Infrasound Signals Measured with Absolute Nano-Resolution Barometers

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Abstract:

Two absolute-pressure Digiquartz® Nano-Resolution Barometers (Model 6000-16B) were co-located at the international infrasound monitoring station IS30 in Isumi, Chiba prefecture, near Tokyo. A third sensor measured ambient pressure in the vault. The sensor noise floor spectrum was approximately 10^{-7} Pa^2/Hz over the infrasound range. Ocean-generated small microbarom signals were measured with amplitudes of 0.1 Pa and a sensitivity of 0.0003 Pa. On 3 October 2009, a massive explosion of Sakurajima Volcano provided a large natural infrasound signal that was measured at IS30.

Fig 1: Sakurajima Volcano in south-west Japan is in Kagoshima prefecture on Kyushu Island [1]. The international infrasound monitoring station IS30 is located near Tokyo almost 1000 km away.

Experimental Setup

The Japanese Weather Association (JWA Group) installed two Digiquartz® Nano-Resolution Barometers (Model 6000-16B) in one of the vaults of the IS30 infrasound station at Isumi in Chiba prefecture near Tokyo (the installation is part of the Comprehensive Nuclear Test Ban Treaty CTBT). Both sensors shared a common pressure manifold consisting of 10 meter long crossed pipes leading to the outside in a forested park. The pipes served as a spatial filter with four inlets, however, since wind was not a factor on the day of the volcano explosion, the exact arrangement of the pressure ports was not critical. It is possible to simply connect the barometers to an existing rosette spatial filter or to a wind-insensitive DigiPort supplied by Paroscientific, Inc.

The barometers were equipped with independent interface boards that include frequency counters with temperature-compensated counter clocks, and serial communication links to a computer. The boards also included the latest version of nano-resolution digital signal processing described elsewhere [2]. For these tests, the IIR (infinite impulse response) filter was used. The filter algorithm operates on fast subsamples which are measured at a nominal 8 kHz rate. The filter settings can be chosen by software commands. For these tests, the filter was a five-stage low-pass filter set with a cutoff frequency of 1.4 Hz (internal setting parameter IA=10). The pressure sensitivity at the chosen setting is 0.5 mPa, or 28 dB re 20 µPa (sound level).

The data stream was generated with a software command trigger at exactly 20 Hz, controlled by GPS time. In the fetch mode the sensor responds within a window of 0.125 ms after receipt of the software trigger. It is possible to synchronize two independent barometers to the intrinsic response time.

The data was collected by data acquisition software on portable computers running under the Linux operating system. The data was organized in hourly files labeled with Universal Time. The recorded data was in the format

mm:ss.000000 (resolution microseconds) 1013.1234567 (hPa with a resolution of 0.01 mPa)

Eruption of Sakurajima Volcano on 3 October 2009 7:45 UTC

Sakurajima [4] is an active stratovolcano with very explosive eruptions. The 1914 eruption was the most powerful in twentieth-century Japan with a large lava flow that lowered the surrounding caldera by a couple of feet. The volcanic activity increased again in 1955 on the southern peak (Minamidake crater). Each year there are many small explosions with ash columns rising to a few kilometers. The ash plume of the eruption on 3 October 2009 was reported by the Volcanic Ash Advisory Center (Tokyo VAAC). At a distance of 4 km from the crater there is a volcano observatory that monitors the eruptions which is important to the residents of a nearby large city, Kagoshima. Mobile infrasound monitoring stations using nano-resolution barometers could be part of the monitoring setup. In the vicinity of the volcano, the pressure wave amplitudes can be very large, so the wide pressure range of absolute barometers can be an advantage over infrasonic differential microphones with limited range.

Sakurajima erupted just a few days after installing the nano-resolution barometers. The eruption started at 7:45 UTC on 3 October 2009. At the speed of sound it took 48 minutes to reach the sensors which were located 987 km away. The propagation of infrasonic sound waves is complex and depends on the temperature profile of the atmosphere and wind distribution. A good introduction to the topic is given by J.B. Johnson in the Journal of Volcanology, Vol. 121 (2003) [5]. Our measurement of the infrasonic wave was only a single-station capture about 1000 km from the epicenter of the explosion. In the future it would be very interesting to establish an array of stationary or mobile sensors to study the propagation more closely.

Fig 2: Sakurajima Volcano erupted 3 October 7:45 UTC (Saturday 4:45 pm local time) in the Minamidake Crater. The explosion shook buildings kilometers away; the shock-wave was huge and the sound of the explosion was heard in nearby Kagoshima City. [3]

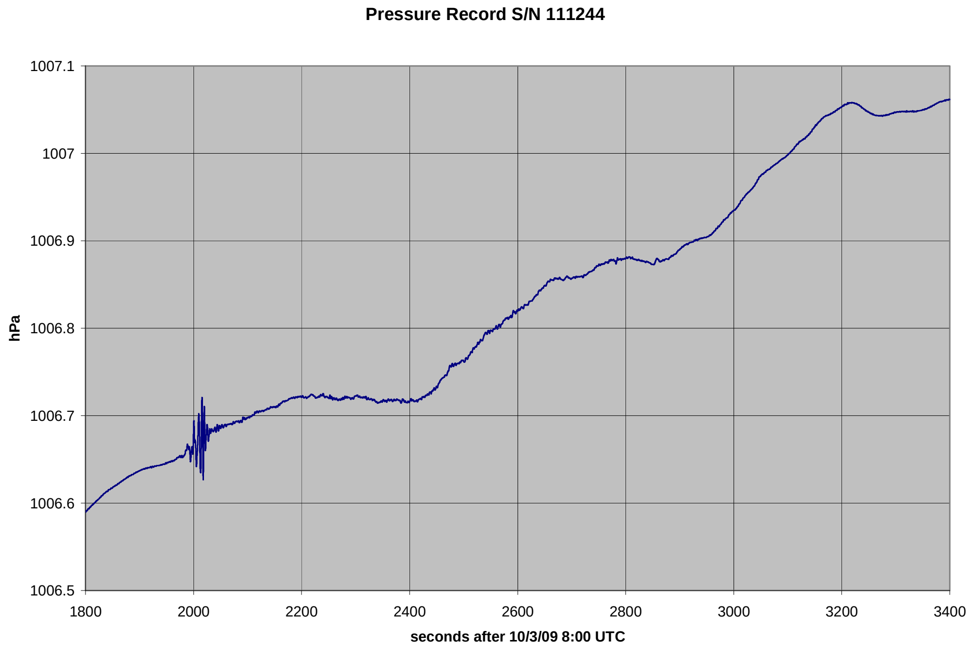

Fig. 3: Pressure recorded for one of two nano-barometers connected to crossed pipes. The recorded pressure is in absolute units of hPa. The volcano signal arrived at 2000 seconds after 8:00 UTC and is visible in the raw pressure record. The atmospheric background signal is very quiet on this particular day.

The recorded pressure is shown in Fig. 3 for one of the two nano-resolution barometers. At the scale shown the pressure time series of the other barometer is identical. The pressure time-series includes all pressure changes pre-filtered below 1.4 Hz to static (0 Hz). If one is interested in particular frequency bands, the data can be additionally filtered. In Fig. 4, a simple single-stage digital high-pass filter was applied at 0.05 Hz (or 20 second period). The vertical scale is shown in Pascal. The main shock wave is visually clipped to show the finer longer-term details. The main shock wave arrived 48 minutes after the eruption and lasted almost 1 minute. Further atmospheric disturbances were measured for another 15 minutes, probably generated by the rising ash plume of the eruption.

Details of the explosion are shown in Fig. 5. Even at this scale, the recordings of the two sensors are identical. Dominant waves are in the infrasonic period range of 4 to 8 seconds.

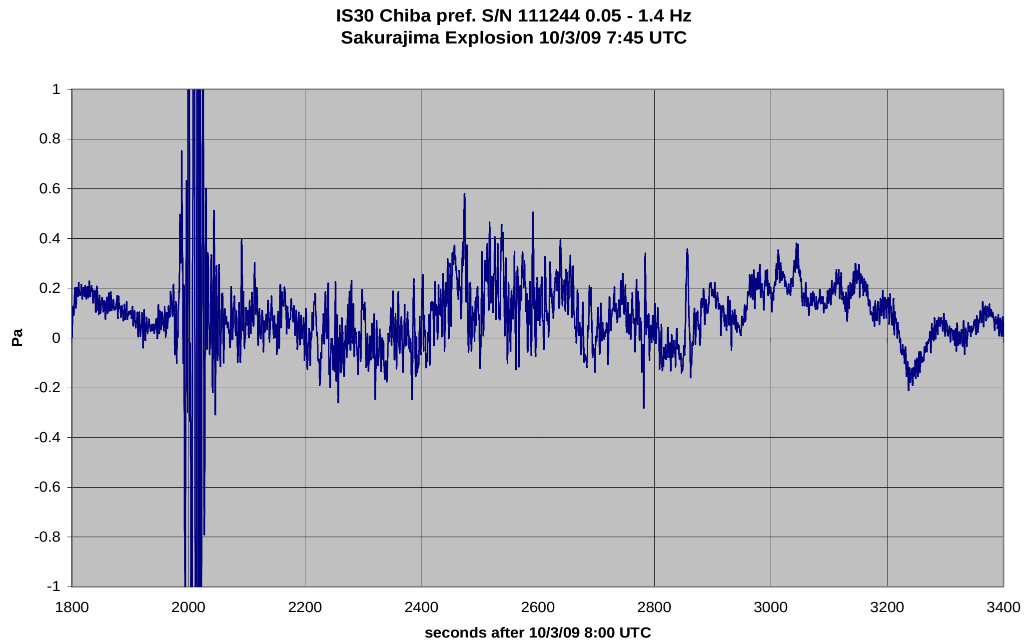

Fig. 4: The pressure data of Fig. 2 high-pass filtered at 0.05 Hz. The infrasound signals from the eruption lasted until 8:50 UTC. Prior to the shock wave and to the far right, the infrasonic background largely consists of microbaroms, generated by standing ocean waves with typical excursions of 0.1 Pa at 0.2 Hz.

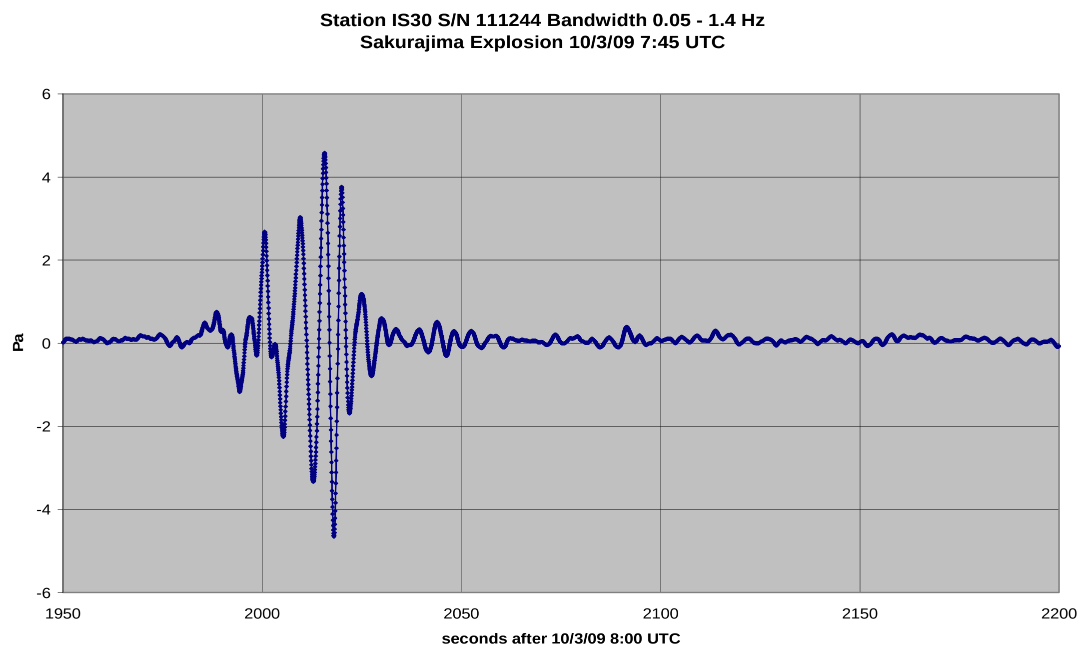

Fig. 5: Detail of Fig. 4. The main shock wave reached the station at 8:33 UTC (48 minutes after the explosion). The wave was dispersed over almost a minute because of different frequency-dependent propagation velocities in the atmosphere, followed by 15 minutes of smaller infrasonic signals. The spacing of data-points (dots) is 50 ms.

Sound Levels

In comparison with audible sound pressure levels (SPL), excess pressure amplitudes (ΔP) can be converted to dB (decibel) relative to 20 μPa.

$SPL = 20 \log (\Delta P/0.00002)$

The measured excess pressure at 987 km from the volcano was 5 Pa (see Fig. 5). The sound level at the sensor location was therefore 108 dB. The sensitivity of the sensor at the chosen filter settings IA=10 is 0.5 mPa or 28 dB. The signal-to-noise level (relative to sensor sensitivity) is 80 dB (10,000 to 1).

Assuming a linear decrease of pressure amplitude with distance, the excess pressure reduced to 100 m from the epicenter is nearly 500 hPa! The pressure sound level was therefore 188 dB near the crater. A sound level meter was located at the Kurokami Observatory about 4 km from the crater. The reported pressure amplitude there was 600 Pa, or 182 dB reduced to 100 m from the epicenter (in close agreement with our measurement near Tokyo). Kagoshima City is 8 km from the volcano and the calculated sound levels were 130 dB. Infrasound is inaudible to the human ear, but in the audible acoustic band, such levels would have been at the pain threshold of the human ear. At the Kurokami Observatory, the sound level reached 150 dB, near the ear drum rupture level.

The evaluation of the infrasound sound level is a simple demonstration of how the information from a single infrasound telemetry station can be used to quickly categorize the source event in terms of sound intensity.

Acoustic Energy of the Eruption

The sound of a volcano radiates hemi-spherically at first, and the acoustic energy (E) can be determined from the time-integrated square of the infrasound pressure amplitude [5].

$E = (2 \pi r^2)/(\rho c) \int (\Delta P)^2 dt$

where r is the distance from the crater to the sensor, ρ is the air density (1.19 kg/m3), and c is the sound velocity (343 m/s). This simple calculation would be very useful to quickly categorize in real-time an important parameter of the eruption. To be reasonably accurate, the sensor should be within a distance wherein the sound propagation is hemi-spherical, i.e. within the scale height of the atmosphere, 10 to 15 km. At larger distances, the sound is refracted in a complex way that depends on the wind and temperature profile of the atmosphere. Just to get a feel for magnitudes, the propagation of the sound wave in the hemispherical area $A= 2 \pi r^2$ radiates more like a disk with $A = 2 \pi r h$, where h is the height of the atmosphere. Integrating the excess pressure ΔP in Fig. 5 from 1980 to 2040 seconds after 8:00 UTC, the acoustic energy in the first 1 minute is of order 100 gigajoules, or tens of megawatt-hours. (This rough estimate, however, has not been confirmed by other local observations.)

The estimation of energy is very important to understand such events as asteroid collisions with the earth. Simply, one would like to know how big the asteroid was if the only measurements are infrasound sensors at widely spaced stations[6]. For that reason, complex models of sound propagation have been made that are difficult to test for lack of atmospheric information and lack of infrasound observations. The Sakurajima eruptions present a unique chance to study and improve these models. Specifically, the energy E(r,t) could be measured as a function of distance and time. A reasonable spacing could be 100 km. Such an idea had been suggested earlier in the context of EarthScope, a grid of seismic observatories spaced at 70 km (USArray). The co-location of infrasound sensors and absolute barometers with seismic instrumentation would benefit both the geophysical observations of infrasound events, and enhance the knowledge of how the atmosphere couples to seismic observations. The availability of easy-to-install mobile absolute nano-resolution barometers makes the co-location cost-effective.

Sensor Sensitivity

The experimental setup of two nano-resolution barometers in parallel served an important purpose. From the difference of the two pressure traces, it is possible to determine the synchronization, data quality, accuracy, resolution, and sensitivity of the sensor.

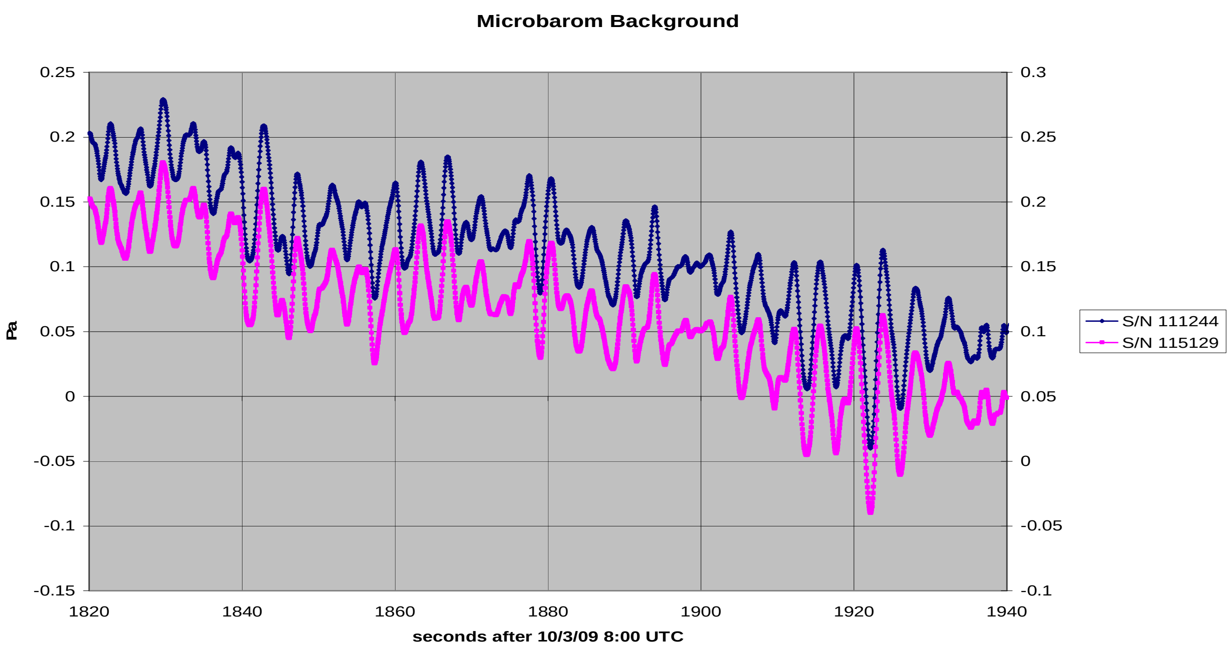

Fig. 6: Typical microbarom background from Fig. 4 just before the volcano sound wave arrived. Sensor 2 (in red) is visually offset by 50 mPa (right vertical axis) to show how well it tracks Sensor 1 (in blue). The amplitudes of the microbaroms vary daily and seasonally. Here they were about 0.1 Pa peak-to-peak (1 microbar – hence the name) with a period of about 5 seconds.

In a separate setup, two nano-resolution barometers were compared at different IIR filter settings. A data set of 100 points was taken at the chosen sampling interval and the pressure differences were calculated. We then plotted the time series of the differences and calculated the standard deviation of the data set. The self-noise of each sensor was evaluated as the standard deviation of the data set divided by the square root of two (assuming that each sensor contributed half of the combined deviation in quadrature). The experimental results were as follows:

IA	Frequency cutoff (Hz)	Sampling interval (ms)	Self-noise per sensor (rms)
7	11	44	7.0 mPa
8	5.5	89	2.4 mPa
9	2.8	178	1.0 mPa
10	1.4	350	0.5 mPa
11	0.7	700	0.3 mPa
12	0.35	1400	0.2 mPa

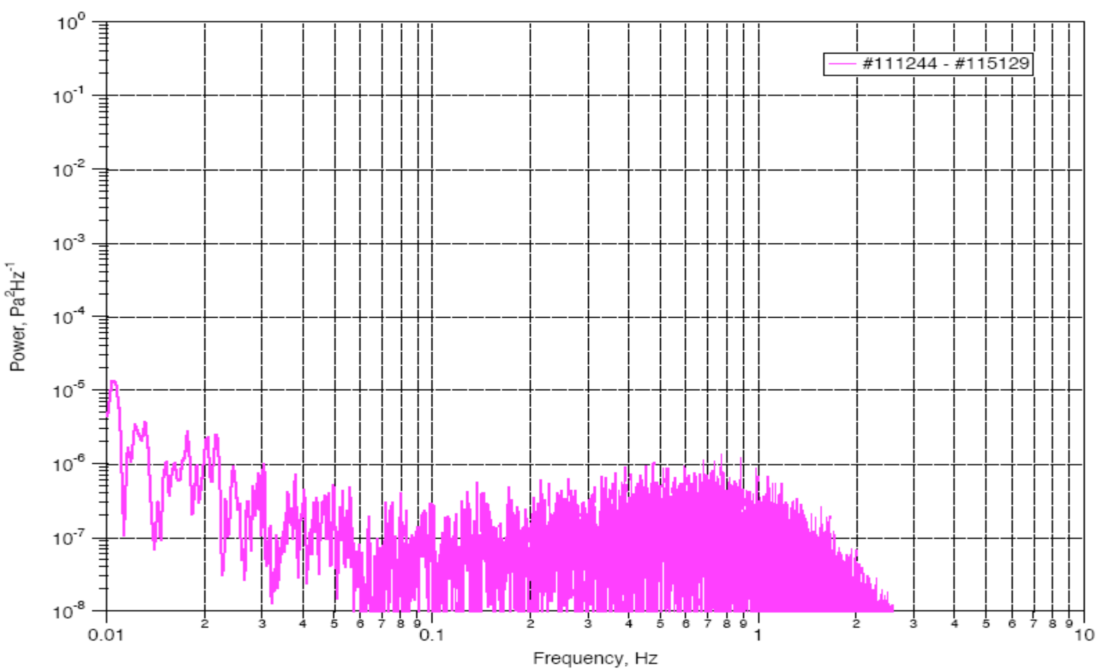

Fig. 7: The uncorrelated noise spectrum between the two nano-resolution barometers provided by the JWA Group. The sensor noise floor spectrum was approximately 10^{-7} Pa^2/Hz over the infrasound range.

Comparison of Results

In the same vault of the monitoring station IS30 was a micro-barometer MB2000 by CEA. This sensor was attached to a pressure manifold that was arranged as a rosette to provide some spatial filtering. The nano-resolution barometers were connected to a separate manifold of crossed pipes, 10 meters in length. The two data streams had slightly different timing and the pre-filtering was different. Specifically, the MB2000 was pre-filtered from 0.01 to 20 Hz and the nano-resolution barometers from 0 to 1.4 Hz. Any comparison is therefore preliminary and should be done under identical conditions. However, as shown below, the comparison within a bandwidth of 0.01 to 1.4 Hz that was common between them was favorable, or, the noise floors of both types of sensors were near or below the ambient background or signal levels. Also, there was little wind during the measurement of the volcano eruption, so the differences between the manifolds were probably not critical.

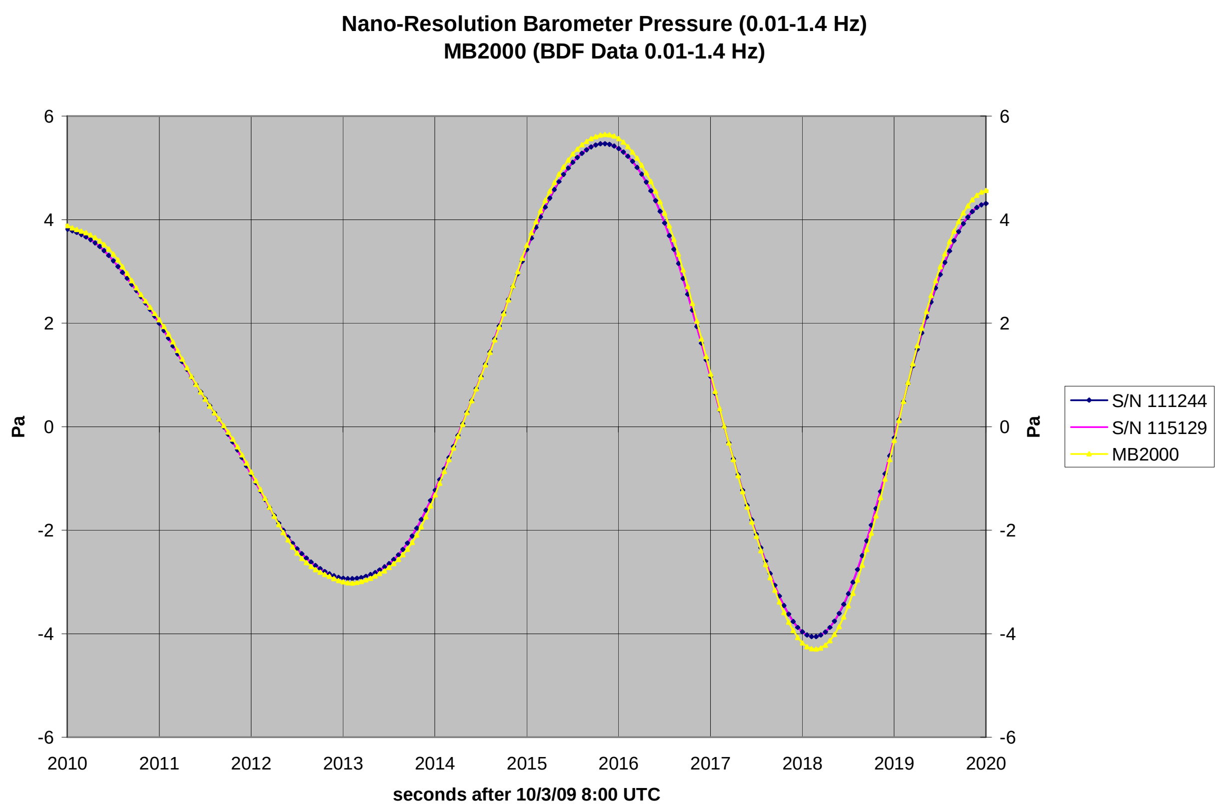

Fig. 8: A comparison of the largest signals recorded after the volcano eruption between two nano-resolution barometers and a micro barometer MB2000. At this scale the nano-resolution barometers track each other perfectly with an NIST traceable scale factor accuracy of 0.01 %. The scale factor of the MB2000 is about 4 % larger.

In Fig. 8 the nano-resolution barometer was high-pass filtered with a single stage at 0.01 Hz and the MB2000 low-pass filtered at 1.4 Hz with 5 stages to make the filtering equivalent.

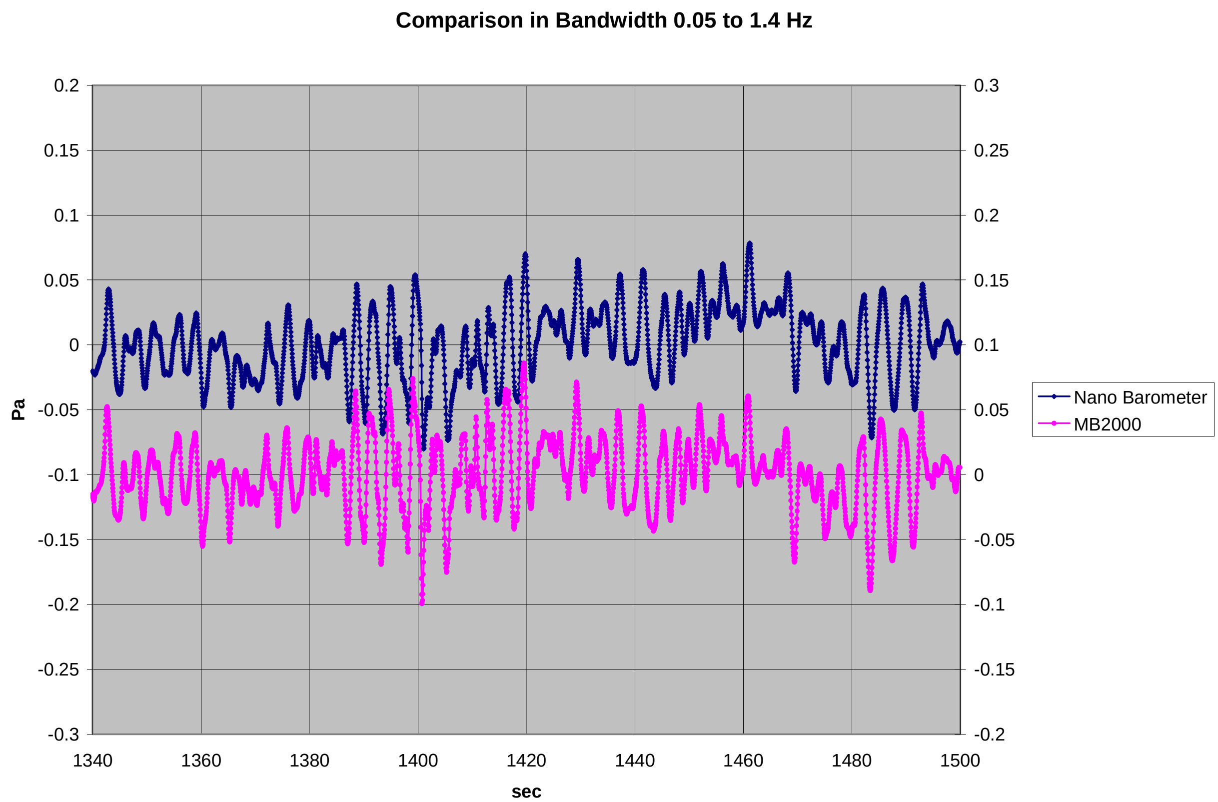

Fig. 9: Typical microbarom background activity measured with a nano-resolution barometer and a micro-barometer MB2000. Both sensors are shown in the bandwidth of 0.05 to 1.4 Hz, but are on different pressure inlets and are pre-filtered differently, so the comparison is not exact. Nevertheless, they track each other well. The comparison of two nano-resolution barometers is shown in Fig. 6.

In Fig. 9, a high-pass filter at 0.05 Hz was applied to the micro barometer in addition to the pre-filter of 0.01 Hz. To make the comparison, the high-pass filter was applied twice to the nano-resolution barometer.

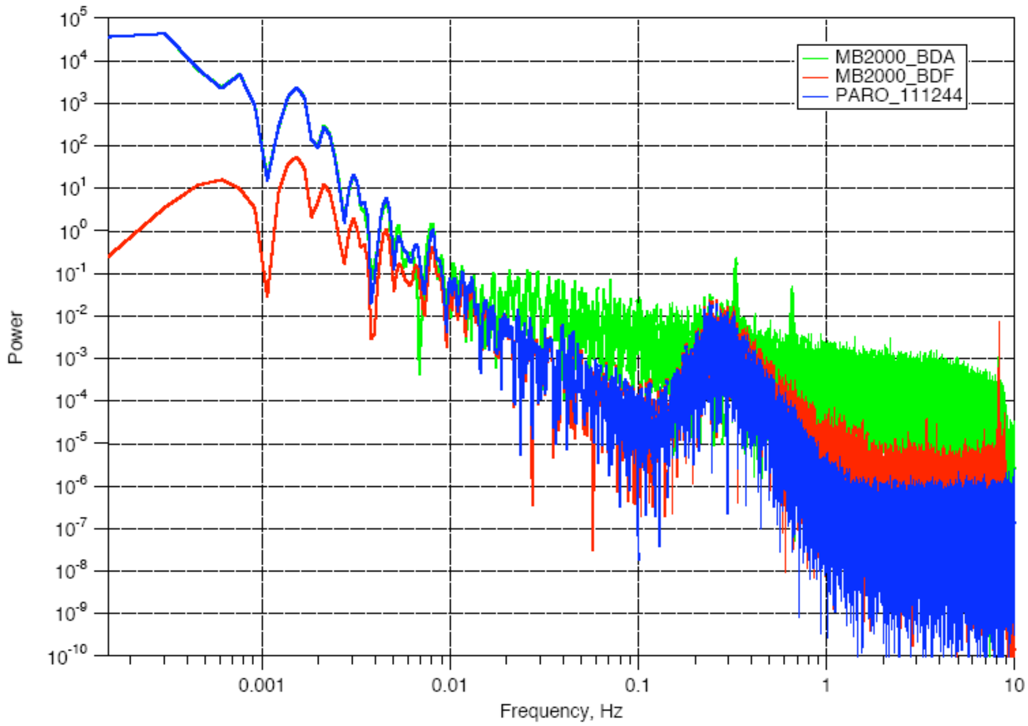

Fig. 10: Spectral comparison of ambient atmospheric background in Pa^2/Hz. The blue curve is a nano-resolution barometer with a low-pass frequency cutoff at 1.4 Hz. The red curve is the MB2000 with a roll-off at 0.01 Hz. Between 0.01 and 1.4 Hz, both sensors should see the same spectral density, however, the MB2000 appears to be noisier around 1 Hz.

In Fig. 10, the JWA Group showed on a frequency spectral density plot that both sensors record typical microbarom activity near 0.2 Hz. The two sensors agree well between 0.01 and 0.3 Hz. The nano-resolution barometer is more sensitive below 0.01 Hz since it records static pressure. The MB2000 either receives more signal background from the rosette filter near 1 Hz or the sensor is noisier. The noise (or background) floor of the MB2000 is above 10^{-5} Pa^2/Hz. The noise (or background) floor of the nano-resolution barometer drops to 10^{-6} Pa^2/Hz near 1 Hz. See Fig. 7 for the sensor self-noise of the nano-resolution barometers.

Conclusions

Infrasound signals ranging from small microbaroms to volcanic eruptions were measured for the first time with absolute nano-resolution barometers.

Digiquartz® Nano-Resolution Barometers are the only **absolute** pressure sensors that can detect infrasonic waves at sound levels specified for nuclear detection. They are suitable for the detection of geophysical and man-made infrasonic events. The Digiquartz® Absolute Nano-Resolution Barometers provide advantages over differential pressure infrasound sensors:

- Large absolute pressure range (500 to 1100 hPa)-(suitable for all barometric measurements including atmospheric noise mitigation for seismometers).
- Low sensor self-noise (less than 0.3 mPa at 1 Hz).
- High bandwidth (from static to a user-settable high-pass frequency cutoff).
- Inherently digital outputs with built-in, anti-aliasing filters.
- High resolution, accuracy and stability (resonant quartz crystal technology).
- Calibrated scale factor (NIST traceable to 0.01 %)-(no need for special dynamic differential calibrators).
- Insensitive to temperature (calibrated from -54 to +60 deg C)-(no pressure reference volume that varies with temperature).
- Insensitive to acceleration, vibration, and orientation (balanced mechanism).
- Easy to interface to DigiPort or spatial filters for reduction of wind noise.
- Easy to interface to data acquisition systems with two-way RS-232 configuration and control.

Acknowledgements

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Fig. 11: Sakurajima Eruption in 1914 [8]

References

1) Map by Volcano Research Center, Earthquake Research Institute, University of Tokyo
2) Theo Schaad, *Nano-Resolution: Oceanic, Atmospheric, and Seismic Sensors with Parts-Per-Billion Resolution*, Doc. No. G8218, Rev. E, 2009, on the Paroscientific, Inc. website. The link is: http://www.paroscientific.com/Nano-Resolution.pdf
3) Picture and comment posted by bionicbong.com
4) Wikipedia
5) J.B. Johnson, *Generation and propagation of infrasonic airwaves from volcanic explosions*, Journal of Volcanology and Geothermal Research 121 (2003) 1-14.
6) A recent event was an explosion of an asteroid on 8 October 2009 over Sulawesi, Indonesia. Energy of 50 kton TNT equivalent and a size of 10 m across were estimated from infrasound measurements at international monitoring stations as far as 10,000 km away.
7) T. Murayama et al, *A development of the low-cost infrasound monitoring system – Trial observation of a digital quartz resonator sensor*, FINATEC Infrasound Technology Workshop 2009
8) Nationaal Archief Den Haag posted on the Commons on Flickr