

Measuring Absolute Accuracy of Altimeters

Presented for Research & Development
NARAM-47

Cincinnati, OH
July 31, 2005

Slightly Harmful
T-609

Christopher Kidwell
Jennifer Ash-Poole

Abstract

To establish an absolute reference, a Roman Vojtech Alti2 altimeter was calibrated using two different methods. First, elevations were measured at 31 sites in Shenandoah National Park, Virginia, at elevations ranging from 670 feet to 3,680 feet. Measured data was compared to elevations reported by U.S. Geological Survey markers. The Alti2 agreed very well to the survey markers, with a relative error of $-0.44 \pm 1.28\%$. The second calibration was performed by Capital Avionics using a standard aircraft altimeter calibration chamber. Altitudes from sea level to 3,000 feet in 100-foot increments, and 3,000 to 10,000 feet in 500-foot increments were simulated. Over the range of 400 to 1,100 feet, the Alti2 relative error was $-1.20 \pm 0.11\%$, and that value was used as a correction factor for subsequent flight tests. A total of 14 flights were made using D12-5 and E9-6 motors. Altitude was measured using the Alti2, as well as Adept A1 and ALT05, PerfectFlite ALT15k, and PicoAlt Pico-LO3 altimeters. Flights were tracked optically using two tracking stations and a baseline of 256.5 meters. Additionally, a Standard Altitude Marker (SAM) was timed from apogee until landing. Optical tracking results agreed extremely well with the Alti2, but measurements from the other altimeters averaged 8-10% low due to calibration errors. The SAM was difficult to see at 1,000 feet, and had a wide variation of results due to atmospheric effects. Computer simulations using RockSim were also shown to be accurate. Finally, a contest was held in which altimeters were required for all altitude flights. If altimeters are to be adopted for contest use, additional rules must be in place to handle special circumstances, and some means of ensuring accurate results must be developed.

Introduction

Our previous work (Kidwell and Ash-Poole, 2004) compared flight results from 11 different altimeters to results from optical tracking. It found that most of the altimeters reported results within 3% of average, with a standard deviation of 2% or less over 13 flights. Results from optical tracking were often much higher or lower than those reported by the altimeters. Since none of the altimeters was calibrated against another standard, it was not possible to determine whether there was a systematic error in the altitudes reported by altimeters or by optical tracking. Additionally, the flights were conducted at 6 different locations with various baseline arrangements and tracking personnel. This report attempts to address those deficiencies by calibrating one altimeter to use as a reference for all other results. Flight tests were all conducted on the same day with the same tracking personnel, thus eliminating any differences due to accuracy of baseline measurement or location. Finally, the use of altimeters in sanctioned competition is discussed.

The altitude measurement devices used in this study are listed in Table I. The altimeters were selected for their practicality in sanctioned competition due to their small size and weight. Using smaller altimeters and fewer of them permitted the use of a much simpler launch vehicle, which allowed for rapid turnaround between flights. In addition to the altimeters, a Standard Altitude Marker (SAM) (Stine, 1994) was used on most flights. It consists of a polyethylene film streamer, 1 inch wide and 12 inches long, with a 3 gram weight (a penny) taped to one end. At apogee the SAM is ejected and timed during descent. Through many tests, Bill Stine found that the SAM descends at a constant rate of 18 feet per second, allowing an easy calculation of altitude from the measured time.

Table I. Altitude measurement devices used

Manufacturer	Model	Dimensions (LxWxD, mm)	Power Requirements	Mass w/Battery (g)	Maximum Altitude (ft)	Resolution (ft)
Adept Instruments	A1	14x17x69	12V A23	14	3,000	5
Adept Instruments	ALT05	14x17x69	12V A23	14	15,000	1
PerfectFlite	ALT15k	14x14x62	12V A23	14	15,000	4
PicoAlt	Pico-LO3	25x10	1.5V N	14	10,000	7
Roman Vojtech	Alti2	38x13x18	6V	20	10,000	1.5
	SAM	25x305		3		

Calibration

To measure the absolute accuracy of an altimeter, a known reference is needed. Altimeters used in aviation are calibrated using a vacuum chamber with precise pressure measurements, which are converted into altitude using the standard atmosphere model (U.S. Standard Atmosphere, 1976). An alternative method for measuring small altitude changes is to sample known points of elevation. The Alti2 altimeter was selected for these calibration tests because it does not have any launch detect trigger. It is designed for use in radio-controlled airplanes, so it records barometric pressure and altitude at configurable rates of 0.2 to 10 Hz as long as the unit is powered. It stores up to 8,180 data points that can later be downloaded to a computer for analysis.

The initial plan was to take the Alti2 to New York City and measure the altitude difference between street-level and the observation deck at the Empire State Building. After consulting with security personnel, it was determined that the Alti2 was a security threat and would not be permitted inside the building. Another thought was to use a helium-filled balloon

on a tether to lift the Alti2, with the altitude measured by the amount of tether that was released. This method had its own set of problems, with winds aloft making a vertical ascent impossible, as well as the difficulty of deploying and measuring the tether.

The final choice was to drive through the mountains of Shenandoah National Park in Virginia. Sampling points were chosen throughout the park in areas easily accessible by vehicle and where U.S. Geological Survey (USGS) markers were present to give an accurate measure of the elevation. A total of 31 sampling sites were selected, with elevations ranging from 670 to 3,680 feet. At each sampling site, readings were collected for 2 minutes and averaged. The total time required to reach all of the sites was estimated to be 3 hours, so the Alti2 was set to collect data at 0.5 Hz so that 5,400 data points would be collected in that time. At each sampling site, the temperature was measured for use in calculating altitude from barometric pressure changes according to the formula

$$dz = \ln\left(\frac{P}{P_0}\right)(-29.153)T \quad (1)$$

where dz is the altitude difference in meters, P_0 is the starting pressure, P is the ending pressure, and T is the temperature in Kelvin. The altitude difference was calculated between each site and the reference point at Sperryville. Barometric pressure at that site changed from 100.9 kPa to 100.3 kPa over the course of all measurements, so a linear extrapolation of that change was used in the calculations. The position and elevation at each site were also measured by GPS (Garmin eTrex Summit).

Results for the first pass going north to south are shown in Table II, and the return trip going south to north in Table III. Relative error for both GPS and Alti2 was calculated using the USGS survey as the reference. Average GPS error was $1.15 \pm 3.53\%$ and average Alti2 error was $-0.44 \pm 1.28\%$ over all measurements. In both cases, the averages are well within the error bars for accurate measurements.

A second calibration was later performed by Capital Avionics at Manassas Airport. The Alti2 was set to record at 1 Hz and was placed in a precision vacuum chamber that is used to calibrate and certify aircraft altimeters. The altitude was ramped up in 100-foot increments from sea level to 3,000 feet, then at 500-foot increments to 10,000 feet, holding for 30-seconds at each level. Results of this calibration are shown in Table IV. At 3,000 feet, the relative error was -0.48% , which correlates very well with the previous calibration. Over the range of 400 to 1,100 feet, the average error was $-1.20 \pm 0.11\%$. This value will be used as an adjustment factor when comparing to other measurement methods in the flight tests.

Flight Tests

For the flight tests, the altimeters were mounted on a plywood board that could be easily removed from the payload section following each flight. The launch vehicle was 1.6" diameter and 25" long. The 13" long payload section had a single vent hole 1/8" in diameter. Optical tracking was performed using a 256.5-meter baseline, as measured by GPS. Vertical midpoint and geodesic calculation methods were both used, although the results were nearly identical. The Standard Altitude Marker was placed on top of the parachute to ensure rapid deployment at ejection. A total of 14 launches were done at Great Meadow, Virginia, on June 5, 2005, using D12-5 and E9-6 motors. Each flight was also simulated in RockSim, using the actual mass and weather conditions for each flight. Results are summarized in Table V and shown graphically in Appendix A.

Table II. Calibration of Alti2 altimeter versus U.S. Geological Survey marks in Shenandoah National Park, Virginia, north to south transit

Location	Temp (°F)	Latitude (deg)	Longitude (deg)	GPS Elevation (ft)	USGS Elevation (ft)	Alti2 Elevation (ft)	GPS Relative Error	Alti2 Relative Error
Sperryville	18	38.6584	78.2255	594	700	700	-15.1%	0.0%
Thornton Gap	19	38.6612	78.3182	2322	2260	2245	2.7%	-0.7%
Park Headquarters	21	38.6628	78.3725	1109	1080	1114	2.7%	3.1%
Thornton Gap	19	38.6612	78.3181	2303	2260	2241	1.9%	-0.9%
Sperryville	23	38.6585	78.2254	692	700	688	-1.1%	-1.7%
Thornton Gap	20	38.6612	78.3181	2292	2260	2238	1.4%	-1.0%
Tunnel Parking Overlook	19	38.6515	78.3112	2586	2549	2522	1.5%	-1.1%
Hazel Mountain Overlook	19	38.6457	78.3075	2742	2775	2690	-1.2%	-3.1%
Pinnacle Overlook	22	38.6225	78.3232	3354	3326	3311	0.8%	-0.4%
Jewell Hollow Overlook	22	38.6275	78.3385	3362	3335	3320	0.8%	-0.5%
Stony Man Overlook	23	38.6120	78.3628	3120	3097	3089	0.7%	-0.3%
Thorofare Overlook	21	38.5875	78.3599	3626	3592	3573	0.9%	-0.5%
Skyland North Entrance	21	38.5925	78.3757	3710	3680	3659	0.8%	-0.6%
Skyland South Entrance	22	38.5858	78.3832	3533	3505	3476	0.8%	-0.8%
Timber Hollow Overlook	21	38.5749	78.3841	3409	3352	3330	1.7%	-0.7%
Hawksbill Gap	20	38.5562	78.3869	3425	3361	3321	1.9%	-1.2%
Old Rag View Overlook	21	38.5455	78.3908	3642	3590	3544	1.4%	-1.3%
Spitler Knoll Overlook	22	38.5481	78.4137	3373	3310	3297	1.9%	-0.4%
Franklin Cliffs Overlook	23	38.5367	78.4197	3195	3135	3128	1.9%	-0.2%
Fishers Gap Overlook	23	38.5342	78.4226	3132	3061	3072	2.3%	0.3%
Big Meadows Wayside	23	38.5176	78.4386	3567	3514	3490	1.5%	-0.7%
Milam Gap	23	38.5002	78.4457	3259	3257	3213	0.1%	-1.4%
Naked Creek Overlook	24	38.4938	78.4508	3269	3247	3230	0.7%	-0.5%
Hazeltop Ridge Overlook	21	38.4784	78.4563	3287	3286	3227	0.0%	-1.8%
The Point Overlook	20	38.4628	78.4108	3254	3235	3193	0.6%	-1.3%
Lewis Mountain Entrance	20	38.4397	78.4785	3411	3396	3351	0.4%	-1.3%
The Oaks Overlook	21	38.4198	78.4886	3132	3123	3089	0.3%	-1.1%
Bald Face Mtn Overlook	21	38.3973	78.5077	3361	3341	3304	0.6%	-1.1%
South River Overlook	22	38.3838	78.5175	2956	2942	2923	0.5%	-0.6%
Hensley Hollow Overlook	23	38.3677	78.5366	2694	2686	2674	0.3%	-0.4%
Swift Run Gap	23	38.3603	78.5493	2277	2285	2279	-0.4%	-0.3%
Stanardsville	29	38.2973	78.4404	622	670	675	-7.2%	0.7%
Swift Run Gap	26	38.3602	78.5492	2335	2285	2297	2.2%	0.5%
Elkton	33	38.4071	78.6186	992	1000	1025	-0.8%	2.5%

Table III. Calibration of Alti2 altimeter versus U.S. Geological Survey marks in Shenandoah National Park, Virginia, south to north transit

Location	Temp (°F)	Latitude (deg)	Longitude (deg)	GPS Elevation (ft)	USGS Elevation (ft)	Alti2 Elevation (ft)	GPS Relative Error	Alti2 Relative Error
Elkton	34	38.6584	78.2255	1032	1000	1044	3.2%	4.4%
Swift Run Gap	27	38.6612	78.3182	2348	2285	2298	2.8%	0.6%
Stanardsville	32	38.6628	78.3725	678	670	690	1.2%	3.0%
Swift Run Gap	25	38.6612	78.3181	2354	2285	2291	3.0%	0.3%
Hensley Hollow Overlook	25	38.6585	78.2254	2756	2686	2679	2.6%	-0.3%
South River Overlook	23	38.6612	78.3181	3014	2942	2927	2.4%	-0.5%
Bald Face Mtn Overlook	23	38.6515	78.3112	3414	3341	3317	2.2%	-0.7%
The Oaks Overlook	21	38.6457	78.3075	3176	3123	3083	1.7%	-1.3%
Lewis Mountain Entrance	22	38.6225	78.3232	3466	3396	3359	2.1%	-1.1%
The Point Overlook	22	38.6275	78.3385	3291	3235	3202	1.7%	-1.0%
Hazeltop Ridge Overlook	22	38.6120	78.3628	3349	3286	3242	1.9%	-1.3%
Naked Creek Overlook	23	38.5875	78.3599	3315	3247	3226	2.1%	-0.6%
Milam Gap	23	38.5925	78.3757	3304	3257	3222	1.4%	-1.1%
Big Meadows Wayside	24	38.5858	78.3832	3586	3514	3501	2.0%	-0.4%
Fishers Gap	24	38.5749	78.3841	3116	3061	3056	1.8%	-0.2%
Franklin Cliffs Overlook	24	38.5562	78.3869	3181	3135	3122	1.5%	-0.4%
Spitler Knoll Overlook	25	38.5455	78.3908	3356	3310	3299	1.4%	-0.3%
Old Rag View Overlook	25	38.5481	78.4137	3620	3590	3560	0.8%	-0.8%
Hawksbill Gap	25	38.5367	78.4197	3396	3361	3347	1.0%	-0.4%
Timber Hollow Overlook	23	38.5342	78.4226	3395	3352	3330	1.3%	-0.7%
Skyland South Entrance	24	38.5176	78.4386	3541	3505	3473	1.0%	-0.9%
Skyland North Entrance	24	38.5002	78.4457	3713	3680	3652	0.9%	-0.8%
Thorofare Overlook	25	38.4938	78.4508	3631	3592	3571	1.1%	-0.6%
Stony Man Overlook	23	38.4784	78.4563	3111	3097	3059	0.5%	-1.2%
Jewell Hollow Overlook	24	38.4628	78.4108	3340	3335	3287	0.1%	-1.4%
Pinnacle Overlook	23	38.4397	78.4785	2781	3326	3278	-16.4%	-1.4%
Hazel Mountain Overlook	24	38.4198	78.4886	3328	2775	2736	19.9%	-1.4%
Tunnel Parking Overlook	24	38.3973	78.5077	2550	2549	2514	0.0%	-1.4%
Thornton Gap	24	38.3838	78.5175	2289	2260	2254	1.3%	-0.3%
Park Headquarters	28	38.3677	78.5366	1115	1080	1121	3.2%	3.8%
Thornton Gap	26	38.3603	78.5493	2320	2260	2257	2.7%	-0.1%
Sperryville	30	38.2973	78.4404	693	700	690	-1.0%	-1.5%

Table IV. Calibration of Alti2 altimeter versus Capital Avionics reference

Calibration Altitude (ft)	Alti2 Altitude (ft)	Alti2 Relative Error
100	100	0.3%
200	199	-0.7%
300	296	-1.2%
400	395	-1.3%
500	493	-1.3%
600	593	-1.2%
700	691	-1.3%
800	791	-1.2%
900	889	-1.2%
1000	990	-1.0%
1100	1088	-1.1%
1200	1189	-0.9%
1300	1287	-1.0%
1400	1387	-0.9%
1500	1487	-0.8%
1600	1587	-0.8%
1700	1688	-0.7%
1800	1787	-0.7%
1900	1887	-0.7%
2000	1986	-0.7%
2100	2088	-0.6%
2200	2186	-0.6%
2300	2288	-0.5%
2400	2386	-0.6%
2500	2486	-0.6%
2600	2586	-0.5%
2700	2684	-0.6%
2800	2786	-0.5%
2900	2886	-0.5%
3000	2986	-0.5%
3500	3503	0.1%
4000	4024	0.6%
4500	4545	1.0%
5000	5069	1.4%
5500	5593	1.7%
6000	6120	2.0%
6500	6649	2.3%
7000	7179	2.6%
7500	7712	2.8%
8000	8247	3.1%
8500	8784	3.3%
9000	9322	3.6%
9500	9862	3.8%
10000	10404	4.0%
0	7	

Table V. Summary of flight data from 14 test flights conducted on 5 June 2005 at Great Meadow, VA

Flight	Motor	Temp (°F)	RH (%)	Pressure (in Hg)	Mass (g)	Optical (ft)	Alti2 (ft)	A1 (ft)	ALT05 (ft)	ALT15k (ft)	PicoAlt (ft)	Streamer (s)	RockSim (ft)
1	D12-5	89	58	29.62	266.4	514	509	465	480	471	b	22.57	430
2	E9-6	89	58	29.64	280.9	1085	1057	955	987	984	959	44.50	1011
3	D12-5	93	57	29.64	267.1	491	495	460	460	452	444	25.78	424
4	E9-6	94	57	29.64	284.5	1100	1086	1060	1022	980	b	45.97	992
5	D12-5	89	58	29.63	268.5	480	464	440	440	431	409	26.50	419
6	E9-6	90	59	29.63	284.7	1011	1021	940	952	942	924	c	989
7	D12-5	92	58	29.64	269.1	502	504	460	475	460	b	25.97	418
8	E9-6	95	56	29.63	282.2	1037	1083	975	997	987	b	d	1006
9	D12-5	93	57	29.64	264.9	479	494	460	465	460	444	20.37	431
10	E9-6	95	57	29.64	280.6	975	984	890	902	901	889	41.91	1015
11	D12-5	93	56	29.63	269.8	494	488	440	460	451	430	20.66	416
12	E9-6	94	56	29.63	288.6	a	1022	925	942	926	b	a	968
13	D12-5	92	56	29.63	269.5	509	504	455	475	468	451	21.69	416
14	E9-6	92	57	29.62	286.0	894	895	820	827	827	805	d	982

^a Flight was launch prematurely due to LCO error, so no tracking or timing data is available

^b Reported altitude in excess of 30,000 ft

^c Timer malfunction

^d Streamer was not visible

Based on the previous calibrations, the Alti2 was used as the “true” altitude after applying the 1.2% calibration factor. Relative altitudes for each of the other measurements were calculated and are shown in Figure 1. Optical tracking agreed remarkably well to the Alti2, and is attributed to the accuracy of the baseline measurement and tight closures (typically < 1%). The other altimeters all reported consistently low values. Similar results were noted in our previous work, but it was assumed the optical measurements were faulty due to baseline measurement errors. It now appears that there may be a systematic calibration error in these altimeters, causing them to report 8-10% low under these conditions. Altitudes calculated by the SAM varied greatly due to air currents affecting the descent rate, but on average were 17% lower than the Alti2. This indicates that the literature value of 18 feet per second is too low, and a value of about 21 feet per second would be more accurate. Additionally, it was impossible to see the SAM at apogee for the E9-6 flights to 1,000 feet. Luckily it descended close to the rocket on most flights, so it could be reacquired prior to landing. RockSim simulations agreed well with the Alti2, although there was a large variation due to weathercocking on several flights.

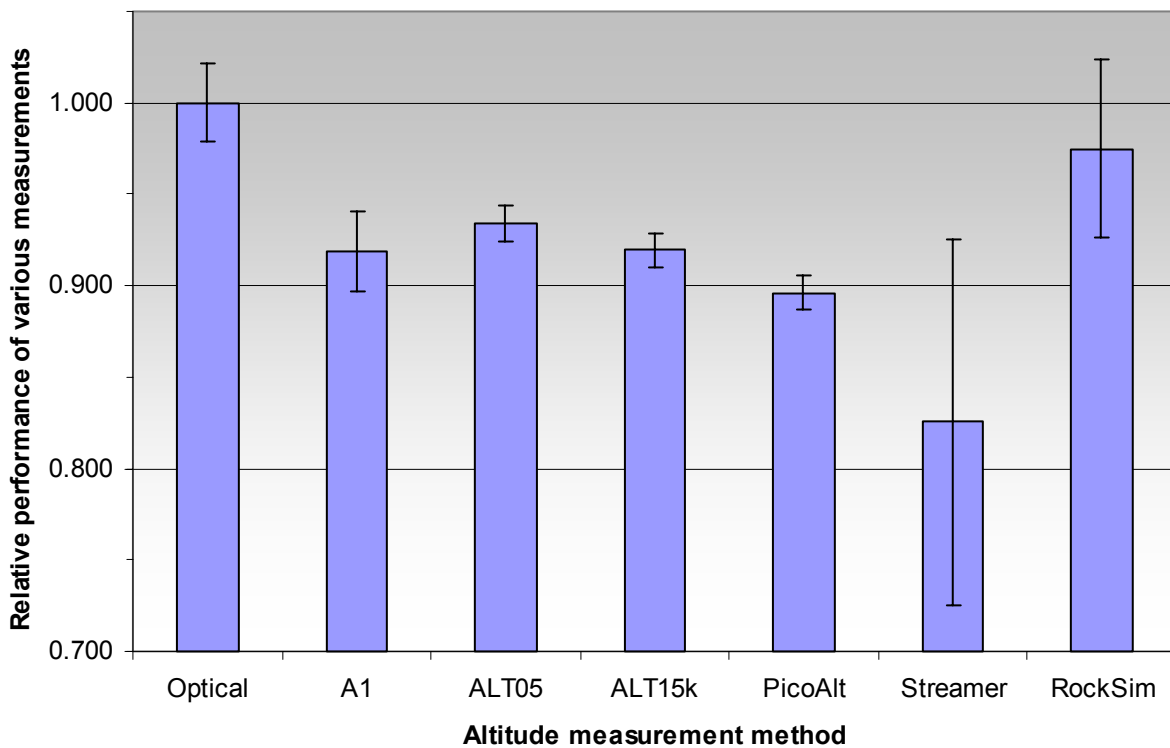


Figure 1. Relative altitude and standard deviation of each measurement method

Altimeter Use in Contests

With altimeters becoming smaller and gaining in popularity, there has been much discussion recently about allowing their use in sanctioned competition as an alternative to optical tracking. Our previous work had proven the accuracy of altimeters, so we hosted a regional meet with the special provision that altimeters be used for all flights in the altitude events: Predicted Altitude, B Payload, and C Altitude. There were 11 competitors for those events, and the altimeters used included: Adept A1 and ALT05, PerfectFlite ALT15k, PicoAlt P1, and Estes MaxTrax. The following are some of the lessons learned from this contest:

- Events need to be chosen such that there is a reasonable chance that flights will be high enough to arm the altimeters. The additional weight from the altimeter should also be factored in. Events such as A Payload, and B Egg Lofting Altitude would not be suitable for general use.
- Contestants were encouraged to purchase their own altimeters, but several units were available on loan for those who did not have them.
- PerfectFlite and PicoAlt altimeters store results between flights. At check-in, the readings from these models were recorded on the flight card to ensure that the flights recorded a new altitude rather than continuing to report the old one due to failure to arm or some other malfunction.
- When no altitude was reported, that flight was counted the same as a track lost.
- The same rule applied for models that were not returned. In the case of B Payload, those flights were still disqualified, as a return is required to inspect the payload.
- One new record was set in C Altitude. The Contest Board decision was that a new category of records would need to be created for altitudes measured by electronic means, similar to how radio-controlled flights are now handled for duration events.
- Ideally, there should be a “Certified Altimeter List” similar to the “Certified Motor List”, where vendors would submit units to a testing authority to be certified for contest use.
- Failing that, clubs could test units on the field using a simple vacuum chamber that would simulate a relatively constant altitude. Additional research would be needed to determine how such a device should be constructed and what range of reported altitudes should be allowed.

Conclusions

After additional calibrations were performed, the Alti2 altimeter confirmed that optical tracking is an extremely accurate measurement method. Simulations performed in RockSim were also proven to be fairly accurate. The other altimeters did not perform as well, averaging 8-10% lower than the Alti2 readings. This is likely caused by a systematic calibration error in all of those units. The Standard Altitude Marker method is a simple means to get an estimate of altitude, but it is not accurate enough for general use and can only be used for low-altitude flights. If altimeters are to be adopted for contest use, additional rules need to be in place to handle special circumstances of altimeters malfunctioning or not being returned. There also needs to be some means of certifying the altimeters are calibrated correctly, either through the use of a “Certified Altimeter List” or by testing units on the field using a simple vacuum chamber.

References

Kidwell, Christopher and Ash-Poole, Jennifer (2004). “A Comparison of Altimeters and Optical Tracking” presented at NARAM-46, The Plains, VA.

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

U.S. Standard Atmosphere (1976). U.S. Government Printing Office, Washington, D.C.

Appendix A

Graphs of Flight Data

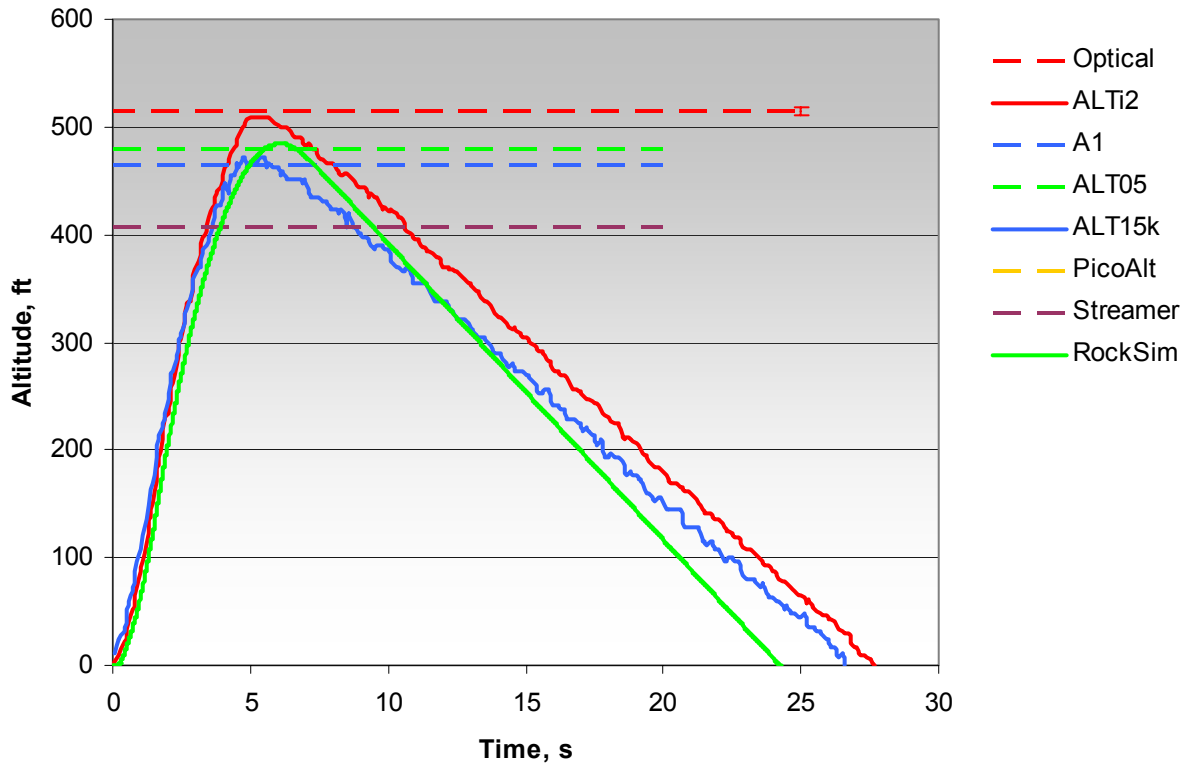


Figure A1. Results from flight 1, 5 June 2005, 9:45 am

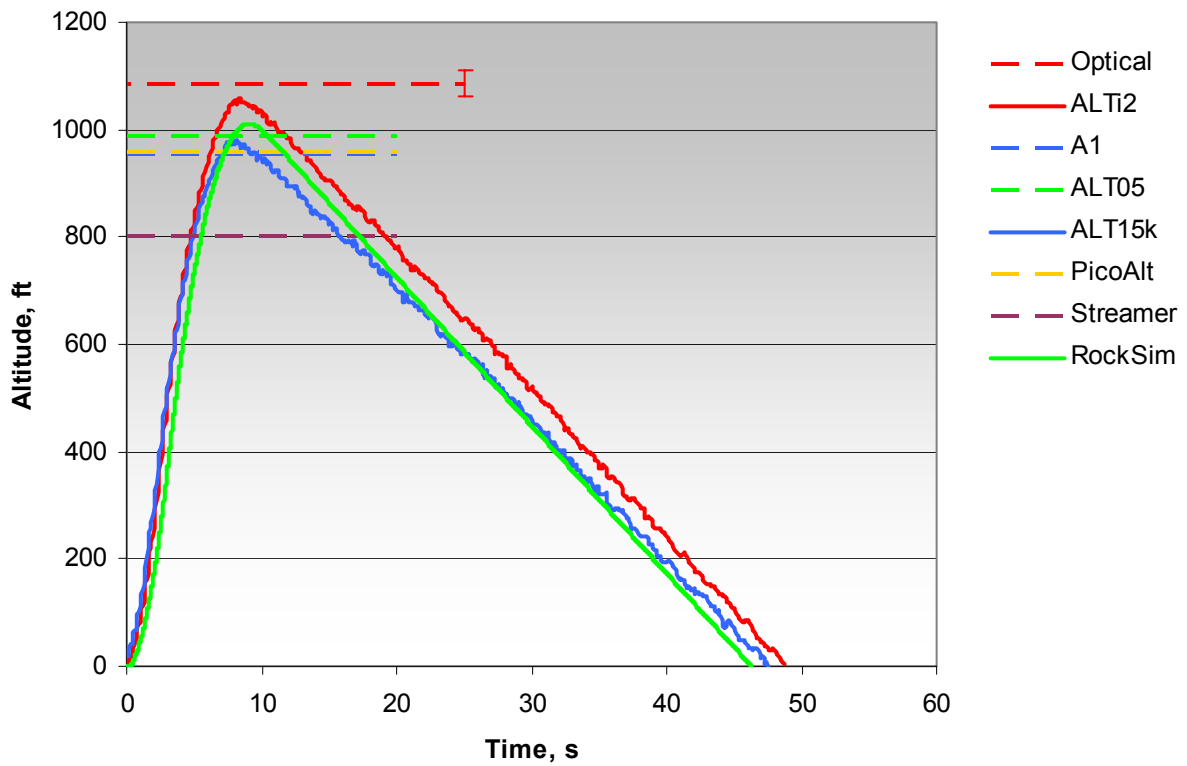


Figure A2. Results from flight 2, 5 June 2005, 10:00 am

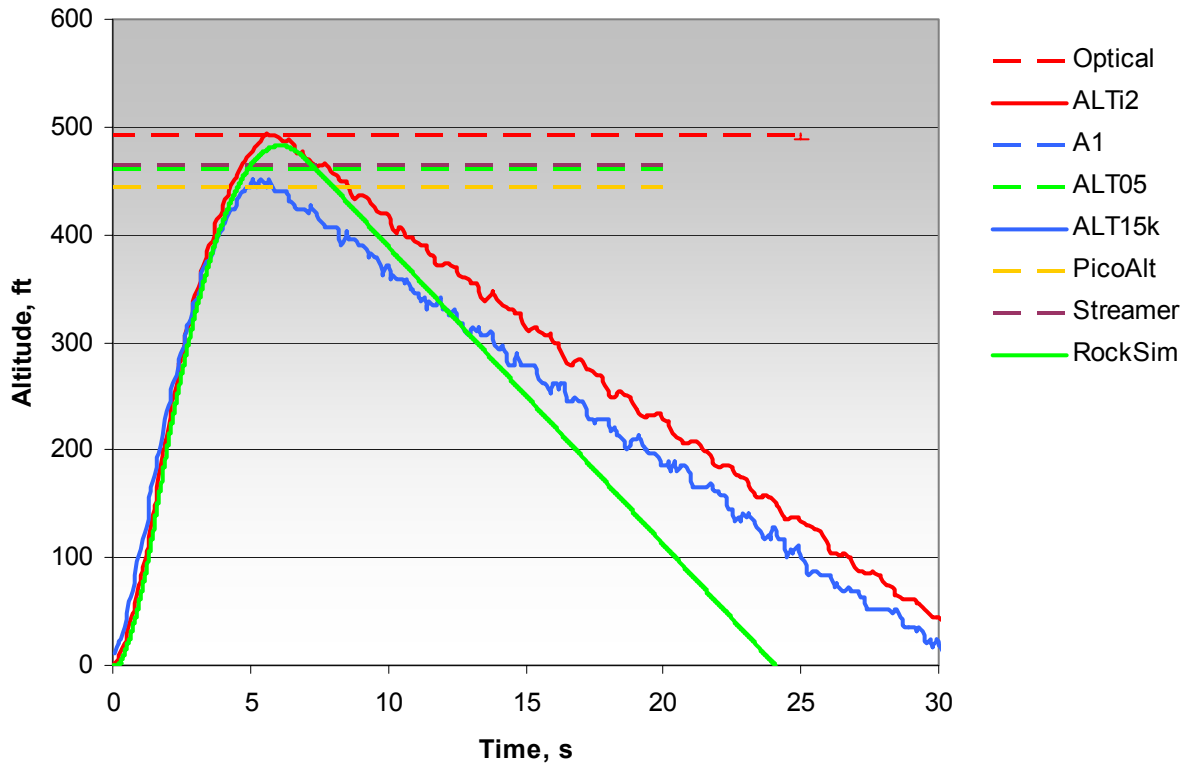


Figure A3. Results from flight 1, 5 June 2005, 10:16 am

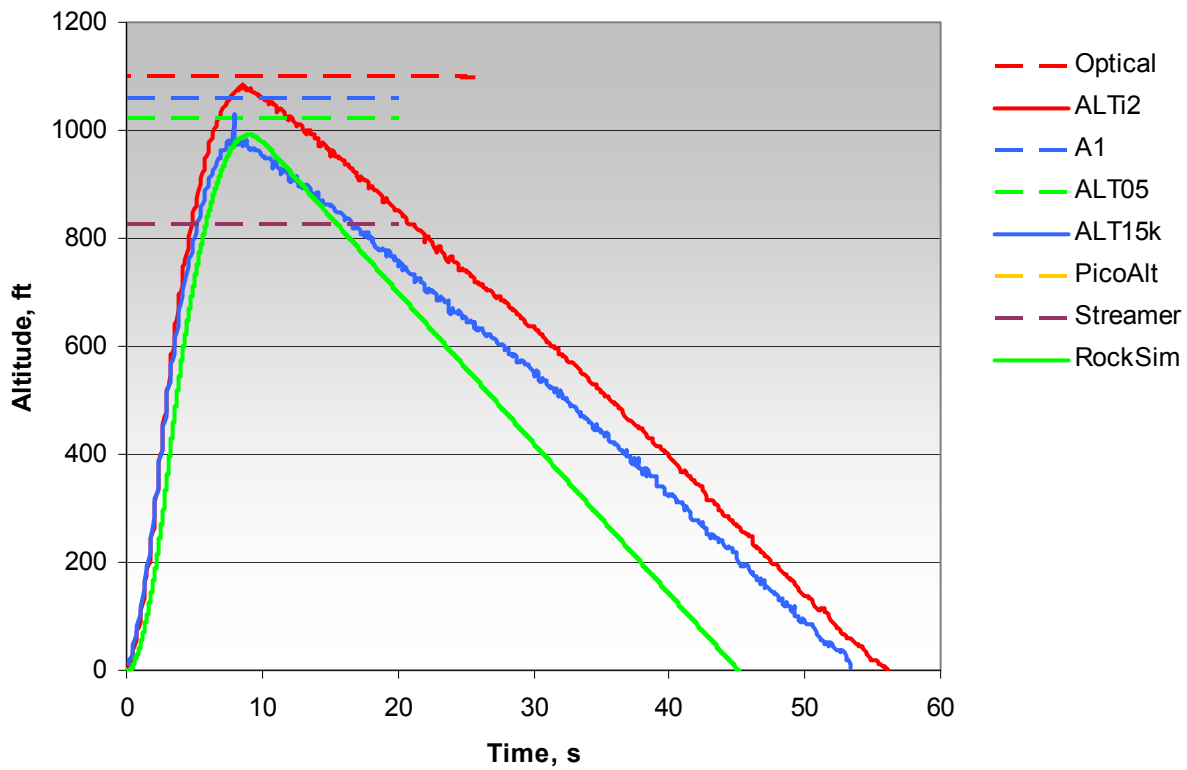


Figure A4. Results from flight 2, 5 June 2005, 10:31 am

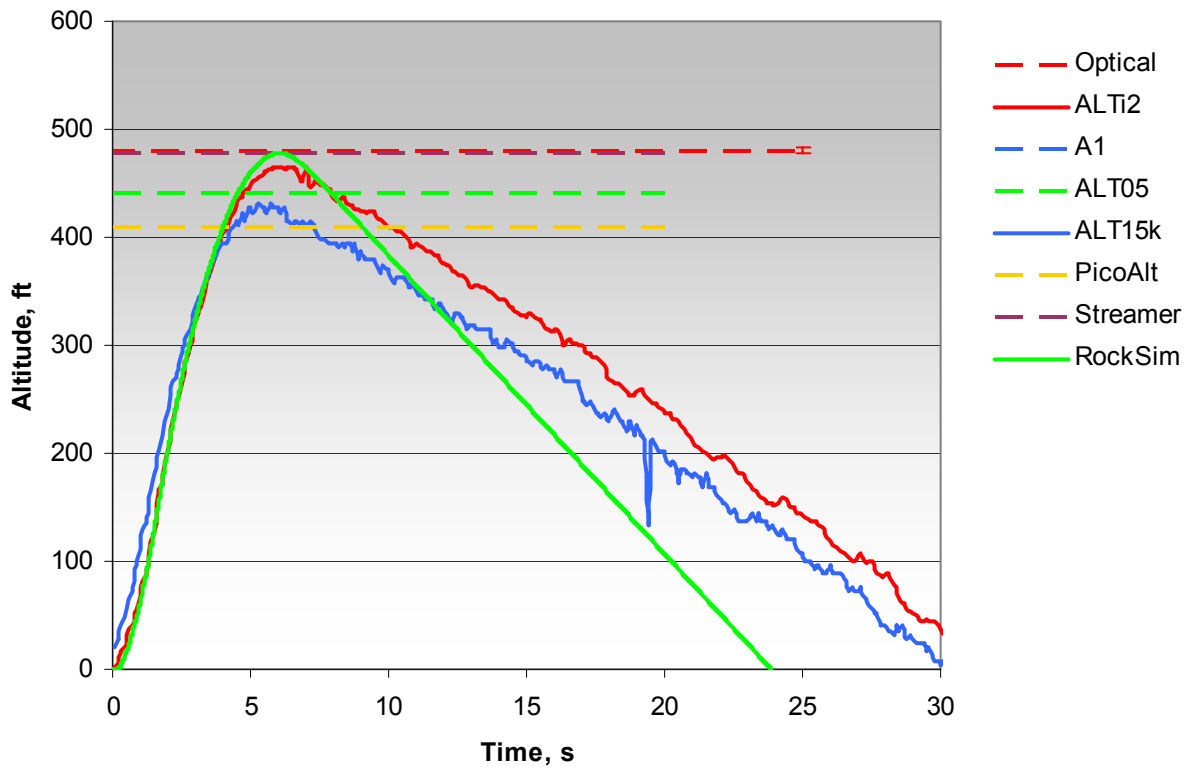


Figure A5. Results from flight 1, 5 June 2005, 10:43 am

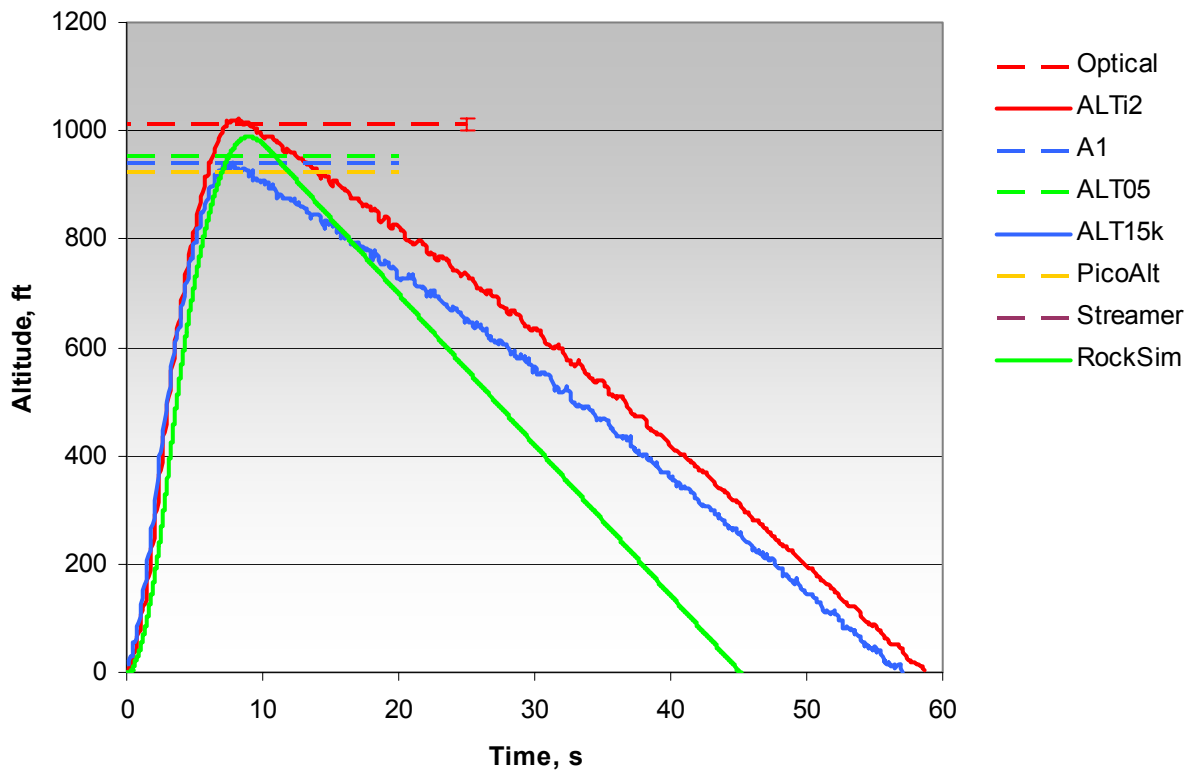


Figure A6. Results from flight 2, 5 June 2005, 10:55 am

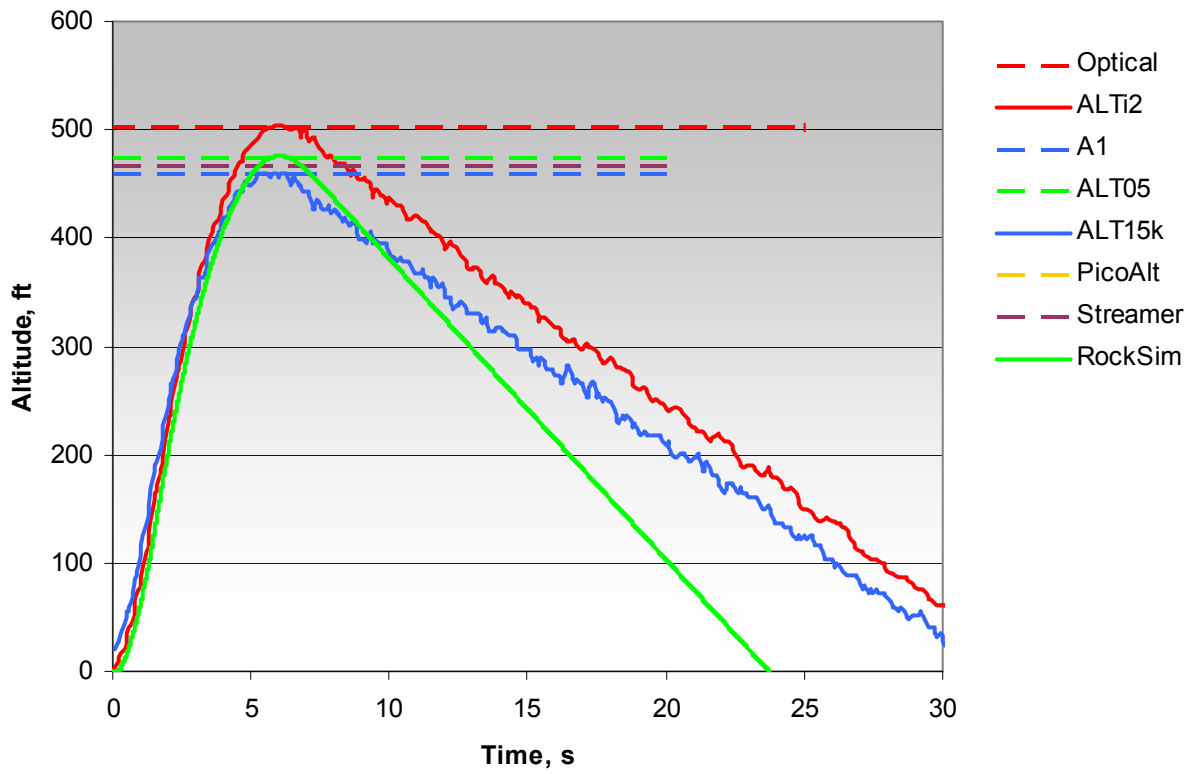


Figure A7. Results from flight 1, 5 June 2005, 11:10 am

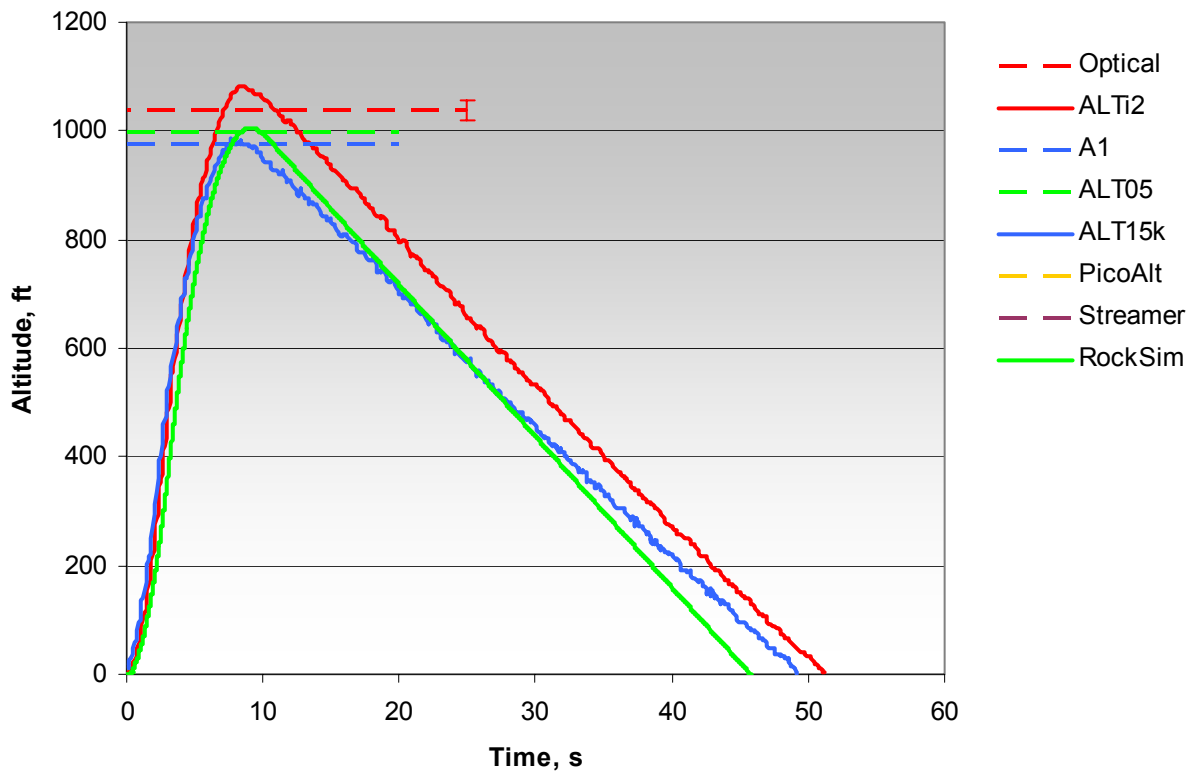


Figure A8. Results from flight 2, 5 June 2005, 11:20 am

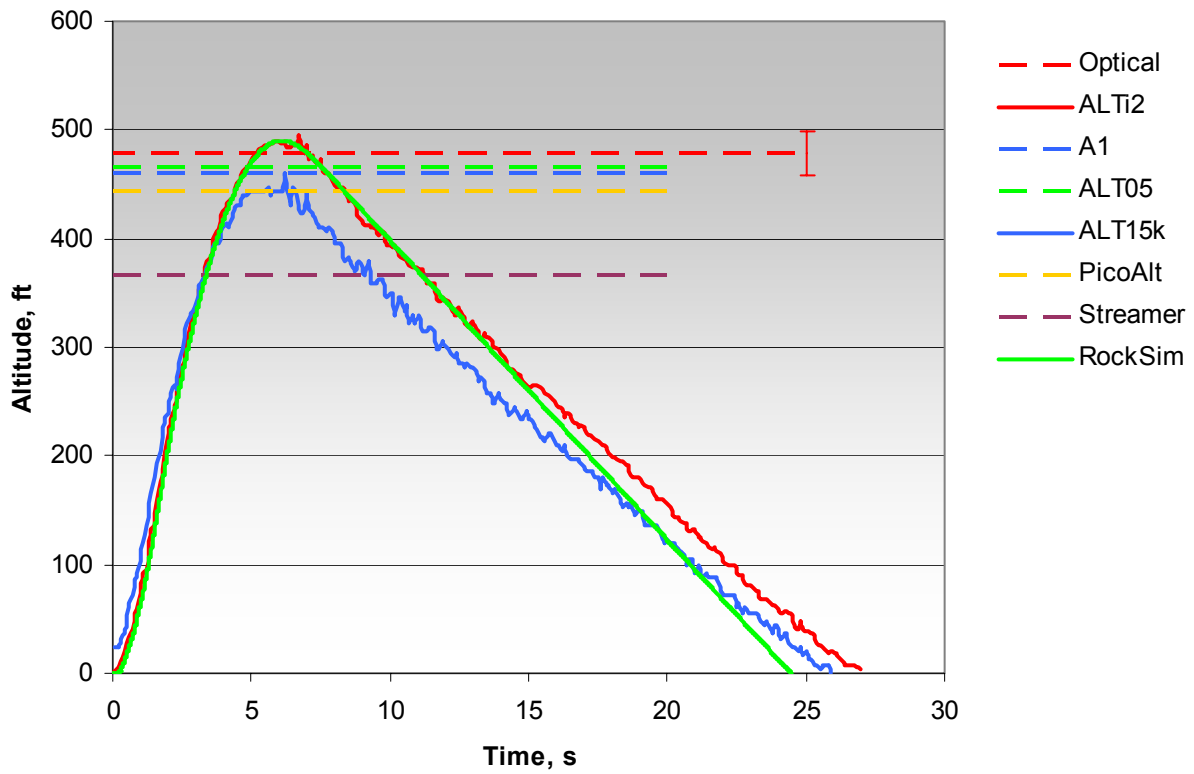


Figure A9. Results from flight 1, 5 June 2005, 11:35 am

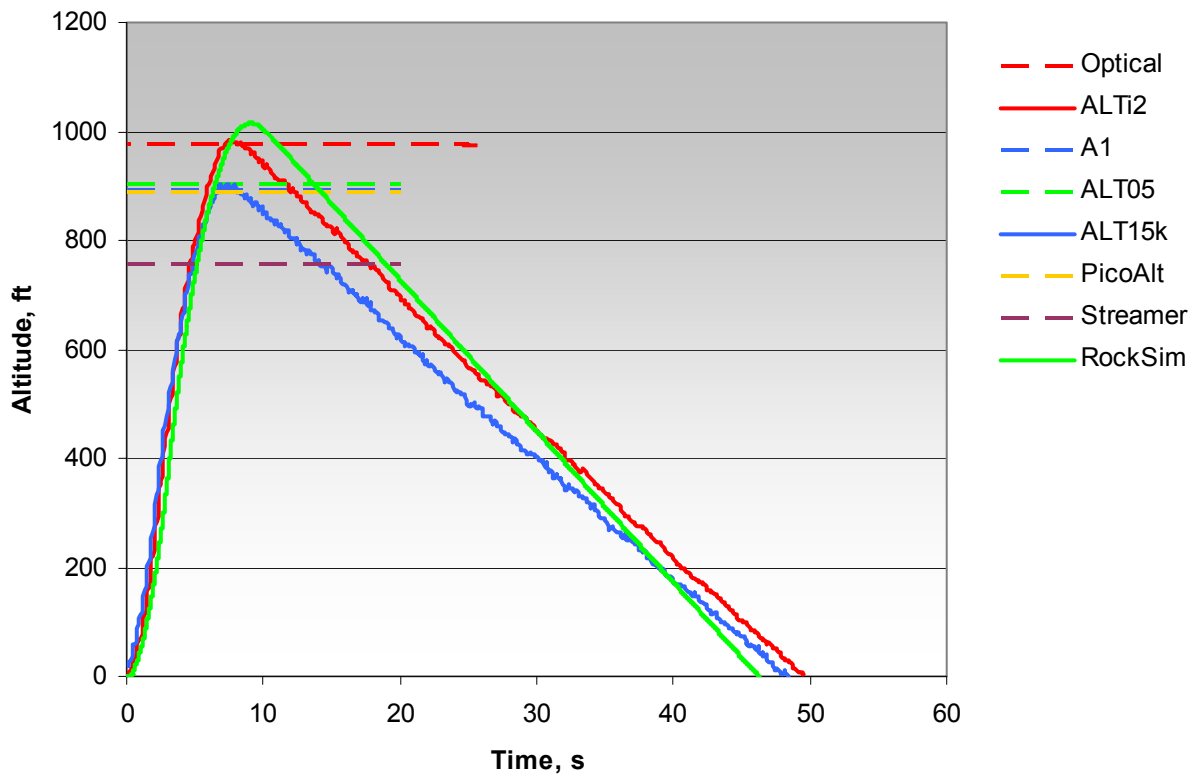


Figure A10. Results from flight 2, 5 June 2005, 11:50 am

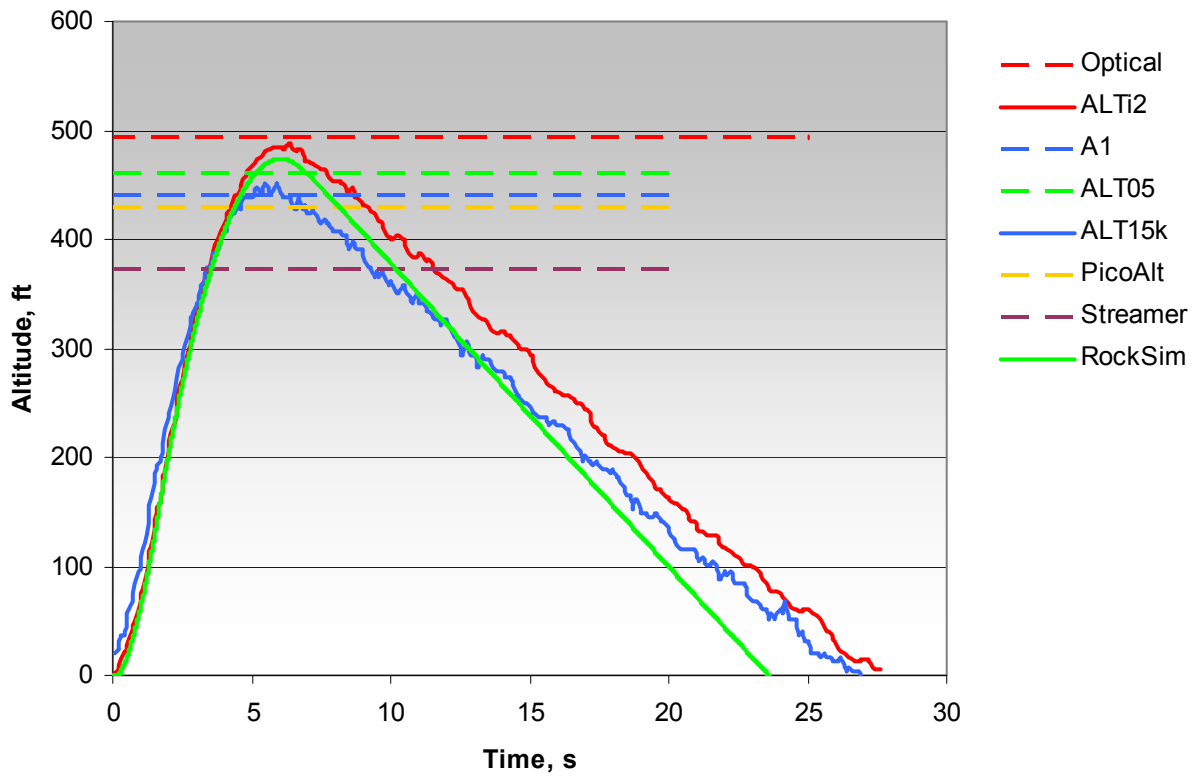


Figure A11. Results from flight 1, 5 June 2005, 12:05 pm

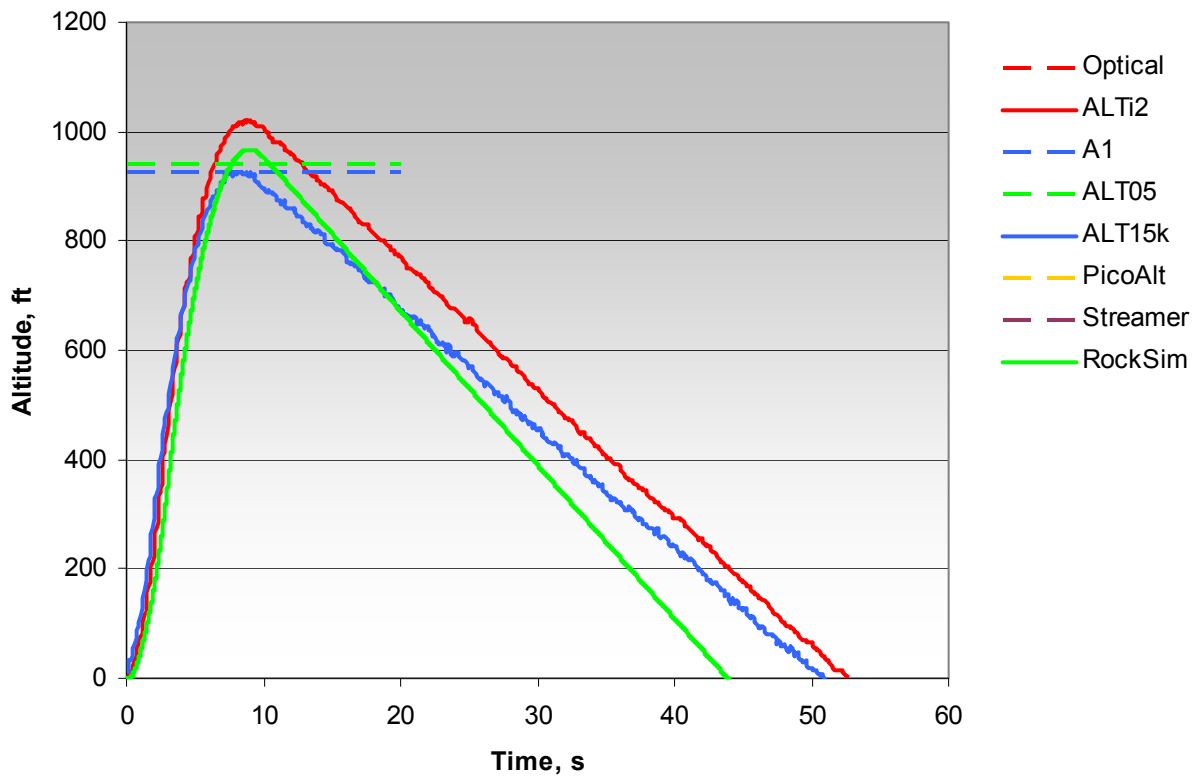


Figure A12. Results from flight 2, 5 June 2005, 12:15 pm

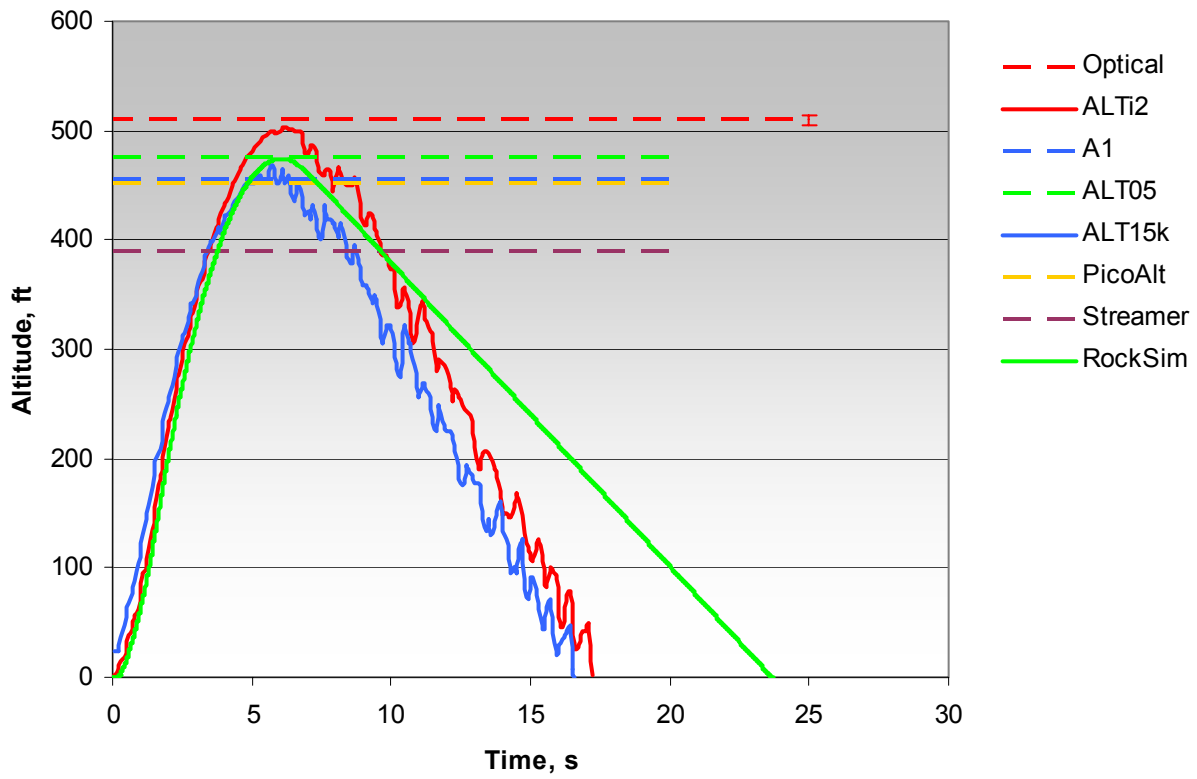


Figure A13. Results from flight 1, 5 June 2005, 12:28 pm

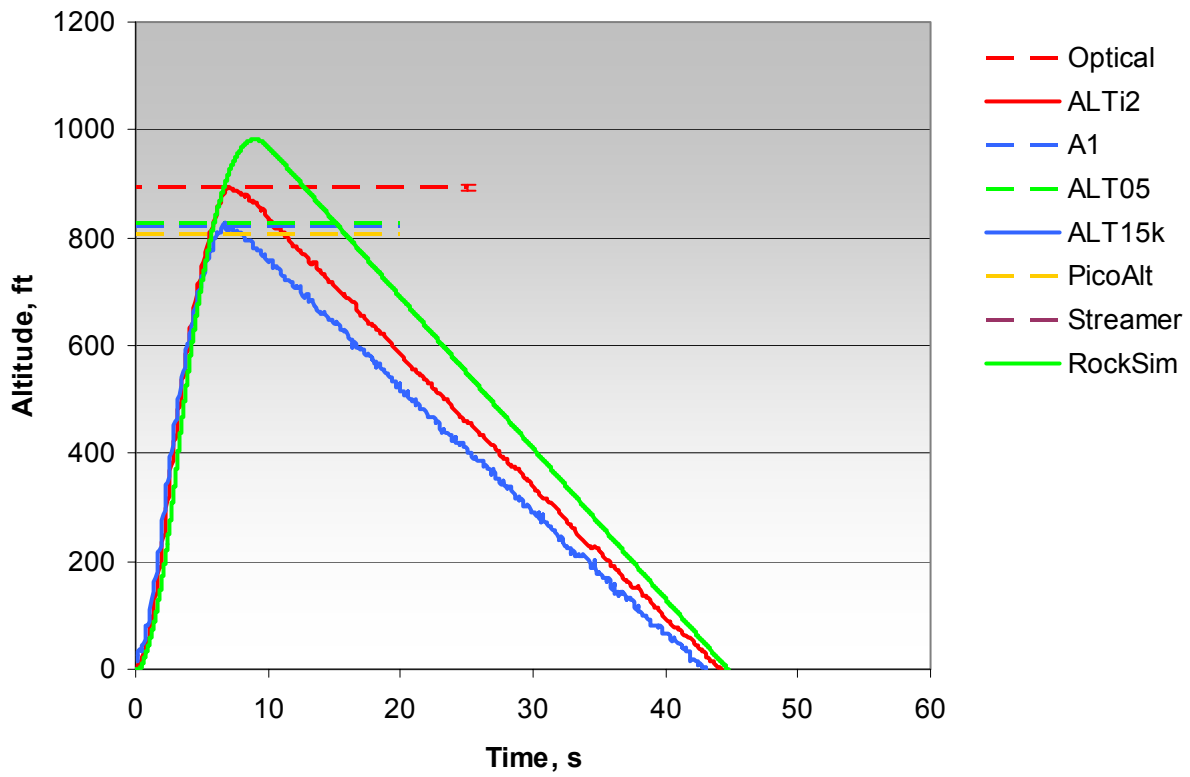


Figure A14. Results from flight 2, 5 June 2005, 12:40 am

Appendix B

Budget

Altimeters	\$410
Batteries	50
Shenandoah Park Fee	10
Capital Avionics Fee	80
Launch vehicle	10
Motors	75
Total	\$635