Geophysical Research Abstracts
Vol. 16, EGU2014-13010, 2014
EGU General Assembly 2014

Seismic characterization of the Chelyabinsk meteor's terminal explosion

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On February 15th, 2013, an exceptionally large meteor in the region of Chelyabinsk, Russia, produced a powerful shock wave which caused unprecedented damage to people and property, the strongest atmospheric infrasound signal ever recorded, and remarkable ground motion.

Here we describe and model the resulting Rayleigh waves, recorded at broadband seismic stations at distances from $\sim$230 to $\sim$4,100 km. Our full-waveform modeling uses a seismogram simulation code specifically tailored to consider wave propagation in the atmosphere and solid Earth, and the coupling at the interface between them.

An isotropic point-like airburst reproduces very well the available seismic observations, without requiring a more complex explanation, such as a moving source. The measured seismic shaking was generated by direct coupling of the atmospheric shock wave to the ground, and then it propagated outwards faster than the atmospheric shock wave itself, at up to 3.9 km/s.

The best-fitting airburst location (61.22° E, 54.88° N) is SW of Chelyabinsk city, exactly at the terminal part of the meteor's trajectory, just after it experienced a dramatic flare, with apparent brightness larger than the Sun's. We estimated the meteor's ground path from published trajectory data, eyewitness observations, and detailed satellite imagery of the exact location where a major meteorite fragment landed, in the frozen Lake Chebarkul (60.32074° E, 54.95966° N).

Fixing the source origin time allowed us calculating that the explosion took place in the stratosphere, at an altitude of 22.5 $\pm$ 1.5 km. This value is lower than the reported altitude of peak brightness (about 29.5 km), but more consistent with the observations of shock wave travel times. Such results highlight the importance of terminal energy release down to lower altitude.

We analyzed a surveillance video recorded inside a factory (61.347° E, 54.902° N) at Korkino, a locality close to the airburst. It shows a time delay of 87.5 seconds between the peak meteor brightness and the powerful shock wave arrival. The calculated atmospheric travel time of the shock wave from the preferred airburst source to the factory site would be $\sim$88 seconds. Thus, this video validates our most likely location for the terminal explosion.

Finally, our best estimate of the equivalent moment magnitude of the airburst is 3.60. This value implies that the Chelyabinsk meteor is the second largest ever seismically recorded, only surpassed by the 1908 Tunguska event.

*** Publication: ***

Sebastian Heimann, Álvaro González, Rongjiang Wang, Simone Cesca & Torsten Dahm (2013):
Seismic characterization of the Chelyabinsk meteor's terminal explosion.
Seismological Research Letters, 84, 1021-1025.