REVISITING ENERGY RELATIONS FOR LARGE BOLIDES: IMPLICATIONS FOR IMPACT HAZARD FROM METER-SIZED ASTEROIDS.

Esther Mas Sanz[1], Josep M. Trigo-Rodríguez[1] , Elizabeth A Silber[2,3], Eloy Peña Asensio[1], Maria Gritsevich[4,5,6] , and Martin R. Lee[7], (1) Institute of Space Sciences (CSIC-IEEC), Meteorites, Minor Bodies and Planetary Science, Cerdanyola del Vallès (Barcelona), Spain; (2) Department of Earth Sciences, Western University, London, ON, Canada, (3) AstrumPrime Space Research Inc., Dartmouth, NS, Canada, (4) Finnish Geospatial Research Institute, Masala, Finland; (5) University of Helsinki, Department of Physics, Helsinki, Finland; (6) Ural Federal University, Ekaterinburg, Russia; (7) School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK.

Introduction: The Earth is constantly bombarded with extraterrestrial objects entering the atmosphere at hypersonic velocities. They are called ***meteoroids*** if they are smaller than one meter or asteroids if larger than that given size [1,2]. Collisions with the atmospheric constituents result in ionization, ablation, fragmentation and light generation, producing fireballs that could be detectable from space [16]. The study of the pre-atmospheric orbits of these objects by monitoring networks (e.g., all-sky camera, telescopic) associate them with parent asteroids or comets [3,4,10,17]. Hence, the composition of meteoroids is as diverse as the populations they come from. While comets are mostly water ice and dust particles originally formed in the outer Solar System, asteroids formed in the inner Solar System and are made of minerals [11]. Thus, in the meteoroid population producing bolides one can find ordinary chondritic materials, carbonaceous chondrites, regular and soft cometary materials and nickel-iron alloys [8,12]. The population of objects residing in the Earth's neighbourhood and that could pose hazard is dubbed NEOs (Near-Earth Objects). It is of great interest to broaden our knowledge about NEOs physical and chemical properties, population and flux of impacting the Earth, while at the same time combining those with pre-orbital characteristics. The aim of such studies is to achieve a better understanding of the characteristics, fragmentation behaviour, energy deposition with height and total energy yield [13] of one of Earth's oldest and most lethal natural hazards.

Large meteoroids have been responsible for catastrophic events on Earth, although their occurence might be rare. However, the recent **Chelyabinsk event** (Russia, 2013 [5]) demonstrated that the damage and destruction can be caused by an airburst of a relatively small asteroid (~18 m), and is predicted to occur every 50 years [6]. Thus, such events provide evidence for the necessity of monitoring NEOs and better constraints on meteoroid energy deposition.

Estimates of the bolide energy are typically obtained from light emissions (e.g., government sensors [7]) and from low frequency acoustic waves (infrasound [8]). **Infrasound** is a byproduct of the shock waves generated by a meteoroid's passage through the atmosphere. The first theoretical approach that used infrasound signals was the weak shock propagation theory, developed by ReVelle [14]. The aim was to predict the properties of the infrasound signal based on the source and to deduce the source function from infrasound signal measurements. The theoretical approach laid the foundations for the use of infrasound signal properties (mainly amplitude and period) for the determination of bolide's energy estimation.

Empirical Relations: Table 1 shows a selected number of empirical relations used for estimating bolide energy.

Formula: $logE = a_0 + a_p log(P)$

	ap	a0	Original Source
$E \leq 200kt$	3,34	-2,28	ReVelle (1997)
$E \geq 80kt$	4,14	-3,31	ReVelle (1997)
	3,75	3,5	Ens et al. (2012)
Multi-Station Average	3,28	3,71	Ens et al. (2012)
	3,68	-1,99	Gi and Brown (2017)
Multi-Station Average	3,84	-2,21	Gi and Brown (2017)

Table 1a.

Formula: $logE = a_0 + a_A log(A) + b log(R^*) + c|\overrightarrow{v_w}|$

	a_a	a_0	b	c	Original Source
$R^* = Rsin(\Delta)$	1	1,54	0,5		Pierce and Posey (1971)
$R^* = \Delta$	2	-1,84	2,94		Clauter and Blandford (1998, AFTAC)
	1,47	-4,96	1,47		LANL (Los Alamos National Laboratory) Whitaker (1995)
	3,03	-9,09	3,03		IDG Russian crosswind
	3,03	-10	3,03		IDG Russian downwind
	1,47	-4,96	2		Whitaker (1995)
	2	-10,62	3,52		Blanc et al. (1997)
	1,55	-8,45	2		Davidson and Whitaker (1992)
Wind-corrected amplitude	1,49	-8,52	2		Mutschlecner and Whitaker (2009)
Wind velocity	1,71	-8,5	3	-0,01	Edwards et al. (2006)
	1,72	-8,79	3	-0,031	Edwards et al. (2006)
	1,47	-8,34	2	-0,026	Davidson and Whitaker (1992)
	1,72	-8,73	3	-0,004	Edwards (2007)

Table 1b.

Table 1. Empirical energy relations that use infrasound data (period, Table 1a) and (amplitude, Table 1b). P is the period in seconds [s] of the signal, A is the amplitude in pascals [Pa], R is range in [km], $\vec{v}_w$ is wind velocity in [m/s] and E as energy in [kt] of TNT equivalent.

Most of the empirical relations that are based on infrasound records were developed for estimating the yield of nuclear and chemical explosions. Those empirical relations were calibrated for explosions that took place near ground level, which is in contrast to bolides that predominantly release their energy higher up in the atmosphere [7]. They were also adapted to bolide explosions by removing the radiation term, as nuclear explosions release almost half of their energy in the form of radiation. The most frequently used energy estimate relation was developed by AFTAC (the US Air Force Technical Applications Centre) to relate infrasound period to nuclear explosion yield [8]. Even though the empirical relations are assumed to provide fairly reasonable energy estimates for bolide events, it remains poorly constrained how robust they are and how well they bode against more reliable means of energy estimation (i.e., space-based sensors).

Many authors had provided energy estimates or improved already existing ones (Table 1), but still different relations predict different results, sometimes leading to contradicting outcomes. In this study, we use well-documented and well-characterized published bolide records and apply various energy relations developed over the years to evaluate the outcomes and implications for impact hazard. Results are compared to estimates determined via space-based government sensors of recent fireballs to constrain the viability of various energy relations for estimating bolide energy.

Results: Here we used the Chelyabinsk bolide as a case study. This was the brightest instrumentally recorded fireball in history, and the most energetic event recorded by infrasound stations ever [9]. An 18 m in diameter asteroid entered the Earth's atmosphere at a shallow angle, and released a total energy of ~500 kt (TNT equivalent). The event generated a shockwave that readily reached the ground and shattered windows on numerous buildings. Most injuries were produced by broken windows, and a UV radiation that resulted in retinal burns in some eyewitnesses [15]. Figure 1 shows the energy estimate resulting from different empirical relations.

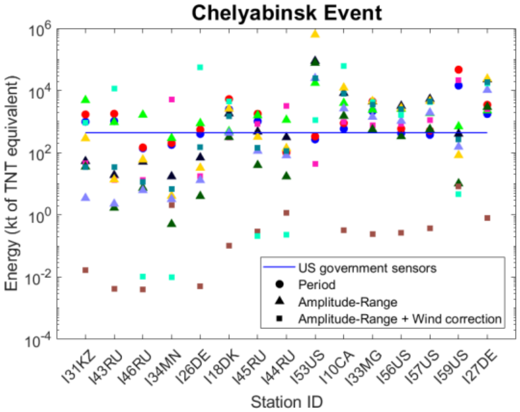

Figure 1. Example of different empirical relations applied to the Chelyabinsk bolide event in 2013 [5]. The relations use the signal period, or the signal amplitude and range (with and without wind correction). The calculated energy is in kt of TNT equivalent. The different relations show large variations across infrasound stations that recorded the event.

The US government sensor energy estimate is plotted for the comparison. There are significant differences:
(1) between different stations applying the same relation, and
(2) at the same station applying different empirical relations.
The difference can be as much as several orders of magnitude, which has significant implications for the choice of relations to be used for estimating bolide energy when infrasound is the only (or one of the few) means of detection.
Most importantly, for a good prediction in impact hazard, it is necessary to reliably estimate bolide energy; thus, it is paramount to reconcile and systematically reevaluate various empirical relations in existence, and establish a tool-set for consistent and robust energy estimates that would be used by the greater scientific community.

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