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EARTHQUAKES, THUNDERSTORMS, AND OTHER 1/F NOISES

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ABSTRACT

Improving an experiment may mean getting better signal-to-noise ratio, perhaps by filtering out a specific source of noise. Each such noise source is likely to have a characteristic frequency or time scale. The noises most difficult to filter are the catastrophic events, fortunately rare, whatever their cause. The ensemble of such events has no characteristic time scale[1]. There are as many repeat times in the interval between 1 and 2 seconds as between 1 and 2 minutes, etc. The distribution is scale-invariant, i.e. logarithmic. Differentiating a logarithmic cumulative distribution results in a 1/f spectral density. Filtering the noise out in any frequency band means the 1/f shape obtains only for frequencies below that band. If you have not found the 1/f spectrum, it is because you have not waited long enough. You have not looked at low enough frequencies.

In designing experiments, one tries to foresee the possible sources of noise and, of course, to eliminate them. Johnson (thermal) noise and shot noise set a floor, a minimum below which noise can not be reduced. Thermal noise and shot noise both have white spectra, i.e. they are flat up to very high frequencies -- what I like to call quantum frequencies -- where the spectra bend down in a Lorentz shape. In this gathering I don't have to demonstrate what white noise sounds like. It is the shshsh sound of rushing water. What characterizes white noise is that, for any given frequency, there is more noise power in the frequency bands above the given frequency than in the bands below the given frequency.

Here I also don't have to demonstrate what flicker noise sounds like. Flicker noise is also called pink noise, because its spectrum is proportional to 1/frequency. There is more noise power at low frequencies than at high. There is twice as much noise power in a 1-Hz band near 1 kHz as in a 1Hz band near 2kHz. Well, I'll do it anyway. In a transistor, the 1/f noise sounds like pshsh, ktshsh, pdk, kshsh... You can hear the individual events. Big events are less frequent than little events. Twice as big occurs half as often. That is the meaning of 1/f spectrum.

UNLIKELY EVENTS

Mandelbrot[1] uses the term Joseph Effect for unlikely events having low characteristic frequencies. The name refers to the biblical Joseph, who predicted the 7 years of plenty followed by 7 years of famine. Clearly the remarkable feature was not the existence of a world-shaking phenomenon with a 14-year period (a frequency of 2×10^{-9} Hz). The remarkable feature was the accuracy of Joseph's prediction.

1/f spectra are so common that there is a large literature exploring noise mechanisms having such a spectral shape over many decades. This paper is not intended to be a contribution to that literature. It takes the opposite point of view. It asks the question: What can the ubiquity of 1/f spectra in widely different situations tell us about unexpected events? The answer is that the ensemble of unforeseen events has characteristic repetition times which have a scale-invariant distribution.

SCALE-INVARIANCE

This is not arcane mathematics. It is elementary. A 1/f spectral shape is the only shape that has no characteristic time, or, if you prefer, no characteristic frequency. If all frequencies are multiplied by a constant, the spectrum does not change: df/f is independent of the units of f. That means that the statistical distribution governing the events that produce that spectrum also has to be scale-invariant. You may find the argument more convincing if we talk about the integrated power spectrum. For a 1/f spectrum the total power in a frequency interval (f_1, f_2) is proportional to $\log(f_2/f_1)$ -- the integral $\int df/f$. The only function of f that is dimensionless is log f. Only this spectral shape has the property that there is the same amount of power between 1 Hz and 2 Hz as between 10 Hz and 20 Hz...

Readers of the Scientific American know by now that the height of the floods of the Nile has a 1/f spectrum[2]. They have read that the music[3] of Bach and Mozart and even jazz is 1/f. Designers of experiments know that the banging of doors is 1/f, and they design their measuring devices to block out such interruptions. By this I don't mean that the spectrum of one bang is 1/f. Indeed, one bang has a lot of high-frequency components. What the 1/f shape of door-banging noise says is that hard slams are scarcer than soft slams and the whole phenomenon does not have a characteristic repetition time. If the soft slams are not recorded, all that remains is the lower-frequency hard slams. Some noises are too big and/or too infrequent to discriminate against. These catastrophic events get through our filters, our vibration-free mountings, our isolation transformers. The term "earthquakes and thunderstorms" in the title is a euphemism for the rare, unforeseen and cataclysmic events that constitute low-frequency noise you just can't block out. They would include the truck crashing into your lab. The better you are at eliminating noise, the more nearly the spectrum of the remaining noise is likely to be 1/f, i.e. scale-invariant.

You conclude that a badly designed experiment may have a 1/f noise spectrum simply because there is a large ensemble of sources of big noise, so large an ensemble that the statistical distribution of characteristic times is scale-invariant. As these noises are removed by better design, what noise remains is likely to be dominated by one or two mechanisms, and to have a characteristic time -- a Lorentzian spectrum. When the predictable noise source has been removed, what remains are the unpredictable cataclysmic events -- the earthquakes and thunderstorms. They are likely to have myriad causes, so again, to have a scale-invariant distribution of characteristic times. Both the very raw experiment and the very mature experiments are likely to have 1/f noise spectra -- at different levels, to be sure.

HIGH AND LOW-FREQUENCY BENDPOINTS

Back in 1952 I was assigned the 1/f noise problem in transistors by William Shockley, who headed my research group at Bell Telephone Laboratories. One of my early worries was the infinities, the divergences at both high and low frequencies. I resolved the high-frequency-divergence worry quickly. Scale-invariance breaks down at high frequencies because Planck's constant determines a scale. The high characteristic frequencies that cause 1/f spectra to curve down to $1/f^2$ shapes I have called quantum frequencies. The existence of atoms determines both a length scale and a time scale on the short end. The low frequency divergence of a 1/f spectrum was resolved by Mandelbrot[4] for the theorists. The experimenters were never bothered by it. They know intuitively that to measure noise at 10^{-1} Hz they have to measure for at least 10 seconds; to measure at 10^{-3} Hz the measuring time has to be at least 10^3 seconds; etc. They know the bandwidth theorem.

I was always looking for a low-frequency cut-off. In other words, I thought there ought to exist a very low frequency below which the flicker noise would be white. I was looking for a time scale on the long-time end. If such a characteristic time were to exist, i.e., if there were a longest characteristic repeat time for random events, then the 1/f spectra would have that shape for only a limited number of decades in frequency. That would imply the existence of a pure number characteristic of the universe, giving the ratio of the quantum frequency bendpoint to that low-frequency bendpoint. The

the events that produce that spectrum also has to be scale invariant. You may find the argument more convincing if we talk about the integrated power spectrum. For a 1/f spectrum the total power in a frequency interval (f_1, f_2) is proportional to $\log(f_2/f_1)$ -- the integral $\int df/f$. The only function of f that is dimensionless is log f. Only this spectral shape has the property that there is the same amount of power between 1 Hz and 2 Hz as between 10 Hz and 20 Hz...

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No attempt is made here at a model for a low-frequency bendpoint. The question at issue is whether scale-invariance might be one of the approximate symmetries of nature. We know it breaks down at the short-time end. We do not know how far into the long-time region it might extend. The ubiquity of 1/f noise spectra is our evidence for conjecturing this symmetry property.

What kinds of experimental evidence would support or contradict this conjecture? To be sure, no matter how many decades long an observed 1/f spectrum might be, not even dozens of such spectra would constitute proof. But if a universal low-frequency bendpoint were to be found, with no 1/f noise at lower frequencies, that would be sufficient to disprove the conjecture.

ENSEMBLE OF PURELY RANDOM PROCESSES

It might be useful to write down the connection between the power spectrum and the statistical distribution of repeat times for purely random processes. A purely random process is one with an autocorrelation function of the form $e^{-t/\tau}$. The power spectrum of such a process has a Lorentz (also called Debye) shape[5]:

$$S(\omega) \propto \text{Fourier Transform of } e^{-t/\tau}$$

$$\propto \tau/(1 + \omega^2\tau^2) \tag{1}$$

If we have a large collection of different random processes, each with its own correlation time τ, then the power spectrum of the whole ensemble depends on the statistical distribution $\rho(\tau)$ of thesecorrelation times. If these processes have not been filtered, then our conjecture is that the weighting function is scale-invariant:

$$\rho(\tau)\, d\tau \propto d\tau/\tau \tag{2}$$

This gives a power spectrum

$$\int_{\tau_1}^{\tau_2} S_\tau(\omega)\rho(\tau)d\tau \propto \int_{\tau_1}^{\tau_2} \frac{\tau}{1 + \omega^2\tau^2}\frac{d\tau}{\tau}$$

$$= \frac{\tan^{-1}\omega\tau}{\omega}\Bigg|_{\tau_1}^{\tau_2} . \tag{3}$$

If the scale-invariance extends over many orders of magnitude, i.e. if τ_2/τ_1 is a large ratio, then the spectrum is $1/\omega$ over a correspondingly large range[6]. For many years we have been scratching our heads to find special mechanisms that would have that special distribution of time constants over many decades. But we do not need special mechanisms. We need simply a large ensemble of mechanisms with no prejudice about scale. The conjecture is that nature is sufficiently chaotic to possess this lack of prejudice.

Some of my friends refuse to call this sort of thing physical theory. They feel it belongs more properly in the realm of philosophy, metaphysics perhaps. It is important to note that whatever the status of this approximate symmetry principle, it does not detract in any way from the work of those who have explored individual noise mechanisms with 1/f spectra.

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