The June 3 Fireball. Terminal Burst Position From British Columbia Seismic Records

Jeremy B. Tatum
University of Victoria

On the morning of June 3, 2004, a major fireball was reported from eyewitnesses in British Columbia (as far north as Prince George), Washington, Oregon and Idaho. It occurred at 2:40 in the morning, Pacific Daylight Time, and at that time of the morning most of the eyewitnesses on Vancouver Island who were contacted were either driving a car, or were indoors and merely saw a bright flash. I did not advertise widely for witnesses, and I did not, unfortunately, locate anyone who was outside and who clearly saw the meteor move across the sky, and so the event was unsuitable for the usual triangulation process resulting from *in situ* witness interviews and altitude and azimuth measurements. On the other hand, a sonic signal from the fireball was recorded on many seismographs, and it is possible in principle to determine the atmospheric trajectory from an analysis of the arrival times of the sound waves at the seismic stations. This fireball was unusual in that the analysis of seismic records became the most important method for computing the trajectory rather than an interesting but incidental sideline.

In addition to the arrival times of the sound waves at the several seismic stations, a most important datum was supplied by Mr Ed Majden of Courtenay, who recorded the event and the time on videotape (see separate article by Majden on this site). The time of the event, as recorded by Majden, was

$$2004 \text{ June } 03^{\text{d}}\ 02^{\text{h}}\ 40^{\text{m}}\ 13^{\text{s}}\ \text{PDT}$$

A meteoroid moving through the atmosphere can produce sound in several ways. Eyewitnesses often report a simultaneous hissing of whirring sound coincident in time with the visual appearance of the meteor. There are some problems with such simultaneous sound, since the distance of the fireball from the witness is usually such that it would take several minutes for the sound to reach the witness. Some of these reports of simultaneous sound may arise from the imagination of the startled witness, although there is some evidence that some such reports are real. It is proposed that there is some "electrophonic" mechanism that generates an electromagnetic signal that travels at the speed of light and is transduced to sound waves somewhere in the vicinity of the witness. While the reality of such simultaneous sound is not accepted by everyone, there is a body of evidence as well as plausible physical mechanisms in its favour. Such sound should be described as *simultaneous sound* rather than *electrophonic sound* except in particular instances when its electrophonic nature is demonstrably and unquestionably established. In any case, it was not simultaneous sound or electrophonic sound that activated the seismograms on June 3; nor were there, to my present knowledge, any witness reports of simultaneous sounds connected with this event, and simultaneous or electrophonic sound is not considered further in this paper.

Delayed sound (or, as some would have it, “real” sound) can arise from a fireball in one of three ways. As the meteoroid moves through the atmosphere at several tens of times the speed of sound, it generates a conical supersonic shock front. Because of the very high speed, the semivertical angle of the cone is small (less than a degree) and the cone is almost cylindrical. When this conical shock front reaches the ground, it causes ground-shake and hence can activate seismographs. Second, because of the steep temperature gradient between the hot surface of the meteoroid and its cold interior, severe thermal stresses can be generated inside the meteoroid, causing a violent, explosive *terminal burst*. This acts as a point source for a spherical sound wave. Lastly, there may be an actual impact of the meteoroid with the ground (the meteoroid is now a *meteorite*), and seismic vibrations are then transmitted through the Earth’s crust. Because sound travels much faster through rocks than through the air, this event (which is the last of the three to happen) may be (but is not necessarily) the first to be detected by seismograms.

The theory of how to calculate the position of the terminal burst or the trajectory of the fireball through the atmosphere has been discussed by Tatum (1999), in which several references are given to other papers on the subject – either theoretical or applications to actual fireballs. The question of how to distinguish between the terminal burst and the supersonic shock front has been considered by Tatum, Parker and Stumpf (2000) as well as by Manville, Sherburn and Webb (2002) in their excellent analysis of the seismic detection of a 1999 New Zealand fireball. It might be remarked that, if a fireball undergoes a number of explosions at quite irregular intervals along its path, such behaviour would play havoc with the most elegant mathematics of the ideal models of a point source terminal burst or of a cylindrical shock front.

In the present case – the 2004 July 3 fireball over Washington State – all I have done so far, owing to lack of time, energy, inclination or ability, or a combination of these, is to adopt the simplest model. Namely, I assumed that the sound was from a point source terminal burst, and I attempted to determine the position of this burst. For my first attempt, I assumed an isothermal atmosphere, in which sound travels at a constant speed in a straight line. For a second attempt I allowed the temperature and hence sound speed to vary with height – and hence the sound paths are no longer rectilinear.

For data, Dr John Cassidy of the Pacific Geoscience Centre kindly provided the coordinates and signal arrival times at 21 British Columbia seismic stations.

First Attempt – Isothermal Atmosphere

I chose a rectangular coordinate system with *xy*-plane tangent to Earth at a quite arbitrary point (I chose longitude 125°W and 48°N, *x*-axis to east, *y*-axis to north, *z*-axis to zenith. Let the coordinates of the *i*th seismo-station be $(x_i\ , y_i\ , z_i)$. (The z_i-coordinate – i.e. the distance from the tangent *xy*-plane – is calculated from the distance below the tangent plane resulting from the shape of the Earth – some spherical trigonometry is necessary.)

Let $(x,\ y,\ z)$ be the coordinates of the terminal burst. Let t_i be the sound arrival time at station i and t be the time of the terminal burst. And let v be the (constant) sound speed. Then

$$f\,(x, y, z) \;=\; (x_i - x)^2 \;+\; (y_i - y)^2 \;+\; (z_i - z)^2 \;-\; v^2(t_i - t)^2 \;=\; 0. \qquad (1)$$

In general, there are five unknowns ($x,\ y,\ z,\ t,\ v$) so that data from five stations are required to solve for them. Thanks to Majden's video recording, t is known, and, for a preliminary solution, I fixed v at 0.33 km s^{-1}. (This, of course, can be refined if need be, if I go any further with this.) Thus a minimum of three stations (three equations) are needed, in order to solve for the remaining unknowns, x, y, z.

The algebraic solution of three simultaneous quadratic equations is a bit daunting, so I solved them by an iterative Newton-Raphson process – making an initial guess and calculating differential corrections. Thus, with a guess of $x + \delta x,\ y + \delta y,\ z + \delta z$, the differential corrections are found by the solution of simultaneous linear equations of the form

$$f\,(x + \delta x\,,\ y + \delta y,\ z + \delta z) \;=\; \frac{\partial f}{\partial x}\delta x \;+\; \frac{\partial f}{\partial y}\delta y \;+\; \frac{\partial f}{\partial z}\delta z\,. \qquad (2)$$

There were 21, rather than just three, linear equations of condition of this type. From these 21 linear equations of condition in $\delta x,\ \delta y,\ \delta \mathrm{z}$, the three normal equations were formed in the usual way in such a manner as to minimize the sum of the squares of the residuals. The corrections were applied to the original guesses, and the iterative procedure repeated until convergence to a precision of $\delta x/x$ and $\delta y/y < 10^{-5}$.

What I found was that, no matter how stupid the first guess, convergence in x and y was reached in four or five iterations – but, no matter how intelligent the first guess, I could not achieve convergence in z. In other words, I could easily find the latitude and longitude of the terminal burst, but I could find no solution for the height.

Faced with this difficulty, I fixed the height successively at 5 km, 10 km, 15 km … up to 50 km and solved for x and y. I found that the solution for x and y was almost independent of my assumed value for z, but there was a shallow minimum in the sum of the squares of the residuals for a choice of z = 20 km. The best solution for the position of the terminal burst from the isothermal atmosphere calculation, then, was

Longitude = 122° 05' W Latitude = 47° 50' N Height = 20 km,

but the height in this solution is very ill-determined.

Second Attempt – Atmosphere with Linear Temperature Lapse Rate

For a second attempt, I did not assume an isothermal atmosphere. I assumed an atmosphere with a ground temperature of 288 K and a uniform temperature lapse rate of 6.5 K km^{-1}. This corresponds to the first 11 km of the International Civil Aviation Organization Standard Atmosphere.

Of course ideally one should use the actual lapse rate and ground temperature for the location and time in question – and these can be obtained from daily meteorological records from high-flying balloons – but the ICAOSA is a good starting point, and the calculations could be refined later if need be. Provided the terminal burst was not higher than about 11 km, it probably makes little difference. Above 11 km, however, in the stratosphere, the temperature lapse rate is significantly different, so the 6.5 K km^{-1} is no longer appropriate. I shall argue below, however, that I believe that the terminal burst may well have been quite low.

I have not included winds in the calculation. That is, I assumed a calm atmosphere. I would argue that wind speed is much less than the sound speed and very much less than the fireball speed, so that correction for winds (which could presumably be obtained from meteorological data) is a minor correction. Truth to tell, however, I haven't developed the mathematics and computer programs to include winds, and indeed the problem, in the words of Sir Isaac, doth make my head ake. The inclusion of winds is something that I might (or might not) think about later.

In an atmosphere with a uniform temperature lapse rate, the sound speed decreases as the square root of height about ground level. Under such circumstances the paths of sounds rays are not straight lines but arcs of cycloids. The theory of these, and the relevant equations with a numerical example, are given in Tatum (1999), in which it will be observed that the analysis is rather more complicated than in the isothermal case.

I carried out the calculations for this model using the same 21 British Columbia arrival times. I shan't give the details of the calculation here, since they are identical to the analysis and example given in the paper cited above. The result was

$$\text{Longitude} = 122^\circ\ 02'\ \text{W} \qquad \text{Latitude} = 47^\circ\ 47'\ \text{N}$$

The height, as in the isothermal case, however, was very ill-determined – so much so in this case that there is no height I can quote as giving a significantly better solution than any other.

Two Comments

i) One wonders why it is that the height was so ill-determined. When z was left as a free parameter, the solution for latitude and longitude converged in four or five iterations, but I obtained no convergence for z. When z was held fixed at values ranging from 5 to 50 km, the solution for latitude and longitude was almost independent of the assumed z, though in the isothermal case there was a very shallow minimum in the sum of the squares of the residuals for $z = 20$ km.

At first I naturally wondered if there was a "bug" in my computer programs. However, they worked perfectly with sample test data. I believe the reason for the lack of convergence for z is that all the seismic stations used were on one side of the sub-burst point – and indeed a long way from it (in units of the likely burst height). In an ideal situation one would want seismic records to be distributed all around the sub-burst point, including a few not far from it. If all the records are a long way from the sub-burst point and all on one side of it, the height of the burst becomes indeterminate. The situation is very analogous to the analysis of eyewitness estimates of azimuth and altitude. If all the eyewitnesses to a fireball are on one side of the ground track of the fireball, the random errors in the estimates of altitude and azimuth (which are, of course, large in the case of eyewitnesses) are such that (as I have often pointed out – with only limited success!) no credible solution of the atmospheric trajectory is possible.

Thus the best solution will be obtainable only if records from *all* seismic stations that record the burst are combined. It is hoped that that might be one of the results to come from this "poster-session conference".

ii) It will be noted that the solutions for the isothermal atmosphere and the constant lapse-rate model are almost identical. This means that there is very little difference in the solution for rectilinear and cycloidal sound paths. This must surely mean that the paths did not differ very much from straight lines, and hence that there was very little temperature difference between ground and terminal burst. This surely means, to my way of thinking, that the burst must have been very low – i.e. only a very few kilometers.

That's as far as I have got at the moment. While there are obvious refinements to be made (e.g. get the actual meteorological data, or investigate the solution on the assumption that the signal was from a conical shock front rather than from a point-source terminal burst), I am not planning to go further in the immediate future, because of other pressing commitments, though I may well return to it one of these days.

References

Manville, V., Sherburn, S and Webb, T. (2004). Seismic Detection of the 7 July 1999 Hawera Fireball. *New Zealand Journal of Geology and Geophysics*, **47**, 269-274.

Tatum, J.B. (1999). Fireballs: Interpretation of Airblast Data. *Meteoritics and Planetary Science*, **34**, 571-585.

Tatum, J.B., Parker, L.C. and Stumpf, L.L.. Sound from a Fireball – Distinguishing between the Hypersonic Shock Front and the Terminal Burst. *Planetary and Space Science*, **48**, 921-923.