Analysis of Altimeter Performance Using Vacuum Chamber Testing and Sensor Monitoring

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NARAM-58
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1. Trip Barber and the FAI SM committee for entrusting me to develop a test procedure for Spacemodeling Altimeters.
2. Trip Barber (again) and the NAR S&T Committee for providing the altitude chamber.
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Project Abstract

The purpose of this project was twofold. First, it was to perform extensive vacuum chamber testing of altimeters approved for NAR contest use beginning in contest year 2016-2017. Second, to develop a test process for verification of altimeters to the FAI EDIC on Spacemodeling Altimeters. Towards that, a method was developed that allowed an altimeter sensor to be monitored and its data extracted independent or in conjunction with the altimeter operations. This data could then be used to calculate altitude data which could be used to verify the performance of the altimeter firmware.

9 altimeters were tested, including 7 on the NAR approved list. The other two of our own design, served as a reference. A vacuum chamber was used to simulate flights that were of low(75m-200m), mid(200m-400m), high(400m-800m) and very high(800m to 2100m) altitudes. 12 tests runs were performed for each altitude range for a total of 48 test runs.

The resultant data was then analyzed for correctness and agreement to the reference altimeter data and for conformance to the NAR Altimeter Requirements. The results uncovered some issues with one supplier's altimeter misreporting the peak altitude and another supplier's altimeter having divergence in the calculated altitude at higher and higher altitudes. Otherwise, the testing revealed solid performance from the sensors themselves and evidence of the employment of smoothing or filtering algorithms in the recording altimeters. Most simulated flights achieved the 1% correlation to the reference altimeter.

This report also proposed the creation of a pressure sensor emulator that could be used to do additional testing and qualification of altimeters. One of the next steps is to implement this device.

Another next step is to reach out to the altimeter suppliers, share this report, and open up a dialog in regards to the issues found.

Finally, the methods and procedures developed during this project can serve as the basis for altimeter testing for the FAI and NAR competition communities.

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1.0 Introduction

The purpose of this research and development project was to perform detailed analysis of altimeter performance using a vacuum chamber. In addition, it included the development of a method of analysis of altimeters using sensor data extraction of an altimeter while in use. A further step, development of a sensor emulator for use with altimeters was proposed and examined, but not implemented.

A second purpose of this R&D report was to develop a test method and procedure for verification of altimeter functionality and performance to the requirements of the FAI EDIC, *"Technical Guidance Notes and Specification for Altimeters Used in Spacemodeling Competition"*, Version 3.0, as published on June 26, 2015. This test method could, in the future, serve as the test procedure for NAR testing of altimeters, or it could be used as a basis of such a procedure if the NAR decides to implement a testing procedure for altimeters in the future.

2.0 NAR Based Altimeter Altitude Today

Altimeter based altitude for use in NAR competition has gained increased popularity. NARAM-57 had 3 altitude events, all using altimeters for the altitude determination method. NARAM-58 will have 2 altitude events, again using altimeters for the altitude determination method. Altimeters have also proven popular for local sections to hold altitude events. For several years contests where no altitude events were held were very common. The size of the host club, manpower available, lack of equipment, lack of experience, and other similar factors were often cited as reasons for not holding altitude events. With the introduction of altimeter based altitude, flying altitude events has become quite prevalent and commonplace at NAR sanctioned (and fun) contests. "Mine flew higher than yours" is a fun aspect of the hobby and NAR competition.

However, in spite of the prevalence and popularity of altimeter based altitude, the implementation method to date has been criticized by several avid NAR competitors. Specifically, the qualification of altimeters based on manufacturer specifications only has been questioned. Prior to the 2015-2016 contest year, altimeter qualification was somewhat arbitrary and adhoc, based on meeting a set of criteria (sampling rate, accuracy) that was verified by examining manufacturing datasheets and field flight experience. The result was a very large selection of altimeters with a wide variety of sensor generations and technologies. The performance levels, benefits and shortcomings of the technologies used in those altimeters was outlined in detail in our NARAM 54 R&D report and won't be discussed here.

However, based on the work published in that report, the NAR did implement an "emergency" RCP to prune the altimeter list to altimeters that were of the 3rd generation pressure sensor vintage. That is, altimeters that have digital output of at least 16 bits and have been factory calibrated. In addition, there are now requirements for pressure accuracy that are difficult to verify on some sensor datasheets, and other datasheets indicate they can't be met. Depending upon the interpretation, no current state of the art pressure sensors could meet the requirements. At the same time, many NAR members in the competition community believe that qualification based on specification sheets only is not adequate and testing needs to done. In spite of all of that, the altimeter set that is considered "qualified" for the 2016-

2017 contest year are all built using the latest generation sensors as recommended in our prior R&D. This is a step in the right direction, and should be applauded.

Another recommendation, this time from our NARAM 57 R&D report, that temperature correction be applied to all altimeter data was *not* submitted as an urgent or emergency RCP. Instead, it was introduced as a standard RCP for the membership to approve or reject. This RCP was rejected by the membership. This has implications for any method of NAR or other competition where winners or qualifiers are selected based on altitude achieved at a local launch (as is currently being considered) but competing against others nationally. A qualification flight of a rocket flown in Minnesota in March when it is 0 degrees C (32F) will report an altitude 13% higher than if it was flown in Arizona in June at 38 degrees C (100F).

In summary, that is the status of NAR altimeter competition today. We are moving in the right direction, but still with opportunities for improvement. Also, it should be pointed out that optical tracking is still a valid method approved for contest use in NAR competition for those who prefer it.

3.0 FAI Spacemodeling Altitude Competition Today

For FAI Spacemodeling, altimeter use has become the *defacto* standard. Altimeters have been used for several years in the FAI World Spacemodeling Championships. Or more accurately, one specific altimeter model has been approved for use for each WSMC. In prior years, it has been the Adrel ALT-LED, and more recently the ALT-USB. The ALT-LED, was a maximum altitude reporting altimeter only, while the ALT-USB was a downloadable altimeter (full flight profile data). Both altimeters used 2nd generation sensors with a 0 to 3V analog output. The altimeters and data reduction for the WSMC events were managed by the Adrel altimeter designer/manufacturer. Unknown by many is that in the data reduction, temperature correction was applied to the results, based on the ambient temperature for each flying round.

For the upcoming WSMC, to be held August 23-29, 2016 in western Ukraine, the newer Adrel ALT-BMP altimeter will be used. This altimeter is based on a 3rd generation, state of the art, digital pressure sensor, the Bosch BMP180.

Long term, the FAI CIAM is looking to the Spacemodeling community to provide compliance to the FAI EDIC for Spacemodeling Altimeters that was published a year ago. The FAI decision on the implementation of the EDIC grandfathered in the Adrel ALT-BMP through the 2016 WSMC, but any altimeter used in FAI competition after that must be qualified to the specifications outlined in the EDIC.

In January of 2016, I was approached by a representative from the FAI about development of a test method and procedure to verify altimeters to the requirements in the FAI EDIC. The FAI is looking to the United States for this work, in part due to the fact that all altimeters other than the Adrel are from US companies. At least one US supplier is interested in producing an altimeter that meets the FAI EDIC and could be used in FAI competition. The EDIC requirements cannot be verified by vacuum chamber testing alone. An understanding and knowledge of the sensor, the sensor data, the firmware, and in particular, the firmware algorithms for pressure to altitude conversion and filtering must be understood and verified as much as practical.

This is a summary of FAI altitude competition today and the task at hand. Based on the work that has been previously done by our team, I (Dan) was approached as someone that might be able to undertake such a task. Since it a) is in good alignment with the direction that many believe the NAR altimeter qualification needs to go, b) fits in well with the knowledge and work we have performed in the past, and c) is a good continuation of the work we have previously done, we agreed to carry out this task.

4.0 Design Considerations and Approach Taken

For testing and qualification of altimeters, two methods were considered and we called one "passive" and the other "active" sensor analysis and simulation.

4.1 Passive sensor monitoring

Passive sensor monitoring we defined as a method where the communication between the altimeter microprocessor and the digital sensor is monitored, collected, and stored by a separate device (computer). The data can then be analyzed to a) see how the altimeter is programmed and how it collects the sensor data, and b) to take the raw sensor data and calculate the altitude independently from the altimeter. In this way, the altitude reported by the altimeter can be verified. Specifically, this will verify the following:

1. What is the mode and method that the altimeter is using to collect data from the sensor? These sensors have several sampling modes that can affect the precision of the pressure reading.
2. How many samples per second is the altimeter actually collecting?
3. How is the altimeter collecting pre-flight data to get a pressure reading at ground level?
4. Are the altitude data points reported in the data file correct? Did the altimeter calculate the altitude correctly?
5. Did the filtering algorithm have an adverse effect on the final result? In other words, report a peak altitude that is significantly lower or higher than the waveform data suggests?

While some of these questions can be answered without the sensor data collection, others cannot. With the data, it makes all of these easier to verify. The figure below illustrates how sensor monitoring would work. The connection is through the I2C sensor interface. All 3rd generation sensors use an I2C

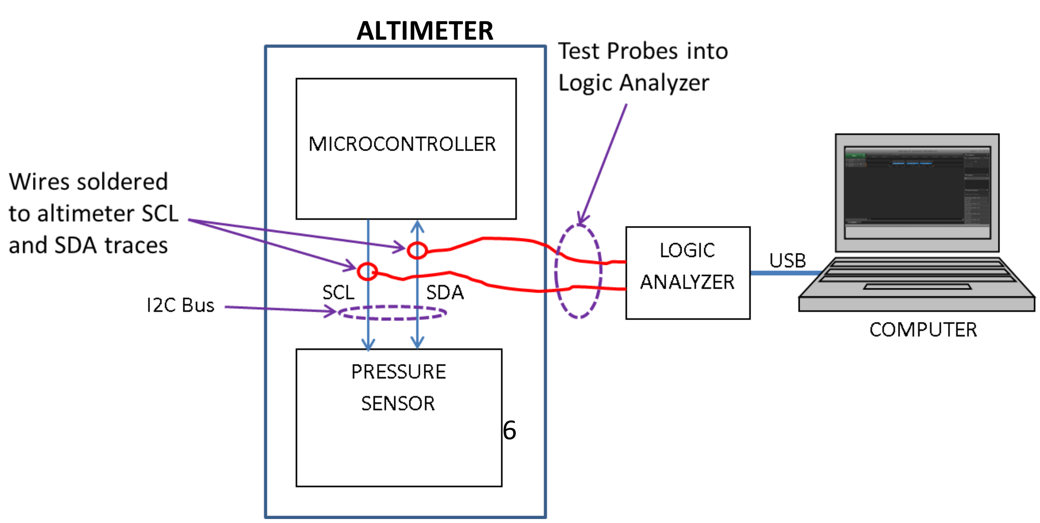


Figure 1 - Illustration of altimeter sensor monitoring with a logic analyzer.

interface to send data to the microcontroller. See Appendix C for details on I2C.

A test setup as illustrated in figure 1 was created and tested. Initially we planned to use the Atmel USBKEY development board from our NARAM 54 project to monitor the data. There were a couple of challenges with that approach. First, the I2C port on the microcontroller is designed to be a slave or master. It doesn't support a snooping or monitoring mode. Thus, the implementation would have to be done with software monitoring discrete input pins on the microcontroller, aka "bit banging." While we have used this approach successfully in the past for serial communication at bit rates of 300 bps or 9600 bps, the IC2 bus standard speed is 100,000 bps with an enhanced version up to 400,000 bps. The software monitoring approach would probably not work. Later we found that the Adrel ALT-BMP runs the I2C bus at ~333,000 bps, so this was a good decision.

Instead, we decided to purchase an inexpensive logic analyzer that could collect data in real time from the I2C bus signals and save it to a file. A search on the Internet found an ideal one in the Saleae logic analyzer. This unit has 4 channels, 2 more than required. In addition, it has built in protocol analyzers, include an I2C bus protocol analyzer. A protocol analyzer takes the signals and decodes them into I2C bus data packets. The unit connects to a computer via the venerable USB bus and uses the computer for the user interface and to save results. The screen shot below shows the GUI for the analyzer after it had acquired data from a sensor. The top waveform is the I2C Clock signal, SCL, the bottom waveform is the bi-directional data signal, SDA. The analyzer was setup to analyze these two signals as an I2C bus and the lower right panel shows the transactions on the I2C bus. These transactions can be saved to a file. This was the perfect solution for this project as the file could then be processed and the altitude data derived from the sensor on the altimeter without using the altimeter software itself. In this way, some aspects of the altimeter software can be verified since the data it is using is the same as the data collected by the analyzer.

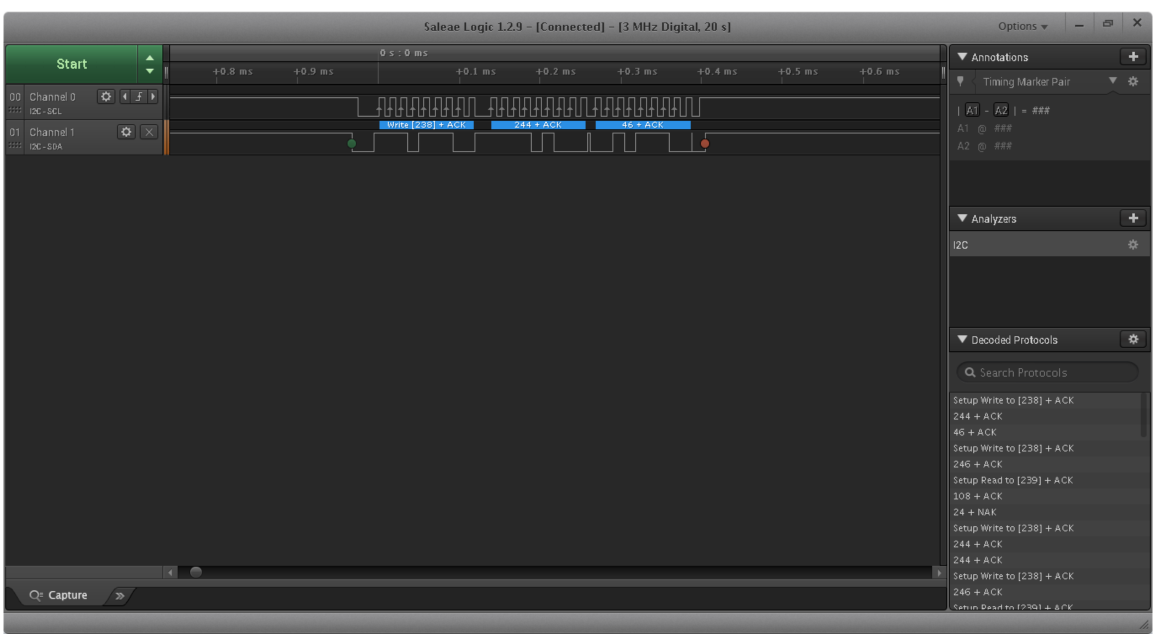


Figure 2 - Screen shot if the logic analyzer GUI.

4.2 Active sensor emulator

Passive sensor monitoring is a valuable tool towards analyzing many aspects of an altimeter's performance as outlined in section 4.1 above. However, using a vacuum chamber with passive sensor monitoring cannot verify some of the performance requirements of an altimeter. Specifically, it cannot verify the launch detect altitude or immunity to wind gusts and other noise to false trigger a launch detect. Also, it cannot measure or assess the ability of the altimeter to filter abrupt changes in altitude such as ejection spikes, staging, etc.

To try to measure the ability of an altimeter to correctly predict launch detect and also to assess its ability to properly deal with noise events, the concept of an active sensor emulator is proposed. A sensor emulator is a device that would replace the sensor IC on an altimeter with a separate microcontroller that connects to the circuit board I2C connections after removing the sensor from the board. The sensor emulator "fools" the altimeter microcontroller into thinking it is "talking" to the sensor, when it reality, the data being sent is coming from the other microcontroller board (sensor emulator). The microcontroller on the sensor emulator acts as an I2C slave. By using canned data files with different raw pressure outputs (some with event anomalies), the unit under test can be subjected to sensor data with pressure spikes from wind gusts, ejection charges, or whatever. Virtually, any set of data could be sent to the altimeter to test virtually any scenario.

Note: Due to time constraints, the active sensor emulator analysis was not completed for this R&D report. It will be discussed in future work.

5.0 Plan for Passive Testing

The basic procedure for passive testing was to use a vacuum chamber with the device under test (DUT) along with a reference pressure sensor/altimeter. The device under test would be instrumented to monitor the data communication between the sensor and the microprocessor on the DUT.

When the altimeter chamber arrived (supplied by NAR S&T), we were surprised by two things. First, the expected valves and multiple chambers were not there. Just one vacuum chamber connected to a vacuum pump through a pressure valve. Second, the size and utility of the chamber was a pleasant surprise. The chamber on the inside is 24 cm in diameter and has a flat shelf that can hold multiple altimeters. While the control of the chamber to do the testing would be a challenge, the ability to test several altimeters simultaneously was a benefit we took advantage of. The decision was made to test as many altimeters as we had on hand, and to do a detailed analysis of all of them. While only the one Adrel ALT-BMP would be instrumented, we believed the extensive testing and analysis we would perform on the other altimeters would be beneficial and of value to the NAR competition community and users of these altimeters in general.

The list of altimeters approved for the 2016-2017 contest year includes altimeters from Adrel (ALT-BMP), Altus Metrum, Jolly Logic, and Perfectflite. A quick inventory of our altimeter range box revealed we had all but the ALT-BMPs, which were then quickly ordered. Therefore the altimeters to be included in the testing were:

1. 1 ALT-BMP (instrumented)
2. 1 ALT-BMP (standard)
3. 1 Altimeter One
4. 1 Perfectflite Pnut
5. 1 Perfectflite Stratologger
6. 2 Altus Metrum Micropeak
7. 2 Wolfmeter 1

The Wolfmeter 1 was described in our NARAM-57 R&D report. It was included as the standard or reference altimeter. We believed it was a good standard because one of the 2 sensors on the Wolfmeters is the MS5611, which we found to be the best performing sensor in our prior work. Also, the pressure to altitude conversion algorithms we had verified in our prior work as well. While this decision may seem questionable, the results from the experiments indicated it was a good reference as the results correlated very well to the data from the other units. Ideally, we would have preferred to have a reference altimeter with 10X the precision and accuracy of the altimeters themselves. However, it is unlikely that there *are* altimeters with better resolution that the current digital pressure sensors being used in the altimeters. However, the issue of sensor accuracy is a valid question. Given the testing was done at room temperature (23C) helps, but even so, the absolute and relative accuracy was a concern going in. Other than sending a sensor, or obtaining a sensor, calibrated in a certified test lab, there are no other easy solutions. Given the cost of that approach, this was the best option available. *Note: When S&T was considering altimeter testing, their approach was to use the BMP180 sensor as the reference for the reasons given.*

Since the Wolfmeter actually has two sensors, each of those units provided two data points. Because the instrumented ALT-BMP had altitude data from the unit directly, plus the altitude data calculated independently from the sensor data that was "snooped", it had two data points. So the total number of altitudes reported started out at 9 per test run. However, it was found that the peak altitude reported from some altimeters did not always correlate to the data collected (in the altitude plot or altitude data table of the altimeter), so additional data points were recorded for the peak altitude in the data tables of the Micropeak and Perfectflite altimeters. This resulted in a total of 16 altitudes reported for each single test run.

The vacuum chamber could not be setup to simulate a rocket launch to a specific altitude. However, by controlling the pressure control valve, the pump on-off switch, and the manual valve that opened and closed the chamber to the pump, it could be controlled well enough to simulate altitudes to different ranges. Thus, we decided to setup a series of simulated flights in 4 altitude ranges: low (75m-200m), mid (200m-400m), high (400m-800m), and very high(800m-2000m). We had planned to run 20 tests in each altitude range, but time only permitted us completing 12 in each range.

The data from the sensor on the ALT-BMP was collected by soldering two wires to the altimeter and connecting them to the Saleae logic analyzer. The logic analyzer is a USB based device that collects electronic data and can save it to a data file on a computer. It must be connected to a computer to function, so the chamber had to be modified to allow the wires connected to the ALT-BMP to be brought out of the chamber to the logic analyzer probes. See pictures below for more details.

The data from the logic analyzer needed to be converted to pressure data. See our prior reports for more details. Initially, we planned to bring the data from the logic analyzer directly into MS Excel and convert it there. However, due to the complexity of the algorithm, we found it more expedient to write a C program on the computer to do it and save the result in another Excel spreadsheet.

6.0 Test Procedure

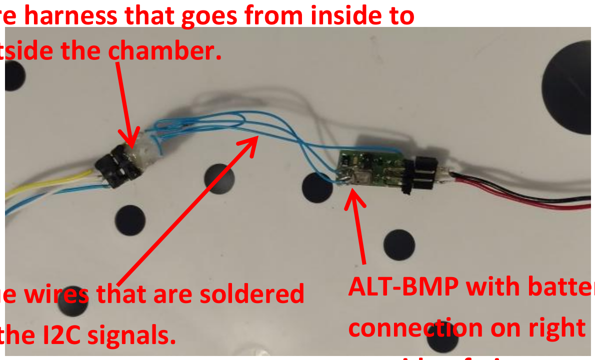
The procedure for running each test was extensive and time consuming. This was due to the number of altimeters to arm, place in the chamber, and then, post "launch", remove from the chamber and collect data files from the altimeters and record the reported altitudes. It took about 30 minutes per test run with some runs aborted part way through the process due to a user error (forgot to arm an altimeter, forgot an altimeter, poor operation of the chamber controls, forgetting to arm the sensor data collection device, etc.) . All told, including dry runs, over 60 test runs were executed.

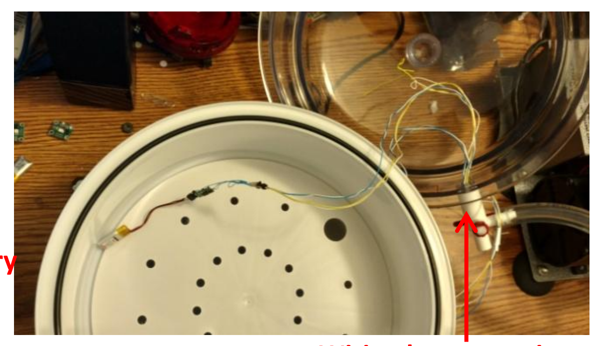
The basic steps involved were these:

1. Remove the cover from the chamber.
2. One by one, arm each altimeter and place in chamber.
3. For the instrumented ALT-BMP, connect it a connector that allowed the sensor signals to be connected to the logic analyzer outside the chamber.
4. Wait for all the altimeters to get to their waiting for launch mode.
5. Arm the logic analyzer and collect and review data from the ALT-BMP sensor to verify the connections were all good prior to the test.
6. Re-arm the logic analyzer and wait 2 seconds.
7. Turn on the pump for the appropriate amount of time to get to the right pressure range (determined by trial and error and adjustment of the pressure valve).
8. Close off/seal the chamber by turning the manual valve with one hand while turning off the pump with the other hand (tricky hand/eye coordination which I'm not good at).
9. Look through the chamber at the Altimeter One and verify altitude was in desired range.
10. Remove all altimeters from the chamber and turn them off.
11. Record the Altimeter One data.
12. Save the data from the logic analyzer into a file and process it to get the sensor calculated altitude (actually, the whole flight data) and save to a file.
13. Record the peak altitude calculated from the sensor.
14. Transfer the data from the MicroPeak altimeters and record the peak data.
15. Transfer the data from the Perfectflite altimeters and record the peak data.
16. Transfer the data from the ALT-USB altimeters and record the peak data.
17. Transfer the data from the Wolfmeter altimeters and record the peak data.
18. Repeat 47 more times.

A picture of the test setup is shown below. The grey/black unit on the right is the pump. Next to it is the vacuum chamber. Inside the chamber are the nine altimeters. The wires attached to the instrumented ALT-BMP go through a hole drilled into the manual valve fitting that was sealed back up with epoxy. The logic analyzer is the small black box with the blue LED at the bottom middle of the picture, connected to the computer via a USB cable. The computer screen shows the logic analyzer GUI. On the bottom left of the table is the assortment of altimeter to computer download cables and boards.

Figure 3 - Vacuum Chamber Test Setup





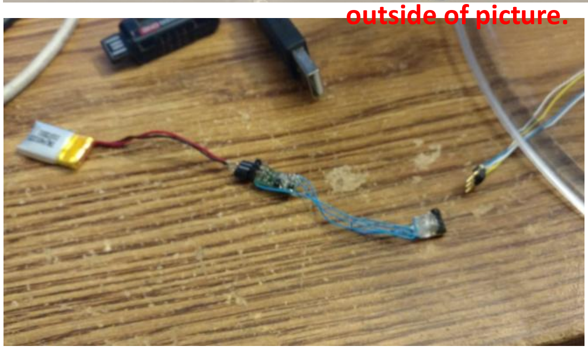


Figure 4 - Details of connection to I2C bus on the altimeter sensor through connectors, through chamber, to the logic analyzer.

6.1 Conversion from Logic Analyzer Data File to Altitude

Once the test run is completed the data from the logic analyzer is saved to a text file that looks like this.

```
Time [s],Packet ID,Address,Data,Read/Write,ACK/NAK
0.000028000000000,0,238,246,Write,ACK
0.000085333333333,1,239,114,Read,ACK
0.000105666666667,1,239,187,Read,NAK
0.000163666666667,2,238,244,Write,ACK
0.000191333333333,2,238,52,Write,ACK
0.032136000000000,3,238,246,Write,ACK
0.032193333333333,4,239,162,Read,ACK
0.032213666666667,4,239,66,Read,NAK
0.032271333333333,5,238,244,Write,ACK
0.032299333333333,5,238,46,Write,ACK
0.064283000000000,6,238,246,Write,ACK
0.128667000000000,14,238,244,Write,ACK
0.128695000000000,14,238,52,Write,ACK
0.160677666666667,15,238,246,Write,ACK
0.160735000000000,16,239,162,Read,ACK
0.160755666666667,16,239,62,Read,NAK
                 .
                 .
                 .
Data continues for remainder of "flight"
```

To parse the data, the header line is removed and the lines prior to the first transaction for a pressure conversion removed and commas replaced with spaces. This is easily done with Notepad. The beginning of the modified file looks like this:

```
0.032341333333333 5 238 244 Write ACK
0.032369000000000 5 238 52 Write ACK
0.064351333333333 6 238 246 Write ACK
0.064408666666667 7 239 162 Read ACK
0.064429000000000 7 239 86 Read NAK
0.064486666666667 8 238 244 Write ACK
0.064514333333333 8 238 46 Write ACK
0.096514000000000 9 238 246 Write ACK
0.096571666666667 10 239 115 Read ACK
0.096592000000000 10 239 52 Read NAK
```

The sequence above writes to the command register (244) to do a pressure conversion (52), waits 32 ms, then does 2 reads from the data register (246) to read a 16 bit raw pressure value. The sequence then repeats, except the write command is to do a temperature conversion. These 8 lines repeat during the entire altimeter operation from pre-launch sitting on the pad, through the flight until landing.

The only difference to this communication sequence from the altimeter microcontroller to the sensor is at initial power up when the microcontroller reads the calibration coefficient registers. This data needed to be collected only once by the logic analyzer as it never changes for a specific sensor.

The data file after parsing was converted to actual pressure by a program written in C on the computer. The original plan was to do the conversion in Excel but it was too complex. We were able to reuse code written for the USBKEY development board from our NARAM 54 project to do the conversion from raw to actual data. The program reads the parsed fie and writes a new file with the pressure data. This is a non-trivial exercise and was why it was difficult to implement as an Excel macro.

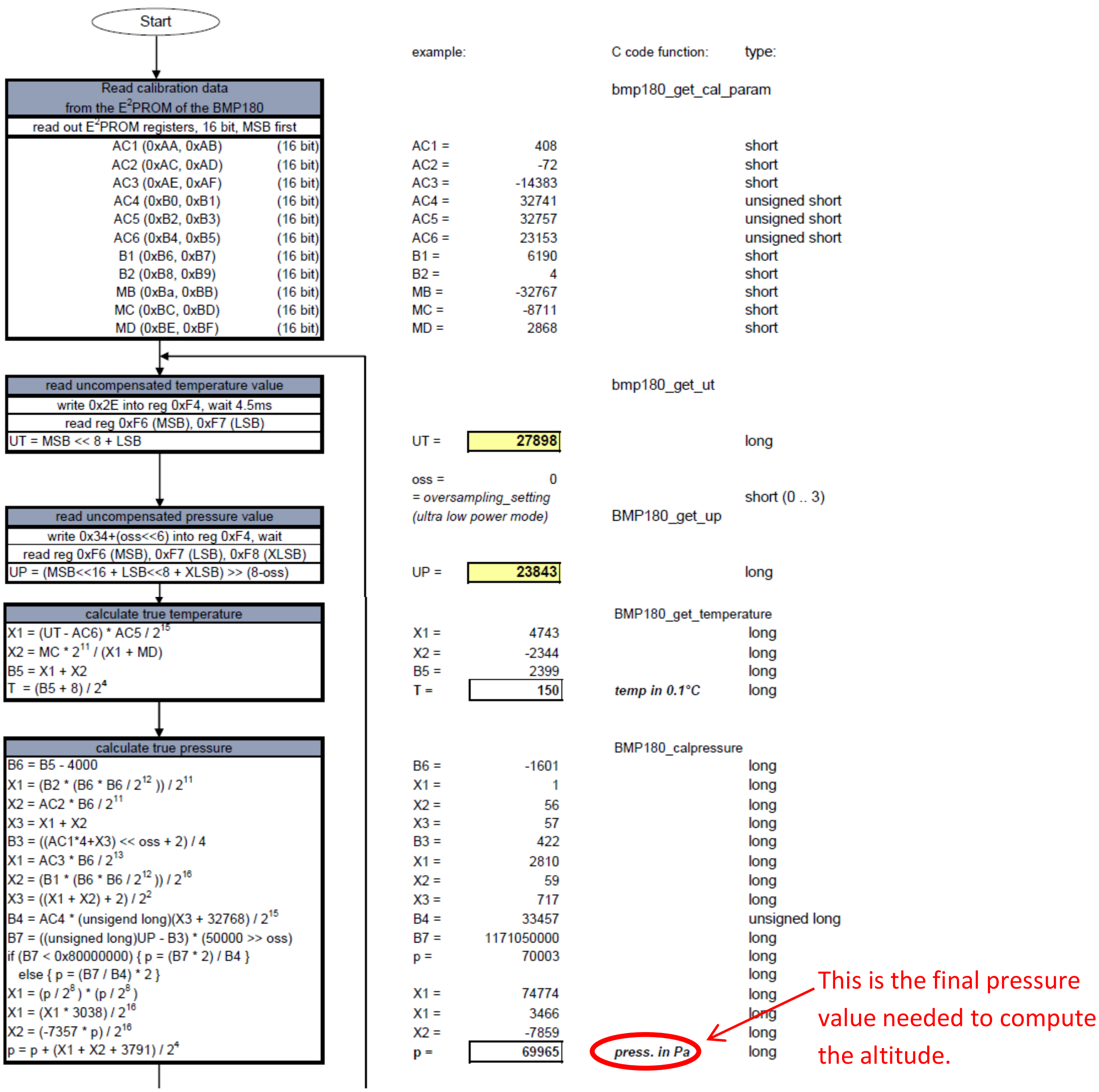


Figure 5 - Conversion algorithm flow chart from the BMP180 datasheet. A non trivial exercise. By doing the conversion in the test setup, it verifies the altimeter is doing it correctly.

The illustration on the previous page shows the steps involved in converting the raw data to actual pressure and temperature values. The code for the program that does this from the modified logic analyzer file is shown in Appendix D.

The process for converting the resultant actual pressure values to altitude was a semi-automated one. First, 30 samples of the pressure data prior to launch were averaged to get the ground pressure. This was put into the pressure altitude equation shown below and this equation was copied to all the cells in the adjacent column of the spreadsheet to calculate the altitude at each step of the flight. The final Excel file result looks like the table below. The derivation of this equation can be found in Appendix F.

Pressure	Altitude
99180	0.424978
99192	-0.59494
99189	-0.33997
99186	-0.08499
99186	-0.08499
99189	-0.33997
99189	-0.33997
99180	0.424978
99146	3.315291
99004	15.39528
98863	27.40409
98722	39.42677
98589	50.78007
98434	64.02701
98310	74.63674
98165	87.05702
98038	97.94769
97918	108.2486
97805	117.9579
97811	117.4422
97888	110.8254
97987	102.3243
98070	95.2025
98137	89.45713
98217	82.60114
98276	77.54775
98347	71.4698

Altitude= ((288.15)/(-0.0065))*(POWER((FP/GP),0.190263189)-1)

Where GP is the ground pressure and FP is the current flight pressure.

Derivation of this equation can be found in Appendix F.

This file can be searched for the maximum altitude. It can be compared to the altimeter data by cut and pasting from the altimeter exported spreadsheet into the sensor spreadsheet. Examples of this will be seen in the data analysis section of this report. This gives us what we were looking for, the ability to calculate the altitude from the altimeter's sensor separately from the altimeter itself.

7.0 Data Results and Analysis

All of the altimeters worked correctly for every test. Reported altitudes were close enough to each other that one would not be able to tell on an actual flight if the altimeter met accuracy requirements with one exception to be discussed.

Low Altitude	1	2	3	4	5	6	7	8	9	10	11	12
ALTIMETER 1	118	147	139	110	176	174	194	192	83	124	187	159
Micropeak 1 - blink	38	134	96	97	169	168	159	187	77	118	175	150
Micropeak 1 - data	116	147	139	110	177	174	193	190	83	124	186	159
Micropeak 2 - blink	42	135	90	98	170	169	159	187	77	118	175	150
Micropeak 2 - data	118	147	139	110	177	175	193	190	83	124	186	159
Pnut	119	147	139	111	177	174	191	189	84	123	186	159
Pnut Data	119	147	139	111	177	175	194	191	81	124	187	160
Stratologger	119	148	140	111	177	173	191	189	85	124	186	159
Stratalogger Data	119	148	140	111	178	175	195	192	85	124	187	160
ALTBMP 1 (SN 446)	115	147	140	111	178	175	193	191	84	124	187	161
ALTBMP1_SENSOR	118	148	140	111	179	175	194	192	85	124	188	160
ALTBMP2 (SN 449)	117	148	140	111	178	175	194	191	84	124	188	161
WM1-1 MS5611	118	147	139	110	177	174	194	191	84	124	186	159
WM1-1 MPL3115	118	149	138	111	178	176	197	191	84	125	188	161
WM1-2 MS5611	117	147	139	110	177	174	194	191	84	123	186	159
WM1-2 MPL3115	117	148	141	112	179	176	194	191	84	125	189	159

Table 1 - Low Altitude Test Results

Mid Altitude	1	2	3	4	5	6	7	8	9	10	11	12
ALTIMETER 1	243	280	243	334	340	266	277	352	293	248	332	330
Micropeak 1 - blink	242	280	248	336	343	273	286	357	299	253	339	324
Micropeak 1 - data	239	278	242	332	339	267	279	350	293	249	331	327
Micropeak 2 - blink	242	280	248	336	343	272	285	356	300	254	339	321
Micropeak 2 - data	242	279	242	331	339	267	278	352	293	249	331	328
Pnut	239	278	242	331	339	267	278	350	292	248	331	329
Pnut Data	243	279	242	333	340	267	279	353	294	248	332	330
Stratologger	238	279	242	331	340	267	278	349	292	248	331	329
Stratalogger Data	242	280	243	333	340	268	278	353	293	249	333	330
ALTBMP 1 (SN 446)	242	281	244	334	341	268	281	354	294	250	335	331
ALTBMP1_SENSOR	243	280	243	333	341	267	280	353	294	249	334	331
ALTBMP2 (SN 449)	243	281	245	336	343	270	281	354	295	251	334	333
WM1-1 MS5611	241	279	243	334	340	267	279	352	293	248	332	330
WM1-1 MPL3115	243	280	245	336	341	269	282	355	296	250	337	331
WM1-2 MS5611	241	279	242	333	340	267	279	353	293	248	332	330
WM1-2 MPL3115	244	281	244	337	340	269	280	355	296	250	336	331

Table 2 - Mid Altitude Test Results

High Altitude	1	2	3	4	5	6	7	8	9	10	11	12
ALTIMETER 1	442	557	545	489	647	551	658	530	421	512	765	673
Micropeak 1 - blink	445	562	548	477	651	556	660	529	430	511	766	687
Micropeak 1 - data	435	556	541	488	646	549	657	529	421	508	761	673
Micropeak 2 - blink	446	561	547	479	651	556	659	528	429	512	766	686
Micropeak 2 - data	437	555	541	488	646	549	654	526	421	506	765	671
Pnut	434	556	539	487	644	550	653	528	421	503	760	671
Pnut Data	442	556	545	488	646	550	656	529	421	509	765	673
Stratologger	434	555	538	488	645	550	653	529	421	503	760	671
Stratalogger Data	441	556	546	488	646	550	656	530	421	510	765	673
ALTBMP 1 (SN 446)	443	561	548	493	653	556	662	534	424	512	773	681
ALTBMP1_SENSOR	443	558	546	489	649	552	658	531	423	510	767	676
ALTBMP2 (SN 449)	443	562	549	493	655	557	663	535	426	513	774	682
WM1-1 MS5611	441	556	544	489	647	551	658	530	421	510	767	675
WM1-1 MPL3115	442	560	548	493	650	556	661	532	424	510	769	676
WM1-2 MS5611	442	556	544	489	647	551	656	530	421	511	765	674
WM1-2 MPL3115	442	558	546	490	651	553	661	532	423	510	769	678

Table 3 - High Altitude Test Results

Very High Altitude	1	2	3	4	5	6	7	8	9	10	11	12
ALTIMETER 1	977	1031	1021	1411	1741	1349	1128	1192	818	1052	1271	2049
Micropeak 1 - blink	981	1032	1024	1426	1738	1359	1139	1197	836	1069	1266	2056
Micropeak 1 - data	975	1028	1019	1409	1737	1343	1123	1190	817	1052	1266	2045
Micropeak 2 - blink	981	1030	1023	1424	1737	1358	1139	1197	836	1068	1265	2057
Micropeak 2 - data	975	1026	1019	1408	1736	1347	1119	1189	816	1047	1265	2046
Pnut	974	1023	1016	1405	1737	1337	1116	1188	815	1047	1261	2045
Pnut Data	976	1030	1021	1409	1738	1346	1129	1189	818	1052	1269	2046
Stratologger	974	1023	1016	1405	1738	1338	1117	1192	815	1047	1261	2046
Stratalogger Data	976	1031	1021	1409	1739	1348	1129	1191	818	1052	1269	2047
ALTBMP 1 (SN 446)	990	1044	1035	1436	1781	1371	1143	1212	828	1066	1289	2104
ALTBMP1_SENSOR	979	1034	1024	1414	1746	1353	1135	1196	821	1056	1273	2054
ALTBMP2 (SN 449)	992	1045	1037	1438	1784	1374	1146	1214	829	1068	1292	2107
WM1-1 MS5611	977	1031	1022	1412	1743	1353	1132	1194	819	1054	1272	2051
WM1-1 MPL3115	983	1036	1028	1417	1752	1358	1132	1198	824	1058	1273	2059
WM1-2 MS5611	977	1032	1023	1412	1743	1352	1131	1195	819	1054	1271	2051
WM1-2 MPL3115	979	1036	1028	1420	1752	1359	1135	1196	824	1057	1272	2057

Table 4 - Very High Altitude Test Results

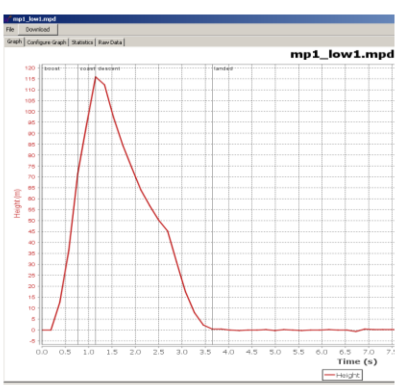
7.1 Low Altitude Tests – Analysis

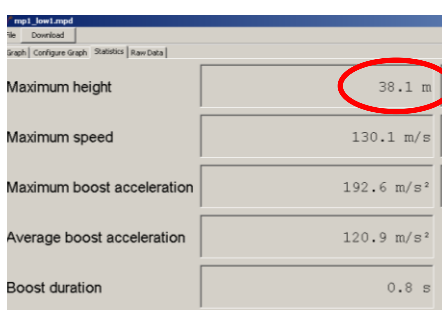
As was described before, the Wolfmeter MS5611 readings were used as the reference. Below is a table showing the percentage deviation (or error) from the average altitude of the two WM MS5611 readings.

Deviation from WM MS5611 average	1	2	3	4	5	6	7	8	9	10	11	12	Avg % Error
WM MS5611 Avg	117.5	147	139	110	177	174	194	191	84	123.5	186	159	-
ALTIMETER 1	0.4%	0.0%	0.0%	0.0%	0.6%	0.0%	0.0%	0.5%	1.2%	0.4%	0.5%	0.0%	**0.3%**
Micropeak 1 - blink	**68%**	**8.8%**	**31%**	**12%**	**4.5%**	**3.4%**	**18%**	**2.1%**	**8.3%**	**4.5%**	**5.9%**	**5.7%**	**14.4%**
Micropeak 1 - data	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.5%	1.2%	0.4%	0.0%	0.0%	**0.3%**
Micropeak 2 - blink	**64%**	**8.2%**	**35%**	**11%**	**4.0%**	**2.9%**	**18%**	**2.1%**	**8.3%**	**4.5%**	**5.9%**	**5.7%**	**14.1%**
Micropeak 2 - data	0.4%	0.0%	0.0%	0.0%	0.0%	0.6%	0.5%	0.5%	1.2%	0.4%	0.0%	0.0%	**0.3%**
Pnut	1.3%	0.0%	0.0%	0.9%	0.0%	0.0%	1.5%	1.0%	0.0%	0.4%	0.0%	0.0%	**0.4%**
Pnut Data	1.3%	0.0%	0.0%	0.9%	0.0%	0.6%	0.0%	0.0%	0.0%	0.4%	0.5%	0.6%	**0.7%**
Stratologger	1.3%	0.7%	0.7%	0.9%	0.0%	0.6%	1.5%	1.0%	1.2%	0.4%	0.0%	0.0%	**0.7%**
Stratalogger Data	1.3%	0.7%	0.7%	0.9%	0.6%	0.6%	0.5%	0.5%	1.2%	0.4%	0.5%	0.6%	**0.7%**
ALTBMP 1 (SN 446)	**2.1%**	0.0%	0.7%	0.9%	0.6%	0.6%	0.5%	0.0%	0.0%	0.4%	0.5%	1.3%	**0.6%**
ALTBMP1_SENSOR	0.4%	0.7%	0.7%	0.9%	1.1%	0.6%	0.0%	0.5%	1.2%	0.4%	1.1%	0.6%	**0.7%**
ALTBMP2 (SN 449)	0.4%	0.7%	0.7%	0.9%	0.6%	0.6%	0.0%	0.0%	0.0%	0.4%	1.1%	1.3%	**0.6%**
WM1-1 MPL3115	0.4%	1.4%	0.7%	0.9%	0.6%	1.1%	1.5%	0.0%	0.0%	1.2%	1.1%	1.3%	**0.9%**
WM1-2 MPL3115	0.4%	0.7%	1.4%	1.8%	1.1%	1.1%	0.0%	0.0%	0.0%	1.2%	1.6%	0.0%	**0.8%**

Table 5 – Low Altitude Tests - Percent error versus Wolfmeter 1 MS5611 average

The obvious point that jumps out from this analysis is the large deviation between all the other reported altitudes and the reported peak altitude from the Micropeak altimeters. It appears that the Micropeak's filtering algorithm is very aggressive or simply does not work properly. Based on these results, data from the Micropeaks was examined more thoroughly. Below are screen shots from the Micropeak #1 first flight data.





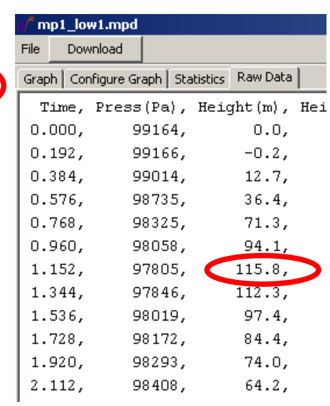


Figure 6- Screen shots from the Micropeak low altitude test one. Maximum height was reported as only 38.1 meters, while the altitude in the data set and on the altitude plot shows a peak of 115.8 meters.

Note the jagged shape of the altitude versus time plot. This is partially because the Micropeak altimeter, while sampling at 10 samples/second, only saves every other data point for an effective 5 samples/second. Compare it to the plot from the Wolfmeter 1 shown below. Although it still has a sharp peak, it is slightly smoother than the Micropeak waveform. The sharp peak is due to the operation of the chamber control. Based on this result, the thought was that perhaps if the pressure change was less sharp, as it probably would be for an actual flight, the Micropeak would calculate the maximum altitude properly. The idea being that the Micropeak is interpreting the sharp point as an ejection spike. However, in later low altitude tests, where the data is smoother, the Micropeak still displayed or calculated the maximum altitude incorrectly. Below are the altitude plots for a couple of them.

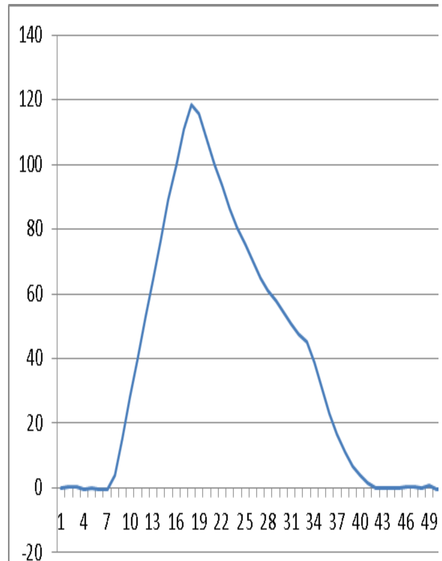


Figure 7 - Flight profile from Wolfmeter data for low altitude flight one.

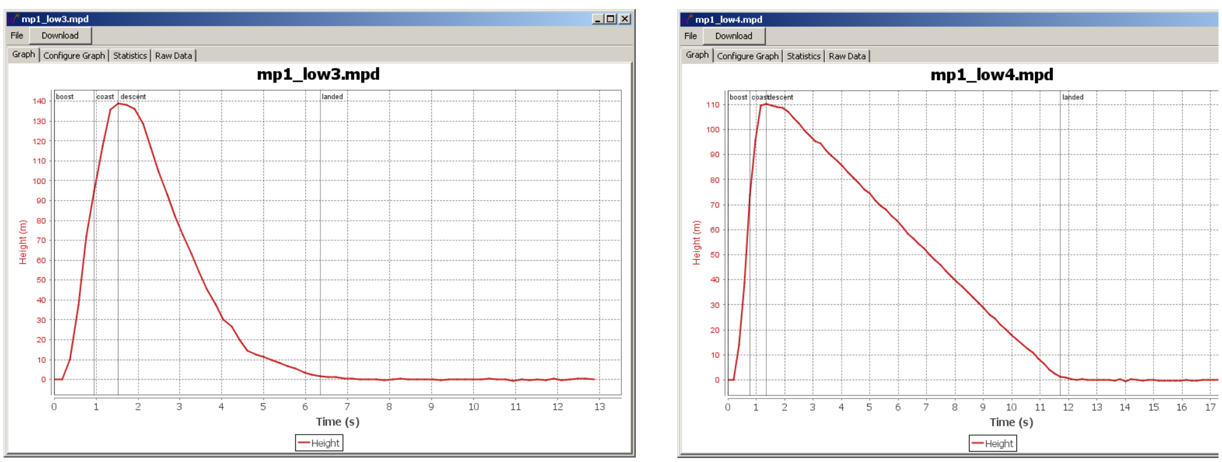


Figure 8 - Two other altitude plots from Micropeak low altitude tests. Smoother peaks, yet altitudes reported still were significantly lower than the flight data.

For these two flights, the hand coordination on the chamber controls was better. There is no sharp peak. However, even on these two flights, the Micropeak misreported the maximum altitude with errors of 31% and 12%. In all cases, the maximum altitude in the flight data from the Micropeaks was very close to the reference altimeter altitude and the other altimeters. It is hard to understand how the Micropeak can misreport the altitude by such a significant amount. Is it only because the flight profiles from the chamber are not close enough to actual flights? Examination of actual flight data files from the Micropeak suggested that for most flights we've made, little difference was found. However, two flights were found where the data did disagree by more than 5%. A B Eggloft Altitude flight has a reported altitude (beeped out) of 82M, but the data in the download file showed an altitude of 88M. A difference of 7%. Fortunately, this was a fairly rare occurrence. In flights where the rocket has a change to slowdown and arc over at apogee and eject later, the results were better. However, in cases where ejection happens early, sharp discontinuities in the data are more likely and the opportunity for a misreported peak altitude may occur. Examples of this are cases where there is no engine available with a long enough delay such as an A3-4T in A altitude or as an upper stage in B altitude.

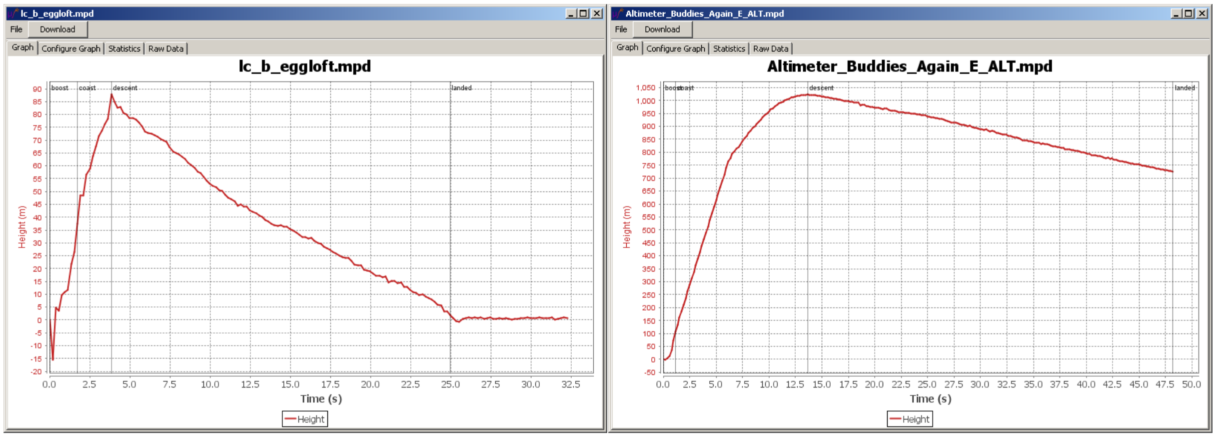


Figure 9 – On left, altitude versus time plot for B Eggloft Altitude flight. Report altitude was 7% lower than peak recorded. On right, same for E Altitude flight. Peak reported matched peak recorded.

Other than the Micropeak issue, the rest of the results from the low altitude tests were very good. Errors against the reference were lower than 1.5 % in all cases except two. One of those was the first low altitude flight with the ALT-BMP with an error of 2.1%. This one is of particular interest because the data read directly from the sensor by the logic analyzer has an error of only 0.4%. Below is a plot of the two datasets together. Red is the altimeter data. Blue is the sensor collected data. The two data sets track quite close except for where sharp changes in the pressure/altitude occur such as at launch and at apogee. A detailed look at the two datasets side by side shows that while the data is close, it is not the same, even though in most of the testing, the final altitudes were the same. This indicates that the altitude data in the file is not the raw altitude data, but it is data after a filtering operation has occurred. It appears that the filtering operation shaved off the peak slightly, accounting for the 1.7% difference. Since this was the first official test run, and the pre-test runs did not reveal this, the issue was monitored closely during the remainder of the tests. Note that in the rest of the low altitude tests the error from the reference was not much different than the sensor direct

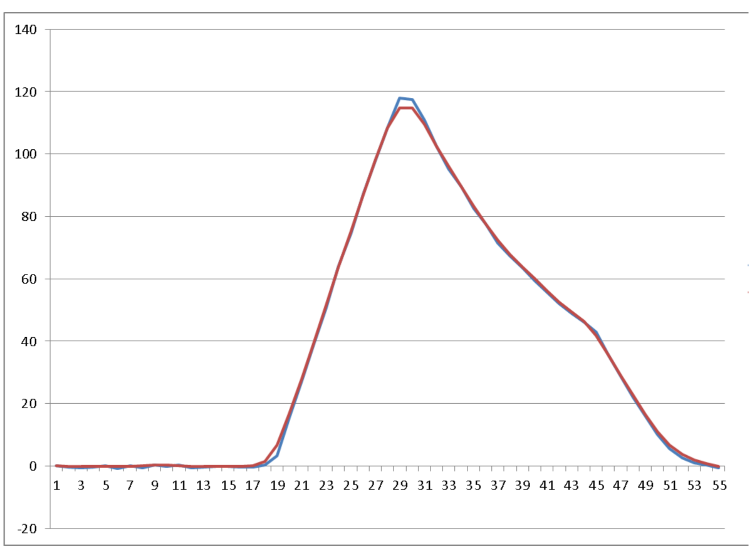


Figure 10 - Altitude plot for ALT-BMP 1 comparing the altimeter reported altitude versus the altitude derived directly from the sensor data.

readings error, but the numbers did vary. It would be good to be able to understand the altitude calculation in the ALT-BMP better as well as the filtering operation. As a comparison, here is low altitude flight 2 data plotted. It is clear from this plot that the altimeter is performing a smoothing/filtering operation on the data. First, the peak in the altimeter data (red) is rounded. Second, the data on descent is much smoother in the altimeter data versus the raw sensor data.

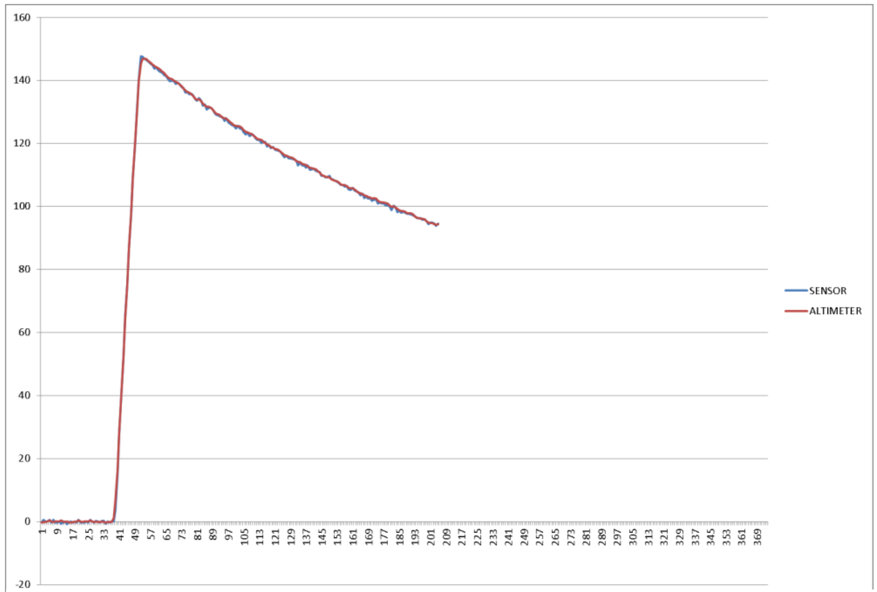


Figure 11 - ALT-BMP low altitude flight 2, sensor data versus altimeter data.

The USMR Sporting Code Requirement for 2016-2017 is an error of 1% or 2M, whichever is greater. The rest of the data all met this requirement except for the Wolfmeter MPL3115 sensors data. This sensor was included in this R&D project because from the datasheet it appeared to be less accurate and precise than the BMP180 or the MS5611. The data proved this to be true. It was hoped it would exceed the data sheet specifications because it is quite a bit less expensive that the other two sensors.

7.2 Mid Altitude Tests Analysis

Beginning with the mid altitude tests, the requirements are that altimeters are accurate to 1%. The 2M limit no longer applies since the altitudes are greater than 200 meters. Below is a summary table of the errors against the reference for the Mid Altitude Tests.

Deviation from WM MS5611 average	1	2	3	4	5	6	7	8	9	10	11	12	Avg % Error
WM MS5611 Avg	241	279	243	333.5	340	267	279	352.5	293	248	332	330	
ALTIMETER 1	0.8%	0.4%	0.2%	0.1%	0.0%	0.4%	0.7%	0.1%	0.0%	0.0%	0.0%	0.0%	0.2%
Micropeak 1 - blink	0.4%	0.4%	2.3%	0.7%	0.9%	2.2%	2.5%	1.3%	2.0%	2.0%	2.1%	1.8%	1.6%
Micropeak 1 - data	0.8%	0.4%	0.2%	0.4%	0.3%	0.0%	0.0%	0.7%	0.0%	0.4%	0.3%	0.9%	0.4%
Micropeak 2 - blink	0.4%	0.4%	2.3%	0.7%	0.9%	1.9%	2.2%	1.0%	2.4%	2.4%	2.1%	2.7%	1.6%
Micropeak 2 - data	0.4%	0.0%	0.2%	0.7%	0.3%	0.0%	0.4%	0.1%	0.0%	0.4%	0.3%	0.6%	0.3%
Pnut	0.8%	0.4%	0.2%	0.7%	0.3%	0.0%	0.4%	0.7%	0.3%	0.0%	0.3%	0.3%	0.4%
Pnut Data	0.8%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.1%	0.3%	0.0%	0.0%	0.0%	0.1%
Stratologger	1.2%	0.0%	0.2%	0.7%	0.0%	0.0%	0.4%	1.0%	0.3%	0.0%	0.3%	0.3%	0.4%
Stratalogger Data	0.4%	0.4%	0.2%	0.1%	0.0%	0.4%	0.4%	0.1%	0.0%	0.4%	0.3%	0.0%	0.2%
ALTBMP 1 (SN 446)	0.4%	0.7%	0.6%	0.1%	0.3%	0.4%	0.7%	0.4%	0.3%	0.8%	0.9%	0.3%	0.5%
ALTBMP1_SENSOR	0.8%	0.4%	0.2%	0.1%	0.3%	0.0%	0.4%	0.1%	0.3%	0.4%	0.6%	0.3%	0.3%
ALTBMP2 (SN 449)	0.8%	0.7%	1.0%	0.7%	0.9%	1.1%	0.7%	0.4%	0.7%	1.2%	0.6%	0.9%	0.8%
WM1-1 MPL3115	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%
WM1-2 MPL3115	0.8%	0.4%	1.0%	0.7%	0.3%	0.7%	1.1%	0.7%	1.0%	0.8%	1.5%	0.3%	0.8%

Table 6 -Mid Altitude Tests - Percent error versus Wolfmeter 1 MS5611 average

The table shows what looks like the same issue with the computed maximum altitude from the Micropeak, although the error is much less. Below is the data from one of those flights.

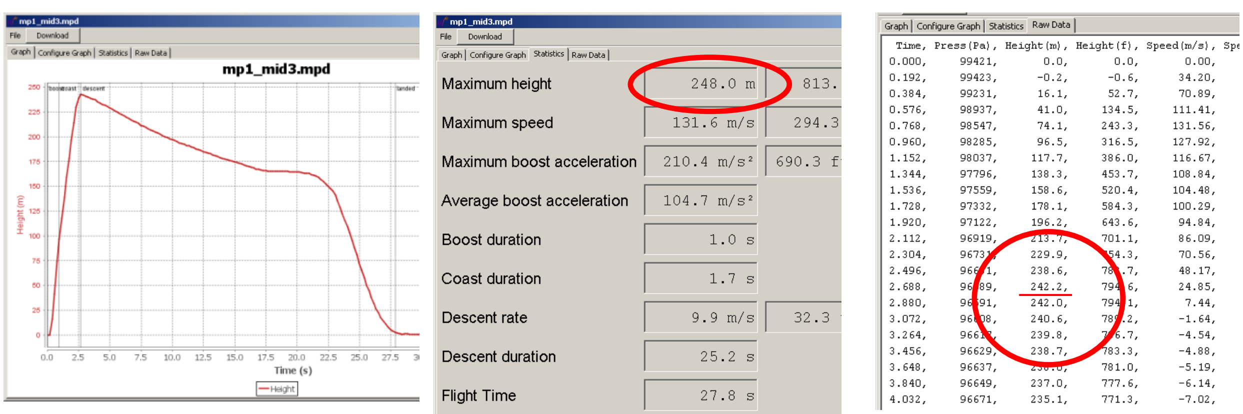


Figure 12 - Data from Micropeak 1, Mid Flight 3. Reported maximum height is 248 meters, but the recorded shows a peak altitude of only 242.2 meters.

Surprisingly, this time the reported maximum altitude is 6 meters *higher* than the peak height shown in the data and on the graph. No explanation for this except that the algorithm in the Micropeak for determining peak altitude has some issues. Note that the peak altitude in the flight data captured by the Micropeak showed great correlation to the reference.

Three other flights showed an altimeter with an error greater than 1%. One was the first mid range flight from the Stratologger. The other two were from the 2nd, non-instrumented ALT-BMP. Note that for the Stratologger case, the data in the file only had a 0.4% error. For the Stratologger flight, to the left is the altitude plot, both the raw data, and what Perfectflite calls the "smooth data" are shown. The raw is in blue and the smooth or filtered data is in magenta. Notice the peak is slightly lower for the filtered data. This explains the difference here. The reference data is unfiltered. This was found to be a recurring theme with the Perfectflite data. The maximum altitude reported (and beeped out) is typically lower than the raw peak altitude. This makes comparison to the reference's altitude difficult unless the reference were to use the same filtering algorithm. It was for this reason the raw data peak altitude was included in the analysis to get a more apples to apples comparison. It is clear from the data that for the Perfectflite filtering and maximum altitude, it is more consistent than the Micropeak and seems correct. In addition, the Perfectflite flight data is pre-filtered while the Adrel data is post-filtered, not allowing for the same type of analysis as was done for the Perfectflite altimeters. The Adrel data's maximum altitude always matches the reported maximum altitude.

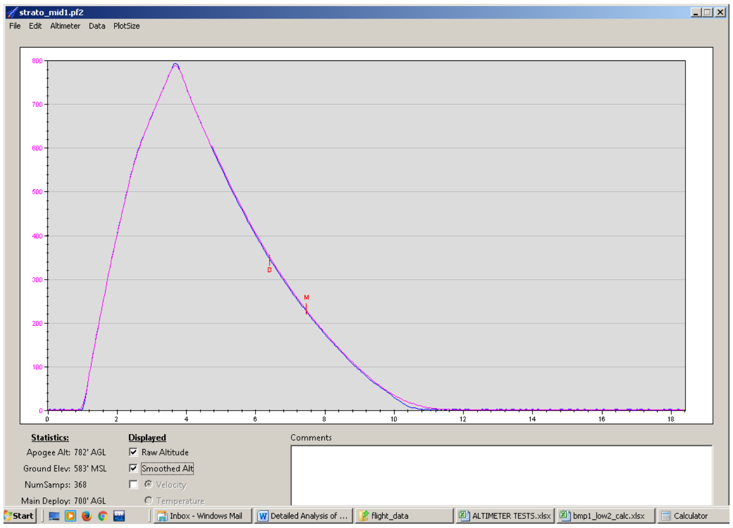


Figure 13 - Plot of Stratologger data for Mid Flight 9 showing filtered versus non filtered data. The maximum altitude is calculated from the filtered data.

For the ALT-BMP 2 readings that were off by more than 1%, the explanation is more difficult to understand. In these cases, the ALT-BMP reported an altitude higher than the reference. No explanation was obvious at this point in the testing except that the ALT-BMP altitudes from both units tended to report slightly higher altitudes than the other altimeters (typically 1 meter).

7.3 High Altitude Tests Analysis

Below is the table of error percentages for the high altitude flights.

Deviation from WM MS5611 average	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Avg % Error
WM MS5611 Avg	442	556	544	489	647	551	657	530	421	511	766	675	
ALTIMETER 1	0.1%	0.2%	0.2%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.3%	0.1%	0.2%	0.1%
Micropeak 1 - blink	0.8%	1.1%	0.7%	2.5%	0.6%	0.9%	0.5%	0.2%	2.1%	0.1%	0.0%	1.9%	0.9%
Micropeak 1 - data	1.5%	0.0%	0.6%	0.2%	0.2%	0.4%	0.0%	0.2%	0.0%	0.5%	0.7%	0.2%	0.4%
Micropeak 2 - blink	1.0%	0.9%	0.6%	2.0%	0.6%	0.9%	0.3%	0.4%	1.9%	0.3%	0.0%	1.7%	0.9%
Micropeak 2 - data	1.0%	0.2%	0.6%	0.2%	0.2%	0.4%	0.5%	0.8%	0.0%	0.9%	0.1%	0.5%	0.4%
Pnut	1.7%	0.0%	0.9%	0.4%	0.5%	0.2%	0.6%	0.4%	0.0%	1.5%	0.8%	0.5%	0.6%
Pnut Data	0.1%	0.0%	0.2%	0.2%	0.2%	0.2%	0.2%	0.2%	0.0%	0.3%	0.1%	0.2%	0.2%
Stratologger	1.7%	0.2%	1.1%	0.2%	0.3%	0.2%	0.6%	0.2%	0.0%	1.5%	0.8%	0.5%	0.6%
Stratalogger Data	0.1%	0.0%	0.4%	0.2%	0.2%	0.2%	0.2%	0.0%	0.0%	0.1%	0.1%	0.2%	0.1%
ALTBMP 1 (SN 446)	0.3%	0.9%	0.7%	0.8%	0.9%	0.9%	0.8%	0.8%	0.7%	0.3%	0.9%	1.0%	0.8%
ALTBMP1_SENSOR	0.3%	0.4%	0.4%	0.0%	0.3%	0.2%	0.2%	0.2%	0.5%	0.1%	0.1%	0.2%	0.2%
ALTBMP2 (SN 449)	0.3%	1.1%	0.9%	0.8%	1.2%	1.1%	0.9%	0.9%	1.2%	0.5%	1.0%	1.1%	0.9%
WM1-1 MPL3115	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%
WM1-2 MPL3115	0.1%	0.7%	0.7%	0.8%	0.5%	0.9%	0.6%	0.4%	0.7%	0.1%	0.4%	0.2%	0.5%

Table 7 - High Altitude Tests - Percent error versus Wolfmeter 1 MS5611 average

The high dataset again showed the Micropeak reported maximum altitude to be higher than the highest altitude in the recorded data. Again, no explanation for this other than there is something wrong with how the Micropeak is filtering or computing the maximum altitude.

The high dataset also had cases (2 each, same flights) where the reported altitude from the Perfectflite units was lower than the reference value's peak altitude by more than 1%. In all cases, the Perfectflite lower reading appears to be due to filtering of the data. Both flights had a sharp peak in the pressure data. The raw data from all of the Perfectflite high altitude flights tracked quite well with the reference. Average error for raw data for the Pnut was only 0.2%, for the Stratologger 0.1%. Excellent correlation.

The high dataset also had 5 cases where the second ALT-BMP had reported altitudes greater than 1% above the reference. In analyzing this data, it was observed that both ALT-BMPs were reporting higher altitudes. There appears to be a divergence in the altitude values of the ALT-BMPs versus the reference and the rest of the altimeters for that matter as the altitude increases. This is not from the sensor as the altitude calculated from it was in agreement with the reference and other altimeters.

7.4 Very High Altitude Tests Analysis

Below is the error summary for the final dataset, the very high altitude tests.

Deviation from WM MS5611 average	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Avg % Error
WM MS5611 Avg	977	1032	1023	1412	1743	1353	1132	1195	819	1054	1272	2051	
ALTIMETER 1	0.0%	0.0%	0.1%	0.1%	0.1%	0.3%	0.3%	0.2%	0.1%	0.2%	0.0%	0.1%	0.1%
Micropeak 1 - blink	0.4%	0.0%	0.1%	1.0%	0.3%	0.5%	0.7%	0.2%	2.1%	1.4%	0.4%	0.2%	0.6%
Micropeak 1 - data	0.2%	0.3%	0.3%	0.2%	0.3%	0.7%	0.8%	0.4%	0.2%	0.2%	0.4%	0.3%	0.4%
Micropeak 2 - blink	0.4%	0.1%	0.0%	0.8%	0.3%	0.4%	0.7%	0.2%	2.1%	1.3%	0.5%	0.3%	0.6%
Micropeak 2 - data	0.2%	0.5%	0.3%	0.3%	0.4%	0.4%	1.1%	0.5%	0.4%	0.7%	0.5%	0.2%	0.5%
Pnut	0.3%	0.8%	0.6%	0.5%	0.3%	1.1%	1.4%	0.5%	0.5%	0.7%	0.8%	0.3%	0.7%
Pnut Data	0.1%	0.1%	0.1%	0.2%	0.3%	0.5%	0.2%	0.5%	0.1%	0.2%	0.2%	0.2%	0.2%
Stratologger	0.3%	0.8%	0.6%	0.5%	0.3%	1.1%	1.3%	0.2%	0.5%	0.7%	0.8%	0.2%	0.6%
Stratalogger Data	0.1%	0.0%	0.1%	0.2%	0.2%	0.3%	0.2%	0.3%	0.1%	0.2%	0.2%	0.2%	0.2%
ALTBMP 1 (SN 446)	1.3%	1.2%	1.2%	1.7%	2.2%	1.4%	1.0%	1.5%	1.1%	1.1%	1.4%	2.6%	1.5%
ALTBMP1_SENSOR	0.2%	0.2%	0.1%	0.1%	0.2%	0.0%	0.3%	0.1%	0.2%	0.2%	0.1%	0.1%	0.2%
ALTBMP2 (SN 449)	1.5%	1.3%	1.4%	1.8%	2.4%	1.6%	1.3%	1.6%	1.2%	1.3%	1.6%	2.7%	1.7%
WM1-1 MPL3115	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
WM1-2 MPL3115	0.6%	0.4%	0.5%	0.4%	0.5%	0.4%	0.0%	0.3%	0.6%	0.4%	0.1%	0.4%	0.4%

Table 8 – Vey High Altitude Tests - Percent error versus Wolfmeter 1 MS5611 average

In the very high altitude tests, the Micropeaks both had two flights where the error was greater than 1% and in both cases, the calculated maximum altitude was *way* above the collected data as was found for the other test runs. For the Perfectflite altimeters, both reported a lower altitude by more than 1% for the same two flights, again due to the low pass filter shaving the peaks.

The most interesting aspect in the very high dataset is that the ALT-BMPs altitudes now consistently report out at 1% to 3% higher than the other altimeters. This appears to be a systemic error in the way the ALT-BMP is computing the altitude. Note that the data read from the ALT-BMP sensor does not show this phenomena. The issue appears to be in the way the ALT-BMP is calculating the altitude. The plot and table below of the altimeter calculated altitude versus the altitude calculated from the sensor for the instrumented ALT-BMP show the divergence of the altitude quite clearly.

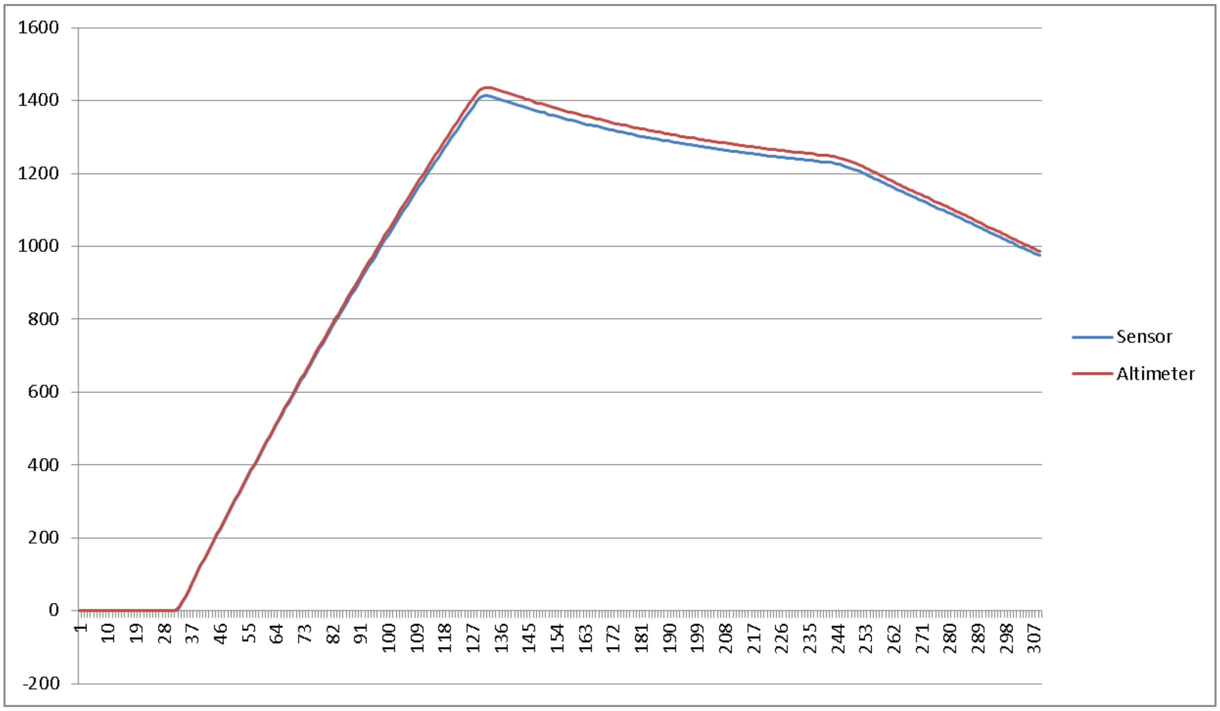


Figure 14 _ Plot of Sensor data versus altimeter data for ALT-BMP 1 Very High FLight 4. AS the altitude increases, the altimeter starts to report out higher altitudes than the sensor data suggests.

Sensor	Altimeter	Sensor	Altimeter	Sensor	Altimeter	Sensor	Altimeter
0	2	779	786	1413	1436	1301	1321
8	12	793	801	1410	1434	1299	1320
24	26	808	816	1408	1432	1298	1318
40	41	822	830	1406	1429	1296	1316
58	58	836	845	1403	1426	1295	1315
75	75	851	860	1401	1424	1293	1313
93	93	865	874	1398	1421	1291	1311
110	110	879	889	1395	1418	1289	1310
127	127	894	903	1392	1416	1289	1309
142	143	907	918	1390	1413	1287	1307
160	160	923	932	1387	1410	1285	1305
175	176	935	946	1384	1407	1284	1304
192	192	949	960	1382	1404	1283	1302
208	209	963	974	1380	1402	1281	1300
225	225	976	989	1377	1399	1279	1299
240	241	991	1003	1374	1396	1278	1298
256	258	1004	1017	1371	1393	1278	1297
273	274	1018	1031	1369	1391	1276	1295
288	290	1033	1045	1367	1389	1274	1293
304	306	1046	1059	1364	1386	1273	1292
321	322	1059	1073	1361	1383	1272	1291
338	339	1073	1087	1360	1381	1270	1290
352	355	1087	1101	1356	1379	1268	1288
370	371	1100	1114	1355	1376	1268	1287
385	387	1114	1128	1352	1374	1267	1286
401	402	1126	1141	1350	1372	1266	1285
415	418	1139	1155	1348	1369	1264	1284
431	434	1152	1169	1345	1367	1264	1282
447	450	1167	1182	1343	1364	1261	1281
463	466	1179	1196	1340	1362	1261	1279
479	482	1192	1209	1339	1360	1260	1278
494	497	1206	1222	1337	1358	1258	1277
510	513	1218	1236	1334	1356	1257	1276
525	528	1231	1249	1333	1354	1256	1274
539	544	1244	1263	1331	1352	1254	1273
556	559	1257	1276	1329	1350	1254	1273
570	574	1270	1289	1327	1348	1252	1271
586	590	1283	1302	1325	1346	1252	1270
601	605	1294	1315	1323	1344	1251	1269
616	621	1307	1328	1320	1341	1249	1268
631	636	1321	1341	1319	1339	1248	1267
646	651	1332	1354	1316	1337	1248	1267
661	666	1345	1367	1315	1336	1246	1265
675	681	1357	1379	1313	1334	1245	1264
691	697	1369	1392	1312	1332	1245	1263
706	712	1383	1405	1309	1330	1243	1262
720	726	1395	1417	1308	1328	1242	1261
735	742	1405	1427	1306	1326	1242	1260
750	757	1411	1433	1304	1324	1241	1259
764	771	1414	1436	1302	1322	1240	1258

Table 9 - Table of altitude values from Sensor and Altimeter for ALT-BMP Flight Very High 4. The reported altitude from the altimeter diverges the higher the altitude.

7.5 ALT-BMP Sensor Operation Mode

One other important item that was observed during the testing was how the ALT-BMP uses the BMP180 sensor. For acquiring pressure data, the sensor has several modes of operation that affect the precision of the reading (by lowering the noise). There are 4 modes total, called the over sampling modes. For each time the sensor is commanded to do a pressure sample conversion, the sampling mode determines how many samples are taken. Possible options are 1, 2, 4, or 8 samples. When the raw pressure value is read after the conversion, it is the average of the number of samples taken. Mode 0 only takes one sample, while mode 3 takes 8 samples. In our previous testing with the BMP180, we always used mode 3 as it has the lowest noise. This would cut the noise in the sensor in half. See table below.

Mode	Parameter *oversampling_setting*	Internal number of samples	Conversion time pressure max. [ms]	Avg. current @ 1 sample/s typ. [µA]	RMS noise typ. [hPa]	RMS noise typ. [m]
ultra low power	0	1	4.5	3	0.06	0.5
standard	1	2	7.5	5	0.05	0.4
high resolution	2	4	13.5	7	0.04	0.3
ultra high resolution	3	8	25.5	12	0.03	0.25

Table 10 - Table from the BMP180 datasheet showing the oversampling modes and the specifications for them.

In the ALT-BMP, the mode selected is single sample mode. The designer of the ALT-BMP may have decided that since the altimeter is moving at a high rate of speed, the averaging would not be valid. However, from the datasheet for the BMP180, it can be determined that the time for each conversion is only 3ms. At apogee, when the rocket is moving slowly, it seems like this would be an easy way to increase precision. We have only used the BMP180 in our initial tests, not in an actual altimeter, so perhaps there are issues when flying this altimeter in oversampling mode. However, we do use the MS5611 in oversampling mode with good results.

There are 2 penalties for using the oversampling mode. One is the time for conversion. The total conversion time for mode 0 is 4.5ms, while the conversion time for mode 3 is 25.5ms. The other penalty is power. The current draw increases significantly and with the small battery on the ALT-BMP, it may not have enough power.

The other observation and opportunity for improvement is the way the ALT-BMP performs conversions. It basically takes the samples/second period and divides it by 4. For simple illustration purposes, let's assume the conversion rate has been set to 10 samples per second (the ALT-BMP lets you select the sampling rate). That is a period of 100ms. The ALT-BMP takes that 100ms and divides it by 4 to have 4 25ms intervals. On the 1st interval it commands the sensor to start a pressure conversion. On the 2nd interval it reads the result. On the 3rd interval it starts the temperature conversion. On the 4th interval it reads that result. Because this is the way the ALT-BMP does its operations, it could not select mode 3 for conversion because it takes 25.5ms, which is longer than the 25ms interval. With the default value of 15 samples per second, or the maximum rate of 20 samples per second, the time allocated would not allow mode 2 or mode 3.

However, the software could be written differently. The temperature conversion only takes 4.5ms (no oversampling for temperature). Yet half of the sample rate period is consumed by this and half by the pressure conversion. If this were allocated differently, more time would be available for the pressure conversion. In addition, it is not necessary to sample the temperature for every pressure sample. The temperature will not change that quickly. This would make the software more complex, but could allow the oversampling modes to be used.

Lastly, it was also observed that the ALT-BMP has other traffic on the I2C bus. The EEPROM used for the flight data storage also shares the bus. So, for the communication, that takes up I2C and processor bandwidth. That could be a limiting factor. Depending upon the processor and amount of RAM memory available, this could be queued up and written to the EEPROM after the sampling is completed to relieve any bandwidth bottlenecks. That is, when the rocket has landed, write the EEPROM data then. It would still be before the rocket is recovered since it only takes a few tenths of a second to write all the flight data. Then, the processor and the I2C bus would both have plenty of bandwidth during the flight.

These are all tradeoffs that the ALT-BMP designer made, and overall the design structure is fine. Plus, there are probably other considerations that we are not accounting for. But if oversampling were implemented to mode 3 by using the methods suggested, the precision of the measurements would increase by 2X.

7.6 Data Analysis Summary

The vacuum chamber tests revealed many interesting things about how each of the altimeters operates. One altimeter not mentioned in the other analysis sections is the Altimeter One. Since it is only a peak reading altimeter, not much analysis can be done. However, it should be pointed out that Altimeter One had the closest correlation to the Wolfmeter 1, MS5611 sensor data. On most test runs the Altimeter One deviated from the reference by less than 0.2% and only 4 flights exceeded 0.5%. All were below 2 meters or 1%. From this it can be concluded that:

1. The Altimeter One altitude calculation is correct (no math errors or divergence).
2. The Altimeter One does not heavily filter the data in a traditional low pass filter sense.

In fact, John Beans from Jolly Logic indicated in a recent ContestRoc group forum post that the Jolly Logic use some type of “event filtering” prior to any smoothing filter. Whether other manufacturers employ this technique is unknown. However, it seems reasonable that such an approach could eliminate spikes from ejection, staging, etc. without having to aggressively low pass filter the data to remove them. With a less aggressive filter, the true peak altitude from the sensor data could be preserved. The true test will be when the active altimeter testing is employed to see how well the Altimeter One and the other altimeters handle these data spikes.

Otherwise, other than the Micropeak maximum altitude issue and the divergence of the ALT-BMP altitude reporting as the altitude increases, the altimeters all performed quite well in this set of tests. The Altimeter One, Perfectflite Units and the ALT-BMP all performed perfectly acceptable for flights to 500M and the Altimeter One and Perfectflite to as high as tested (2050M).

8.0 Conclusions and Next Steps

Using a vacuum chamber, this project performed extensive tests of altimeters from all four suppliers whose altimeters are approved for NAR contest use in the 2016-2017 contest year. It is the most extensive vacuum chamber testing of altimeters ever performed, as far as we know. The results revealed much about how the different suppliers' altimeters operate. The table below summarizes these results.

Altimeter Supplier	Units Tested	Observations	Other Notes
Adrel	ALT-BMP	Filters data and saves data *after* filtering. Raw sensor data agrees well with reference altimeter. Altimeter data output starts to diverge (reports higher than all altimeters including reference) as the altitude increases. Appears to be a calculation error or uses a different atmospheric model.	Some features in SW are cryptic (filtering parameters, setting temperature).
Altus Metrum	Micropeak	Saves data *prior* to filtering. Maximum altitude that is beeped out and reported out in the data download is incorrect and doesn't match the actual saved data at all. Could be the filtering algorithm.	Hardest unit to get to download. Uses an LED and sensor link. Dififcult to use.
Jolly Logic	Altimeter One	Had the best correlation to the altitudes reported by the reference. Does the least aggressive, or perhaps no filtering. Will be interesting to see how it would handle ejection spikes as compared to the other altimeters.	Field use by myself and others has had the unit come back with 0 altitude reported. However, worked flawlessly in these tests.
Perfectflite	Pnut and Stratologger	Saves the data *prior* to filtering. Because of this, peak altitude in the data matched the reference closely while the reported maximum was sometimes lower, particular for test runs where the pressure changed abruptly which may not happen a lot in actual flight. Overall the most consistent recording altimeter.	Wins ease of use and usability over all the others. Wish they had a smaller unit that records.
Homebrew	Wolfmeter 1	Had no issues. Testing showed that the NxP MPL3115 sensor does not perform as well as the MS5611, particularly at lower altitudes.	Found some bugs in the beep routine, but otherwise was solid.

Table 11 - Altimeter Test Summary

The altitude chamber has limitations and could be improved. In particular, all testing was done at an elevation of 180 meters. Both the NAR and FAI requirements specify altimeters meet all specifications at a base altitude from 0 meters to 2000 meters with flights to 4000 meters. This requires a more sophisticated chamber than the one used for this project. In fact, a significant amount of development time and expenditure may be needed to test to these requirements. Testing over the full temperature range would be problematic as well. Datasheet information may have to be used here. In which case, the requirements may need to be “opened up”.

Another significant outcome from this project was the successful implementation of monitoring sensor data communication. While this was only done for the ALT-BMP in this project, the technique can be applied to any altimeter as long as attachments can be made to the I2C interface SCL and SDA data lines. This does not appear to be an issue on the altimeters we examined (Pnut, Stratologger, Micropeak).

An additional test method using a sensor emulator was proposed that could further assess altimeter operations and performance, but time prevented it from being implemented. This will be a topic of future research.

Another future step is to send this report to all the suppliers whose altimeters were tested and to open a dialog with them. This will occur after peer review of this report by judges and NAR members at NARAM 58. The report will be shared with the BoT and NAR Contest Board for consideration and discussion of implementing an altimeter certification test process.

Finally, Appendix D is a draft of the test procedure for verification of the ALT-BMP to the FAA EDIC on altimeters for use in Spacemodeling Competition.

Appendix A – References

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23. FAI EDIC , July 2015, Technical Guidance Notes and Specification for Altimeters Used in Spacemodeling Competition, Revision 3.0.

Appendix B – Equipment Used & Expenditures

1. Personal Computer (Already had)
2. Microsoft Excel (Already had)
3. Microsoft Word (Already had)
4. Soldering Iron and Solder (Already had)
5. Two Adrel ALT-BMP Altimeters with download unit $120
6. Altimeter 1, Micropeak, Pnut, Stratologger altimeters (Already Had)
7. Data transfer units for Micropeak and Perfectflite altimeters (Already Had)
8. Vacuum Chamber (obtained from NAR)
9. Saleae Logic Analyzer - $119
10. DevC++ Compiler (free download)

Total Expenses for project $139

Appendix C – I2C Specification

I²C (Inter-Integrated Circuit), pronounced I-squared-C, is a multi-master, multi-slave, single-ended, serial computer bus invented by Philips Semiconductor (now NXP Semiconductors). It is typically used for attaching lower-speed peripheral ICs to processors and microcontrollers in short-distance, intra-board communication.

I²C uses only two signals (wires), Serial Data Line (SDA) and Serial Clock Line (SCL), pulled up with resistors. Typical voltages used are +5 V or +3.3 V. I²C bus speeds are the 100 kbit/s standard mode and the 10 kbit/s low-speed mode, but arbitrarily low clock frequencies are also allowed. Recent revisions of I²C can host more nodes and run at faster speeds (400 kbit/s Fast mode, 1 Mbit/s Fast mode plus or Fm+, and 3.4 Mbit/s High Speed mode).

I²C defines basic types of messages, each of which begins with a START and ends with a STOP:

- Single message where a master writes data to a slave;
- Single message where a master reads data from a slave;

Virtually all modern pressure sensors use the I2C protocol for interfacing with single messages as described above.

For more details on the I2C bus, refer to the I2C specification here:
http://www.nxp.com/documents/user_manual/UM10204.pdf

Appendix D – Pressure Conversion Program

```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[])
{
    FILE *fp, *fpo;
    char str[60];
    int n;
    float tf, i2ctime;
    unsigned int  i2csqn, i2cadd, i2cdata,rawpressure,rawtemperature;
    char i2cdir[10], i2cack[10];
    int pvalue;

    int ac1 = 7520;
    int ac2 = -1064;
    int ac3 = -14522;
    unsigned int ac4 = 34419;
    unsigned int ac5 = 25387;
    unsigned int ac6 = 20665;
    int b1 = 6515;
    int b2 = 37;
    int mb = -32768;
    int mc = -11786;
    int md = 2584;
    int x1,x2,x3, b5, bmp180_temp, bmp180_pressure;
    int b3,b4,b6,rp256;
    unsigned int b7;


    n=0;
    fp=fopen("bmp_test.txt", "r");
    fpo=fopen("bmp_out.csv", "w");

    while (fgets (str,60,fp) != NULL)
    {
        sscanf(str, "%f %d %d %d %s %s", &i2ctime, &i2csqn, &i2cadd, &i2cdata, i2cdir, i2cack);
/*        printf("%f %d %d %d %s %s \r\n", i2ctime, i2csqn, i2cadd, i2cdata, i2cdir, i2cack); */
/* Each read from the sensor is five lines in the file.  Assumes starts with pressure (52) versus
   temperature.
   First line of five is to write the address for the command register.
   Second line is to write the command.  52 means pressure, 46 means temperature.
   Third line is to write the address of the MSB of the data.
   Fourth and fifth lines are the raw data value, pressure or temperature)  */
/* Note: Discovered that the ALT BMP EEPROM is I2C also.  Therefore, have to ignore reads
and writes to the EEPROM, which always appears to be address 160, so adding an
"if else" for that */
      if (i2cadd != 160)
         {
         if (n==1)
            {
            if (i2cdata == 46)
                pvalue = 0;
            else
               pvalue = 1;
            }
         if (n==3)
            {
            if (pvalue == 1)
                rawpressure = i2cdata * 256;
```

```
            else
                rawtemperature = i2cdata * 256;
            }
         if (n==4)
            {
            if (pvalue == 1)
                rawpressure = rawpressure + i2cdata;
            else
                {
                rawtemperature = rawtemperature + i2cdata;

/* Now have the raw pressure and temperature values.  Time to convert to actual
temperature and pressure */
/* debug print of raw values printf(" %d  %d  \r\n", rawtemperature,rawpressure);  */
/* Note - copy of code from bp datalogger verfied against datasheet flow chart */
/* Conversion from raw value to actual pressure is not trivial, appears to be right */
               x1 = ((rawtemperature - ac6) * ac5) / 32768;
               x2 = (mc*2048)/(x1+md);
               b5 = x1 + x2;
        bmp180_temp = (b5 + 8)/16;
        b6 = b5-4000;
               /*****calculate B3************/
        x1 = (b6*b6)/4096;
               x1 *= b2;
               x1 = x1 / 2048 ;
               x2 = ac2*b6;
               x2 = x2/2048;
               x3 = x1 + x2;
               b3 = (((((ac1)*4) + x3) + 2)/4);
               /*****calculate B4************/
        x1 = (ac3 * b6) /8192 ;
               x2 = b1 * ((b6*b6) / 4096);
        x2 = x2/65536;
               x3 = ((x1 + x2) + 2) / 4;
               b4 = (ac4 * (x3 + 32768)) / 32768;
               b7 = (unsigned long) (rawpressure - b3) * 50000;
        if (b7 < 0x80000000) bmp180_pressure = (b7*2)/b4;
                 else bmp180_pressure = (b7 / b4) * 2;
               x1 = bmp180_pressure / 256;
               x1 *= x1;
               x1 = (x1 * 3038) / 65536;
               x2 = (bmp180_pressure * (-7357)) / 65536;
               bmp180_pressure = bmp180_pressure + (x1 + x2 + 3791) / 16 ;/* pressure in Pa*/
        printf("%d  %d \r\n",bmp180_temp,bmp180_pressure);
        fprintf(fpo,"%d,%d \r",bmp180_temp,bmp180_pressure);

         /*       system("PAUSE"); */
                }
            n = 0;

            }
          else
            {
            n=n+1;
            }
            }
    }
  fclose(fp);
  fclose(fpo);
  system("PAUSE");
  return 0;
}
```

Appendix E – FAI Altimeter Test Procedure

On the next page is a draft of the FAI SM Altimeter Process. Part 2 is the checklist of items to be verified. This is from the FAI EDIC on SM Altimeters. The numbers for each item correspond to numbers from the EDIC. Later this will be followed by part 3, the actual procedure. In the interest of this report I have made notations for each of the checklist items as follows:

A: Can be verified by altimeter and its datasheet
V: Can be verified by using a vacuum chamber
P: Can be verified using the passive sensor monitoring with a vacuum chamber
E: Can be verified using active sensor emulation method
N: Not verifiable (partially by datasheet specifications)

In some cases, items have multiple choices. Notes are here for those:

AP: The reporting of peak altitude can be verified with the altimeter only, but passive monitoring can determine the correctness of the reported altitude.

AV: Can be done without vacuum chamber, but chamber makes it easier or more practical

PE: Passive sensor monitoring can verify the presence of a filtering algorithm and determine if it is causing the altitude to be determined incorrectly. However, it cannot gauge the effectiveness for filtering out abrupt pressure changes.

VN: Can be partially verified using vacuum chamber and datasheet inspection.

SM ALTIMETER APPROVAL CHECKLIST

This procedure is used for evaluation of SM Altimeter devices and is in accordance with that contained in the EDIC document. The same paragraph numbering is retained

Manufacturer	
Device(s)	
Tested by	
Completion Date	

2.1 Check list of compliance to the Altimeter Technical Specification
(*General Functional Requirements)*

(a)[A] Uses barometric pressure measurement technique.

(b)[AV] Records the launch pad altitude and the difference between the launch pad altitude and the altitude achieved at each sampling moment after launch.

(c)[AV] Retains the flight data after power is removed.

(d)[A] Has a data communication interface for managing the altimeter and retrieving flight information.

(e)[A] Has an audible and/or visual indication of its operating status.

(f)[A] Has no configurable settings or adjustments that allow the user to modify its operation such that it will operate outside the requirements of the competition rules.

(g)[A] Is powered by a flight battery having sufficient capacity to power the device for a minimum of 5 hours without replacement or recharging. ☐

(h)[A] Altimeter and its battery fit in a cylindrical airframe of 17.5 mm diameter and 30 mm length. ☐

(i)[A] Weight of the altimeter and battery is less than 2.5 grams. ☐

Specific Detailed Requirements to be verified, related to functionality and performance.

2.1.1 Verification of the Barometric Measurement Method

- a)[P] The altimeter converts pressure measurements to altitude (height) based on the International Standard Atmosphere, as defined in ICAO Document 7488/2. See Section 2.2 of the SM Altimeter EDIC.
- b)[N] The method for converting pressure to altitude (height) performed by the altimeter firmware maintains the specified accuracy up to a height of 4000 meters above sea level.
- c)[PE] The altimeter has a filtering or smoothing algorithm that removes or rejects abrupt pressure changes caused by ejection or staging.
- d)[VN] Has an accuracy of 1% or 2 meters, whichever is greater over a ground pressure range from 750 to 1050 hPa and across an ambient ground level temperature range of 0 to +50 degrees. This includes the performance of the barometric sensor.
- e)[P] The calculation of pressure correctly incorporates the calibration coefficients provided by sensor manufacturer if provided.
  Note: Temperature measurements from the sensor shall not be used in the calculation of pressure to altitude, only for correction of sensor data.

2.1.2 Verification of Operating Parameters

- a)[A] The altitude data is recorded to a precision of one decimal place.
- b)[VN] The working range of the altimeter is at least 2000 meters, even when operated at launch site elevations of 2000 meters.
- c)[P] Samples data at a rate of at 10 samples per second or greater.

2.1.3 Verification of Sequence of Operation

- a)[A] At power up, the altimeter can determine if it is in data communication mode or in altimeter mode (data collection).

2.1.3.1 Verification of the Flight Recording Mode

- a)[A] On power up the altimeter status is indicated by a sequence of flashes. If in flight ready mode, the flash sequence is single flashes at a rate of once every 4 seconds. If the altimeter has not been reset from the previous flight, it altimeter flashes 3 single flashes every four seconds.
- b)[A] Upon altimeter reset, the altimeter waits (no data sampling) for three minutes. After 3 minutes, the altimeter measures launch pad pressure (ground pressure) at least once per minute.
- c)[AV] The altimeter is launch ready after 3 minutes.
- d)[E] The altimeter detects launch after a height change of 30 meters. The altimeter records the altitude for at a minimum of 45 seconds after launch is detected. The launch status after flight completion changed to 3 flashes every 4 seconds.
- f)[A] The altimeter stays in this state until power is removed.

2.1.3.2 Verification of Data Communication Mode

Note: These items are performed when the altimeter is connected to the download device with interface software displayed.

a)[A] The display shows the firmware version
b)[A] The display shows the serial number of the altimeter
c)[AP] The display shows the peak altitude above the launch pad achieved during flight
d)[AV] The display shows the altimeters altitude versus time data in a graphical or tabular form.
e)[A] The altimeter can be reset and ready for the next flight with all altitude data cleared. When returned to flight mode, the blink sequence indicates the altimeter ready state.

2.1.3.3 Verification of additional features

a)[A] The serial number marked on the altimeter matches the serial number read from the altimeter firmware

VERIFICATION PROCEDURE

Note: Process steps for verifying items in 2 above.

3.1 Verification Procedure

TBD

Appendix F – Derivation of Altitude Pressure Equation

Pressure is expressed as force per unit area. In SI units, the force unit is Newtons, something all rocketeers understand. The unit area is meters squared (m*m). In the SI system, the pressure unit is Pascals. Most modern pressure sensors found in altimeters report the pressure directly in Pascals.

1 Pascal = 1 Newton / meters squared = N(m*m)

A Newton as we all know, = 1 kg * m/(sec*sec)

Pressure changes with height by Delta P = (density of air) * g * delta height If you look at the units this works out because we have:

P = (kg*m)/(s*s) = density * g * h = (kg/(m*m*m))* 1m/(sec*sec) * m

If you cancel out the labels on the right, both sides end up with Pascals. Rewriting, most derivations of pressure versus altitude typically start with this equation:

dP/dz = -rho*g (1)

This is from any freshmen physics textbook.

It's equation (17-1) in my 1967 copy of Halliday and Resnick (3rd edition), one of the few college text books I still use.

Definition of terms:
P = pressure (later pressure at apogee)
P0 = launch site pressure
z = height (altitude)
rho = air density
g is gravitational acceleration = -9.80665

Most derivations then invoke the ideal gas law to get rid of rho. Some may question that, but for the altitudes that most of us fly rockets to (< 4000M) this a very good assumption. So from freshman chemistry:

P = rho*R*T -- ideal gas law

Two new terms:
R = gas constant for air = 287.058
T = temperature

Note: Temperature is in Kelvin, altitude in meters

If I solve for rho, then:

rho = P/(R*T)   (2)

Subsituting that back in 1:

dP/dz = -(P*g)/(R*T)   (3)

We can immediately see there is a relationship between altitude and the air temperature. Assuming g is contant, again, a good assumption for the altitudes we fly too, and also, assuming a LINEAR relationship between temperature and altitude. Then:

dP/dz (z) = -g/R*(P(z)/T(z)) (4)

From freshman calculus, to solve we must integrate. So:

P(z) = P0* e^(-g/R* (integral[1/T(x)dx])) (5)

Because of the linear lapse rate, the integral solves to:

integral solved = (Log (T0 + Lz) - Log(To))/L (6) -- I used www.integral-calculator.com to get this

Finally, we substitute that back into equation 5 and get:

P(z) = P0*(g/R)*((Log (T0 + Lz) - Log(To))/L)   (7)

Solving for z:

z = (T0/L)*((P/P0)^-LR/g - 1)   (8)

Notice this equation has the temperature at launch site level (T0), and the lapse rate L.

Substituting in the constants:

z = T0/(-.0065)*((P/P0)^((-.0065)*(287.053)/(-9.80665)) - 1)   (9)

Simplifying

z = (T0)*(153.846)*(1 - (P/P0)^0.1902632))   (10)

Equation 10 is the money equation. You can see that the relationship between altitude and temperature is linear, and that is why the correction factor for the altitude reported by the altimeter is simply T0/288.15. The 288.15 being 15 C that all the altimeters use for their reporting (based on the standard atmosphere, 15.2 C), and T0 being the ambient temperature.

If we substitute standard atmosphere values in equation 10, the equation becomes:

Z= 44330.7249 *(1 - (P/P0)^0.1902632)   (11)

Since all altimeters assume standard atmosphere values, this is the equation used.

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