High Resolution Temperature Measurement

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Abstract
We have developed a high resolution temperature measurement system, able to measure down to 0.1 mºC, inexpensive and easily portable. We propose a measurement based on thermistors fed with an ac signal to have a better signal to noise ratio and comparing two different configurations: absolute and differential measurements. It works either in a volumetric or surface environment, for non-invasive temperature determination. As an application, we have measure temperature fluctuations in the body skin, on different arteries, and we have extracted the heart rate from the recorded temperature pattern. We have achieved a good signal to noise ratio in both configurations and using different types of thermistors. Wide range of application possibilities, from biomedical to aerospatial measurements, are possible with this system.

Keywords
Thermistor, temperature measurement, heart rate.

INTRODUCTION
High resolution temperature measurements are required in many fields, from aerospatial to bioengineering research [1,2]. However, present equipments able to measure temperatures down to 1 mºC are non-portable (and thus, not convenient for ambulatory measurements) and have a high cost (usually around 4000 $) [3].

With respect to body temperature measurement, the measurement of skin temperature is still a challenging issue. On the one hand, skin temperature is directly connected to the body metabolism [4,5] but the exact correlation between the body and skin temperature is not well established [8]. While the use of the mercury thermometer is reliable and repetitive but fragile and slow, electronic thermometers based on thermistors or infrared detection are faster and more reliable but at the cost of exactitude and precision [6].

Another interesting issue is the measurement of temperature fluctuations if they can be related to the fluctuation of another magnitude whose characterization is less accessible. This is particularly interesting in ambulatory measurement of human physiological parameters: if skin temperature fluctuations could be measured with high resolution, other parameters could be extracted. Dupuis et al. [7] suggest the possibility to measure the heart beat and breath rhythm after blood fluctuations. Further investigations on differential measurements correlate temperature fluctuations with allergies and skin reactions [8]. Other studies based on infrared cameras also relate skin temperature fluctuations with different diseases [9,10] or with nervous reactions or *stress* [11].

Heart beat is usually measured by means of the Electrocardiograms (ECG) or pulsemeters. Using ECG, three electrodes are required to infer the cardiac frequency by means of temporal series. This system is not convenient for ambulatory or long term measurements due to the incommodity that represents on the patients along with the degradation of the electrodes with time. Accelerometers can be also used to measure the heart rate [12]. They are based in the detection of the mechanical variation induced by the pulse but at the same time are very sensitive to movement artifacts. Commercial pulsemeters are also based on an optical sensors, which detect position changes after light deviations [13].

The purpose of this work is to design a non-invasive system able to measure the temperature difference between the artery blood temperature and its environment on the skin using thermistors. We infer the heart beat from these fluctuations. The detection system must have a good signal to noise ration to detect a signal of hundreds of mV, it must be comfortable for ambulatory and long term measurements and must have a low consume and low cost for ambulatory purposes.

MATERIALS & METHODS

Requirements

The purpose of the work is to achieve a system able to measure temperature fluctuations of about 0.1 mºC in the range 29 ºC - 33 ºC. This implies a dynamic range well above 100 dB. The bandwidth of the whole system has to resolve the cardiac rhythm in the range 0.1 Hz - 4 Hz. Thermistors and acquisition system have been selected to meet these specifications. We present three different thermistors and analyze two different circuits to achieve these requirements.

Thermistor description and setup

We used three different types of thermistors: NTC Betatherm ref. 30K6A1A, Omega On 909-44004 and NCP 15XH103J03RC (depicted in Fig. 1). Manufacturer specifications are given in table 1. Omega thermistors are specially designed for surface measurements. Their were provided with wire contacts, which were isolated with plastic film. To carry on the measurements on the skin, thermistors were attached on a cardboard holder. SMD thermistors were soldered on a board with wire rap AWG30. Contacts were electrically isolated with a coating film to avoid that the contact with skin acted as a parallel resistance and wire was thermally isolated to avoid thermal perturbations. A critical parameter for temperature measurement is thermistor sensitivity in the range from 28 ºC to 33 ºC. Its exponential behavior has been linearized with a resistor in parallel.

Thermistor response is characterized by the thermal time constant τ, which is of the order of 1 s for all thermistors. Due to the fact that temperature variations are around 0.1 mºC, the time to detect such a variation is of the order of microseconds, which is enough for the heart rate detection .

Thermistors have been attached on a cardboard support in order to be placed on the skin as shown in Fig. 2.

Table 1 – Thermistors basic characteristics. A and B are the parameters obtained after linearizing the thermistor response. A stand for the effective sensitivity.

	SMD	Betatherm	Omega
Packaging	SMD	Epoxy	Stainless steel
R (25º)	10 kΩ	30 kΩ	2.252 kΩ
A (kΩ/ºC)	-36.35	-184.75	-11.4
B (kΩ)	4.04	15.74	1.06
τ_{max}(s) (liquids)	-	1	1
V(mm^3)	~0.175	~14	~0.56 stainless steel 127

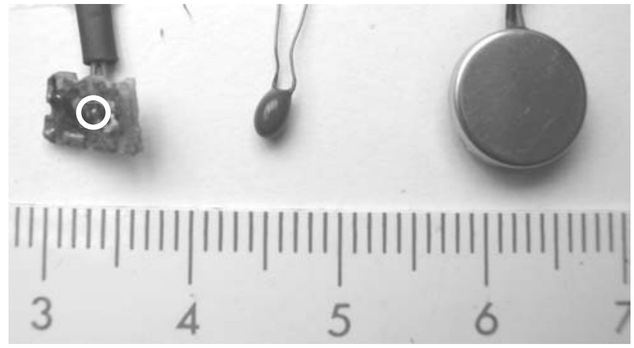

Figure 1. From left, SMD thermistor (inside the circle) soldered on a holder, Betatherm thermistors and Omega thermistor for surface measurement. Scale in cm.

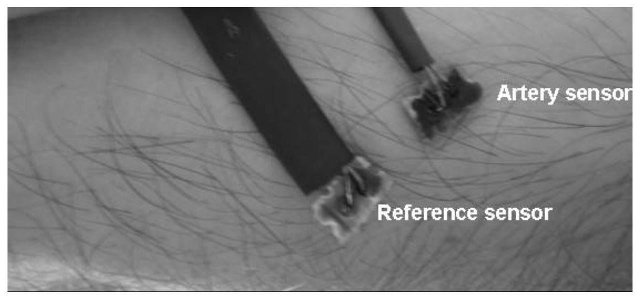

Figure 2. Thermistor disposition on the wrist in a differential configuration. One sensor is located on the artery and the other 1 cm away.

Circuit description

The goal of using an ac modulation is to achieve a better signal to noise resolution. We have used two different configurations to measure temperature fluctuations. The first one, depicted in Fig. 3, is based on an amplifier bridge and the second one is based on differential detection of a bridge, as shown in Fig. 4. Circuit is powered between –5 and 5 V, required for the MAX038 generator. Thermistor signal change will be around 0.1 mV. The dynamic range of the measurement is then 100 dB. Both circuits are based in a bridge feed with an ac signal of 1 kHz signal. Temperature fluctuations are connected to resistance variations of the thermistors. The signal is filtered and differenced first and it is demodulated and filtered with a Butterworth filter of order 3 later. The last step amplifies the signal up to a easy detectable threshold voltage, and limiting the spectral window to 0.1 Hz – 4 Hz. The acquisition has been carried out with a Agilent Data Acquisition 34970 A of 6.5 digits controlled by a computer with a bandwidth of 12.5 Hz. The transfer function for the unipolar circuit is given by the expression:

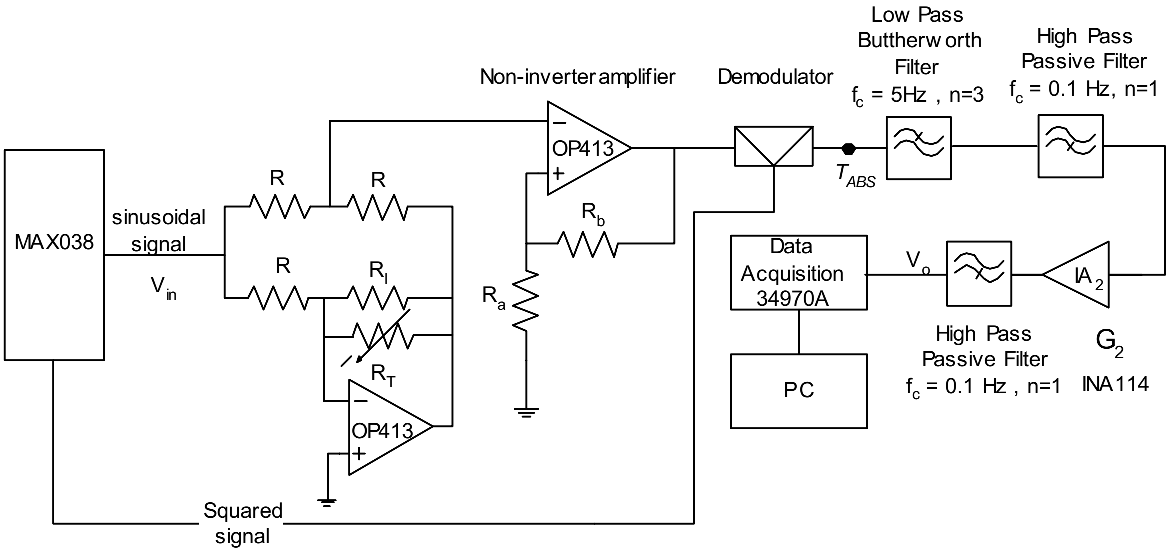

Fig.3:Thermistor signal is amplified and modulated and then filtered, demodulated, amplified, monitored in a data acquisition system and recorded in a computer.

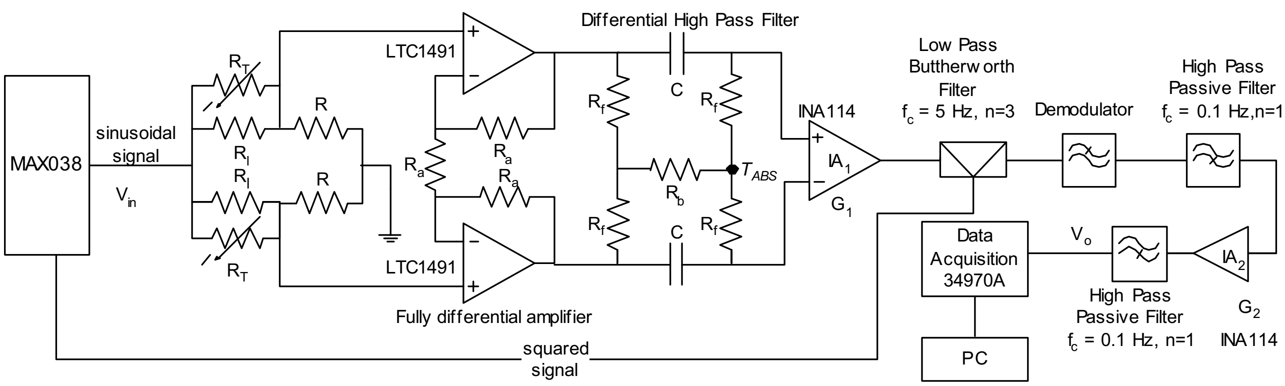

Fig. 4: Differential configuration to measure temperature fluctuations. The bridge is fed with an ac signal (MAX038), filtered, amplified and monitored in a data acquisition system.

$$V_o = G\frac{V_{in}}{2}\left(1+\frac{A\cdot T+B}{R}\right) \tag{1}$$

where the gain is given by the product of the individual gains:

$$G = G_{NIA}\cdot G_{BWF}\cdot G_{dem}\cdot G_{HPF}\cdot G_2\cdot G_{HPF} = 5\cdot G_2 \tag{2}$$

G_{NIA} is the gain of the non-inverter amplifier, *BWF* stands for Butterworth filter, *dem* for demodulator, G_{HPF} the passive high pass filters. All of them are kept constant. G_2 is the gain of the instrumentation amplifier, which is conveniently tuned for each measurement. A and B are constants obtained after linealizing the thermistor response, and they are given in Table 1.

The transfer function for the differential configuration is given by

$$V_o = G\frac{A\cdot T+B}{4R}V_{in} \tag{3}$$

where the gain G is the product of the different gains:

$$G = G_{dif}\cdot G_1\cdot G_{Butterworth}\cdot G_{dem}\cdot G_2 = 760\cdot G_2 \tag{4}$$

G_{dif}, is the fully-differential amplifier gain. The offset term related to B is conveniently filtered in both configurations to maximize the dynamic range. Differential configuration allows a larger amplification in the different steps of the circuit as it is inferred from equation 4. This implies a larger dynamic range than in that of the unipolar circuit. Though we are focused on temperature fluctuation we also notice that it is possible to extract the absolute temperature if measuring in test point labeled T_{ABS} in the Figures 3 and 4.

The restrictive requirement of the system to have a dynamic range of 100 dB needs a high signal to noise ratio. The purpose of measuring in ac at 1 kHz is to minimize the noise in the detection band. Analyzing the noise introduced by the integrated circuits and resistances, we find that the dominant contribution is due to the instrumentation and operational amplifiers, with the bandwidth window limited by the acquisition system of 12.5 Hz. Average noise at the output is of the order of 0.1 mV_{ef} while signals can be of the order of 1 V, achieving a good signal to noise ration.

RESULTS AND DISCUSSION

We present first the results of thermistor selection using a differential configuration (which has a larger dynamic range from equation 4) and then we compare the performance of the two circuit configurations. We characterize the required gain, the frequency range and the noise response of the different configurations.

Thermistor and configuration selection

We have tested three different types of thermistors, with different characteristics as described in the previous section. In Figure 5 we depict the results for the SMD thermistor measured on the wrist using the differential circuit. We detect a pulsed signal in the temporal graph, which is clearly reflected in the frequency graph. Frequency response has been obtained by extracting the Fourier Transform of the temporal spectra.

We have characterized the Betatherm and Omega thermistors but we do not find reliable results. Betatherm thermistors have the larger sensitivity, which should lead to better results. However, the requirement of measuring a surface temperature fluctuation makes the thermistor ratio volume/surface a critical issue. It has to be kept at a minimum to avoid having measurements biased by the stem effect [14]. This can be observed in Figure 6, where the thermistor is disposed on the wrist subjected by a finger. The whole thermistor is kept then at the same temperature. This results are interesting in the case that the temperature fluctuations are not to be measured on a surface but in a volume environment, like liquid flows. Omega thermistor is especially designed for surface measurement. But in this case, sensitivity (-11 kΩ/ºC) is not enough for a reliable detection.

Temperature measurement is obviously connected to the position of the thermistors. One of the thermistors must be just on the artery. In the differential configuration, we have found that best resolution is achieved with the other perpendicular to the artery, at a distance of 1 cm (as shown in Figure 2). Putting both thermistors on the artery lead to a signal with a lower resolution.

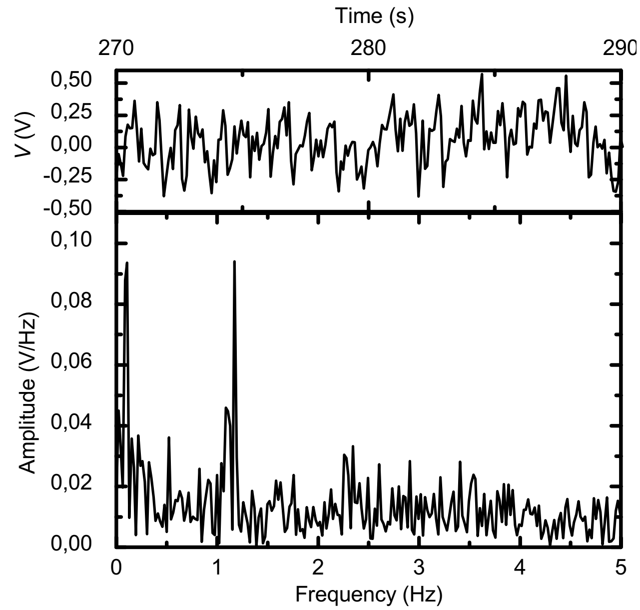

Figure 5. SMD thermistor response in differential configuration.

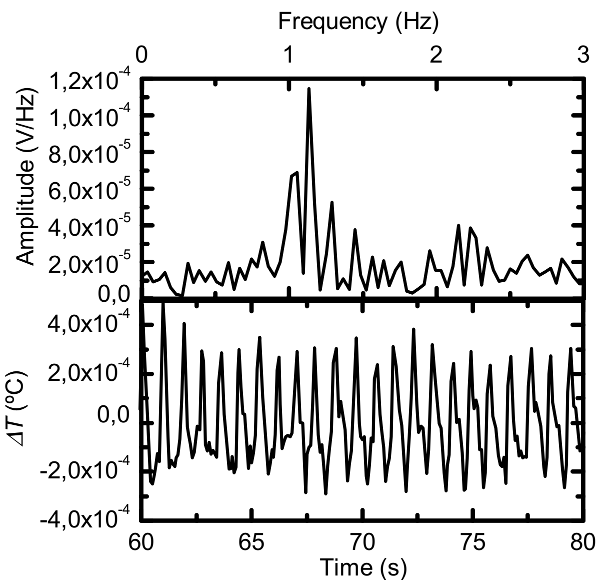

Fig. 6: Temperature pattern at the wrist skin (bottom) and the frequency spectrum showing a clear peak at 1 Hz (top), using the differential configuration and a volume thermistor.

The system is thought to be used in ambulatory measurements. We believe that the measurement on the wrist is the most comfortable for the patient. However, better results are achieved measuring on the neck artery. Results are for this case are depicted in Figure 7.

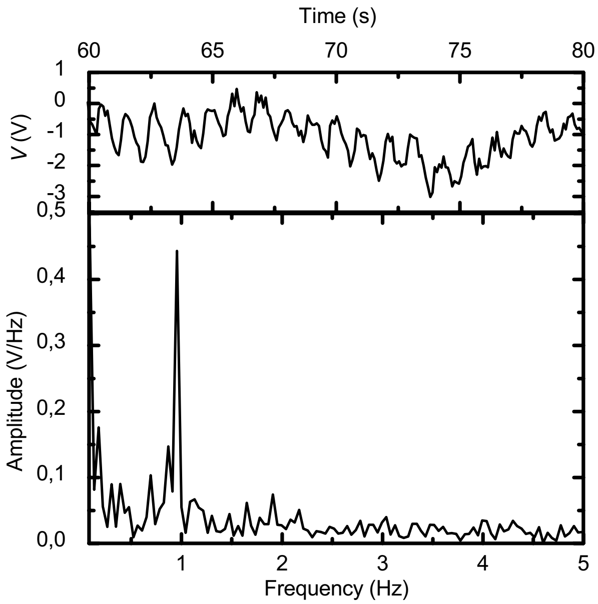

Figure 7. Measurement on the neck .The monitored signal appear perfectly defined. However, positioning the thermistors on the neck is more uncomfortable.

Circuits comparison: Unipolar vs. Differential

In previous section we have depicted results obtained from differential circuit depicted in Figure 2. According to our results, this circuit shows a better resolution than the unipolar circuit, depicted in Figure 1. Differential measurement show better performance because the presence of two thermistors allows an improving of T contrast between one an the other. In case of using one thermistor (unipolar), then it is necessary to work with high sensitivity thermistors. We have found good results only for betatherm thermistors, which have the larger sensitivity but at the cost of measuring under volume conditions. In fact, using this configuration we have not been able to monitor any signal with the SMD and Omega thermistors. In Figure 8 we depict the temperature pattern measured at the wrist skin using the absolute setup proposed in Figure 1. Temperature fluctuations of the order of 0.5 mºC are clearly detected. We believe, according to these results that in volume conditions, unipolar system shows good performance with high sensitivity Betatherm thermistors.

Frequency response

It is expected that the thermistor behaves as a low pass filter. Our goal is to have a system responding well up to 4 Hz, which is the normal range of heart beat. The cutoff frequency must be thus above the established. In Figure 9, where we have recorded a signal during rest and effort conditions. We clearly distinguish one peak at 1 Hz in rest conditions and increase up to 2 Hz in effort conditions.

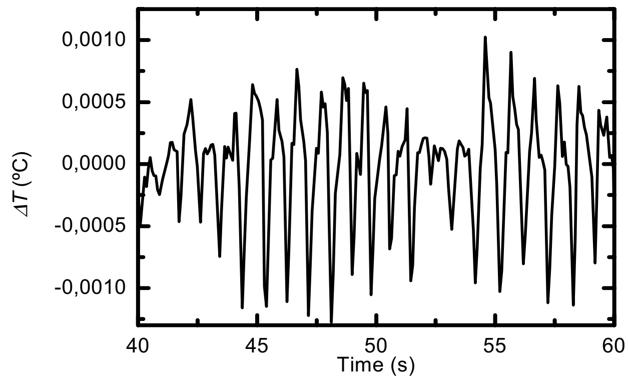

Figure 8. Unipolar measurement for Betatherm at a embedded at a constant temperature.

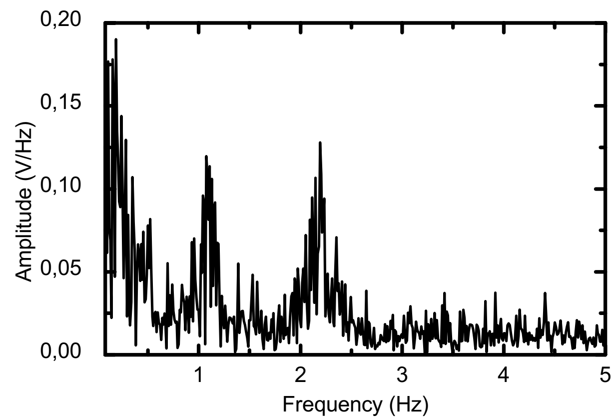

Figure 9. FFT of a spectra performed on a person riding a bike. The two differentiated peaks reflect the change of effort conditions and speed.

Peaks are clearly resolved, and the signal is rather noisy because of the transition from rest to effort conditions. Furthermore, the measurement of pulse and temperature after sport efforts shows an increase of the signal resolution, probably due to the fact that the temperature difference between the inner temperature and the radial temperature is higher because of the low exchange time.

To get further frequency dependency we have investigated temperature changes due to pulsed air currents, depicted in Figure 10. Good results are monitored up to 2 Hz. Signal decreases for frequencies in the range 3 – 4 Hz but is still perfectly detectable.

Other tested aspects

Artifacts

A critical issue in this kind of systems is the stability against external artifacts. Position changes or pressure of the thermistors with respect to the artery lead to spikes in the voltage measurement. These artifacts should be minimized in a convenient mechanization of the thermistor holder. They are manifested as spikes in the recorded signal patterns.

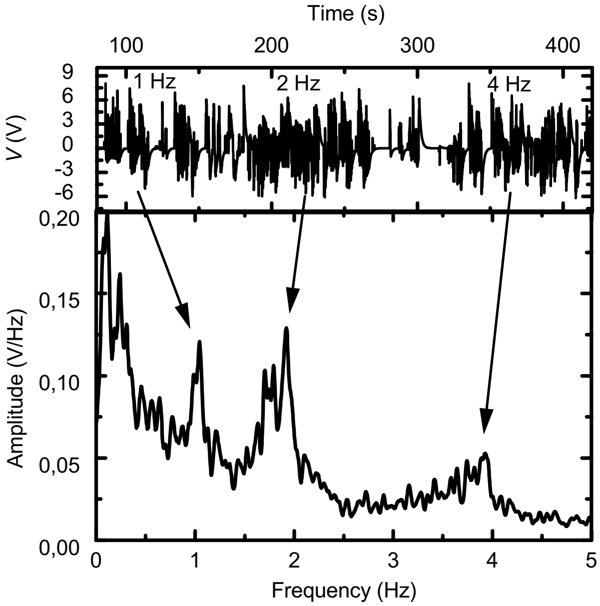

Figure 10. Spectra recording a pulsating air flow at 1, 2 and 4 Hz. The system response is kept stable up to 2 Hz. However, the signal at 4 Hz is clearly resolved.

Temperature vs. frequency

The increase of pulse after exercising leads to an increase of thermal signal. Thus, up to the frequency measured (2 Hz) the low pass frequency behavior of the thermistor is compensated by the increase of thermal activity in the body. Although this experiment has been carried out in physical exercise conditions, it has been shown that physiological speed up of cardiac rhythm is also accompanied by a temperature change [15].

CONCLUSIONS

In conclusion, we have proposed a differential circuit with SMD thermistors able to measure thermal fluctuations down to 0.1 mºC and infer the heart beat after these fluctuations. The system has a dynamic range over 100 dB and a good resolution and signal to noise ration. We have shown the convenience of trading off between thermistor sensitivity and geometrical dependence. We have validated the system response in the 0.1 Hz – 4 Hz.

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