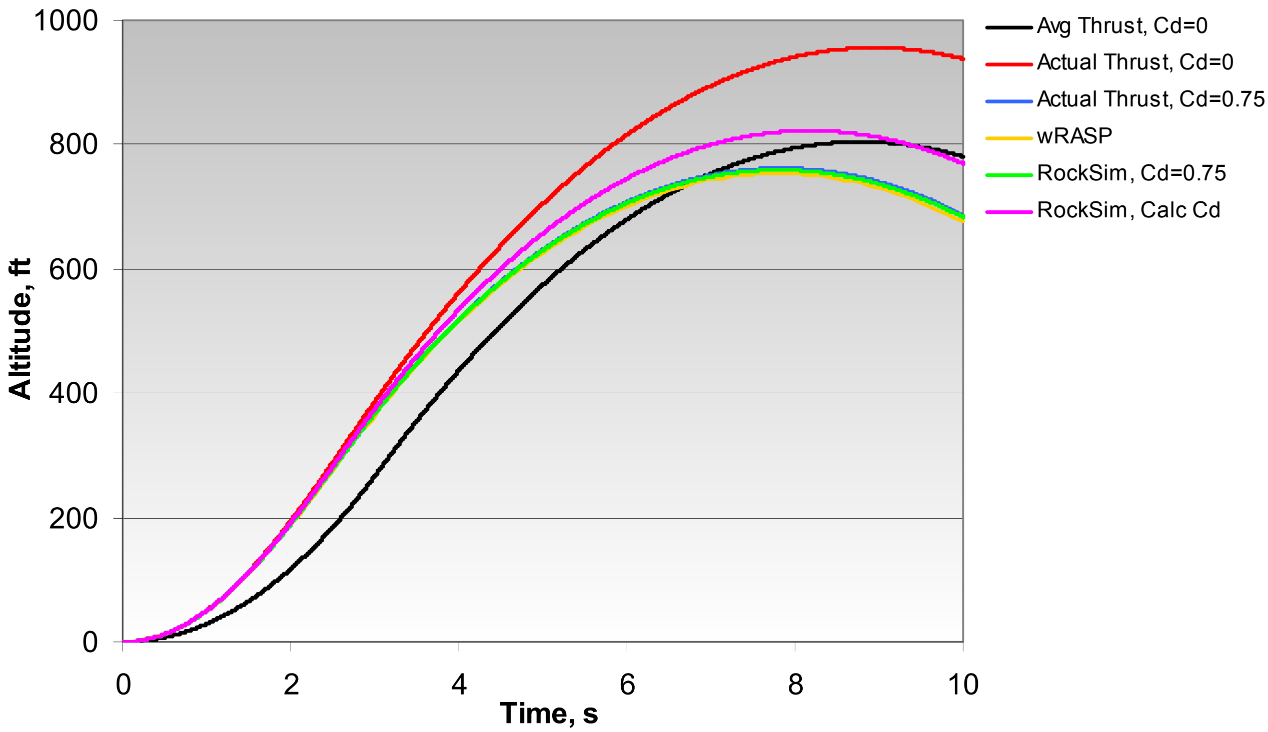

Figure 4. Comparison of various computer simulations

In-Flight Altimeter Comparison Setup

The primary objective of this project was to launch several different altimeters in a single rocket and compare the results to optical tracking. The first task was to procure the altimeters. The models used, along with various other relevant details, are listed in Table 2.

Table 2. Altimeter models used in flight tests.

Manufacturer	Model	Type	Trigger	ADC Resolution	Pyro Channels
AcceloRocket	AR250	accelerometer	G-switch	10-bit	apogee
Adept	A1	barometric	pressure	14-bit	
Adept	ALT05	barometric	pressure	16-bit	
Adept	ALT1R	barometric	pressure	14-bit	
Adept	RA2	barometric	G-switch	16-bit	
AED Electronics	R-DAS Compact	hybrid	G-switch	10-bit	apogee, 500 ft
G-Wiz	LC	accelerometer	G-switch	8-bit	apogee
G-Wiz	MC	hybrid	G-switch	12-bit	apogee, 400 ft
MissileWorks	RRC2X	barometric	pressure	8-bit	apogee, 500 ft
PerfectFlite	MA4A	barometric	pressure	14-bit	apogee, 300 ft
Transolve	P3000	barometric	pressure	8-bit	apogee, 600 ft

Several of the models used include circuitry to fire ejection charges at apogee and/or a preset altitude. Since the R-DAS has two extra analog input channels, a separate component was developed to record a total of 8 signals from those pyro channels. The circuit diagram is shown in Figure 5. On each altimeter, a 10Ω, 1W resistor was connected across the pyro channel outputs. The positive and negative terminals are normally both at the battery voltage. When the channel fires, the negative terminal drops to ground to fire the charge. This signal was first sent through a 5V Zener diode for voltage regulation, then into an inverter. The resulting 8 TTL signals were converted to 2 analog signals using a pair of 8-bit digital-to-analog converters. Only the 4 most significant bits were used to ensure adequate resolution of the analog signal. The 2 analog signals were then fed to the R-DAS for recording.

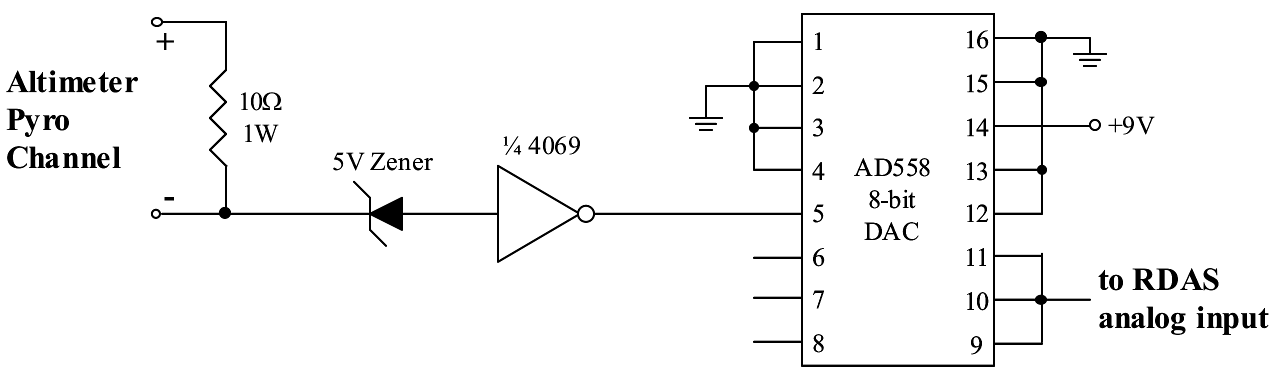

Figure 5. Digital-to-analog circuit to record altimeter events

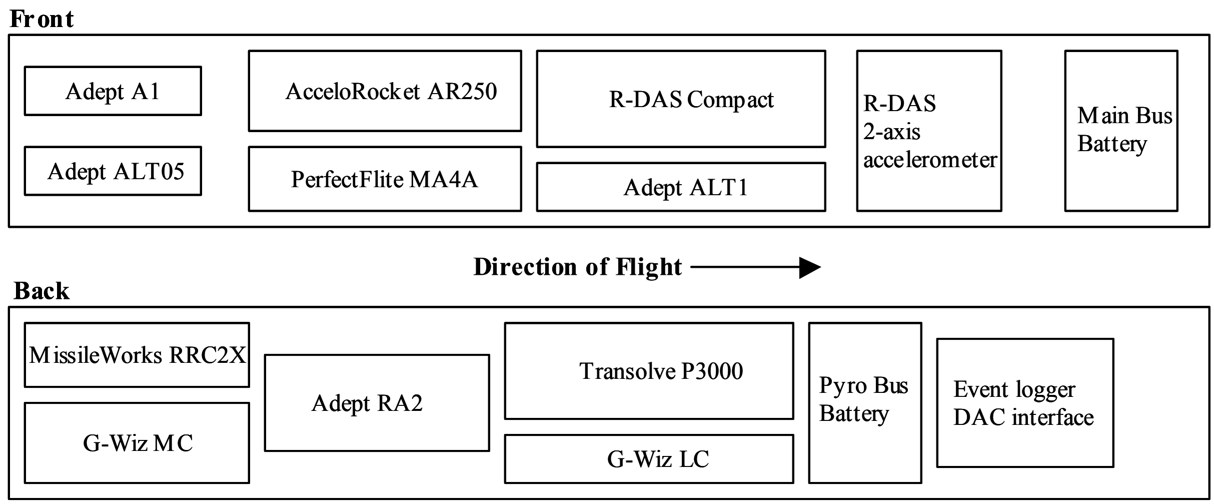

Figure 6. Layout of electronics payload.

The altimeters were mounted front and back to a piece of 2.5x24x1/8” basswood for support, as shown in Figure 6. Power to all of the 9V components was supplied by a single NiMH battery pack. A separate 9V alkaline battery supplied power to the pyro charges. Individual 12V alkaline batteries powered the Adept A1, ALT05, and ALT1. The entire board was inserted into a 2.6” diameter payload bay, vented by 4 ¼” holes. After each flight, the board was removed from the payload bay to allow easy access to all of the altimeters for recording data.

For each of the test flights, the rocket was launched vertically using either a G40-7 or G80-7 single-use motor. Winds were generally less than 5 m/s and did not affect the flight profile. Each flight was tracked to apogee using one or more sets of optical scopes. A summary of the flight data is shown in Table 3. Graphs of the full flight data and detail of the apogee area from each flight are shown as Figures A1 – A26 in Appendix A. The simulations were only calculated for the first flight, so they are omitted on all others. Results from the AcceloRocket AR250, Adept ALT1, and Transolve P3000 are also omitted due to persistent problems reading data. Noise from the R-DAS raw data was smoothed by computing a running average of altitudes over a 0.1 second range.

Table 3. Summary of flight data.

Flight	Date	Location	Motor	Baseline (m)	Comments
1	4/20/2002	The Plains, VA	G40-7	267	Straight up
2	6/8/2002	Middletown, MD	G40-7	300	Tipped 20°
3	6/15/2002	Center Valley, PA	G40-7	150	Tipped 10°
4	6/15/2002	Center Valley, PA	G40-7	150	Catastrophic motor failure
5	8/5/2002	McGregor, TX	G40-7	472 (average of 6)	Tipped 5°
6	8/6/2002	McGregor, TX	G40-7	472 (average of 6)	Straight up
7	8/6/2002	McGregor, TX	G40-7	472 (average of 6)	Payload board ejected
8	10/5/2002	Jonesburg, PA	G80-7	217	Tipped 5°
9	10/5/2002	Jonesburg, PA	G80-7	217	No parachute deployed
10	8/5/2003	Evansville, IN	G80-7	342	Nice roll on boost
11	8/5/2003	Evansville, IN	G80-7	342	Straight up
12	8/6/2003	Evansville, IN	G80-7	342	Straight up
13	8/6/2003	Evansville, IN	G80-7	342	Straight up
14	8/6/2003	Evansville, IN	G80-7	342	Straight up

Discussion of Flight Results

Flight 1 was the first full-scale launch with all components operating. All of the altimeters and optical tracking were in general agreement of 750 ± 25 feet at apogee. Optical tracking reported the highest altitude, but the 3.1% closure range overlapped with altitudes reported by RRC2X and ALT05. All three simulations showed excellent agreement to the measured altitude after forcing Cd to be 0.75. Parachute deployment was late, as evidenced by the rapid descent to 600 feet.

Flight 2 tipped about 20° from vertical during flight and arced toward the tracking baseline. This may help explain the poor closure of 10.1%. It is not enough, however, to explain the very low reading from the LC. Since the LC measures altitude using only an accelerometer, it is expected to report low for a non-vertical flight. The error on 20° from vertical is only 6%, but the LC reported 20% below average. Excluding results from optical and LC, apogee was 630 ± 17 feet. The sharp drop in reported altitude by then R-DAS and MC just before apogee was caused by slight pressurization of the payload compartment by the ejection gases.

Flight 3 had a tip of about 10° away from the baseline and showed excellent agreement among all of the altimeters. The optical measurement was low, but with good closure of 2.4%. This difference could come from various factors such as an improper baseline measurement or trackers not being zeroed. Excluding optical, apogee was 780 ± 11 feet.

Flight 4 suffered a catastrophic failure of the motor on ignition. The motor burned through the casing and destroyed the lower half of the rocket. None of the electronics were affected.

Flight 5 (with a rebuilt lower half) was another typical launch. Optical was higher than all of the altimeters, and again had a good closure of 2.9%. Excluding optical, apogee was 770 ± 18 feet.

Flight 6 was on the same range, with the same baselines as Flight 5. This time, optical was slightly lower than the altimeters, though the 2.1% closure does overlap. The RRC2X gave an unexplained high reading. Excluding RRC2X, apogee was 850 ± 18 feet.

Flight 7 was again on the same range, and again optical was higher than all altimeters. To add to the excitement on this flight, the nose cone came off at apogee, allowing the altimeter board to slide out of the payload bay and fall freely. It landed in grass and suffered only minor damage. Several of the mounting posts broke off of the board, and one wire disconnected from the LC, but the other components survived with no damage. Excluding optical, apogee was 820 ± 15 feet.

Flight 8 (with a rebuilt altimeter board) again showed excellent agreement among all of the altimeters. Optical was very high, with a poor closure of 14.3%. Excluding optical, apogee was 860 ± 20 feet.

Flight 9 had much better optical closure and agreement with altimeters, with the exception of RRC2X, which was inexplicably high again. No data was collected for the RA2 because it was not turned on. The parachute failed to deploy, resulting in a very hard landing. The payload section was badly crimped, and the altimeter board cracked in one place, but none of the altimeters suffered any damage. Excluding RRC2X, apogee was 780 ± 22 feet.

Flight 10 had several problems with the altimeters. No data was collected for the RA2 because it was not turned on. The LC and MA4A also had no data for unknown reasons. Those that did report were in fair agreement, with the RRC2X and optical high again, but not unreasonably so. Apogee was 1020 ± 26 feet.

Flight 11 again had the RRC2X and optical readings higher than all the other altimeters. No data was available for the ALT05 for unknown reasons. Excluding the RRC2X and optical, apogee was 980 ± 17 feet.

Flight 12 finally had all the altimeters working, and once again showed the RRC2X and optical readings higher than all the other altimeters. The RA2 had a constant offset of about -30 feet relative to the R-DAS and MC. This may have been caused by an inaccurate baseline reading prior to launch. Excluding the RRC2X and optical, apogee was 1000 ± 16 feet.

Flight 13 again had the RRC2X and optical readings higher than all the other altimeters. No data was available for the MA4A for unknown reasons. The recording altimeters (RA2, R-DAS, and MC) measured a decreased descent rate between T+20 and T+30 seconds, likely the result of thermal activity. Excluding the RRC2X and optical, apogee was 980 ± 12 feet.

Flight 14 continued the trend of the RRC2X and optical readings higher than all the other altimeters. It is interesting to note that the RRC2X reported exactly the same altitude for Flights 10 – 14. On-field tests showed that the altimeter was working properly and was reporting other altitudes in vacuum tests. Excluding the RRC2X and optical, apogee was 950 ± 10 feet.

Of all the altimeters, the A1 and ALT05 appeared to be the most consistent among all flights. To measure the variability of the measurements, each apogee altitude was divided by the average altitude reported by the A1 and ALT05. The relative altitude and standard deviations of each measurement method are shown in Figure 7. As was noted in the flight discussion, optical and RRC2X were consistently higher than average. The LC was consistently low, possibly due to non-vertical flights and/or calibration errors. All of the other altimeters were within 2% of the average. The A1 and ALT05 were consistently low and high, respectively. This observation will be investigated further in the next section.

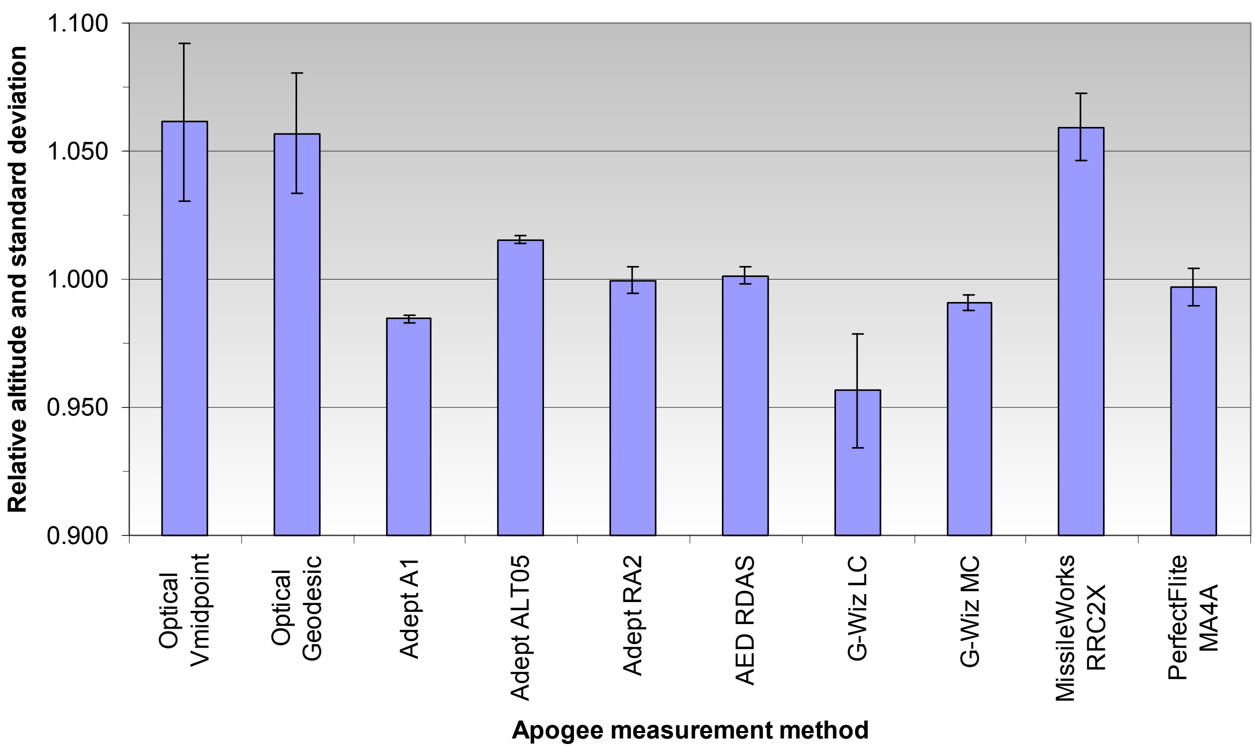

Figure 7. Relative altitude and standard deviation of each measurement method.

Vacuum Chamber Tests

Based on the results shown in Figure 7, additional tests were performed in a more controlled environment using a vacuum chamber. The A1, ALT05, and RRC2X altimeters were chosen for these tests because they are all barometric based and also trigger on pressure change. The altimeters were placed in the chamber, and the vacuum pump was activated for 2 seconds to simulate an altitude of approximately 3000 feet, the maximum range of the A1. A total of 20 runs were completed, with the results shown in Table 4.

Note that the RRC2X reports discrete altitudes of 2729, 2830, 2931, 3032, 3133, and 3239 feet. This clearly demonstrates the lack of precision of the 8-bit ADC used to read the barometric pressure sensor. It also explains why the RRC2X read the same altitude for flights 10 – 14. Clearly, greater than 8-bit precision is needed to report altitudes to better than 100-foot resolution. The A1 and ALT05 use 14-bit and 16-bit ADCs, respectively, and these appear to give satisfactory resolution.

To compare the differences on the three altimeters, each altitude was divided by the average, with results shown in Figure 8. These tests confirm the results shown in Figure 7, where the RRC2X reads higher than the ALT05, which is higher than the A1. Readings from the A1 and ALT05 appear to be correlated, but the RRC2X is not. Repeating the analysis without the RRC2X highlights the differences even better in Figure 9. The average relative altitudes reported by the ALT05 and A1 are 1.019 +/- 0.002 and 0.981 +/- 0.002, respectively. Based on these results, there is a repeatable calibration difference of 3.8 +/- 0.2% between the ALT05 and A1.

Table 4. Reported altitudes in feet from vacuum chamber tests.

Run	Adept A1	Adept ALT05	MissileWorks RRC2X
1	2835	2963	3032
2	2630	2743	2830
3	2545	2643	2729
4	2940	3048	3239
5	2750	2853	3032
6	2835	2928	3133
7	2665	2773	2931
8	2830	2943	3133
9	2960	3078	3239
10	2750	2858	3032
11	2815	2933	3032
12	2855	2963	3133
13	2775	2878	3032
14	2915	3013	3133
15	2785	2893	3032
16	2885	2987	3133
17	2830	2948	3133
18	2930	3033	3239
19	2805	2913	3032
20	2825	2953	3133

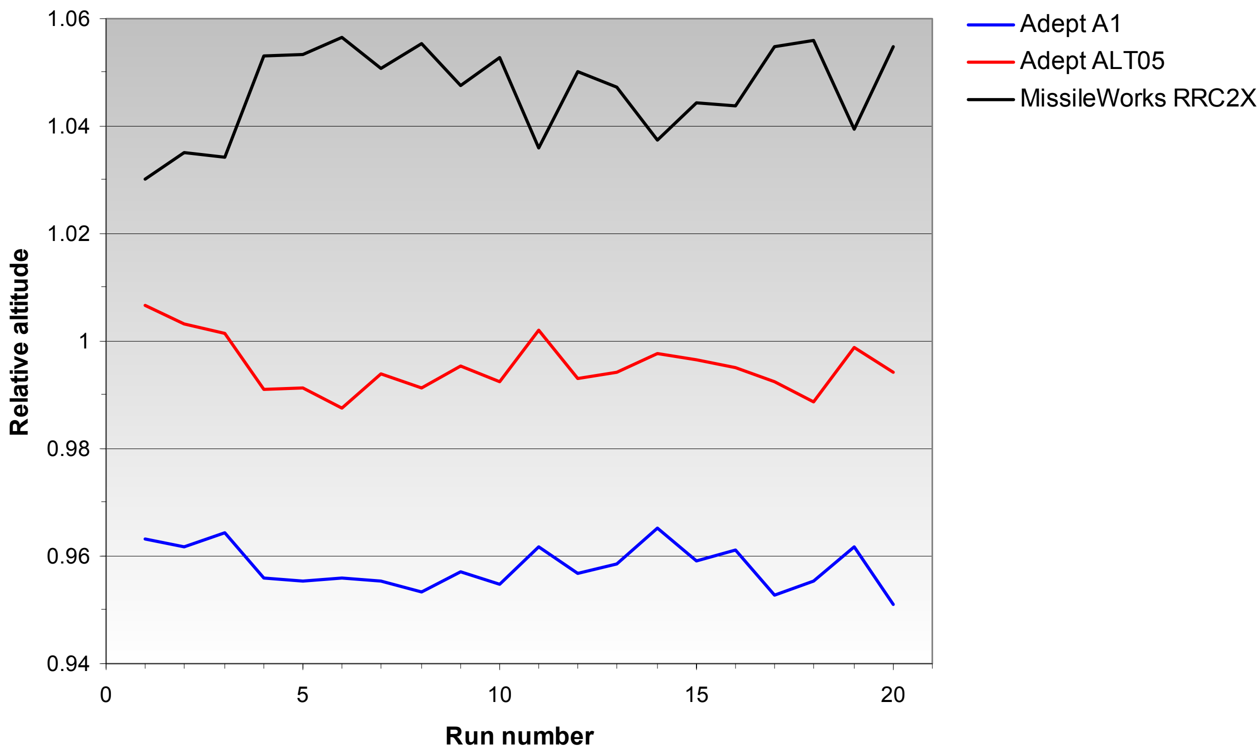

Figure 8. Relative altitudes reported in vacuum chamber tests.

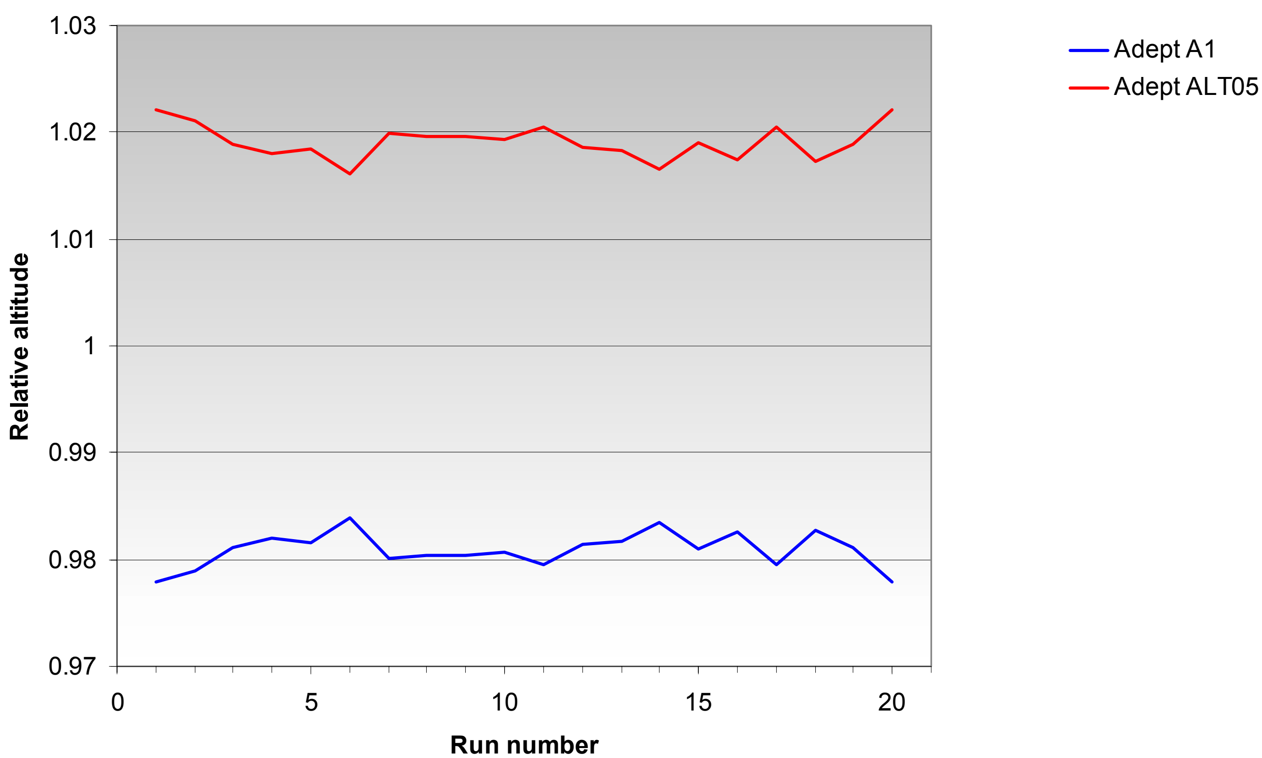

Figure 9. Relative altitudes reported in vacuum chamber tests, excluding RRC2X.

Conclusions

Through a series of flight tests, results from various altimeters were compared to optical tracking and computer simulations. The simulations proved to be very close to reality, after specifying a reasonable C_d of 0.75. Altimeters with only 8-bit ADCs (G-Wiz LC and MissileWorks RRC2X) had significantly lower accuracy and precision than those with higher resolution ADCs. Of the altimeters with at least 12-bit ADCs, results were all within 3% of average, with standard deviations of 2% or less over 13 flights. These results are far better than the allowed 10% error for optical tracking and show that altimeters should be allowed for altitude measurements in competition. One possible problem, however, is in calibration differences in individual altimeters. In altitude competition, the altimeter that consistently reads high will obviously be preferred over one that reads low. Using altimeters only in precision altitude events would be a compromise solution.

References

Hoffmann-Wellenhof, B. H. and Collins, J. (1994) *GPS: Theory and Practice,* 3rd ed., Springer-Verlag, New York.

Stine, G. Harry (1994). *Handbook of Model Rocketry*, 6th ed., John Wiley & Sons, New York.

Appendix A

Graphs of Flight Data

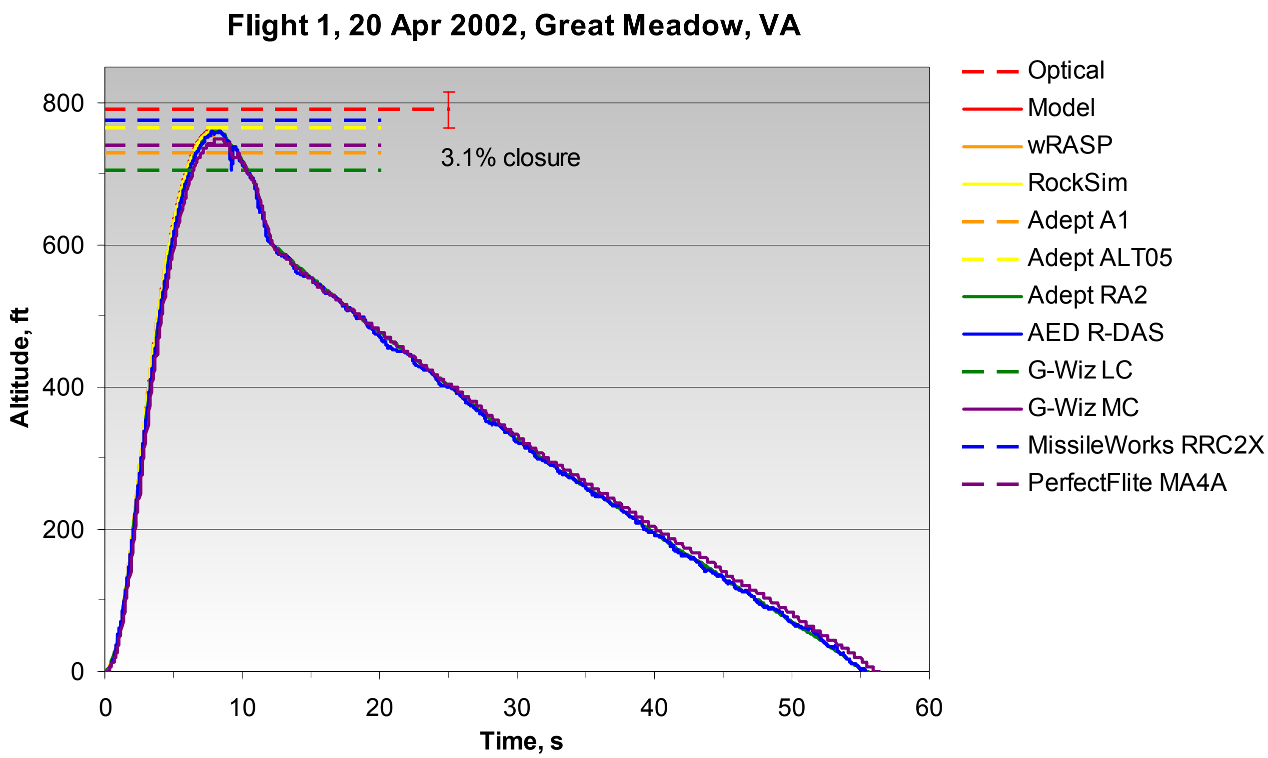

Figure A1. Flight 1 results from altimeters, optical tacking, and computer simulations.

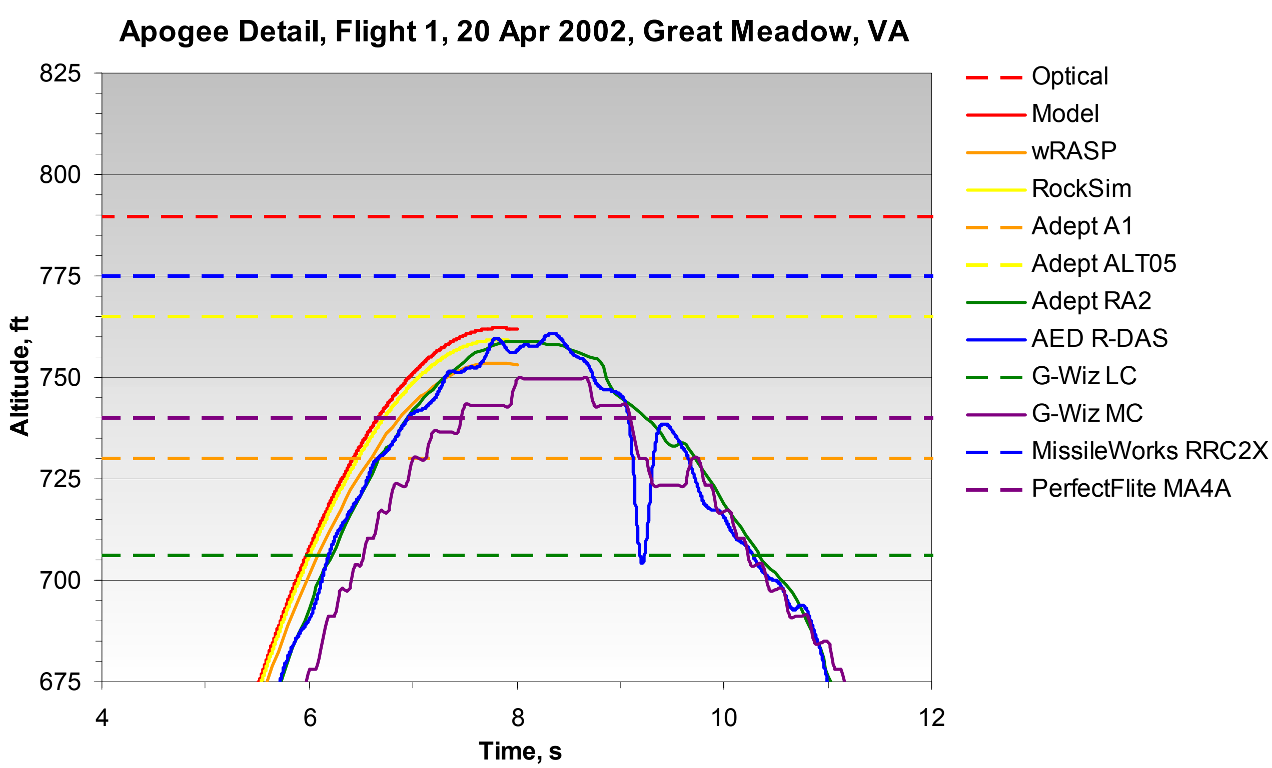

Figure A2. Apogee detail of flight 1 results.

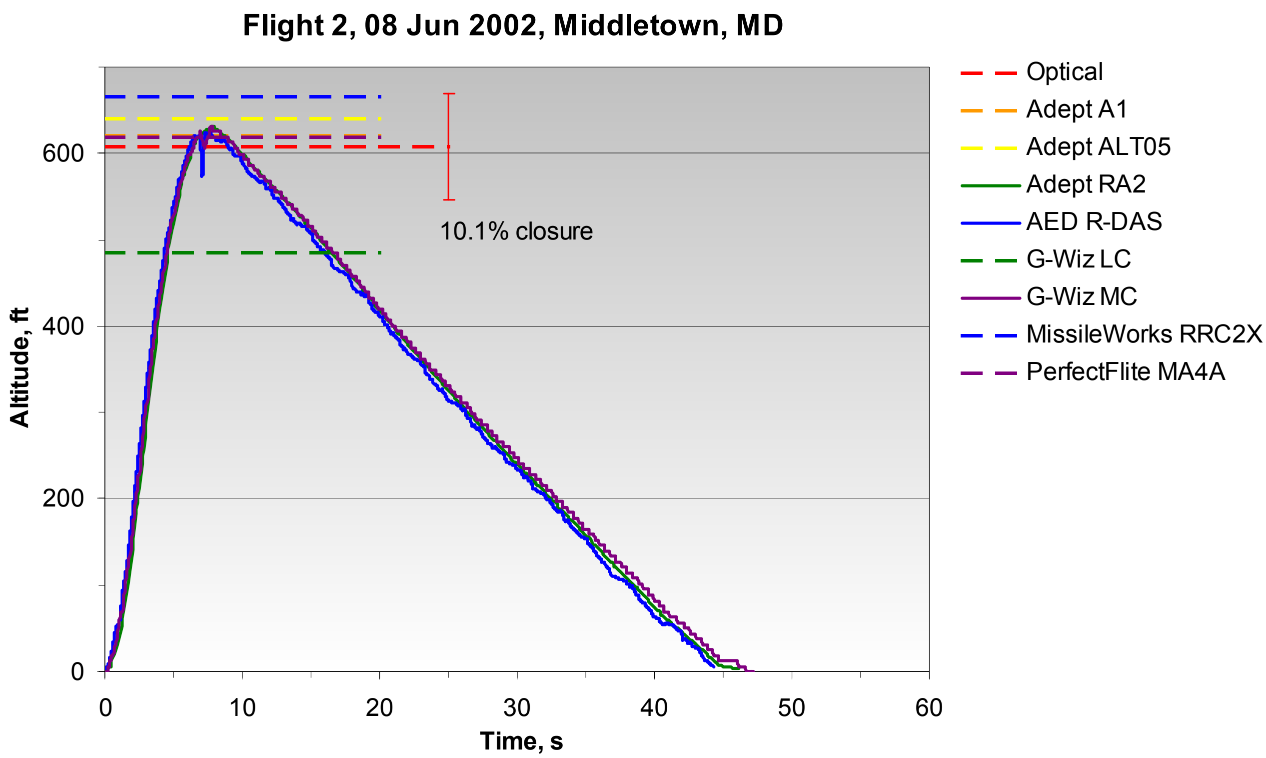

Figure A3. Flight 2 results from altimeters and optical tracking.

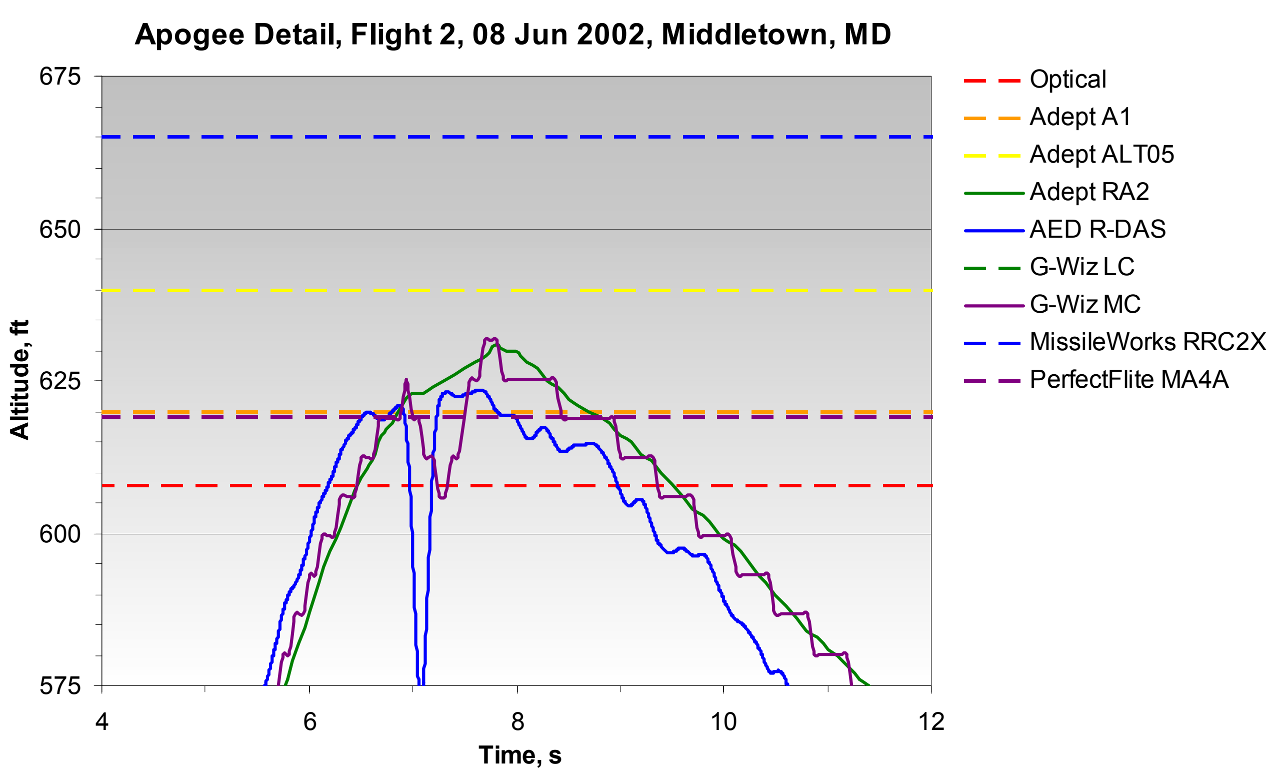

Figure A4. Apogee detail of flight 2 results.

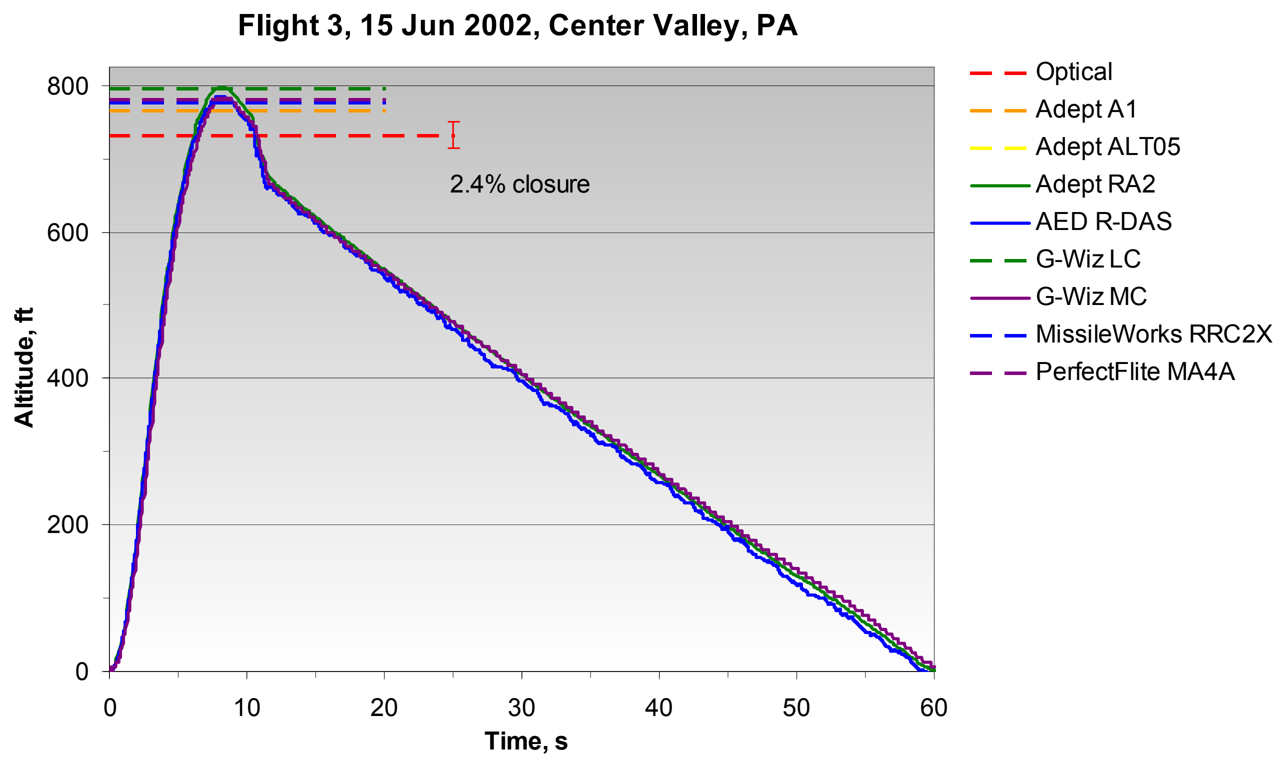

Figure A5. Flight 3 results from altimeters and optical tracking.

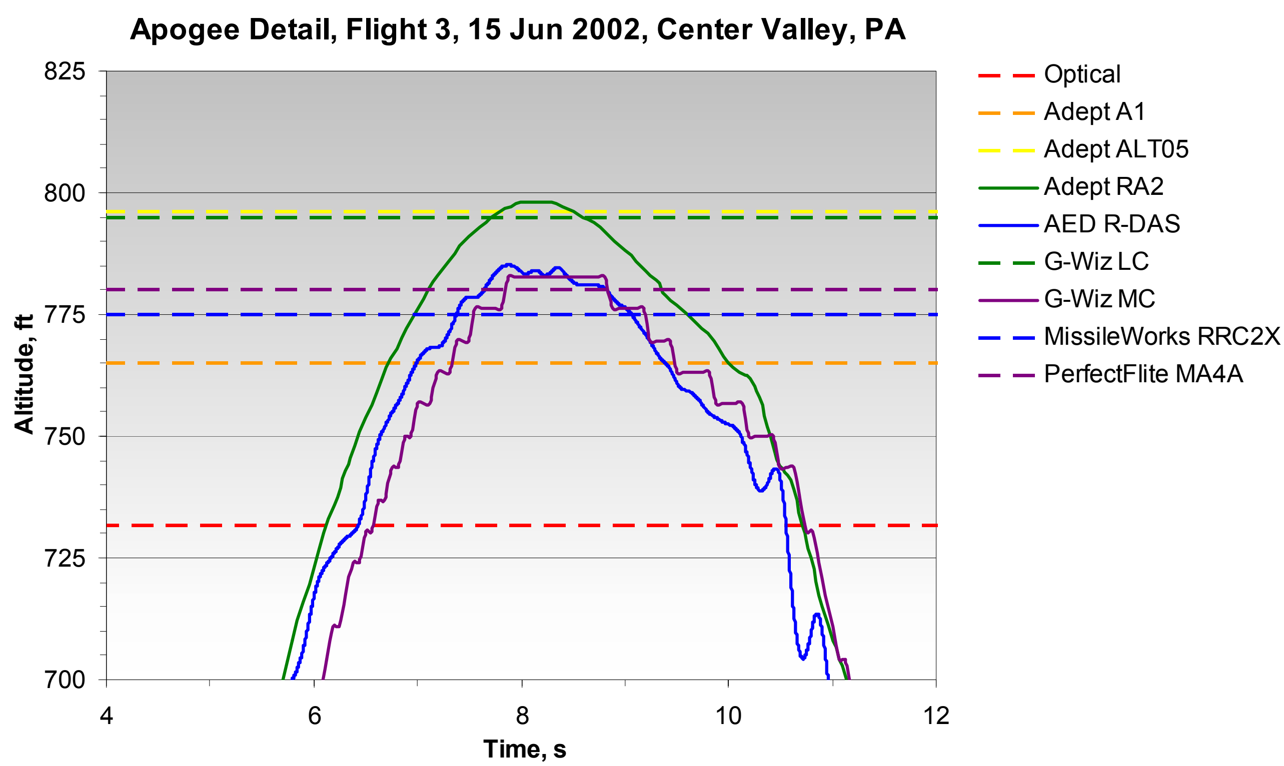

Figure A6. Apogee detail of flight 3 results.

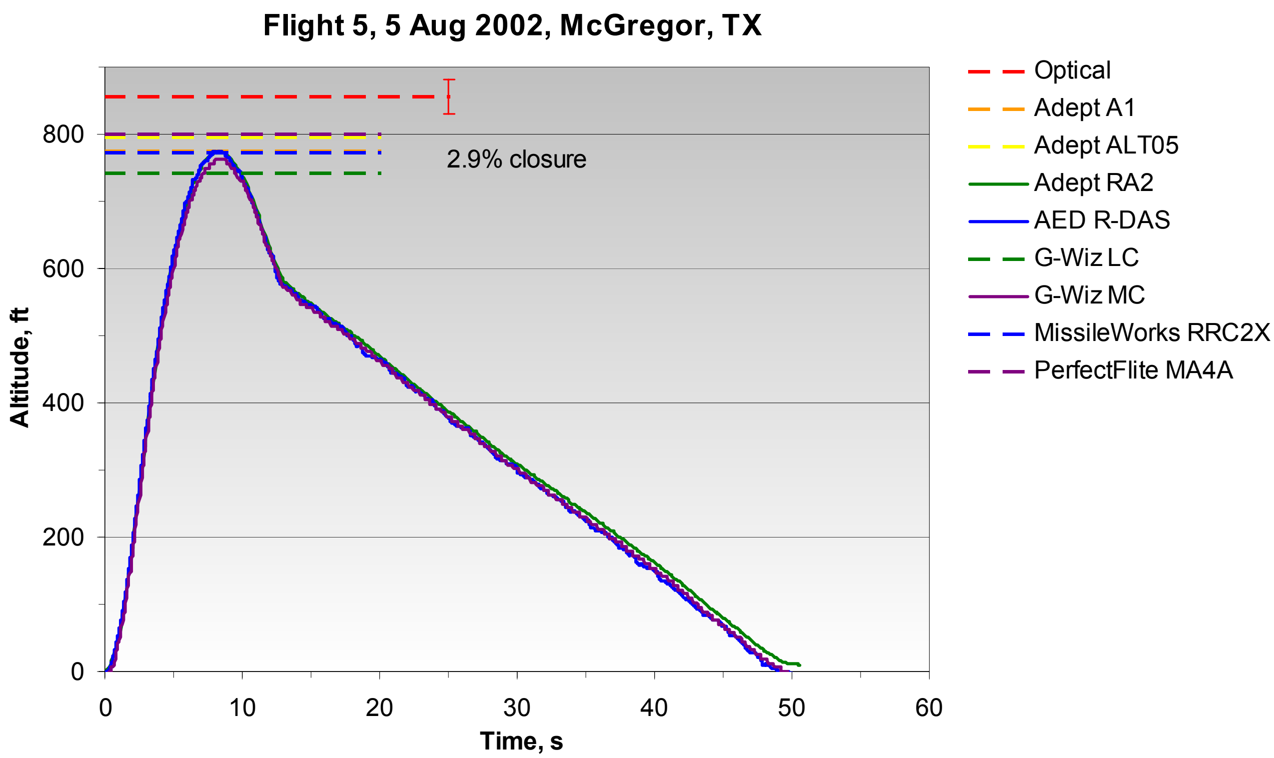

Figure A7. Flight 5 results from altimeters and optical tracking.

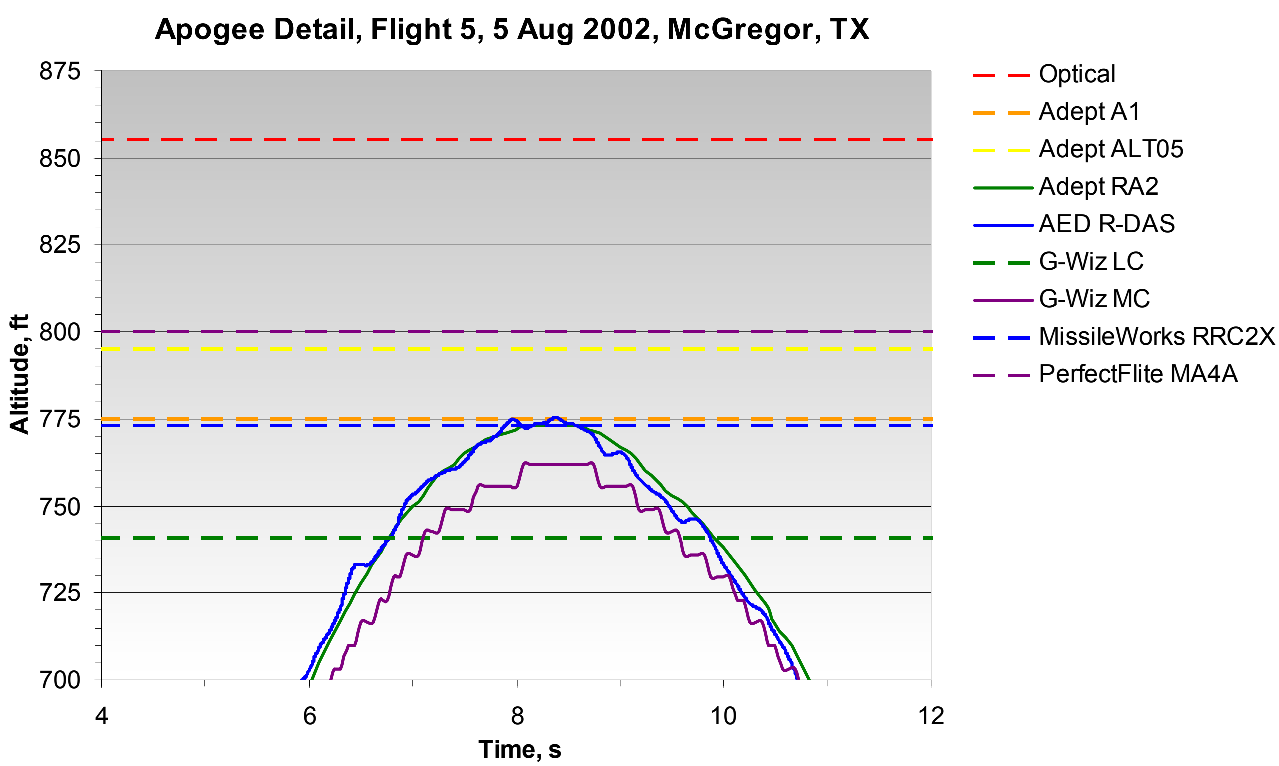

Figure A8. Apogee detail of flight 5 results.

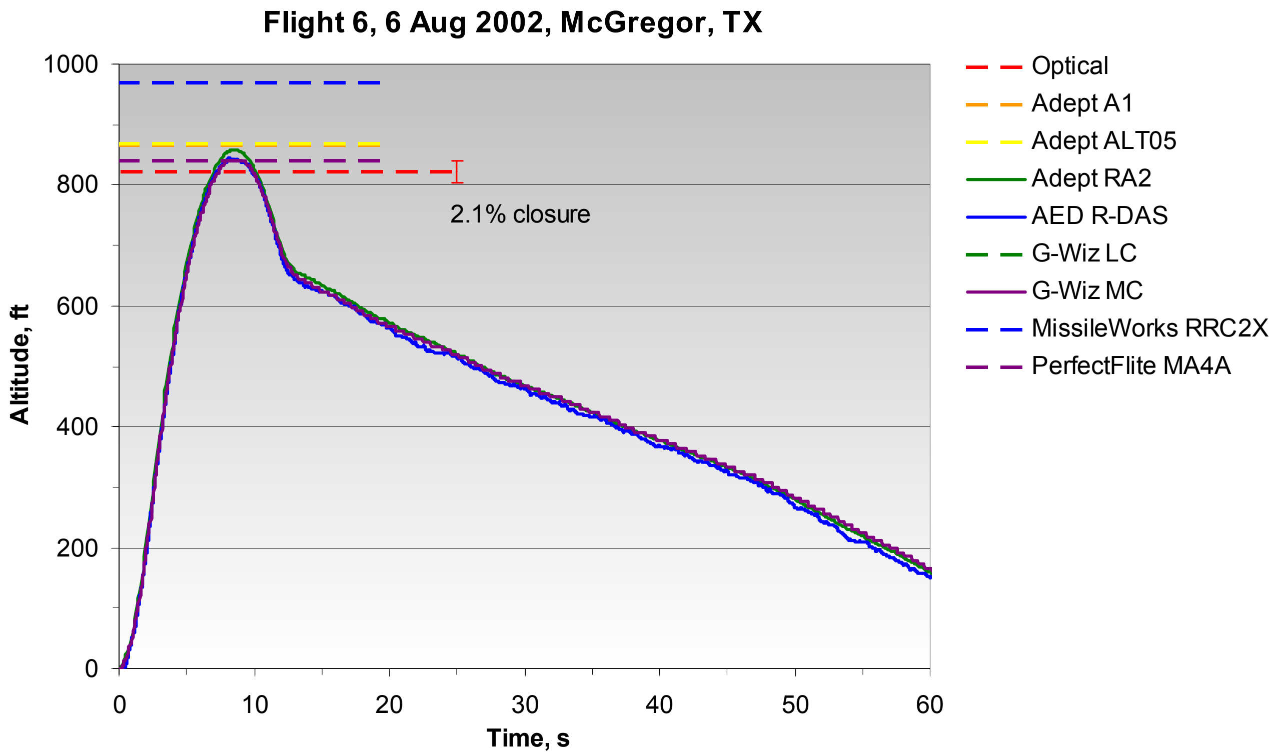

Figure A9. Flight 6 results from altimeters and optical tracking.

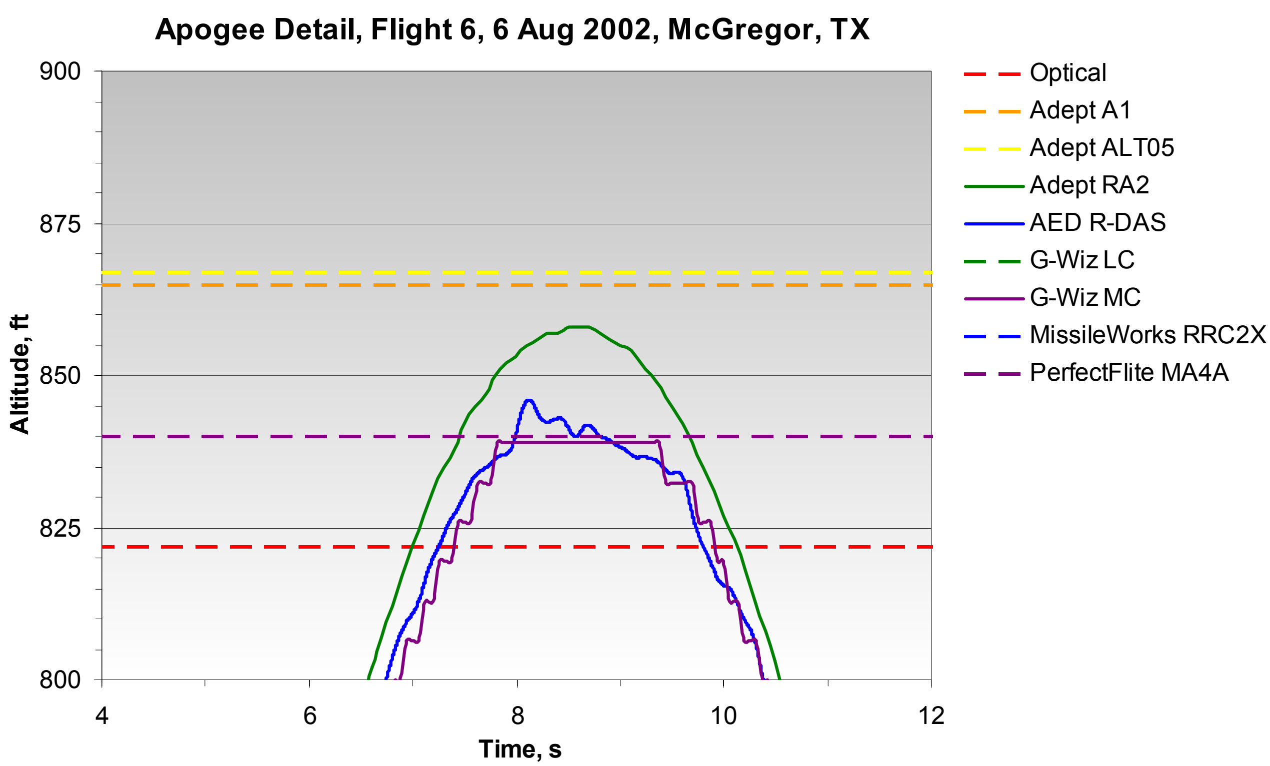

Figure A10. Apogee detail of flight 6 results.

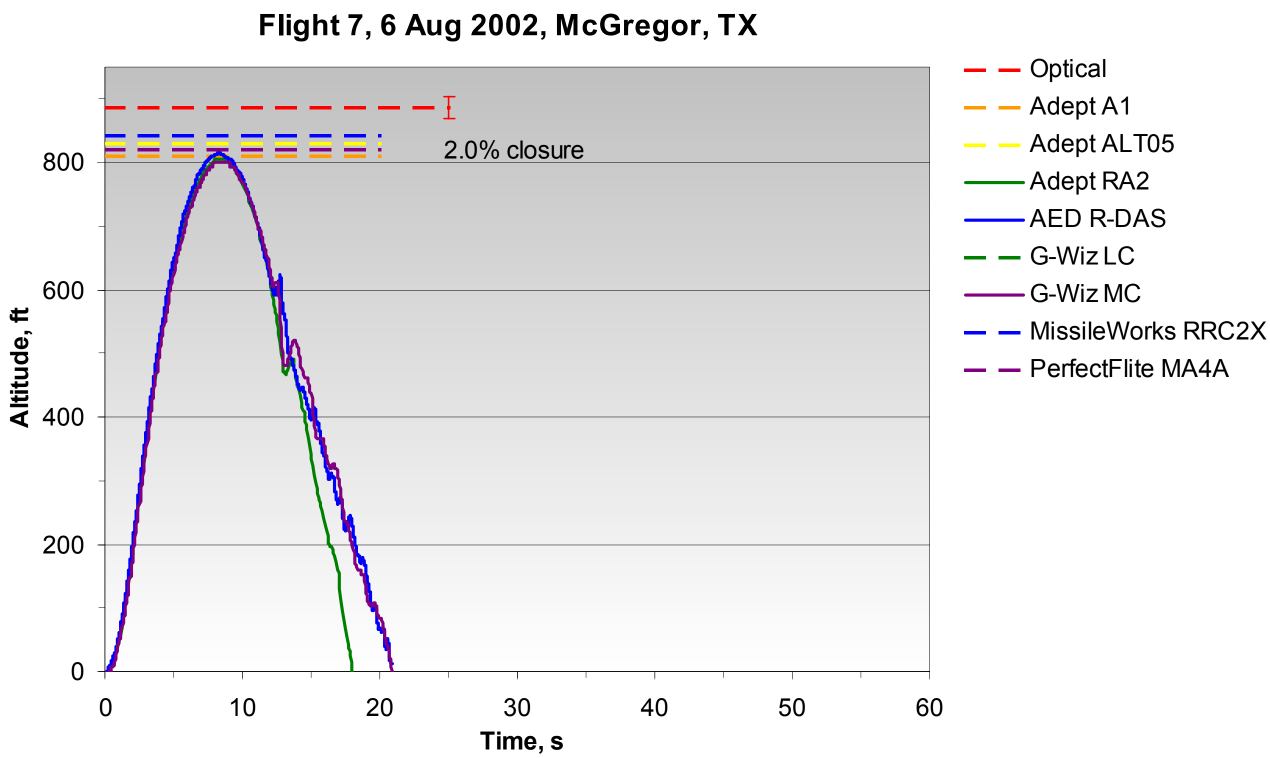

Figure A11. Flight 7 results from altimeters and optical tracking.

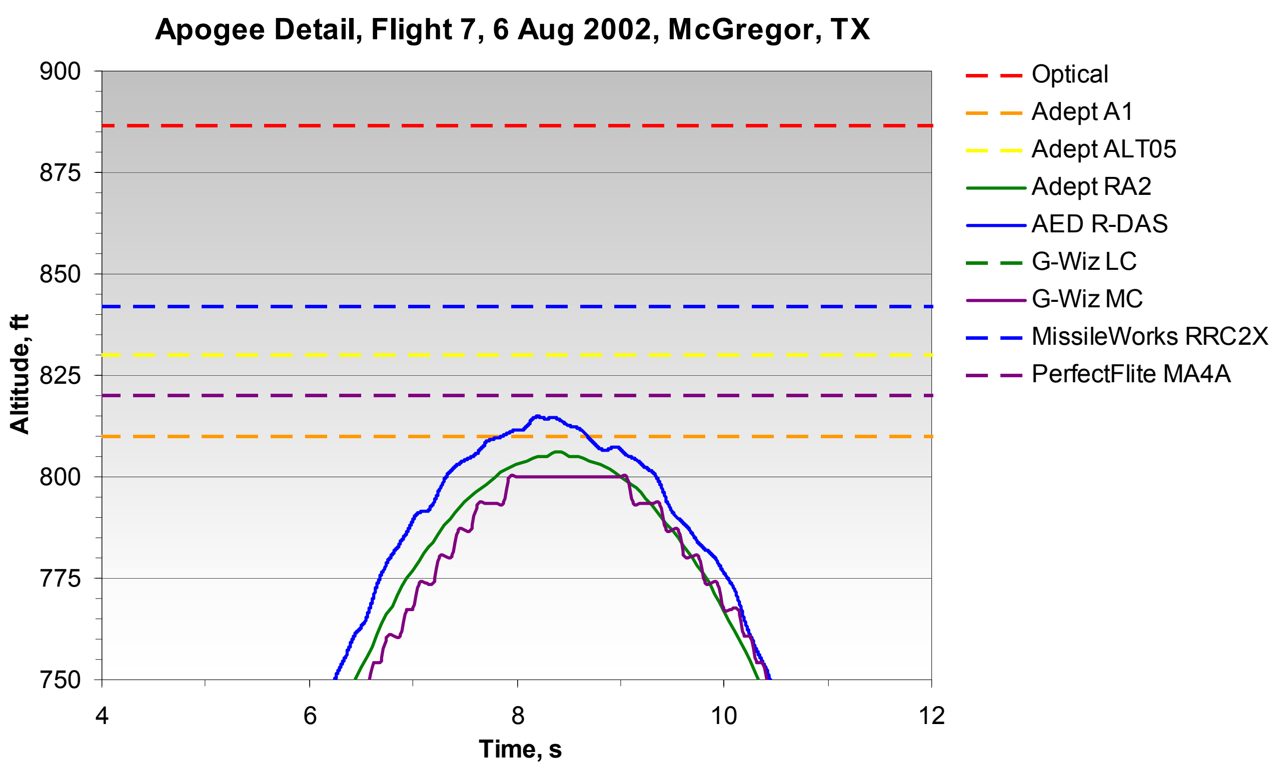

Figure A12. Apogee detail of flight 7 results.

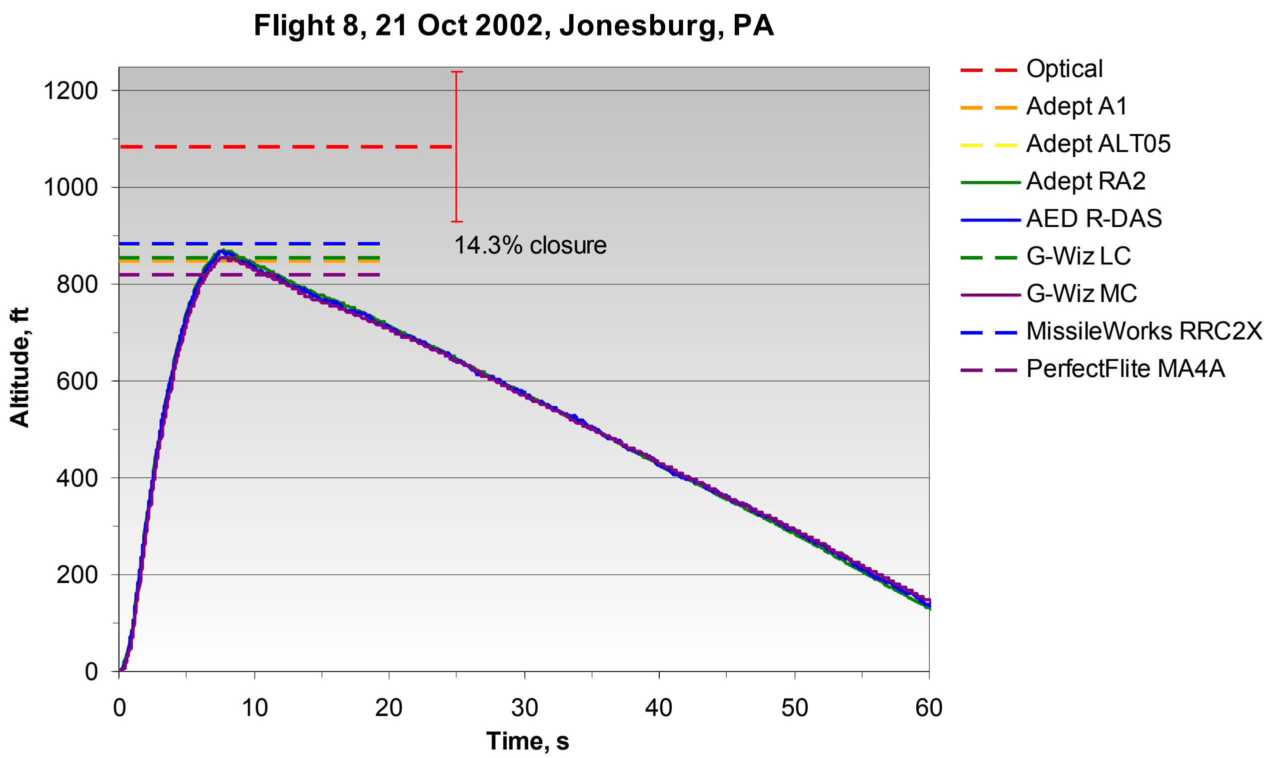

Figure A13. Flight 8 results from altimeters and optical tracking.

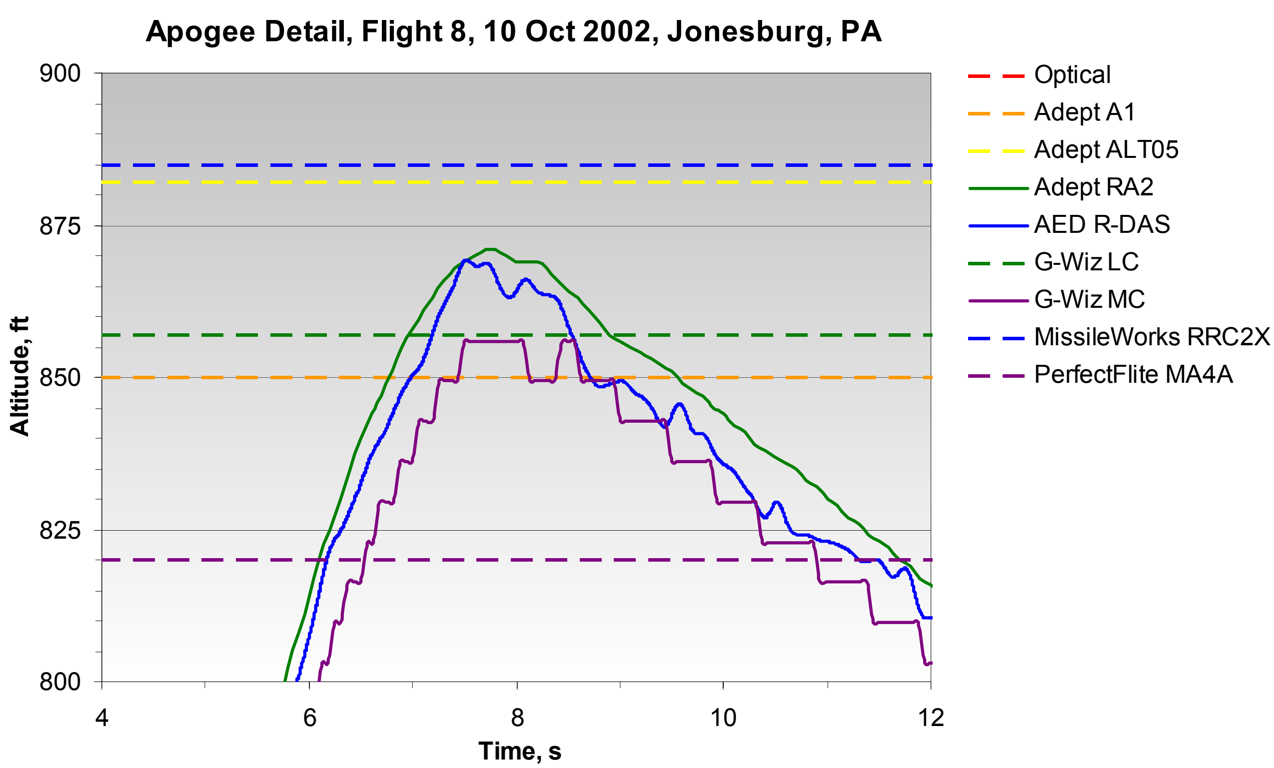

Figure A14. Apogee detail of flight 8 results.

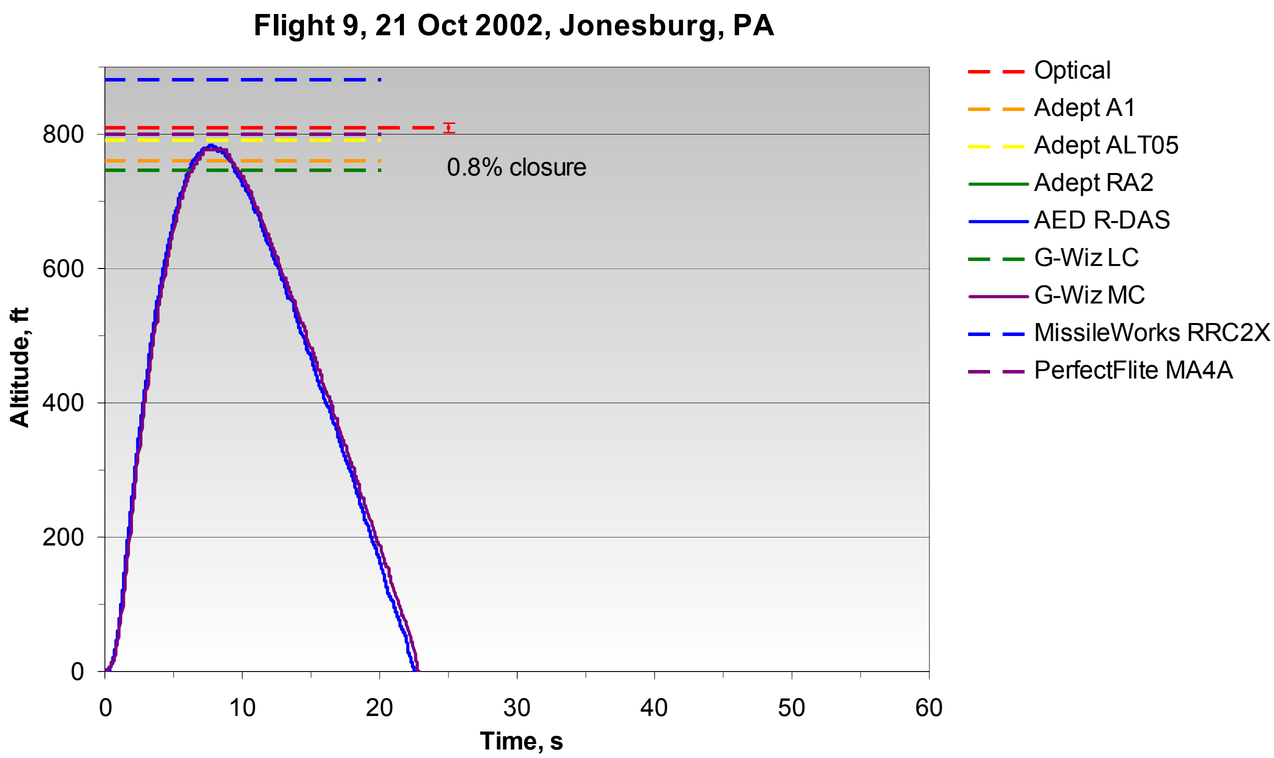

Figure A15. Flight 9 results from altimeters and optical tracking.

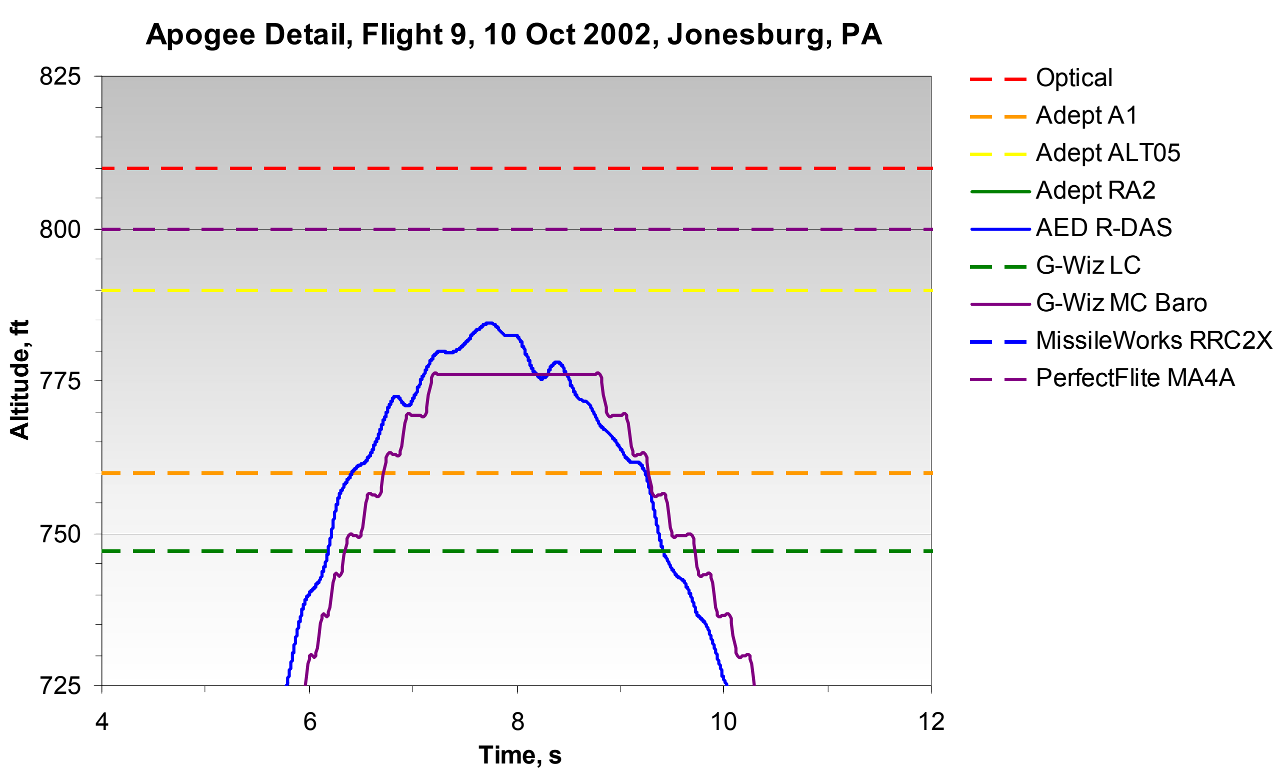

Figure A16. Apogee detail of flight 9 results.

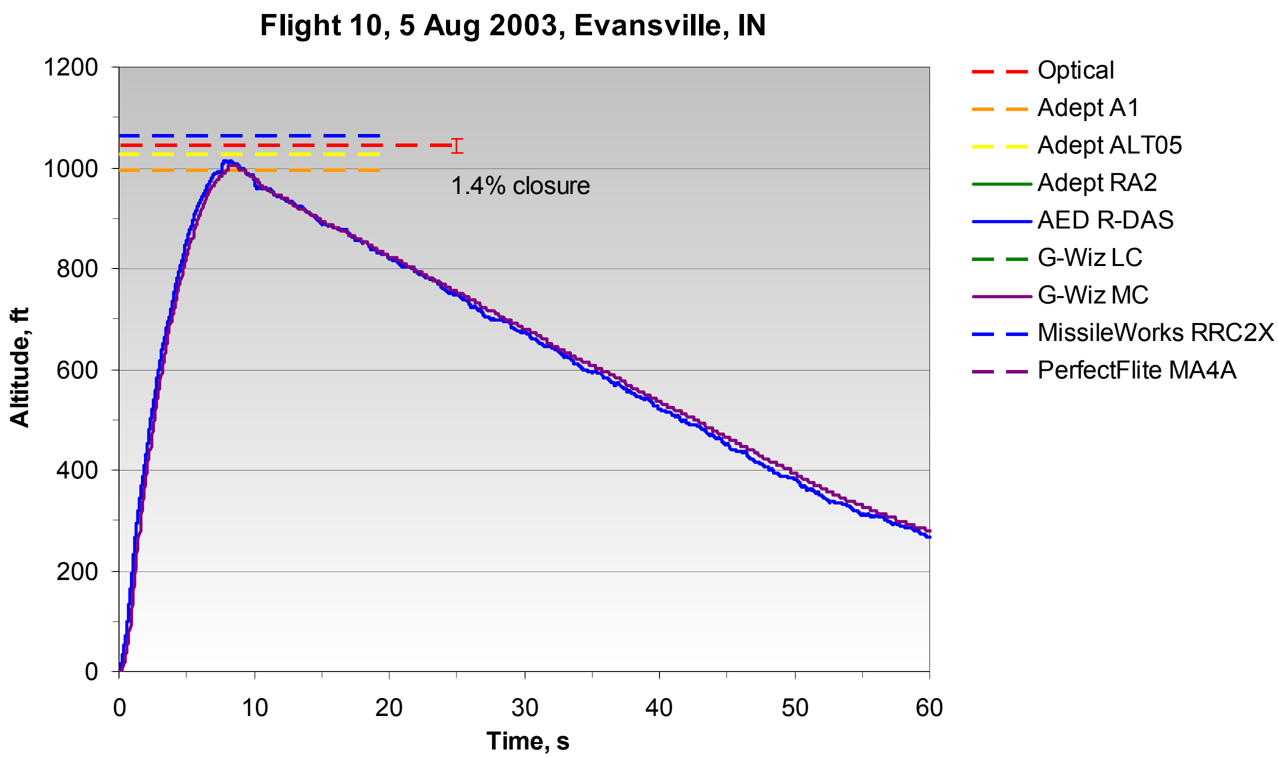

Figure A17. Flight 10 results from altimeters and optical tracking.

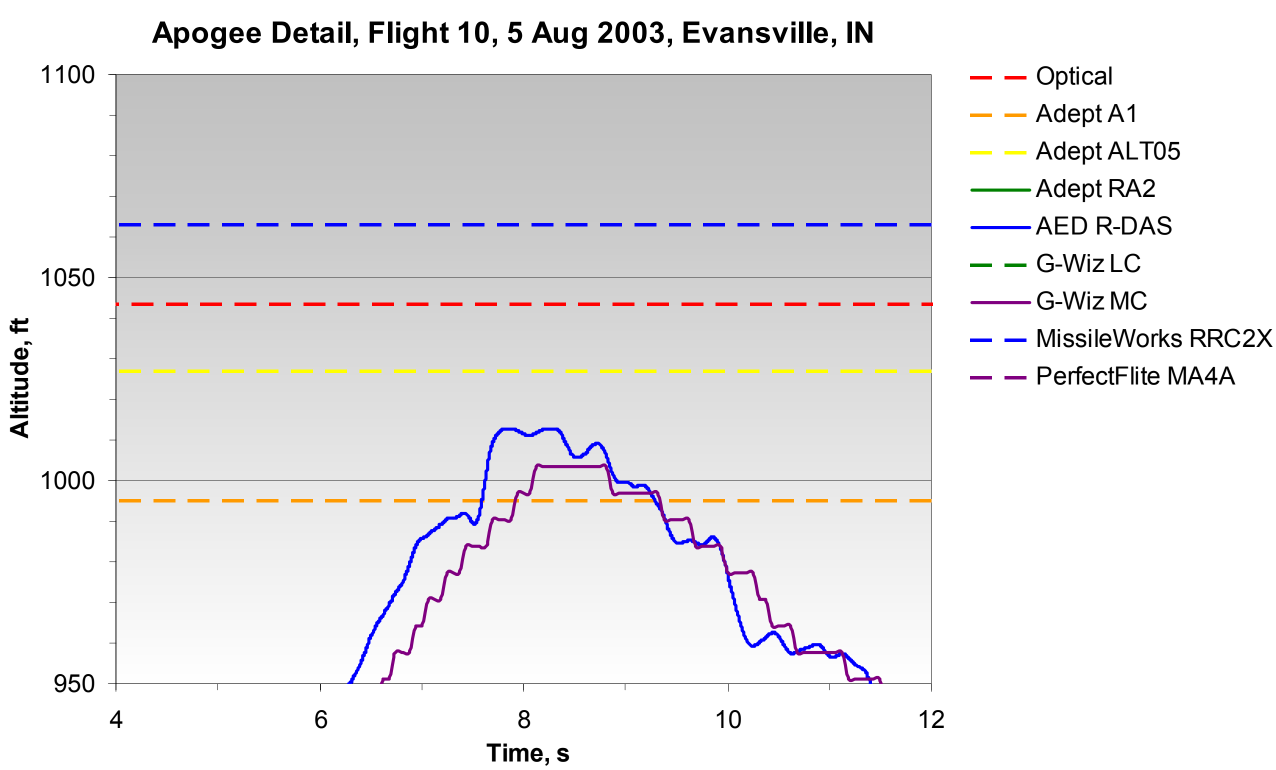

Figure A18. Apogee detail of flight 10 results.

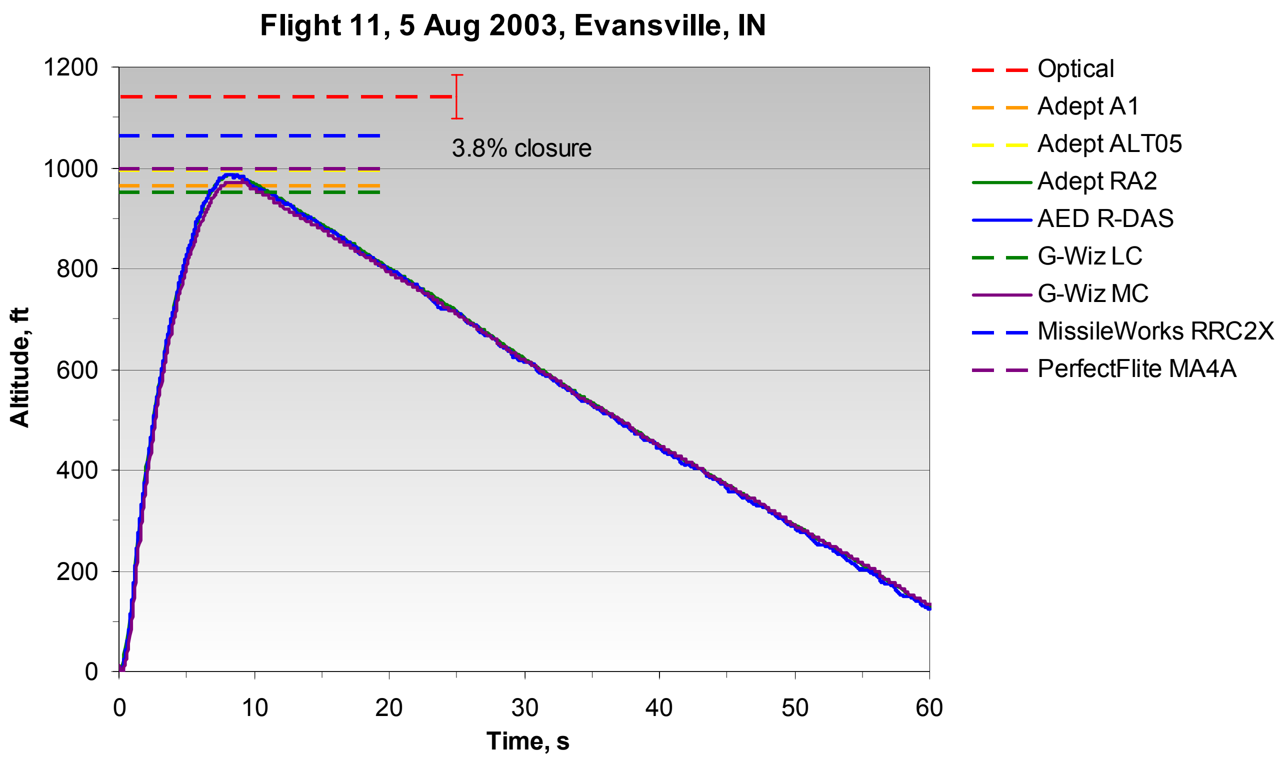

Figure A19. Flight 11 results from altimeters and optical tracking.

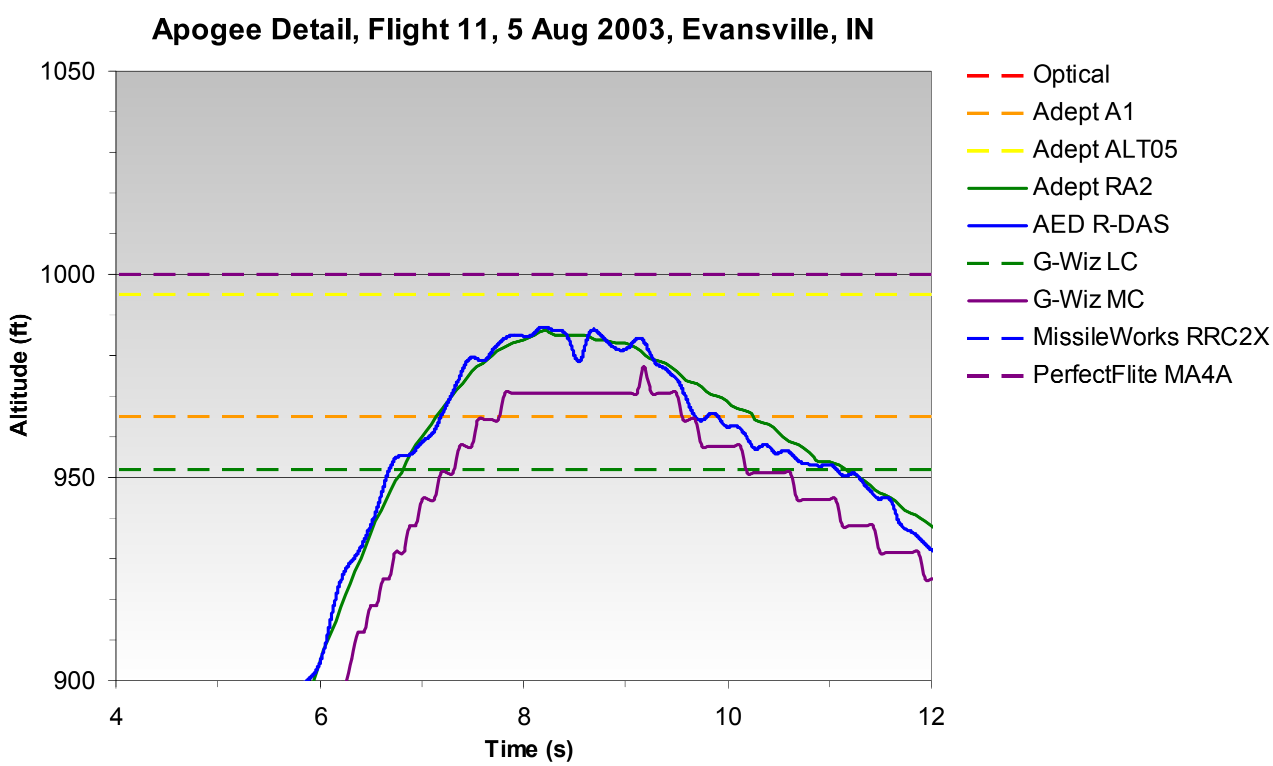

Figure 20. Apogee detail of flight 11 results.

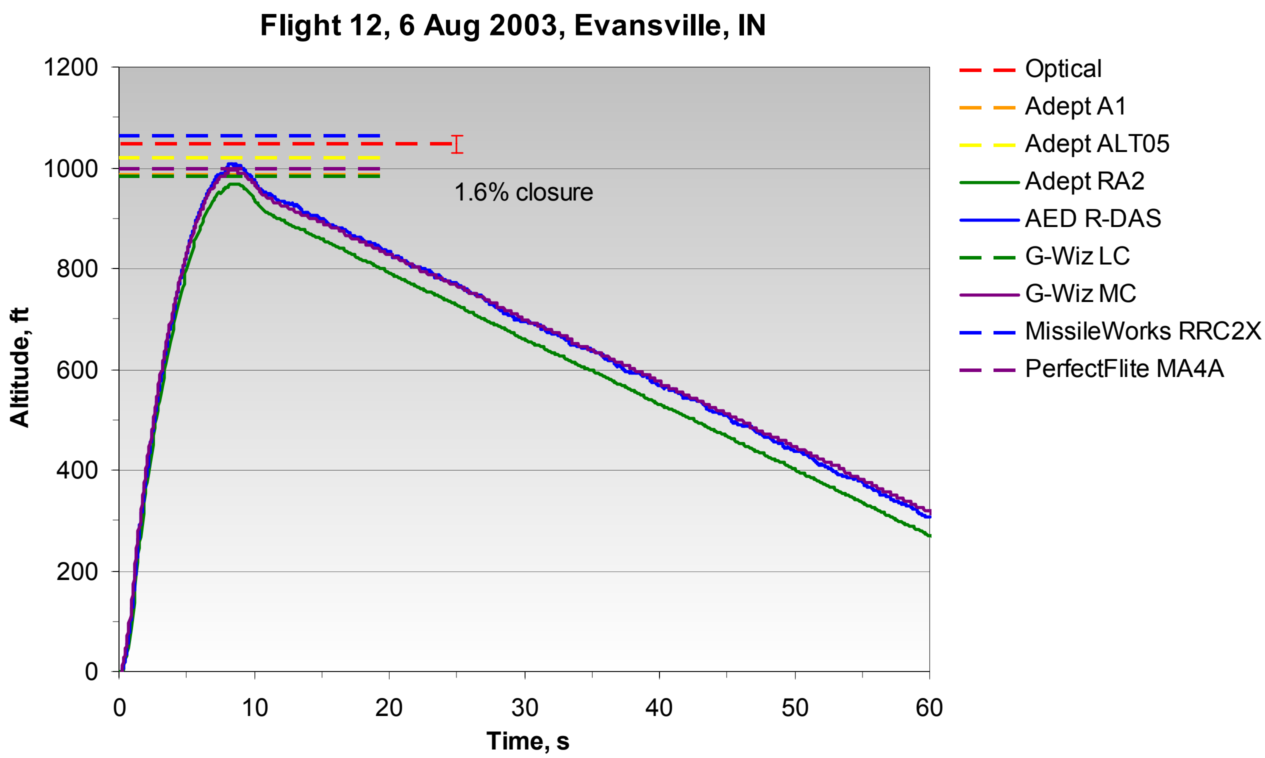

Figure A21. Flight 12 results from altimeters and optical tracking.

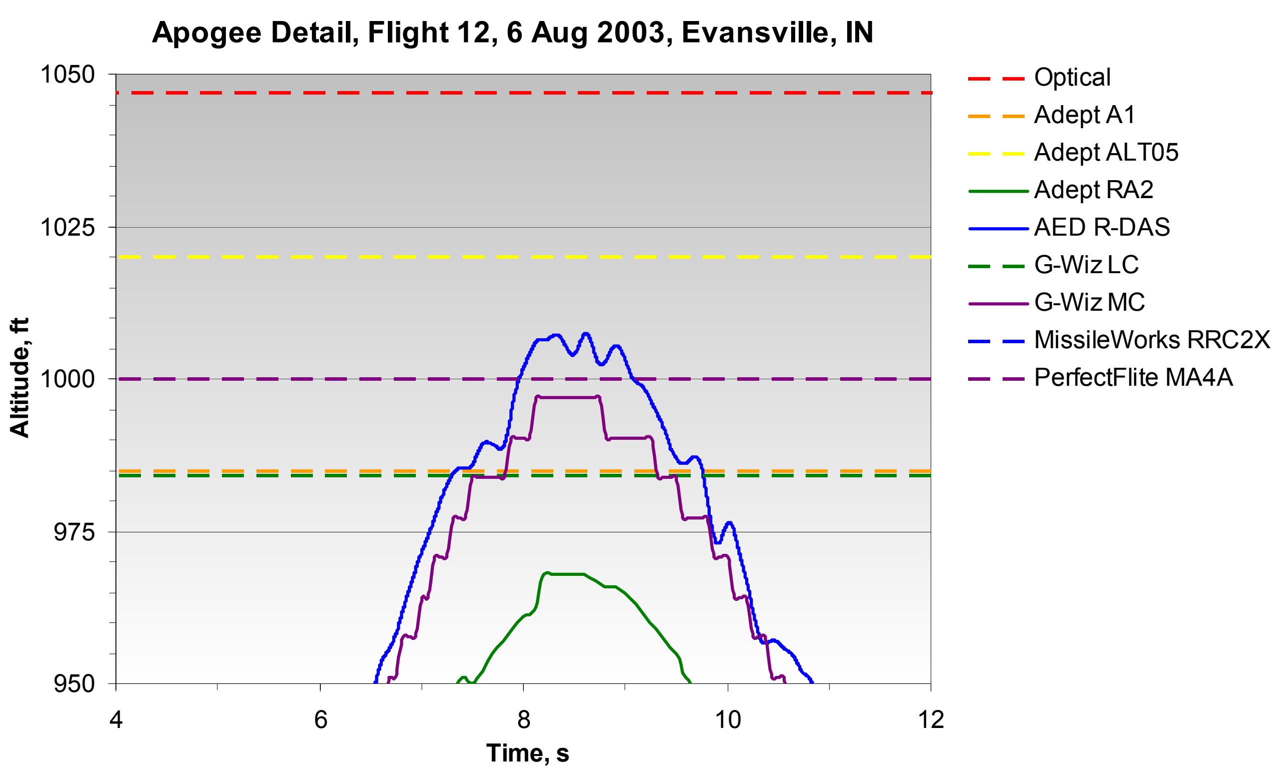

Figure A22. Apogee detail of flight 12 results.

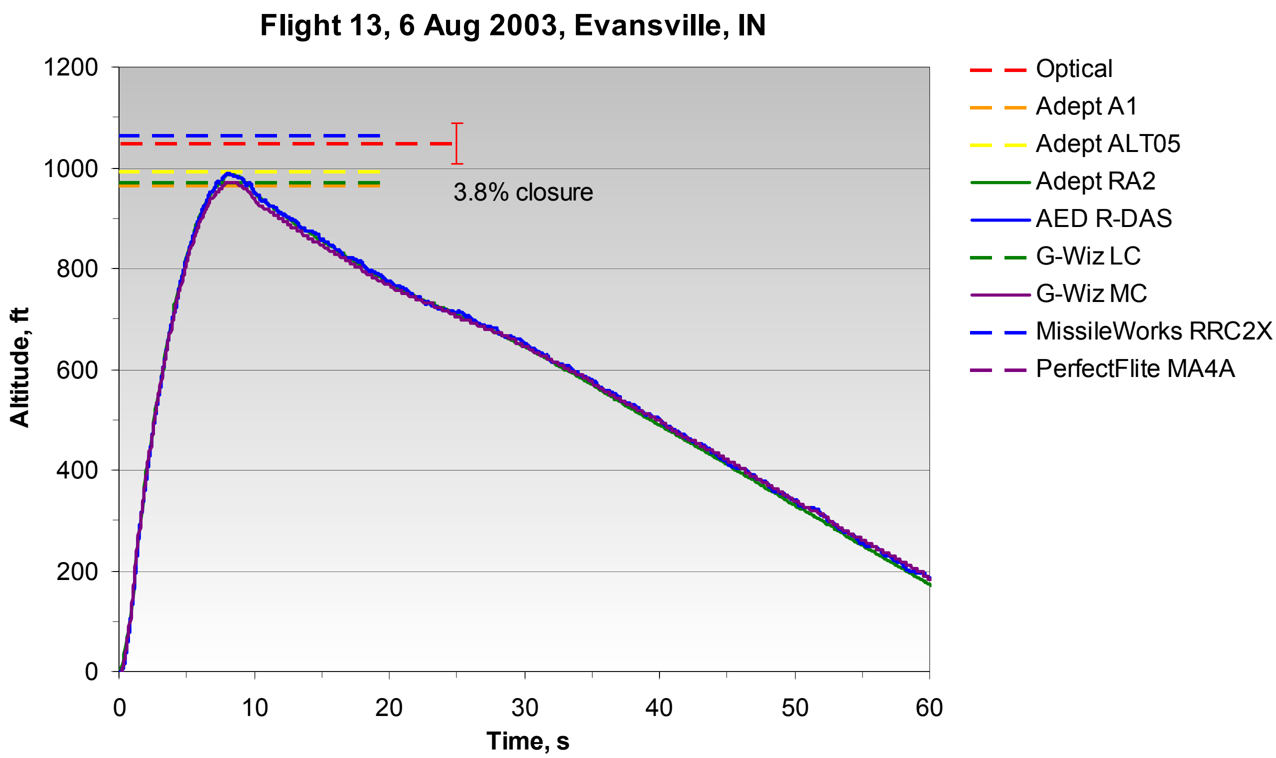

Figure A23. Flight 13 results from altimeters and optical tracking.

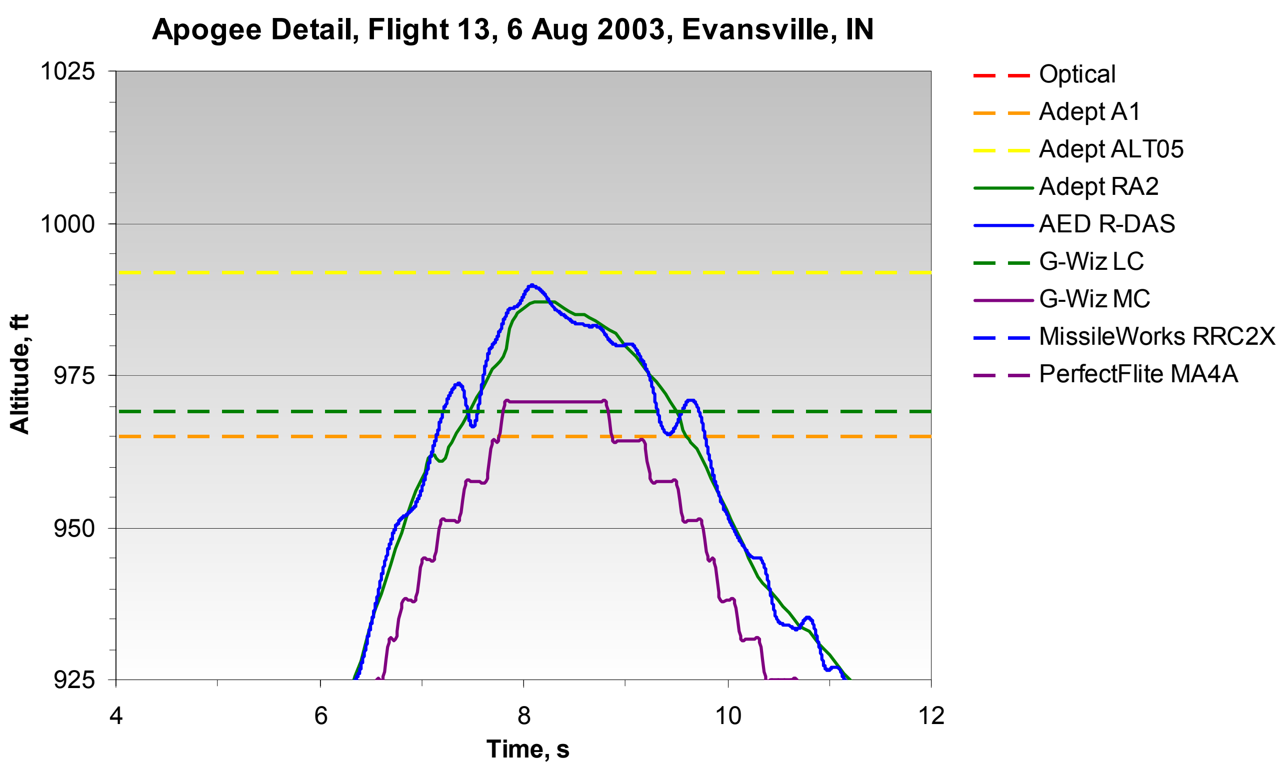

Figure A24. Apogee detail of flight 13 results.

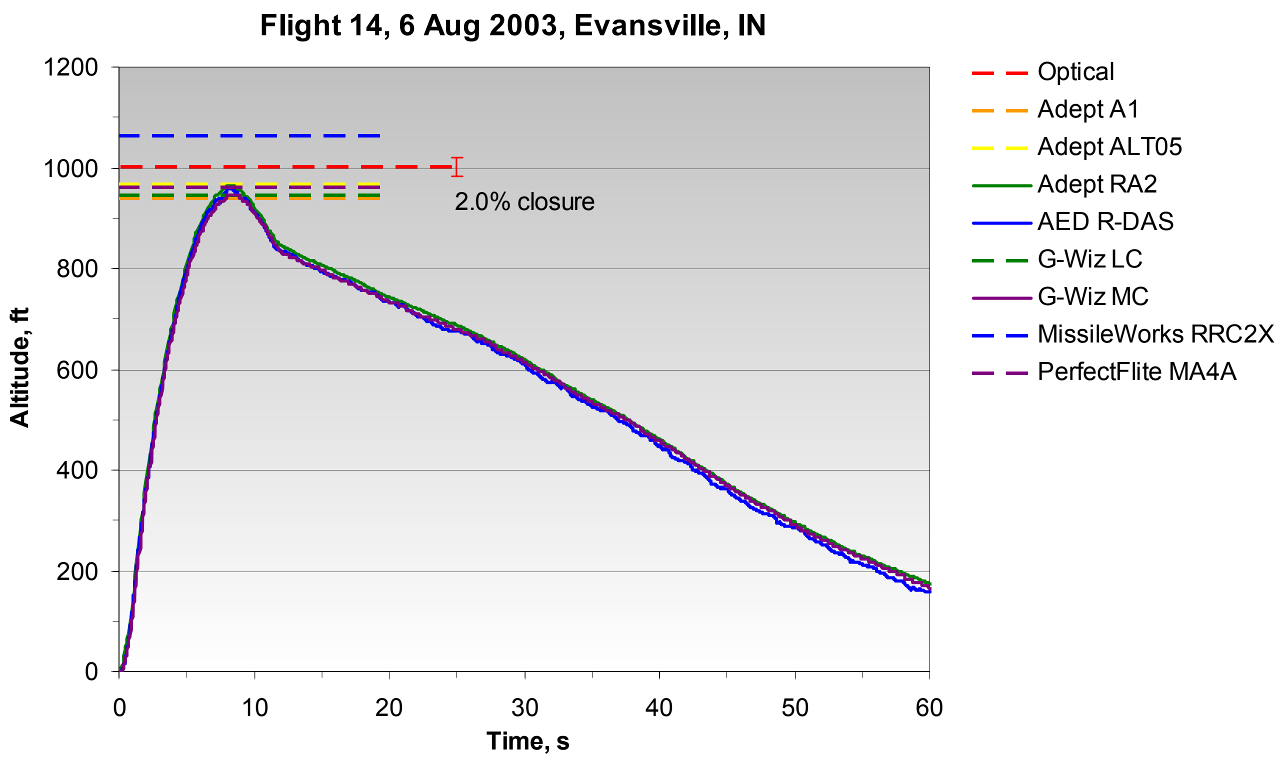

Figure A25. Flight 14 results from altimeters and optical tracking.

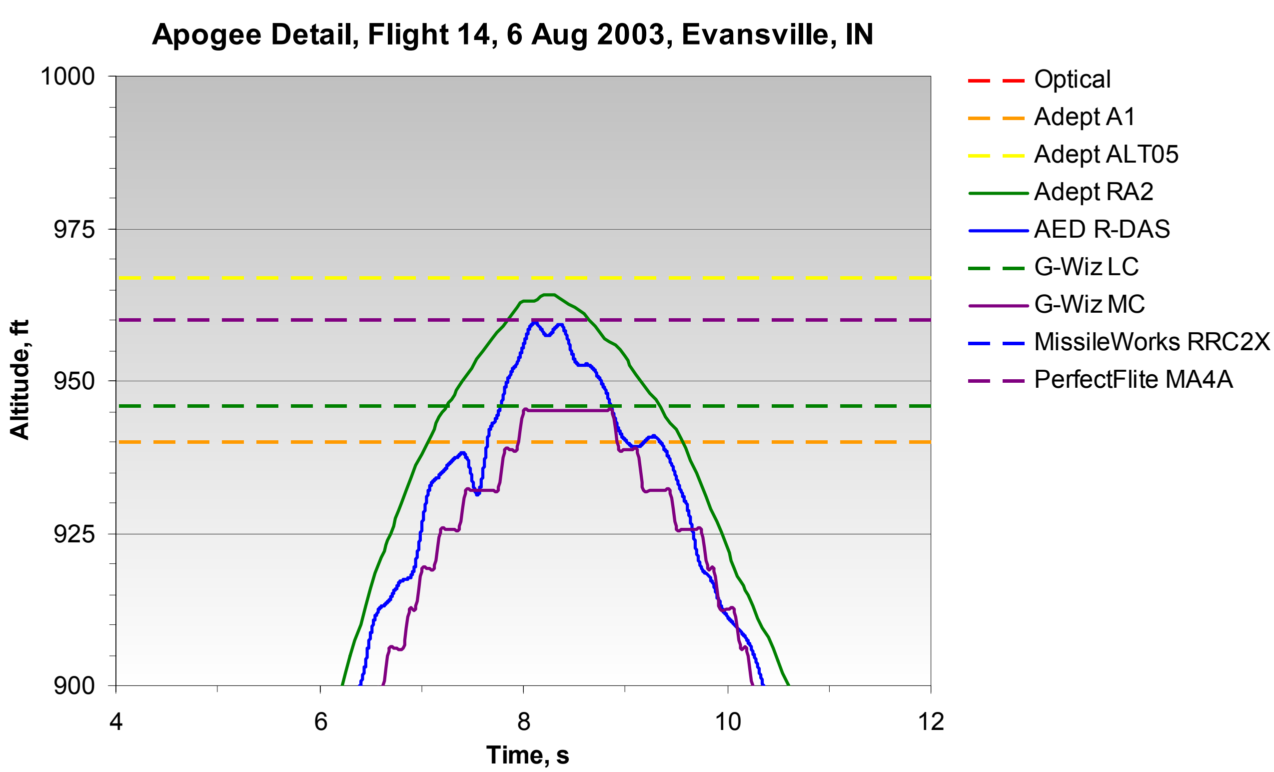

Figure A26. Apogee detail of flight 14 results.

Appendix B

Budget

Altimeters	$1,200
NiMH battery packs	100
12V batteries	25
Charger	25
Launch pad and rod	125
Launch vehicle	50
Electronic components	75
Motors	225
Vacuum chamber	25
Total	$1,850