Trajectory Analysis of June 3rd Washington State Fireball

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Introduction

Thursday morning, June 3rd, 2004, I received word that a significant fireball had occurred over the Pacific Northwest in the early morning hours. Many witnesses in the Puget Sound area reported a bright flash around 2:40am PDT (in most cases seen from indoors), followed some minutes later by sharp sonic booms. Unfortunately, the majority of these witnesses did not see the actual meteor, but rather its reflected light off local surroundings, so they were unable to provide information about the meteor's trajectory. Still, the sonic booms suggested that there was a decent chance that some material survived to reach the ground.

One of the earliest news stories of the meteor came from the *Seattle Times*, which along with a number of witness' reports provided video images of the event captured by a suite of security cameras at the Harborview Medical Center:

http://seattletimes.nwsource.com/html/localnews/2001946256_webflash03.html

Unfortunately, none of these cameras shows the actual bolide – only its lighting effects on the ground. However, a couple of cameras briefly recorded fast-moving shadows caused by the meteor's rapid passage, and with some (considerable) effort it would be possible to estimate the azimuth and elevation of the bolide from this particular location. (To my knowledge, no such effort has yet been undertaken.)

That Thursday afternoon, news broke on Bill Allen's *Asteroid/Comet Connection* (A/CC) news journal that Ed Majden of Courtenay, British Columbia, had recorded the fireball with his Sandia Labs all-sky video camera:

http://www.hohmanntransfer.com/mn/0406/03.htm

The fireball itself is clearly visible, low in the southeast, but more importantly the video is time-tagged. Mr. Majden later compared the camera's clock with signal pips from WWV, and determined that the camera was running almost exactly two seconds fast. The meteor first appears at 2:40:10.3 (:12.3 seconds in the video) and continues to be visible until 2:40:13.87. The brightest outburst occurs in the consecutive frames corresponding to 2:40:12.90 and 2:40:12.93. To date, this is the only known video recording that shows the actual meteor in flight.

Seismic Analysis

Friday morning, the *Seattle Times* reported an important development in the efforts to track down the meteor's path, namely that dozens of University of Washington's Pacific Northwest Seismic Network (PNSN) seismographs recorded sonic effects from the meteor, allowing triangulation:

http://seattletimes.nwsource.com/html/localnews/2001947342_meteor04m.html

UW seismologist Steve Malone determined that rather than a moving signature, the seismic network indicated a single explosion site "6.4 miles northeast of the town of Snohomish and 27 miles above ground." From this he concluded that what they had recorded was the sonic signature of the meteor's terminal burst. Malone also ventured, "…it looks like it entered the atmosphere at a fairly steep angle." Tom Paulson at the *Seattle Post-Intelligencer* also reported on this development that Friday:

http://seattlepi.nwsource.com/local/176336_meteor04.html

Friday afternoon I located a press release about the meteor detection at the Pacific Northwest Seismic Network news page, along with webicorder records showing the sonic wave arrivals at over 50 seismic stations:

http://www.pnsn.org/WEBICORDER/INTERESTING/welcome.html

Steve later e-mailed me the exact coordinates of his solution: 47.9717º N, 121.9782º W, alt. 43.45 km. Anxious to see if I could reproduce his result, I pulled up the waveforms for each station and estimated the signal arrival times for 24 of them that had unambiguous detections. I found each station's geographical coordinates at:

ftp://ftp.ess.washington.edu/pub/seis_net/wash.sta.txt

and put together an Excel spreadsheet to record the station coordinates and pulse arrival times. For simplicity, I initially assumed an isothermal atmosphere, fixed the terminal burst altitude at Malone's 27 miles, and iteratively solved for the latitude and longitude that produced the lowest rms residuals in predicted vs. actual sonic pulse arrivals at each station. Despite the low-fidelity approach, my first result was surprisingly close to Malone's computed location – within a couple of miles. However, I noticed that when I decreased the assumed burst altitude, the residuals decreased, and the position shifted slightly. Conversely, when I increased the altitude, the residuals increased. The minimum residual occurred at an altitude of around 24-25 miles, below which the residuals started to rise again.

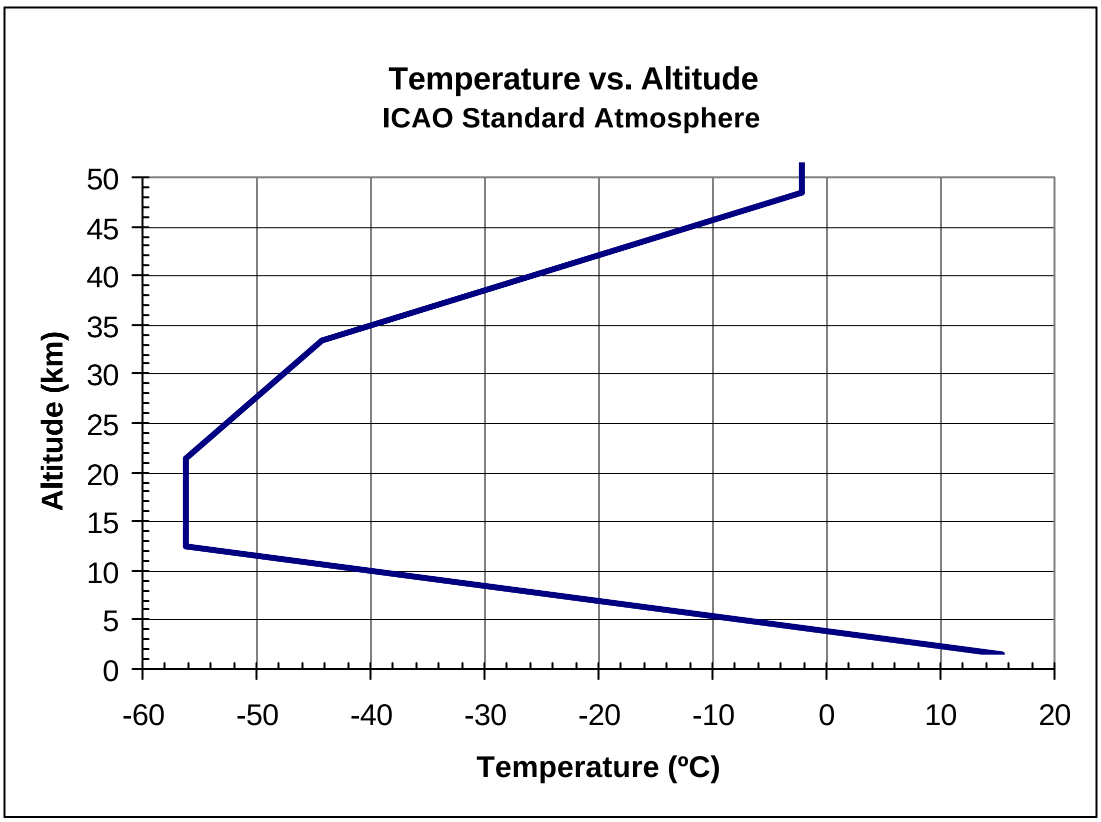
A little experimentation revealed that I could erase the altitude discrepancy by simply adjusting my value for the speed of sound. Since I had chosen the speed of sound somewhat arbitrarily, it was hardly surprising that I had converged on an altitude different than Malone's. But it was equally clear that I could not continue to treat the speed of sound as an independent variable – I needed to compute it.

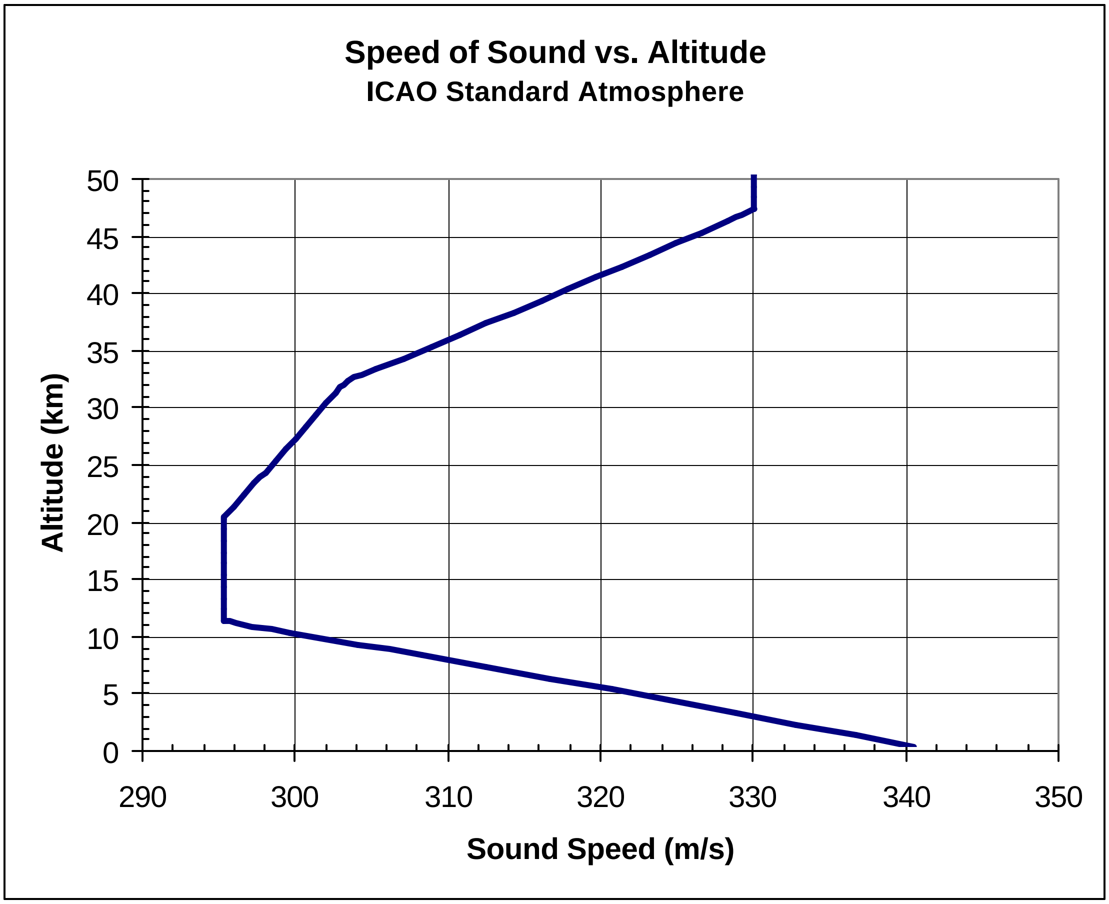
The speed of sound varies with temperature (and to a much lesser extent, humidity), and temperature of course varies with altitude. To compute the transit time of a sonic pulse traveling from the terminal burst point to a spot on the ground, one must integrate $dx/v(a)$ along the flight path, where x is the linear dimension along the flight path, and $v(a)$ is the instantaneous speed of sound at altitude a. The speed of sound in dry air is given by:

$$V_{\text{sound}} = 20.0558 * (273 + T)^{½}$$

where V_{sound} is in m/s, and T is the temperature in degrees Celsius. All that remains is an expression to convert between altitude and temperature.

Ideally, this should be done using meteorological data collected by balloon radiosonde at a time and location close to that of the terminal burst. Lacking such data, the next best alternative is to use a standard atmosphere. I used the ICAO Standard Atmosphere, which assumes a surface temperature of 15º C, and a lapse rate of 6.5º C/km in the troposphere (0-11 km). In the tropopause (11-20 km), the Standard Atmosphere has a constant temperature of –56.5º C. From 20-32 km, the temperature increases with altitude at a rate of 1.0º C/km, and from 32-47 km the rate increases to 2.8º C/km. From 47-51 km, the Standard Atmosphere temperature is assumed constant at –2.5º C. This profile is summarized in the plot below, followed by the corresponding plot of speed of sound vs. altitude:





After solving the integral, the minimum transit time Δt (seconds) for a signal from the terminal burst altitude, H_{burst}, to the ground altitude, H_{gnd} is:

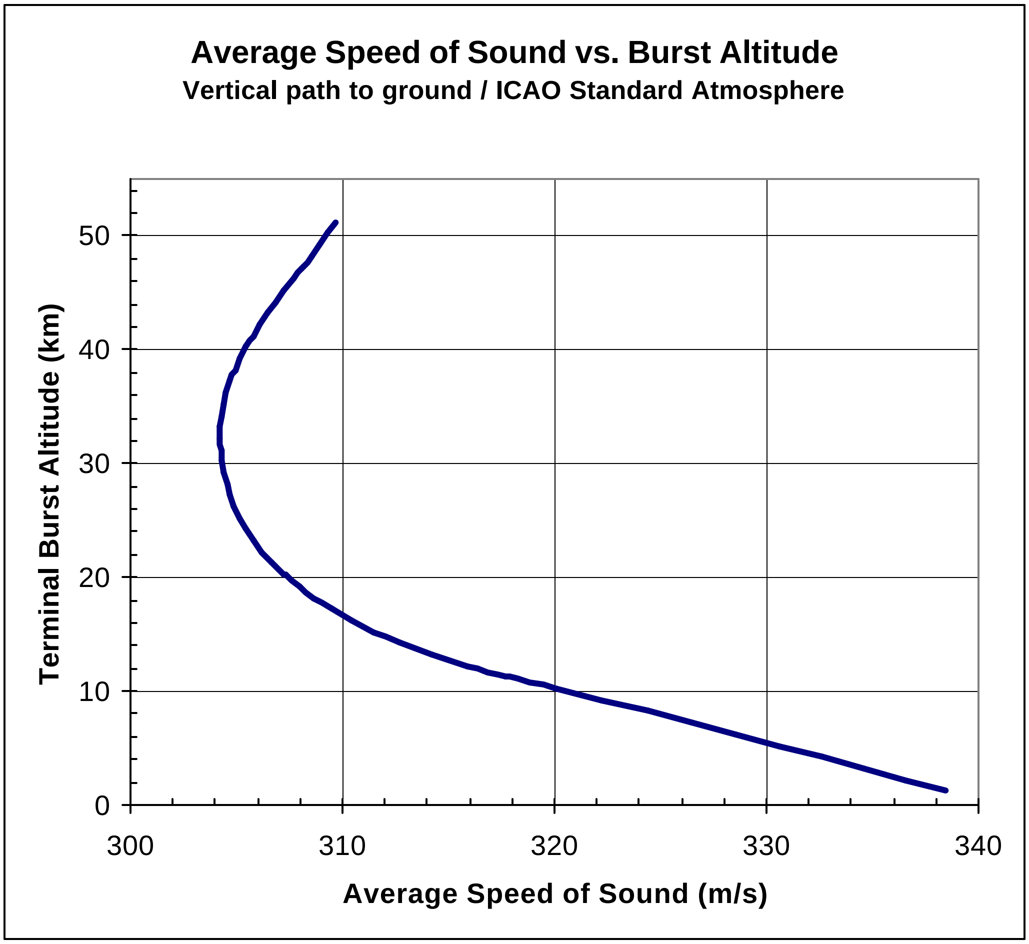
$$\Delta t = 35.6152 * (138.9 + 2.8* H_{burst})^{½} + 15.3417 * (288 - 6.5* H_{gnd})^{½} - 693.489$$

$$\text{when } H_{gnd} < 11 \text{ km and } 32 \text{ km} < H_{burst} < 47 \text{ km}$$

(Similar equations can be derived for the various cases when H_{burst} < 32 km, but the above equation is the applicable one for this bolide.) The average speed of sound over this distance is then:

$$\overline{v_{sound}} = (H_{burst} - H_{gnd}) / \Delta t$$

The following plot shows the mean velocity of sound as a function of terminal burst altitude when H_{gnd} is zero:



This curve suggests that for seismic stations distant from the terminal burst location, a rectilinear path may not be the fastest one, since sound travels faster at low altitude than at high altitude. However, for PNSN stations within 100 km of the terminal burst, the time differential between the fastest path and the rectilinear path is inconsequential.

When a static speed of sound is replaced by the above-derived function of station altitude and terminal burst altitude, the best-fit solution becomes:

Latitude: 47.971º N Longitude: 121.978º W Altitude: 38.3 km
r.m.s. residuals (23 stations): 0.51 seconds, 96 meters

The latitude and longitude exactly agree with Steve Malone's position to within the r.m.s. uncertainty; however, the altitude is 5.15 km lower. Steve used a static value for the speed of sound in his calculations, so given the sensitivity of the computed burst altitude to speed of sound, this difference did not surprise me. Still, I wanted to have some feeling for the accuracy in my altitude determination, so I decided to explore what happens to the solution when I use only the six stations closest to the terminal burst. The reasoning here is that the closest stations are most sensitive to differences in the burst altitude, since a significant component of their line-of-sight distances is vertical.

Using only stations EVCC, EVGW, LEOT, JCW, EARN and ATES, the solution is:

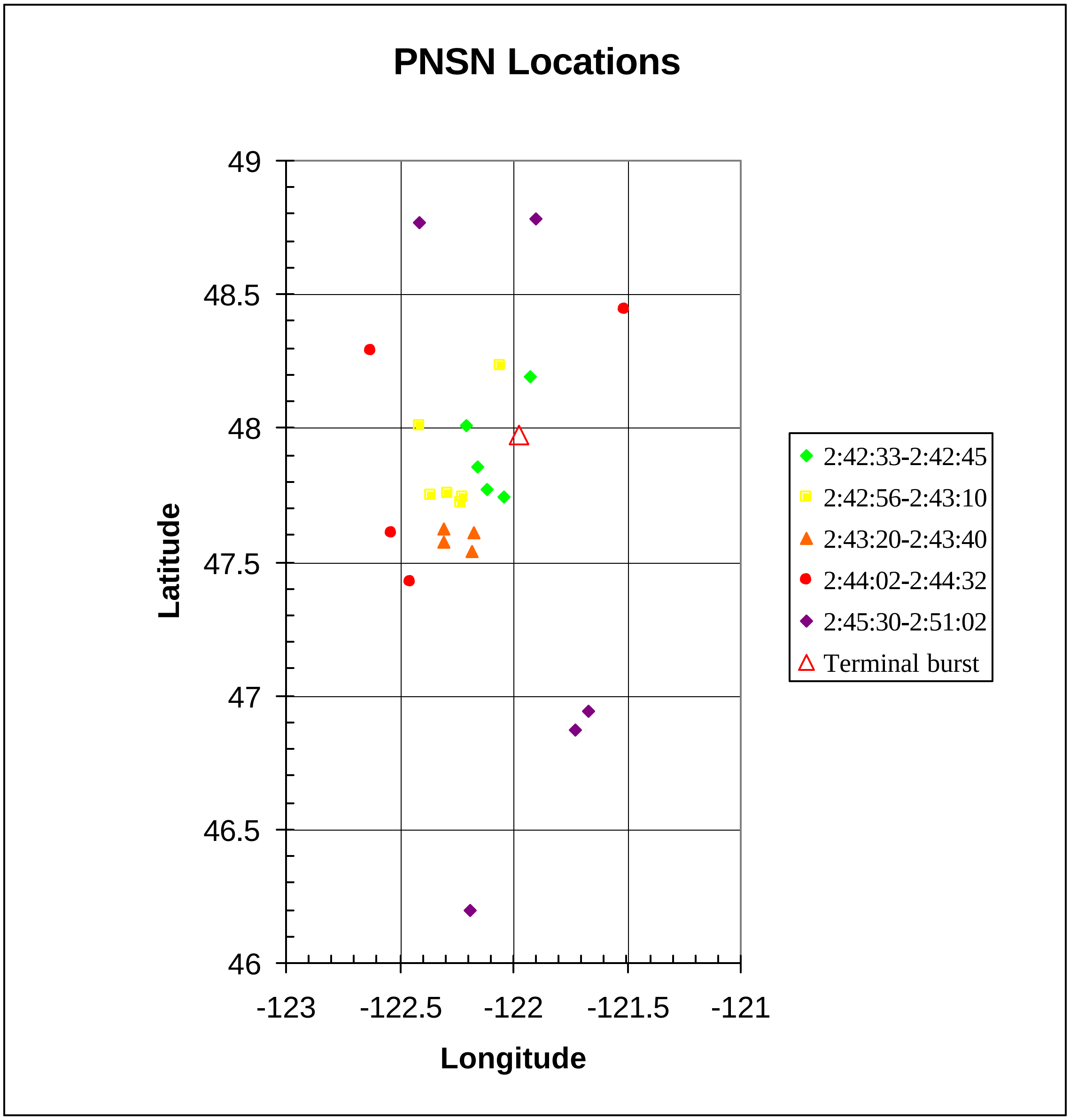
Latitude: 47.965º N   Longitude: 121.970º W   Altitude: 38.7 km
r.m.s. residuals (6 stations): 0.15 seconds, 27 meters

The location has shifted only about 900 meters SE, and 400 meters higher, so the solution is looking quite stable. Station EVCC was closest the burst (48.0075º N, 122.2043º W) at a range of only 42.67 km from the 6-station solution above, which corresponds to a 65º elevation angle. Station EVGW was nearly as close (47.8544º N, 122.1534º W) at a range of 42.73 km. Together, these two stations place tight constraints on the burst altitude since small changes in altitude result in relatively large changes in signal arrival time.

Since the closest stations provide the most accurate altitude determination, but all stations contribute about equally to the latitude/longitude solution, I've chosen for my nominal terminal burst solution the 6-station altitude and the 23-station latitude and longitude:

Latitude: 47.971º N   Longitude: 121.978º W   Altitude: 38.7 km
r.m.s. residuals (23 stations): 0.54 seconds, 101 meters

The following plot shows the locations of the 24 PNSN stations I analyzed, color-coded by their distance from the terminal burst location (which appears as a red triangle). *Note: the furthest station from the burst, SEP, had unacceptable residuals and was not used in the 23-station triangulation solution.*


PNSN Locations
49
48.5
48
47.5
47
46.5
46
-123
-122.5
-122
-121.5
-121
Latitude
Longitude
2:42:33-2:42:45
2:42:56-2:43:10
2:43:20-2:43:40
2:44:02-2:44:32
2:45:30-2:51:02
Terminal burst