Infrasonic waves generated by supersonic auroral arcs

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[1] A finite-difference time-domain (FDTD) model of infrasound propagation in a realistic atmosphere is used to provide quantitative interpretation of infrasonic waves produced by auroral arcs moving with supersonic speed. The Lorentz force and Joule heating are discussed in the existing literature as primary sources producing infrasound waves in the frequency range 0.1–0.01 Hz associated with the auroral electrojet. The results are consistent with original ideas of Swift (1973) and demonstrate that the synchronization of the speed of auroral arc and phase speed of the acoustic wave in the electrojet volume is an important condition for generation of magnitudes and frequency contents of infrasonic waves observable on the ground. The reported modeling also allows accurate quantitative reproduction of previously observed complex infrasonic waveforms including direct shock and reflected shockwaves, which are refracted back to the earth by the thermosphere. **Citation:** Pasko, V. P. (2012), Infrasonic waves generated by supersonic auroral arcs, *Geophys. Res. Lett.*, *39*, L19105, doi:10.1029/2012GL053587.

1. Introduction

[2] Atmospheric infrasonic waves are acoustic waves with frequencies ranging from ~0.02 to ~10 Hz [e.g., *Blanc*, 1985]. The importance of infrasound studies has been emphasized in the past ten years from the Comprehensive Nuclear-Test-Ban Treaty verification perspective [e.g., *Le Pichon et al.*, 2009]. A proper understanding of infrasound propagation in the atmosphere is required for identification and classification of different infrasonic waves and their sources [*Drob et al.*, 2003]. In the present work we employ a FDTD model of infrasound propagation in a realistic atmosphere to provide quantitative interpretation of infrasonic waves produced by auroral arcs moving with supersonic speed. Similar modeling approaches have recently been applied for studies of infrasonic waves generated by thunderstorms [e.g., *Few*, 1995], quantitative interpretation of infrasonic signatures from pulsating auroras [*Wilson et al.*, 2005], and studies of infrasonic waves generated by transient luminous events in the middle atmosphere termed sprites [e.g., *Farges*, 2009]. The related results have been reported in *Pasko* [2009], *de Larquier et al.* [2010], *de Larquier and Pasko* [2010], and *de Larquier* [2010], respectively.

[3] The auroral infrasonic waves (AIW) in the frequency range 0.1–0.01 Hz associated with the supersonic motion of auroral arcs have been studied in, [e.g., *Wilson and Nichparenko* [1967] and *Wilson* 1969, 1972, 1975, 2005, and references therein]. The pressure wave is usually observed around 6 min after the aurora arrives at the zenith. In order to generate auroral infrasonic waves the supersonic motion of the arc should be in the direction that has a component parallel to the Lorentz force $\vec{J} \times \vec{B}$, where $\vec{J}$ is the current flowing westward along the arc and $\vec{B}$ is the magnetic field [*Wilson et al.*, 1976]. *Brekke* [1979] discusses relative importance of Joule heating of atmosphere and the Lorentz force mechanism for the generation of the auroral infrasonic waves.

[4] *Wilson and Nichparenko* [1967] reported observations within the northern auroral zone suggesting that the occurrence and characteristics of most of the infrasonic disturbances associated with aurorae can be accounted for by the supersonic movement of large scale auroral forms. On one specific day of observations (February 23, 1966) although there was great auroral activity, there were only two large scale supersonic motions and only two associated infrasonic signals [*Wilson and Nichparenko*, 1967]. As discussed in *Wilson and Nichparenko* [1967] the smallness of the number of auroral infrasonic signals compared with the number of moving aurorae is consistent with the relatively small number of aurorae which attain supersonic speed. *Wilson* [1967] provided an elegant explanation for the anisotropic radiation of infrasonic waves from moving aurorae using a shock wave model. It was demonstrated that the acoustic waves, as observed on the ground at a site ahead of the moving aurora, are amplified in the direction parallel to the auroral motion by superposition of wave fronts if the auroral form is moving at supersonic speed. This mechanism was further supported by observations reported in *Wilson* [1969]. Figure 1 provides an example of observations of infrasonic wave packets from *Wilson* [1969]. Average amplitude of the observed signals is typically 2 dynes/cm^2 peak to peak (0.2 Pa) [*Wilson*, 1969]. Figure 2a is reproduced from *Wilson* [1969] and illustrates the shock wave model originally proposed in *Wilson* [1967]. Figure 2a also illustrates an interesting effect of arrival of a secondary wave after the arrival of the direct wave. This secondary wave is clearly seen in experimental data shown in Figure 1 as arriving 12 minutes after the primary wave. This secondary arrival is explained by the ground reflection followed by the thermospheric reflection of the direct wave as shown in Figure 2a.

[5] *Wilson* [1972] postulated that the basic acoustic pulse within the electroject arcs is caused by collisions with the neutral gas of positive ions that are driven by electrodynamic drift in the E region of the auroral arc. The Lorentz force was identified as the coupling mechanism between the electroject current carriers and the neutral gas. *Wilson* [1972] further stated that an ionization collision process occurs within the auroral arcs for those arcs that are moving supersonically in

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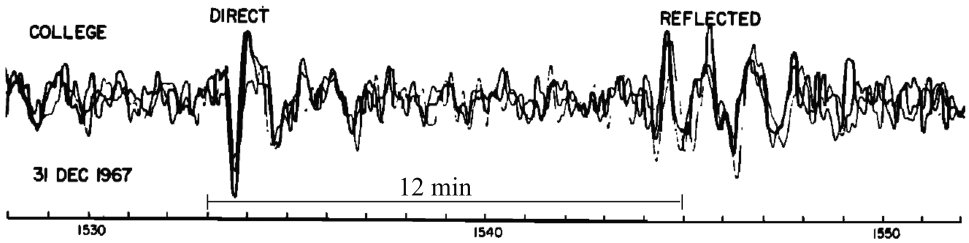

Figure 1. Examples of direct and reflected infrasonic waves observed at College, Alaska on December 31, 1967 generated by an auroral arc moving with a supersonic speed [*Wilson*, 1969]. The reflected wave is delayed by 12 minutes with respect to the direct wave. The mechanism of appearance of the reflected mode of propagation is explained in Figure 2a and further illustrated in Figure 3.

a direction parallel to the direction of the neutral ionization drift. It was assumed that the frictional force (i.e., due to collisions) between the positive ions and the neutral gas is the root cause of the effective momentum transfer from ions to neutrals and the resulting body force acting on the neutral gas.

[6] We emphasize that up to now no quantitative multi-dimensional modeling of infrasound generation and propagation in a realistic atmosphere in association with supersonic auroras has been conducted. Such modeling and modeling interpretation of infrasound signatures observed on the ground represent the goal of the present work.

2. Model Formulation

[7] The model employed in the present study utilizes linearized equations of acoustics with atmospheric gravitational stratification effects to solve for perturbations in density ρ', pressure ρ' and velocity $\vec{v}$ [e.g., *Pasko*, 2009]. The model is implemented in two-dimensional (2-D) axisymmetric simulation domain. In the model, the altitude and frequency dependent attenuation coefficients provided by *Sutherland and Bass* [2004] are included in classical equations of acoustics in a gravitationally stratified atmosphere using a decomposition technique recently proposed by *de Groot-Hedlin* [2008]. The details of implementation of the decomposition technique can be found in *de Larquier et al.* [2010]. The altitude distribution of speed of sound c_s is adopted from *Sutherland and Bass* [2004]. The equations are solved using a numerical scheme (fourth order in space and second order in time) discussed in [*Sparrow and Raspet*, 1991].

[8] The action of supersonic aurora is described by adding to the right hand side of the momentum conservation equation a body force $\vec{F}$ in N/m^3 acting on a unit volume of air. The body force is specified as a given function of time and coordinates. The physical nature of the force can be best understood in terms of momentum transfer collisions between charged species and air molecules and is the same as in plasma actuators actively investigated in recent years for purposes of aerodynamic flow control [*Boeuf and Pitchford*, 2005]. For charged species of type s have density n_s, mass m_s and velocity $\vec{V}_s$ the total force acting on a unit volume of air is $\vec{F} = \sum_s n_s m_s \nu_{\mathrm{sm}} \vec{V}_s$ where ν_{sm} are momentum transfer collision frequencies. For a Southward moving auroral arc at 100 km altitude possessing Southward directed electric field $\vec{E}$ the electrons can be considered as magnetized since $\nu_{\mathrm{en}} \ll \omega_{\mathrm{He}}$, where ν_{en} is electron collision frequency for momentum transfer and ω_{He} is electron cyclotron frequency. In this case electrons move preferentially perpendicular to $\vec{E}$ with Eastward directed velocity $\vec{V}_e \simeq \vec{E} \times \vec{B}/B^2 \simeq 1083$ m/s, assuming values of $E \simeq 65$ mV/m and $B \simeq 6 \times 10^{-5}$ T [e.g., *Wilson*, 1972]. The ions are not magnetized ($\nu_{\mathrm{in}} \gg \omega_{\mathrm{Hi}}$) and move parallel to $\vec{E}$ with Southward velocity $\vec{V}_i \simeq \mu_i \vec{E} \simeq$ 28.5 m/s. For these estimates we assumed that primary ions at these altitudes are NO^+ ions that are characterized by $\nu_{\mathrm{in}} \simeq 7.3 \times 10^3$ s^{-1} and mobilities $\mu_i \simeq 438$ m^2/V/s. An excellent discussion on preferential directions of motions of

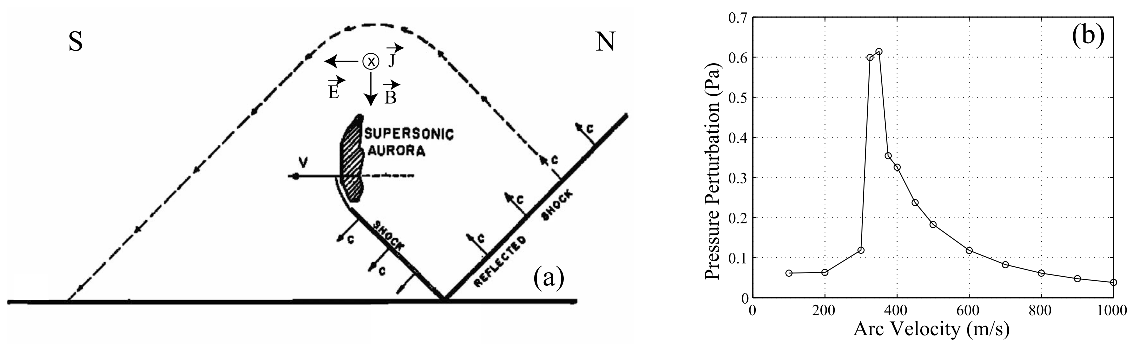

Figure 2. (a) Shock wave model of infrasonic wave generation by supersonic auroras, showing direct shock and reflected shock that is refracted back to the Earth by the thermosphere [*Wilson*, 1969]. This mechanism is further illustrated by modeling results presented in Figure 3. (b) Magnitude of pressure perturbation on the ground as a function of auroral arc velocity.

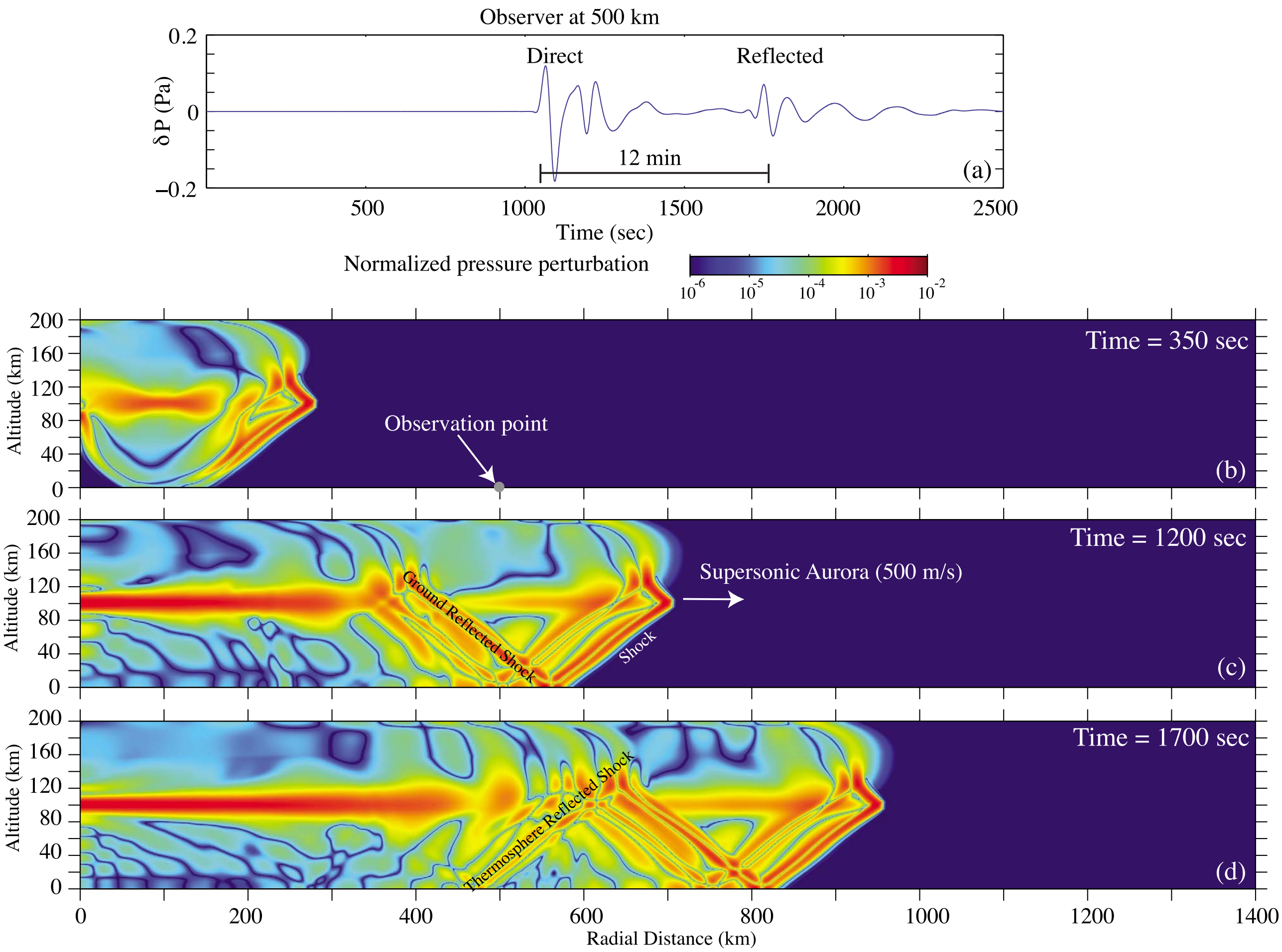

Figure 3. Modeling results on infrasound generated by a supersonic auroral arc moving with velocity 500 m/s. (a) Model pressure perturbation at a ground observational point. (b–d) Two-dimensional distribution of pressure perturbation (normalized as $\frac{p'}{p_0(z)}\sqrt{\frac{p_0(z)}{p_0(z_{\rm ref})}}$, where $z_{\rm ref} = 100$ km) launched by the modeled auroral arc in a cylindrical azimuthally symmetric simulation domain at three instants of time, 350, 1200, and 1700 sec, respectively.

electrons and ions in crossed electric and magnetic fields in the auroral arc can be found in *Wilson* [1972]. The current density $\vec{J}$ is defined mostly by $\vec{E} \times \vec{B}$ drift of electrons and therefore is Westward directed (see schematics in Figure 2a). Its magnitude is $\vec{J} \simeq \vec{J}_e = -q_e n_e \vec{V}_e \simeq 4.85 \times 10^{-4}$ A/m^2, where we assumed plasma density $n_e = n_i = 2.8 \times 10^6$ cm^{-3} [*Wilson et al.*, 1976]. For an auroral arc at 100 km altitude $\nu_{en} \simeq 4 \times 10^4$ s^{-1}, the body force $\vec{F}$ on air is dominated by ion-neutral collisions $\vec{F} = q_e n_e \vec{E} \simeq 2.9 \times 10^{-8}$ N/m^3 and is directed Southward. Having combined expressions provided above the same force can be directly expressed in a form $\vec{F} = \vec{J} \times \vec{B}$ [*Chimonas and Hines*, 1970; *Chimonas and Peltier*, 1970; *Wilson*, 1972; *Swift*, 1973; *Wilson et al.*, 1976], however, it is important to emphasize that physical nature of the force is defined by ion-neutral momentum transfer collisions.

3. Results and Discussion

[9] Figure 3 presents model results for a case when a uniform radially directed body force $\vec{F} = 2.9 \times 10^{-8}$ N/m^3 is assumed to act in an electrojet volume with cross-sectional area 10 km by 10 km at 100 km altitude. The region of body force application is assumed to move with speed 500 m/s representing action of a supersonic auroral arc. We use 'shock' terminology in this figure following original notation by *Wilson* [1967, 1969] (see also Figure 2a). The solutions shown in Figure 3 are linear solutions, which are sufficient for the correct quantitative description of the observed phenomenon. Modeling results shown in Figure 3a closely resemble observational data presented in Figure 1 and discussed above with relationship to Figure 2a. The peak magnitude of the pressure perturbation in this model case is ~0.18 Pa (see Figure 2b).

[10] The pressure perturbation in Figures 3b–3d is shown using logarithmic scale covering four orders of magnitude. In addition to acoustic/infrasound signatures the application of the moving source considered in the present work leads to broadband excitation of gravity waves propagating through the simulation domain and populating stratospheric and lower thermosphere ducts [e.g., *Snively and Pasko*, 2008], as well as to formation of quasi-static perturbations of density ρ' and pressure ρ' arising from balance of gravity and pressure gradient forces (i.e., $\rho' g = -\partial p'/\partial z$, where z is vertical coordinate and g gravitational acceleration). The related structures are visible in Figures 3b–3d after the passage of the main perturbation.

[11] Figure 2b provides a summary of simulations similar to those shown in Figure 3 in terms of peak magnitude of pressure perturbation observed on the ground as a function of auroral arc velocity. The pressure perturbation peaks around ~300 m/s when arc velocity becomes synchronized with local speed of sound c_s at 100 ± 5 km altitude [*Sutherland and Bass*, 2004]. The synchronization condition means that body force acts on the same phase of the acoustic wave being excited by the auroral arc and therefore allows very efficient energy exchange between body force and the wave. Our results are broadly consistent with previous conclusions by *Swift* [1973]. It is shown in *Swift* [1973] that unless the subsonic electrojet is moving at speeds very close to the speed of sound, the frequency components generated would be so low that the wave would be unobservable. Supersonic electrojets will generate enough high-frequency components to be observable over a wide range of speeds, but with diminishing amplitude as the speed increases above the sonic speed [*Swift*, 1973].

[12] One of the interesting aspects of infrasound waves generated by supersonic auroral arcs is that they are never observed propagating in a poleward direction, and it was generally established that even highly supersonic poleward motions of arcs with strong electrojets do not produce infrasonic bow waves [e.g., *Wilson*, 1972]. Statistical studies indicate that auroral infrasound waves are observed at College, Alaska only from directions that are eastward or westward parallel to the auroral oval in the morning and evening sectors or equatorward transverse to the oval in the midnight sector, but never poleward [*Wilson*, 1975]. The Lorentz force and Joule heat are usually discussed in the existing literature as primary sources producing infrasound waves associated with an auroral electrojet [*Chimonas and Hines*, 1970; *Chimonas and Peltier*, 1970; *Wilson*, 1972; *Swift*, 1973; *Wilson et al.*, 1976; *Chimonas*, 1977; *Brekke*, 1979]. Although in original work [*Wilson*, 1967] used a terminology of shock wave, it is generally understood now that the observed waveforms can be generated by a relatively weak body force providing a linear excitation [e.g., *Swift*, 1973].

[13] *Chimonas* [1977] argued that visual similarities of the arcs in no way guarantee a similarity of their electrojets and indicated that arcs which produce infrasound belong to a special class in which the electrojet current is of unusually concentrated nature. *Wilson et al.* [1976] reported estimated current of electroject moving with speed 500 m/s at 100 km altitude to be 2.8×10^5 A. Assuming that this current flows in electroject volume with relatively small cross section 10 km $\times$10 km we can estimate the magnitude of body force on neutral air in electrojet volume due to the Lorentz force $\vec{J} \times \vec{B}$ to be $\sim 10^{-7}$ N/m^3. As demonstrated by the results of the present work shown above depending on auroral arc velocity a factor of 3–10 smaller body force is fully sufficient to produce 0.1 Pa peak to peak (1 dynes/cm^2) pressure perturbation on the ground in good agreement with the average observed 0.2 Pa (2 dynes/cm^2) [*Wilson*, 1969]. We note that the total current corresponding to $J_e \simeq 4.85 \times 10^{-4}$ A/m^2 estimated in the previous section is 4.85×10^4 A, that is significantly lower than 2.8×10^5 A.

[14] We note that although the modeling we present allows straightforward reproduction of experimental data in terms of magnitudes and time structuring of complex waveforms observed on the ground, the mechanisms described in the present work do not explain why poleward supersonic motions of auroral arcs do not produce detectable infrasound signatures [e.g., *Wilson*, 1975]. The magnitude of model pressure perturbations is sensitive to the magnitude of the body force and the velocity of auroral arc, but is not sensitive to the direction of the auroral arc motion.

4. Conclusions

[15] The principal results and contributions, which follow from studies presented in this paper, can be summarized as follows:

[16] 1. 2-D FDTD modeling of infrasound generation and propagation in atmosphere in association with supersonic auroral arcs has been conducted. The attenuation is described using a decomposition technique proposed by *de Groot-Hedlin* [2008].

[17] 2. A body force $\vec{F} = q_e n_e \vec{E} \simeq 2.9 \times 10^{-8}$ N/m^3 acting in the electrojet volume with cross-sectional area 10 km by 10 km at 100 km altitude is sufficient to produce the observed pressure perturbations on the ground ~0.2 Pa (2 dynes/cm^2). The body force arises due to momentum transfer collisions between ions and air molecules and depends on plasma density $n_e = n_i = 2.8\times 10^{-6}$ cm^{-3} [*Wilson et al.*, 1976] and applied electric field $\vec{E} \simeq 65$ mV/m [e.g., *Wilson*, 1972].

[18] 3. Quantitative modeling results are reported on complex infrasonic waveforms generated by supersonic auroral arcs that include direct and reflected waves, which are refracted back to the earth by the thermosphere [*Wilson*, 1969].

[19] 4. In agreement with *Swift* [1973] it is quantitatively demonstrated that the synchronization of the speed of auroral arc and phase speed of the acoustic wave in the electrojet volume is an important condition for generation of magnitudes and frequency contents of infrasonic waves observable on the ground.

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