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Infrasonic Observations of Thunderstorms at High Latitudes: Time Scales

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Abstract

The present work summarizes the results of infrasonic observations of thunderstorms recorded by the Swedish-Finnish Infrasound Network (SIN). A lightning in the atmosphere is a source of cylindrical shock waves. When the distance from the source increases, more and more energy is transferred into the low-frequency range through the same mechanism as for shock waves from supersonic aircraft. It is difficult to estimate maximal distances at which infrasound from a single lightning may be detected. It is, however, clear that distances between the SIN arrays (250 – 600 km) are, in most cases, too large in order to identify the same individual lightning from at least two arrays. During the summer of 2006, at few occasions, the same thunderstorm cell, and even the same lightning, could be observed by two arrays. That means that intense lightning may be, during favourable meteorological conditions, observed at distances up to 300 km. The infrasonic data may be used to determine the angular extent of the discharge, as seen by the array, its radial extent (in kilometres) and its acoustical intensity. Frequently, semi-regular sequences of lightning with similar orientation and nearly constant repetition frequency are observed. For that reason the spectrum of time delays between individual strokes is studied. It has been found that the apparent random occurrence of strokes seems be a result of superposition of several processes with slowly varying time scales.

The Swedish-Finnish Infrasound Network (SIN)

The Swedish Institute of Space Physics operates, since the beginning of 1970:ies, four infrasound stations: Kiruna, Jämtön, Lycksele and Uppsala (see Table 1). In October 2006 the Uppsala station was moved to Sodankylä in Northern Finland.
All original time series collected since 1994 are stored in a data base accessible to the general public at the Internet home page of the Swedish Institute of Space Physics together with all standard software needed for data analysis. Each station consists of a tripartite microphone array located in the corners of an isosceles triangle, oriented in the NS-EW directions. Microphones used in the network are unique, high sensitivity Lidström-microphones, manufactured in Sweden. The time series from all three microphones are stored in a compressed binary format, in 30-minutes files. The recording equipment covers the frequency range 0.5 – 9 Hz.

Name	Latitude (Degrees)	Longitude (Degrees)
Kiruna	67.8°N	20.4°E
Sodankylä	67.42°N	26.39°E
Jamton	65.87°N	22.51°E
Lycksele	64.61°N	18.71°E
Uppsala (until Oct. 2006)	59.85°N	17.61°E

Table 1: Stations in the Swedish-Finnish Infrasound Network (SIN).

Infrasound from thunderstorms

A lightning in the atmosphere acts like a source of cylindrical shock waves. When the distance from the source increases, more and more energy is transferred into the low-frequency range through the same mechanism as for shock waves from supersonic aircraft. The overview display presented on the SIN home page, showing the angle-of-arrival and the horizontal trace velocity of incoming infrasonic signals, may be used to view the development and movement of thunderstorm cells around each array, typically within a 100 km radius. On an example showing an angle-of-arrival *vs.* time graph, three thunderstorm cells passing by the Kiruna-array are shown.

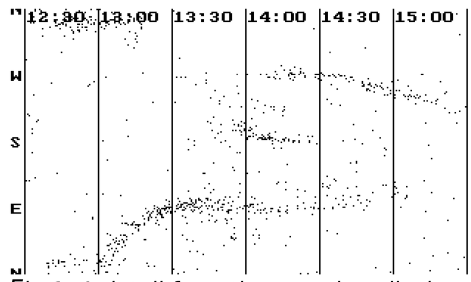

Fig 1: A detail from the overview display presented on the SIN home page for the Kiruna-array on July 8, 2005. The horizontal axis shows the UT (30-minute vertical marks) and the vertical axis shows the angle-of-arrival of infrasonic signals. A signal from each single lightning is shown as a dark dot. Three individual thunderstorm cells may be seen moving by the array (diffuse dark bands).

High resolution analysis

In order to study the fine structure of individual signals, a high-resolution presentation has to be used. A small fraction of the period shown in Fig. 1, shortly before 1400UT, is shown in Fig. 2. Accumulations of points on the upper graph correspond to signals from distant flashes: short in time and limited in azimuth which correspond to cloud-to-ground (CG) flashes, while signals extended in time, and often in azimuth probably correspond to intra-cloud (IC) flashes or CG flashes with substantial horizontal extents. IC flashes can produce spectacular infrasonic signals, often longer than 30 seconds. The longest observed infrasonic signal from a single flash lasted for 78 seconds! These long-duration signals may be easily distinguished on infrasonic recordings.
Sloping long-duration traces, as the first two IC-traces in Fig. 2, correspond to flashes more or less perpendicular to the line-of-sight from the array.

When the line-of-sight from the array coincides with the direction of the discharge channel, horizontal traces, as the third IC trace in Fig 2, are observed.

When the thunderstorm cell, characterized by a high flash frequency, is located far from the array and differences between angle-of-arrival from individual flashes no longer may be seen, the cell appears on recordings as a single, continuous, source of infrasound.

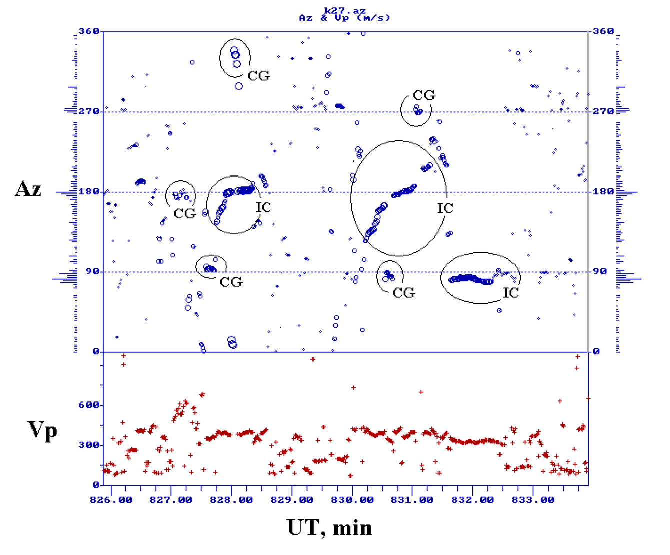

Fig 2: High-resolution recording of infrasonic signals at the Kiruna-array between 1346 and 1354 UT. The upper graph shows the angle-of-arrival of infrasonic signals, the lower one shows the horizontal trace velocity. The size of the symbols on the upper graph is proportional to the cross-correlation across the array. Infrasonic signals from CG and IC flashes are encircled.

Examples of infrasonic long-duration traces

During the final part of a thunderstorm sequences of similar infrasonic long-duration traces are often observed. An example of sloping long-duration traces is shown in Fig. 3. Each sloping trace corresponds to a flash stretching over a wide range of azimuths.

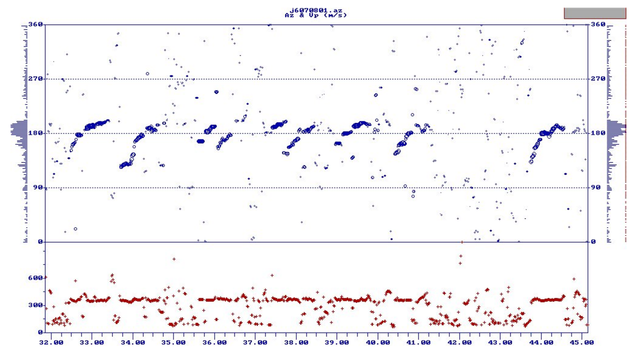

Fig 3: A sequence of long-duration infrasonic signals, probably from IC flashes, directed, more or less, across the line-of-sight from the array (July 8, 2006, Jämtön-array). The time axis starts at 00:32 UT.

Time scales of the discharge process

The semi-periodic character of lightning discharges indicates the existence of regions in the atmosphere where the recovery of the electric field is stable. In the simplest case there would be a constant speed of recovery, resulting in flashes with a constant repetition frequency/time scale. It has been found in the present study that time scales may be easy to study using the time series of the average cross-correlation (or the product of all three cross-correlation coefficients between microphones in the array), a variable, which is closely related to the signal-to-noise ratio. The variable includes signals arriving from all directions.

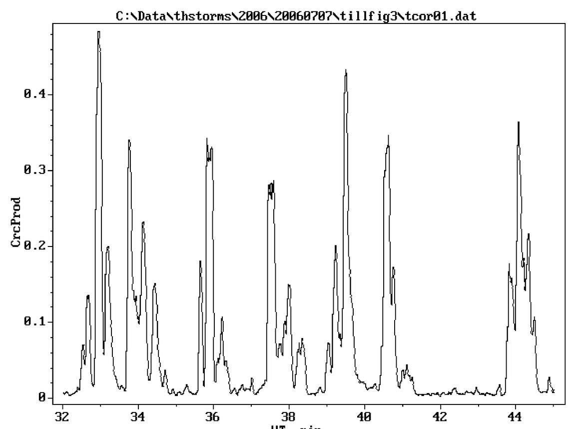

Fig 4: The cross-correlation product across the array during the same sequence of lightning as shown in Fig. 3.

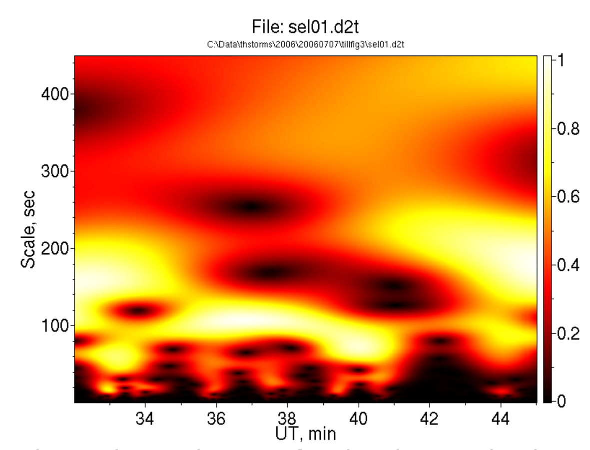

Fig 5: The scalogram for the time series in Fig. 4. The X-axis represents the time along the time series in minutes UT, the Y-axis shows the time scale in seconds, while the color of the graph represents the wavelet coefficient magnitude.

The procedure of estimating the time scales is illustrated for the sequence of flashes shown in Fig. 3. The time series of the cross-correlation product is shown in Fig. 4.
The time series is analysed using the Morlet-wavelet and a spectrum of the time scales (a scalogram) is obtained. The scalogram for the actual time series is shown in Fig. 5. The X-axis represents the time along the time series in minutes UT, the Y-axis shows the time scale in seconds, while the color on the graph represents the wavelet coefficient magnitude.

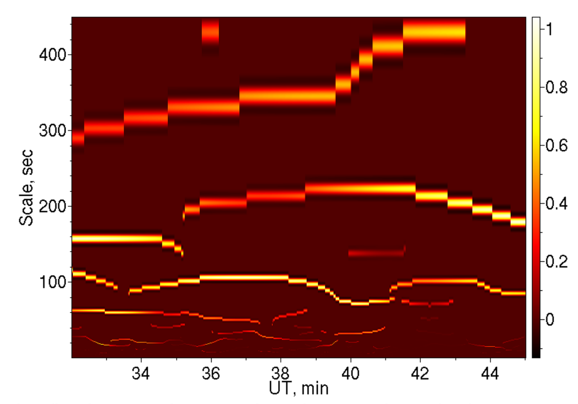

Fig 6:The scale maximal wavelet skeleton spectrum derived from the scalogram of Fig. 4

The scalogram may be converted into a wavelet skeleton spectrum. There are two kinds of wavelet skeleton spectra. The scale maximal wavelet skeleton spectrum keeps only those wavelet components that are locally of maximum amplitude at any given time-scale. The instantly maximal wavelet skeleton spectrum keeps only those wavelet components that are locally of maximum amplitude at any given time. The scale maximal wavelet skeleton spectrum derived from the scalogram of Fig. 5 is shown in Fig. 6.
When comparing Figs. 5 and 6 it is obvious that, using the wavelet skeleton, it is easier to see individual time scales involved in the process and their temporal variations. Values of local maxima are represented by the color scale. The dominating repetition frequency of flashes (~1 per 100 seconds), which may be seen in Fig.3, is clearly visible as the most intense line oscillating around the time scale of 100 seconds. It may be seen that the repetition frequency of flashes seems to be controlled by a few independent processes, represented by lines in the upper part of the wavelet skeleton spectrum (above 80 seconds). The weaker lines in the lower part of the spectrum represent, most likely, the duration of infrasonic signals from flashes and their modulation.
It is not clear what causes the modulation of the cross-correlation of infrasonic signals across the array. The modulation, visible on most of individual traces of the azimuth plot (Fig. 3), is even clearer in Fig. 4. The time scale of that modulation is usually of the order of 10-20 seconds, which may be seen in Fig. 6. For that reason, the modulation is visible only on the long-duration traces from IC flashes. The modulation may be a propagation effect, or a result of geometry of the infrasound-generating discharge channel.

Time scales in thunderstorm cells

When a thunderstorm cell, like one of those visible in Fig. 1, passes by the infrasound array, the dominating time scales may be studied. The infrasound data are divided, as a standard, into 30-minute files and processed.
Two cases recorded at the Lycksele-array are shown:
1. 3.5 hours sequence of July 9, 1998 14:00 – 17:39 UT
2. 2 hours sequence of August 10, 2002 17:00 – 19:00 UT

The results of the analysis of both sequences are displayed in the Appendix.
The uppermost series of graphs shows plots of the angle-of-arrival. The middle series of graphs shows the product of all three cross-correlation coefficients in the array. The lowermost series of graphs shows the spectrum of wavelet skeletons corresponding to the dominating time scales in the sequence of infrasonic signals from individual flashes.

Case 1.
During this sequence it is possible to distinguish at least 5 thunderstorm cells in the SE-sector (90 - 180°) and 3 cells around N (315 - 20°). It may be seen on the angle-of-arrival graphs that thunderstorm cells visible on the southern sky are moving towards the East, while the cells on the northern sky do not show any clear movements, probably being more distant. The lightning map for that day (http://www.wetterzentrale.de/topkarten/fsbeobl.html) shows that the thunderstorm activity covered a large part of Middle and Northern Sweden, see Fig. 7.
The wavelet skeleton spectra shown in the bottom set of graphs show that there are a few dominating time scales, which vary during the period of observation. The superposition of these time scales produces the apparent semi-regular sequences of flashes. It is not clear what the cause is of these varying time scales. These specific combinations of time scales may be connected with individual thunderstorm cells. However, the sequence of storm cells in Case 1 is very complicated and it is not possible to connect the individual storm cells with particular time scales.

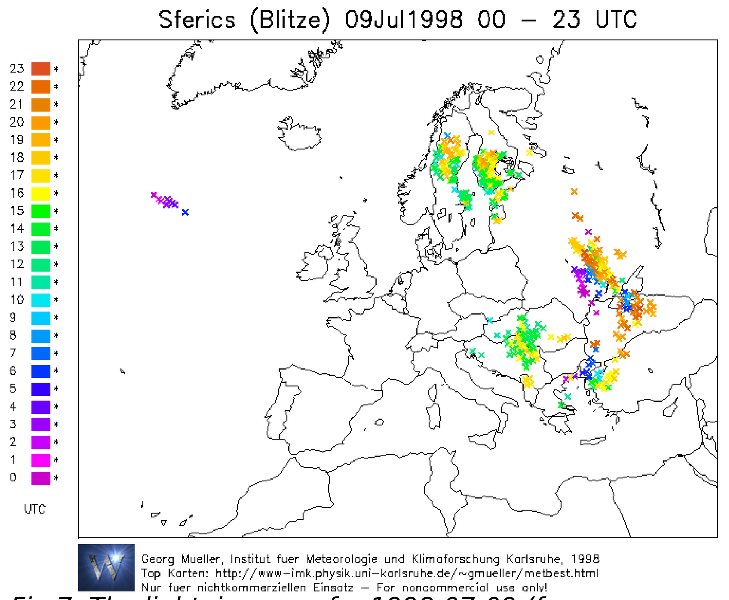

Fig 7: The lightning map for 1998-07-09 (from http://www.wetterzentrale.de/topkarten/fsbeobl.html)

Case 2.
During this sequence there are most likely only two thunderstorm cells: one close in the northern sky and one, distant, in the southern sky, lasting for approximately 85 minutes.
Within the first cell, infrasonic signals from individual flashes may be easily distinguished. Isolated flashes from the NE-sector of the sky are visible during the entire observation period.

The second, distant cell is characterized by a large number of flashes, which coalesce into a single infrasonic source.
The lightning-map for that day (see Fig. 8) shows a concentration of lightning SW of the Lycksele-array during the actual afternoon and also isolated flashes over a large part of Northern Sweden.

The wavelet skeleton spectra shown as the bottom set of the graphs of the Appendix, indicate, the same range of time scales as those observed in Case 1. It may be seen that the second cell is dominated by the time scale oscillating around 100 seconds, while the first cell shows a longer dominating time scale (150 – 220 seconds).

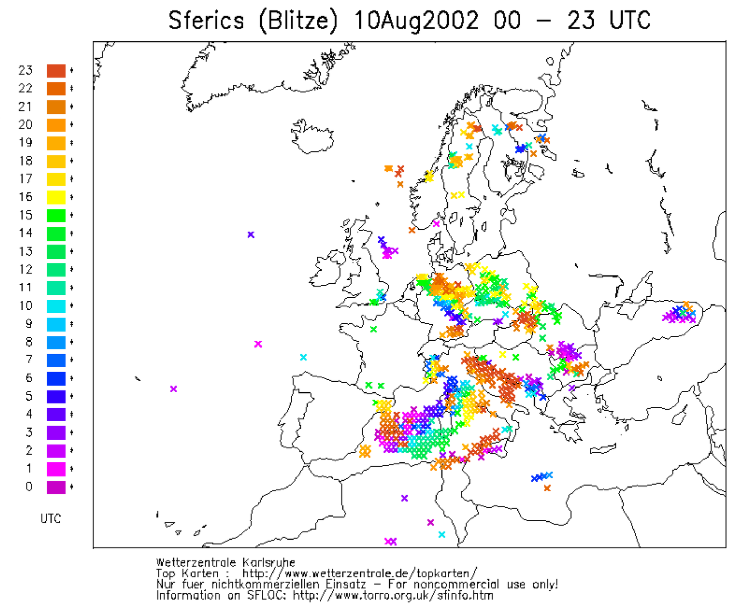

Fig 8: The lightning map for 2002-08-10 (from http://www.wetterzentrale.de/topkarten/fsbeobl.html)

Conclusion

It is plausible to assume that the repetition frequency of flashes in a thunderstorm cell must be controlled by a process restoring the cell's electric field. However, it is not clear how much of the flash frequency, observed with the infrasound, is influenced by the propagation of infrasound. A comparison of electromagnetic and infrasonic measurements would be needed to resolve this uncertainty.

Appendix; Analysis of infrasonic observations of two sequences of thunderstorm cells

Case 1.

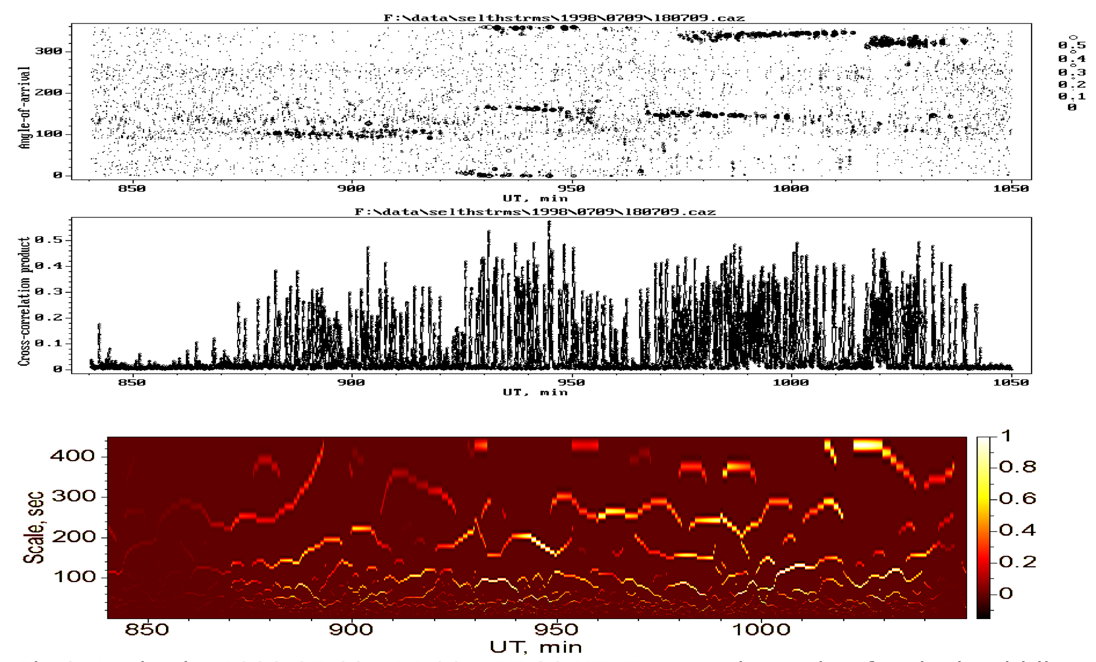

Fig 9: Lycksele, 1998-07-09 14:00 – 17:30 UT. Top graph: angle-of-arrival, middle graph: cross-correlation product, bottom graph: dominating time scales (wavelet skeleton spectrum).

Case 2.

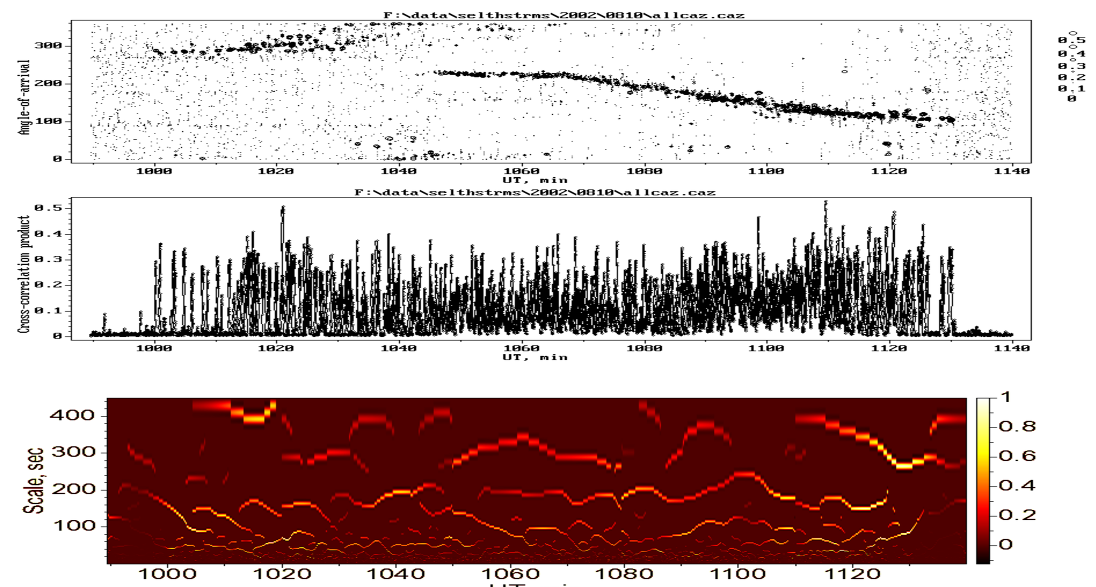

Fig 10: Lycksele, 2002-08-10 16:30 – 19:00 UT. Top graph: angle-of-arrival, middle graph: cross-correlation product, bottom graph: dominating time scales (wavelet skeleton spectrum)