Locating Bolide Terminal Bursts using Seismic Arrival Times: A Supracenter Location Program.

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Introduction: When sizable asteroidal or cometary fragments enter the Earth's atmosphere, atmospheric friction upon the falling object(s) produce fireball phenomena. As a projectile penetrates into denser layers increasing ram pressures usually cause the object to fracture in a cascading fashion leading to violent disintegration of some or all of the projectile. The resulting explosions produce acoustic waves that propagate to the ground where their arrival can be recorded by nearby seismic stations. If several adequately separated seismometers record the same event it is possible to locate the position of the explosion or "supracenter" in four dimensions (3 spatial, 1 temporal) using ray tracing in a process analogous to locating earthquake hypocenters in the solid earth. SUPRACENTER has been designed with this use in mind. Since these explosive events or terminal bursts often mark a position near the end of a bolide's supersonic travel, their position is of particular interest to any meteorite recovery effort.

SUPRACENTER Program: Several attempts have been made previously to locate explosive events in the atmosphere using the currently available programs and isotropic atmospheric models [1, 2, 3] with some amount of success. However, unlike current hypocenter location programs, SUPRACENTER uses a stratified atmosphere and includes the effects of atmospheric winds on ray propagation, which, if ignored, may mislocate events by several kilometers. SUPRACENTER uses the generalized tau-spline method of Garces *et al.* [4] to calculate the direct arrival traveltimes in a moving atmosphere and the residual minimizing methods of Nelson & Vidale [5] and Sambridge & Gallagher [6] to locate the best fitting position to a given set of arrival times. To achieve versatility over multiple platforms SUPRACENTER has been developed in Matlab and uses simple ASCII text files for the input of atmospheric models and seismic station information. Both automated and manual search methods are available along with several fitting and weighting options.

Case Studies: To test the effectiveness of the SUPRACENTER program in locating terminal bursts, locations for the explosions of fireballs were determined and compared to burst positions that had been, using independent methods, determined previously.

El Paso Superbolide: On October 9th, 1997 during local noon hour a large fireball exploded near El Paso, Texas. The fireball and its dust cloud was extensively witnessed, photographed and videotaped allowing a triangulation of the fireball's terminal burst position [7]. Using (i) nearby radiosonde measurements of atmospheric temperature and winds, (ii) the arrival times from the nearest three seismic stations that recorded the blast, and (iii) the terminal explosion time as observed by satellite (18:47:15 UT), SUPRACENTER produces a position of 31.790°N, 106.080°W at an altitude of 27.6 km a.s.l.. This position lies ~2.1 km WSW (Figure 1) from that reported by Hildebrand *et al.* [7] and after accounting for the ~0.5 km radius of supersonic shock around the event is consistent with both eyewitness reports and photographic evidence of the burst. An independent altitude constraint comes from the burst lying just below a significant wind shear near 30 km altitude.

Mt. Adams Fireball: On January 25th, 1989, at 12:51 pm, a fireball was observed heading southeast over northwestern Washington state. The fireball split into two separate fireballs that exploded separately near the flank of Mt. Adams [8] resulting in two separate events being recorded on the ground by 26 seismic stations [3].

Using radiosonde measurements from nearby Spokane, Washington and modeled temperatures and winds above Spokane at the time of the radiosonde release using the NASA/GSC MSIS-E and Naval Labs Horizontal Wind models [9,10], an atmospheric model was constructed to reproduce the conditions present at the time of the fireball. This atmospheric model was then used in conjunction with the arrival times of the two events in SUPRACENTER to locate the two burst positions.

The two bursts, A and B, were found to be 2.5 and 2.7 km NNW (Figure 2) from those positions reported by Qamar [3] who employed an isotropic atmosphere. This shift in position is consistent with the dominant northerly winds recorded by the Spokane sounding. Though slightly lower heights and later occurrence times are found, the two terminal burst positions remain consistent with the NW-SE trajectory and occurrence time of the fireball reported by Pugh [8] (A at 12:51:14.5 pm and B at 12:51:15.1 pm). This location shift is explained by the cold seasonal temperatures of the atmosphere at the time of the fireball. This leads to slower acoustic velocities that result in slightly lower heights and later occurrence times to fit the observed arrivals.

Residuals for both events A and B were found for 21 of the 26 available seismic observations, most with values less than one second (the remaining 5 stations were distant and direct arrivals could not be found). Event A (northernmost event) produced an mean absolute residual of 0.925 seconds with a standard deviation of 1.2 seconds, while event B produced an mean absolute residual of 0.903 seconds and a standard deviation of 1.5 seconds.

Although residual statistics were not given for Qamar's solutions [3], residuals were found using a similar isotropic velocity model (305 m/s) for the atmosphere that produced locations almost identical to those of [3]. In comparison to SUPRACENTER results the residuals were larger (mean abs residuals: A=1.39s, B=2.66s) with a greater range in residual values (std: A=1.94s, B=7.81s) illustrating the precision and greater consistency of the solution incorporating the real atmosphere.

Additionally with these two fixed points on the fireball's trajectory, the orientation and speed of the object can be determined. Speed of the bolide is estimated by the time and distance between points A & B and is found to be 11.7 km/s with an azimuth angle of 152° and elevation angle of 43°. The speed found for the bolide is at the low end of the range for observed infalling astroidal materials and the orientation angles are consistent with the initial investigation of the fireball performed by Pugh [8].

Energy Estimates: Calibration of the ground motion response as recorded by the seismographs from terminal bursts at known distances also allows estimation of the energy released in the burst.

Conclusions: The adjustments of terminal burst positions on the order of 2-3 km due to the effect of atmospheric winds is important to any attempt at meteorite recovery as these distances are comparable to the widths of many known strewn fields. Also, SUPRACENTER can provide one or more accurate locations on a fireball trajectory within a day of its occurrence, which will allow more efficient use of the early days in a fireball investigation. Meteorite recovery efforts have a new tool to assist in the determination of fireball trajectories and to guide searchers in the field.

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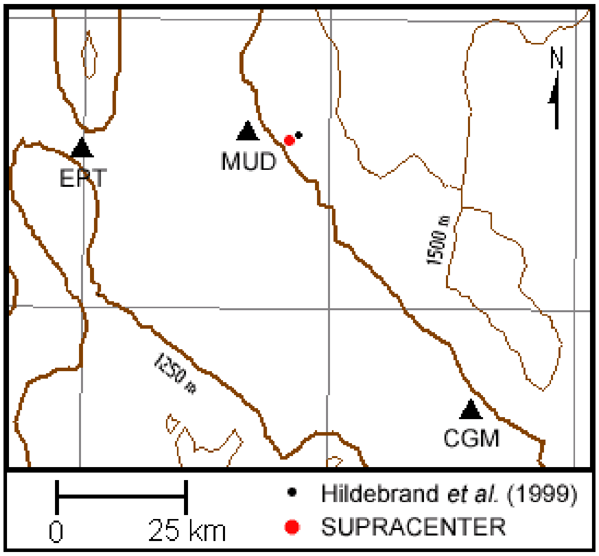

Figure 1: Comparison map for the El Paso superbolide terminal burst. Locations of seismic stations shown as black triangles. Contour interval = 250m

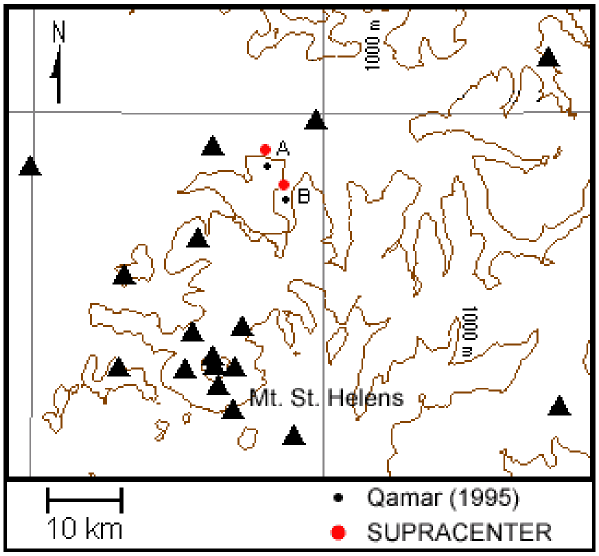

Figure 2: Comparison map for the Mt. Adams fireball terminal bursts. Contour interval = 1000m