SEISMIC INVESTIGATION OF A METEOROID AIRBURST IN GREENLAND AS A TERRESTRIAL ANALOG FOR ICY REGIONS WITH AN ATMOSPHERE IN THE SOLAR SYSTEM.

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**Introduction:** On July 25, 2018, a meteoroid-associated airburst occurred near Qaanaaq, Greenland, at approximately 22:00 UTC (20:00 local time). The event generated seismic waves that were recorded by two stations of the Danish Seismological Network (TULEG and NEEM), and the bolide trajectory was consequently calculated by the NASA Center for Near-Earth Object Studies (CNEOS). The total impact energy, calculated by CNEOS was 2.1 T of TNT and the brightest point on its trajectory corresponds to an altitude of around 43 km, at a distance of about 50 km S of Qaanaaq and 50 km N of the TULEG station at Thule Air Force Base [1] as shown in Figure 1.

This airburst occurring over the ice sheet of Greenland represents a rare terrestrial analog for atmospheric bolide processes in regions of the Solar System where both an atmosphere and an icy surface coexist. In particular, the surface on Titan, the biggest moon of Saturn [e.g., 2-3], has an icy surface composition and mountains that are formed by tectonic activity in ice [4]. Titan is also the only moon in the Solar System that has a relatively thick atmosphere, composed mainly (94\%) of nitrogen [5].

The characterization of atmospheric meteoroid-associated seismic sources for Titan is of particular interest as the presence of craters on its surface is extremely low, estimated by [3] to be only about 0.4\%, which translates into 50 potential craters. The most likely reasons for this low cratering of the surface is the erosion and the presence of the thick atmosphere, into which many of the meteoroids are entirely ablated into dust. The recent bolide flux can thus be determined by identifying airbursts via direct observation or indirect sensing methods [6]. Here we present a methodology for the detection, location, and characterization of an airburst as a seismic source and the modeling of the associated generated seismic waves. Any recorded bolide seismic signal at Titan will either be a direct atmospheric wave (nonlinear shock wave, or linear acoustic wave) or a seismic wave generated through the coupling of the atmospheric and solid/ice part.

**Qaanaaq Airburst Data:** Figure 2 shows the direct wave and the coupled seismic waves that were recorded at the TULEG station, which is the nearest (about 50 km) to the point of the final explosion and therefore the lowest point of the trajectory. In this data the following

![Figure 1](image1.jpg)

*Figure 1.* The projected zone of impact of the bolide is represented by the black dots. The red asterisk indicates the brightest point on the meteoroid trajectory. The red triangles show the locations of the seismic stations. The map is reproduced after [8].

![Figure 2](image2.jpg)

*Figure 2.* The seismic data associated to the bolide, as they were recorded at the TULEG station. The waveforms correspond to the vertical component of the ground velocity. It is shown that the considered direct wave is recorded in a wide frequency range above 5 Hz, whereas the seismic waves of the solid part are mainly detected in a range between 5 and 15 Hz.
characteristics are observed: a) The direct atmospheric wave is detected in a wide range of frequencies, higher than 5 Hz and up to 40 Hz, b) A second wave is detected in the frequency range between 5 and 15 Hz, and it is hence candidate for a coupled seismic body wave, potentially associated with the bolide (or fragment(s) of the bolide), c) There is no detectable signal in low frequencies (below 1 Hz), indicating that this kind of event would not generate any high amplitude surface waves at short epicentral distances (less than 1000 km) in a subsurface which contains an icy surface cover.

Methodology: In the present study, our aim is to perform a seismic investigation of the Greenland ice sheet with the use of the recorded airburst-associated seismic source. This effort has been divided into several tasks, including the application of a technique which approaches the bolide as an atmospheric seismic source [7], the calculation of the distance of shock wave propagation in the atmosphere, the description of the mechanism of generation of the seismic waves in the atmosphere and the solid-icy part.

When the bolides enter the atmosphere of the Earth or that of any other body, shock waves are generated along the trajectory of the meteoroid. These waves are characterized by the overpressure that they generate, which creates a clear pressure discontinuity in the atmosphere, referred to as the nonlinear part of the shock wave propagation. The propagation distance of this nonlinear wave is associated to the ratio of the meteoroid speed to the ambient sound speed, also known as the Mach number, as well as the physical diameter of the meteoroid [6]. In this work, we compute this distance for the Earth case and for the known trajectory of the detected and examined bolide [1,8].

However, the atmospheric shockwave and the subsequent consequent acoustic wave can explain only partially the generation of the seismic signal, recorded by the stations located in a range of hundreds of kilometers (less than 1000 km) far from the meteoroid trajectory. Therefore, we estimate the arrival time for the direct airwave, and the seismic waves which are produced through a coupling between the atmosphere and the ice shell. For the last one, a velocity model for the ice shell is needed, and consequently, it can serve as a tool for the identification of the ice structure.

The calculated propagation of the shock waves provides evidence for the secondary seismic source on the top of the ice shell, which generates the seismic waves recorded by the seismometers of both stations. Therefore, we are able to identify the direct and the coupled recorded waves in the signal and consequently estimate the velocities in the solid part. For the latter task, we use assumptions for velocity models of the ice structure in order to perform seismic wave modeling and validate the arrival times of the recordings.

Contribution to future missions: The methodology developed in this study can serve the seismic investigation of structures covered by ice on planets or planetary bodies with a relatively thick atmosphere, where airbursts can occur due to the friction of the meteoroid with the ambient atmospheric material. An ideal example of this case are the icy mountains of Titan, which are known to be formed by tectonic activity on the Saturn’s moon [4]. The future Dragonfly mission to Titan will carry a seismometer as part of the DraGMet (Dragonfly Geophysics and Meteorology Package) payload [9]. Even if the primary goal of the mission is the characterization of the regolith properties, an eventual airburst and collection of seismic data near these mountainous icy structures, would present a great opportunity to investigate the properties of this icy cover, its depth and composition.