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# Reanalysis of the Historic AFTAC Bolide Infrasound Database

**Douglas O. ReVelle · Elizabeth A. Sukara · Wayne N. Edwards · Peter G. Brown**

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**Abstract** We have recently digitized and partially reanalyzed the historic bolide infrasonic database. These 10 events were originally detected by the U.S. Air Force Technical Applications Center (AFTAC) from ~1960 to 1974. In this paper we present the first preliminary reanalysis results for two of the 10 bolide events, namely the Revelstoke bolide of 3/31/1965 as well as the Prince Edward Islands (P.E.I). S. African bolide of 8/03/1963, which were among the largest bolides detected during this time period. These bolides have been investigated initially since they are most likely to have had a significant effect on the computed global influx rate of ReVelle (Global Infrasonic Monitoring of Large Bolides, pp 483–490, 2001) as indicated in Brown et al. (Nature, 420:314–316, 2002). We are in the process of recomputing all relevant infrasonic propagation quantities such as plane wave back azimuth, signal velocities, power spectra, spectrograms, as well as energy estimates using multiple techniques. In a future paper we will present a complete digital reanalysis of the AFTAC bolide infrasonic data and its final resulting global bolide influx implications.

**Keywords** Bolides · Infrasound · AFTAC · Atmospheric acoustic-gravity waves · Global influx rate of largemeteor-fireballs

## 1 Introduction and Overview

### 1.1 Bolide Infrasound

ReVelle (1976, 2001, 2004, 2007a, b) has interpreted and analyzed bolide infrasound data from numerous sources. We have also used this data in combination with a number of other

D. O. ReVelle (✉)
Atmospheric, Climate and Environmental Dynamics Group, Earth and Environmental Sciences Division, Los Alamos National Laboratory (LANL), Los Alamos, NM 87545, USA
e-mail: revelle@lanl.gov

E. A. Sukara · W. N. Edwards · P. G. Brown
Department of Physics and Astronomy, University of Western Ontario (UWO), London, ON Canada N6A 3K7

detection techniques as well (photographic, satellite, seismic, etc.) in order to compute the bolide mass and source energy, (cf. ReVelle et al. 2004). The primary source of bolide infrasound is from the propagation of the line source cylindrical blast wave modified by fragmentation processes. This source type can only occur for sufficiently large masses in hypersonic near-continuum flow where the line source blast radius, $R_o$, is directly proportional to the dominant wave period. Secondarily, wake turbulence as well as close range supersonic flight can also produce audible sounds, but acoustic amplitudes are generally insufficient to be observed at ranges >100 km, unlike the blast waves, which have been detected reliably out to 14,000 km for very large events.

### 1.2 The Historic AFTAC Database

As summarized in ReVelle (1997), between 1960 and 1974, U.S. Air Force Technical Applications Center (AFTAC) recorded acoustic-gravity waves (AGW) at very great ranges from numerous explosive sources including those from "airwave objects" as the bolide signals were first designated (ReVelle 1997). Infrasonic signals constitute only the higher frequency part of this atmospheric AGW spectrum. ReVelle and Wetherill (1978) were able to obtain this data from the US Air Force and subsequently work began on its implications for the global influx rate. Almost all events had their detections and energy levels confirmed by other available methods. One uncorroborated events was the S. African bolide (near the S. African Prince Edward Islands (P.E.I) in the far S. Atlantic region-hereafter just the S. African event) currently being reanalyzed. This very large bolide and the famous Canadian Revelstoke meteorite fall were among the very largest events (ReVelle 1997) in this database with source energies of the S. African and Revelstoke bolides of 1,100 kt and 26 kt respectively (where1 kt, TNT equivalent = $4.185 \times 10^{12}$ J). These large events largely control the slope of the resultant global influx curve determined using infrasonic detection techniques. For this reason alone, they are now being extensively reexamined.

Each array consisted of at least four microbarometer pressure sensors that were placed 6–12 km apart at a minimum of 16 locations worldwide. The sensor response ranged from many minutes down to 8.2 Hz which was subsequently filtered in two specific wave bands, namely: (i) Internal gravity wave band: 440–44 s and (ii) Infrasonic wave band: 25 s to 8.2 Hz. Signal processing was done using completely analog methods including cross-correlation until 1972–1974 when digital techniques were introduced. Numerous sources were detected such as earthquakes, volcanic eruptions, aurora, bolides, Microbaroms, etc. In addition, the 10 bolide events that were detected were independently verified by additional detection techniques (seismic, VLF, i.e., very low frequency radio wave emission from a bolide, etc.). This dataset included a very small $\sim$0.20 kt event over Western India, a single very large and very remote 1,100 kt event, the fall of the Revelstoke meteorite ($\sim$26 kt) and two 10–15 kt events that fell in the middle east almost exactly one day apart. Only the Revelstoke and S. African bolides will be discussed further below.

## 2 Previous Analyses

### 2.1 Previous Analyses of AFTAC and Other Bolide Infrasonic Records

Wetherill and ReVelle (1978) and ReVelle (1980, 1997, 2001) analyzed the numerous records from these events. Through 1997 only the original AFTAC data were analyzed, but by 2001 a number of additional detections were also available that had been recorded at the Los Alamos National Laboratory regional infrasound arrays. These newer regional scale events were much smaller in source energy than those recorded previously on global scales. The new bolide detections allowed a set of analysis relations predicted by ReVelle (1976, 2001) and by ReVelle et al. (2004) for weak shock waves propagating from idealized line sources at relatively close ranges to be examined. These relations are now in routine use for regional scale infrasonic propagation and bolide detection studies within the Physics and Astronomy Department at the University of Western Ontario (Brown et al. 2007; Edwards et al. 2007; ReVelle 2007b).

### 2.2 Global Influx Results

Earlier Wetherill and ReVelle (1978) as well as ReVelle (1980, 1997, 2001) analyzed the data to predict the global meteoroid influx rate. They determined an influx rate that exceeded, but was close to that predicted in Brown et al. (2002), i.e., a constant power law type solution. These previously computed relations are summarized below:

(i) Infrasound (ReVelle 2001): Final compromise result

$$N(\geq E_s) = 5.66 \cdot E_s^{-0.724};\ r^2 = 0.954 \tag{1}$$

(ii) Satellite data ground-truthed with infrasound/meteorite falls (Brown et al. 2002):

$$N(\geq E_s) = 3.70 \cdot E_s^{-0.90};\ r^2 = 0.99724 \tag{2}$$

We also note finally that Bland (2005) has recently provided an overview summary of the global terrestrial meteoroid influx rate. Also, Ortiz et al. (2006) have presented lunar impact flash data that seem to be in better agreement with the infrasonic influx rate deduced by ReVelle, but is subject to luminous efficiency parameter uncertainties and needs additional calibrations to be fully accepted in our opinion.

## 3 New Research Efforts

### 3.1 Signal Digitization

During 2006, LANL and UWO decided to digitize the analog chart records. This arduous task was almost completely undertaken by one of us (Sukara). Please note that all source-observer ranges quoted below are the computed great circle paths on a spherical earth.

### 3.2 Reanalysis of the AFTAC Bolide Events

#### *3.2.1 Analysis: March 31, 1965, Revelstoke Bolide: Arrays MF and PD Reconstruction of the Event*

In Fig. 1a and b, we plot the filtered time series using the high frequency (HF) pass-band: From 25s to 8.2 Hz.

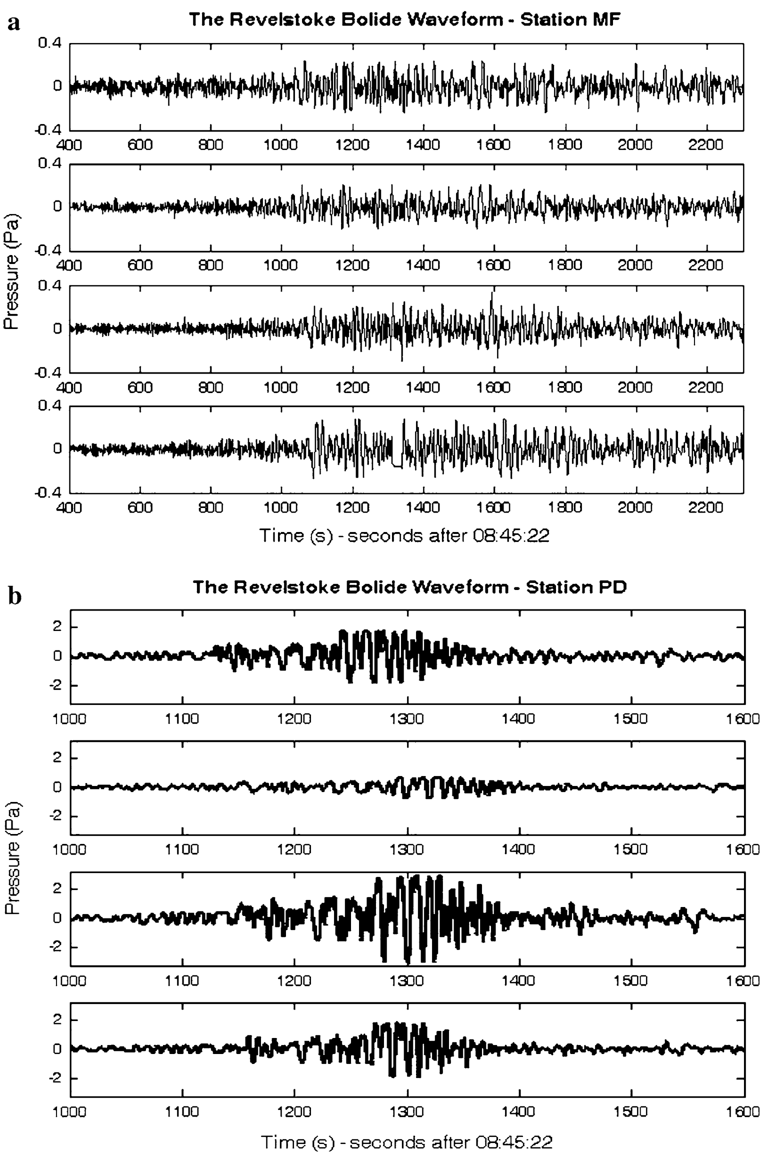


**Fig. 1** (**a** and **b**) HF time series of amplitude (in Pa) for the Revelstoke airwave data for the Alaskan array-MF (**a**-top panel) and for the Greenland array-PD (**b**-bottom panel). The seismic/acoustic triangulated source location is: 51.1°N, 117.6°W

Given the Revelstoke signal variability (also observed at a range ≅1,550 km in Boulder, CO with Δp ≅ 0.80 Pa—see ReVelle 1976), we suspect that focusing, source altitude and line source blast radius effects, or non-steady or range-dependent influences may have contributed to this variability.

We computed signal velocities and back azimuths (its origin time = 05:48 UT and the assumed arrival time in Fig. 1a and b was at 1,100 s).

(i) MF array—2497.7 km range: Signal velocity = 320 m/s, Back azimuth = 145.8°: 2 h, 10.28 min travel time
(ii) PD array—3497.1 km range: Signal velocity = 322 m/s; Back Azimuth = 196.8° for a 3 h, 0.867 min travel time

These velocities are too large for Stratospheric returns. Including errors, they could be Stratospheric or Lamb wave returns at PD (ReVelle 2007b).

### *3.2.2 Preliminary Analysis of the August 3, 1963, S. African, P.E.I. Bolide Reconstruction of the Event*

We also analyzed the propagation for the S. African bolide. AGW/infrasonic waves originated from a remote region in the S. Atlantic and took many hours to reach these two arrays. In Fig. 2 (a and b) we plotted the signals recorded at array PB (at 13,824 km range) and at array JB (at 11,327 km range).

## 4 Preliminary Global Influx Rate Reanalysis

For Revelstoke we reduced the source energy from 26 to 1.4 kt based upon the nominal Edwards et al. (2006) solution for Revelstoke which determined its source energy to be from 0.61 to 3.2 kt. Similarly, for the S. African bolide we have reduced the source energy from 1,100 to 266 (±90 kt), again based upon the wave amplitude calibration work of Edwards et al. (2006) where the observed amplitudes from the digitized records were combined with known source-receiver ranges and averaged Stratospheric winds to arrive at these energy estimates. The errors reflect the standard deviation in the mean winds and the best-beam amplitudes. For these revised source energies, a preliminary revision to the global bolide influx rate using infrasonic methods alone including all AFTAC bolide data can be written (where N is the cumulative number of bolides per year over the entire earth of source energy, $E_s$ and with $r^2$, the square of the resulting least-squares correlation coefficient for a constant power law curve fit):

$$N(\geq E_s) = 10.02 \cdot E_s^{-0.865}; \;\; r^2 = 0.93741 \quad (3)$$

The new result above is not only *not* self-consistent with a predicted influx rate of 700–1,000 years for a 10 Mt energy release for Tunguska, but in addition for a source energy = 1.4 kt for Revelstoke, this unique event is predicted to occur >11 times each year over the earth, almost an order of magnitude above either the satellite estimated influx rate (Brown et al. 2002) or the lunar cratering influx rate of Werner et al (2002) at this energy. We consider this reoccurrence frequency for Revelstoke type events to be extremely unlikely. The reoccurrence timescale made using (3) for a 10 MT event is once every 287.53 years.

Revelstoke was so unique that it was studied for more than 2 years by US Geological Survey (USGS) researchers. The USGS detected the event seismically as well as infrasonically at ranges $\lessapprox$1,000 km (Jordan and Bayer 1967; Bayer and Jordan 1967) in the Pacific Northwest. The overriding conclusion from the seismic body waves recorded as far away as 250 km from the event was that Revelstoke impacted the earth in a very remote region of some of the tallest mountains of the Canadian Rockies with an expected crater

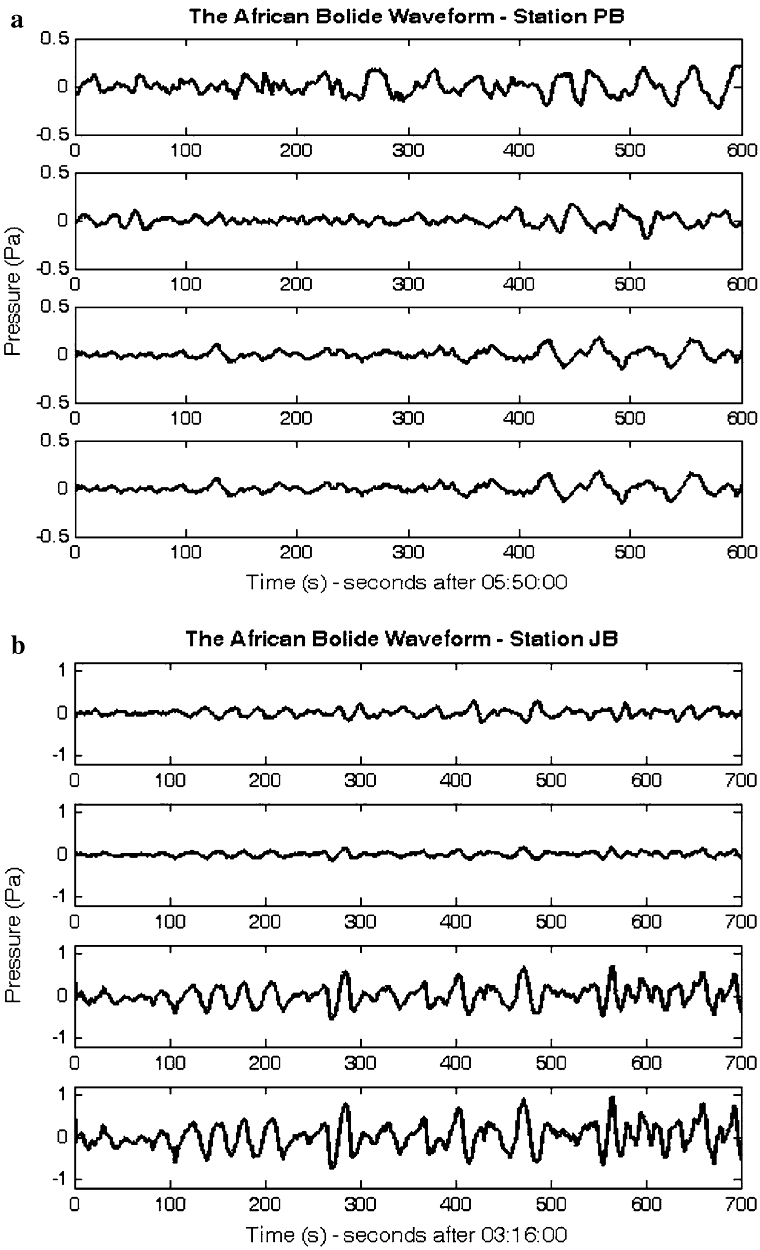


**Fig. 2** (**a**) HF time series of amplitude (in Pa) for the S. African airwave data at the AFTAC European array-PB. (**b**) HF time series of amplitude (in Pa) for the S. African airwave data at AFTAC array-JB

diameter (using the deduced seismic body wave magnitude) of ~24.4 m. This impact is extremely unlikely to have occurred for source energies as small as 1.4 kt.

Finally, we further evaluate source energy issues by examining the source energies using observations solely of the wave period at maximum signal amplitude. Historically the wave period has been used as a good diagnostic for the bolide source energy since amplitudes have been observed to be highly variable due to a number of additional causes. In the statistical analyses of Edwards et al. (2006), horizontal mean winds in the Stratosphere were also included and this helped significantly in some cases to reduce the scatter of the statistical plots of amplitude versus range as a function of the bolide source energy. Nevertheless, since the atmospheric is a dynamic, time dependent medium, propagation effects will always cause uncertainty to remain that at times will be very significant for both wave period as well as wave amplitude, but in differing ways.

We assumed in this analysis that the wave period at maximum amplitude is increased by weak nonlinearity and atmospheric dispersive propagation and that each bolide was similarly affected by these processes. If the S. African bolide had a source energy $\cong 270$ kt, we may ask what Revelstoke source energy is self-consistent with both the S. African bolide and with its own observed wave period at maximum amplitude. We already know that the wave period is $\propto$ to the blast radius, $R_o$ and that the source kinetic energy is $\propto$ to $R_o^3$ (ReVelle 2004, 2007a). Given that the S. African bolide had a maximum period $\cong 48$ s and that the Revelstoke bolide had a maximum period $\cong 16$ s, we find that the Revelstoke source energy must be reduced by $\sim 27$ times ($3^3$) or that its source energy should thus be at least $\sim 10$ kt. This value is also fully consistent with our entry modeling work (ReVelle, 2007a, b).

Using 10 kt as the Revelstoke source energy, with all else the same as in Eq. 3, we determined an additional preliminary influx relation:

$$N(\geq E_s) = 10.21 \cdot E_s^{-0.843}; \ r^2 = 0.90447 \tag{4}$$

This relation predicts a Tunguska reoccurrence time interval = 229.75 years.

Further systematic reanalysis of all of the digitized data thus seems to be very important in order to assess the above uncertainties more carefully. Future efforts will be more thorough and will of course include an evaluation of the standard errors as well as an additional reevaluation of the influx rate with the most uncertain values (probably the largest and smallest source energies) having been removed. Until the latter effort is completed, the “true” influx probably lies somewhere between the previous estimates of Brown et al. (2002) and that deduced in Eq. 4 above.

## 5 Conclusions

We have just begun to systematically reanalyze the digital version of the historical AFTAC bolide infrasound database. At this time we have only reevaluated the source kinetic energies for two of the most energetic bolides within this dataset, namely the August 3, 1963 S. African bolide and the April 1, 1965 Revelstoke bolide, first using the wave amplitude methods of Edwards et al. (2006) and subsequently using the wave period at maximum signal amplitude as an energy diagnostic for these two events. We have also analyzed additional factors such as the plane wave back azimuth, arrival times and we have also computed the power spectra using discrete FFT algorithms for a number of additional AFTAC bolides. Finally using different values for the source energies of the S. African and the Revelstoke bolide, we have made two preliminary revisions of the global influx rate. Both revisions predict that the famous Tunguska bolide of June 30, 1908 should reoccur on a timescale of 200–300 years rather than the 700–1,000 years reoccurrence timescale reported in Brown et al. (2002). Our future analyses of these bolides will be reported on later. These analyses will include wind data from atmospheric global models such as those from the United Kingdom Meteorological Office (UKMO).

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