Canceling Quantum Noise

A new technique uses an 'anti-noise' signal to cancel out the unavoidable quantum noise associated with precision measurements like those needed for gravitational-wave detection.

By **Philip Ball**

When light is used to detect motion with high-precision—for example, in accelerometers or gravitational-wave detectors—its ultimate sensitivity is limited by quantum noise, which is unavoidable. A research team has now demonstrated a tabletop device that can reduce the disruption of quantum noise by modifying a light beam before using it to make a measurement [**1**]. This beam preparation cancels out the noise in a manner reminiscent of noise-canceling headphones [**1**]. Working across a wide frequency range and potentially offering up to 77% noise reduction, the system might ultimately find additional uses in quantum information processing.

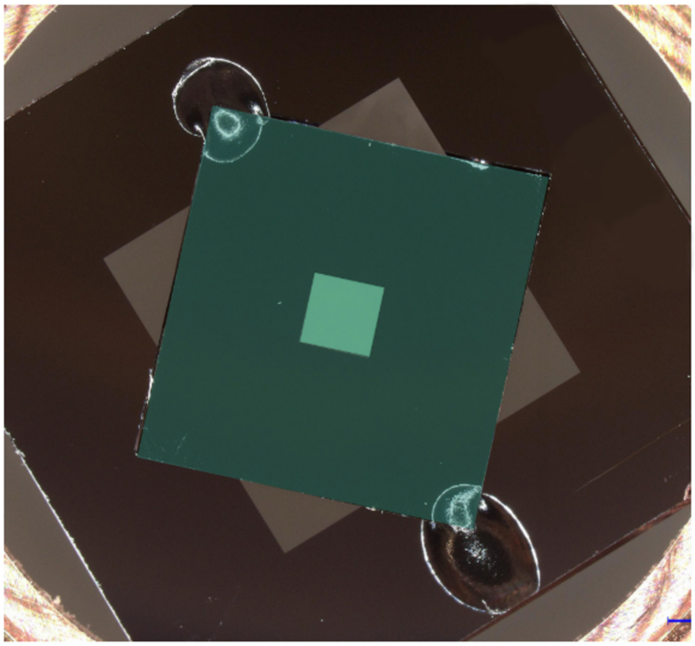
Wave catcher. Gravitational waves are sensed by the tiny changes they induce in the relative lengths of the two arms of a gravitational-wave detector, such as the Virgo facility near Pisa, Italy. These changes are detected via interference of light beams bouncing back from mirrors at the far ends. The sensitivity of such measurements is limited by noise in the light fields.
Credit: The Virgo Collaboration (CC0 1.0)

Observing gravitational waves involves detecting changes in the interference pattern created by a pair of interacting laser beams, each of which has bounced off a remote mirror whose distance changes slightly when a wave passes. Such detections require very high sensitivity, which is compromised by inherent quantum fluctuations in the light field. To reduce quantum noise, researchers currently use a technique called squeezing, in which the quantum fluctuations can be shifted from one parameter, such as the phase, to another, such as the intensity [**2**, **3**].

However, this method requires expensive and bulky devices. Another approach, first proposed in 2010 [**4**], is quantum noise cancellation, where an optical signal is created that is out of phase with the noise and can thus cancel it by destructive interference. Such active cancellation is common in classical acoustic and electronic devices but is more challenging to implement for quantum systems.

"The analogy to classical noise cancellation is useful but only up to a point," says Jonas Junker, an expert in quantum optics at the the Friedrich Schiller University in Germany. In the quantum case, the noise is not inherent in the external signal being measured but is a product of the measurement itself, he explains. In an optomechanical measurement, the light field probing an object's motion has quantum fluctuations that exert a varying radiation pressure. In response to this fluctuating force, the object's motion injects additional noise back into the light beam, an effect called quantum backaction.

In 2022, researchers at the Max Planck Institute for Gravitational Physics in Hannover, Germany, showed theoretically that one could cancel backaction noise by generating an "anti-noise" component in the probe light beam [**5**]. In this scheme, before



A noiseless quantum drum. A resonating silicon nitride membrane like this, used as an optomechanical sensor, could be used to test the new approach to quantum noise reduction.
Credit: Bernd Schulte/Max Planck Institute for Gravitational Physics

the light enters the optomechanical system (OMS) making a measurement, it traverses an oscillator comprising a cavity containing two mirrors between which the light reflects many times. This cavity is designed to produce oscillations that will cancel those of the OMS. So the light entering the OMS will already have acquired a component that will cancel the back action noise. The oscillator is said to have an effective negative mass, in analogy with a mechanical system: if one could push on a negative mass, it would move in the direction opposite to the force.

Now Junker and others have collaborated with some of the Hannover researchers to build the effective negative-mass oscillator (ENMO) needed for the scheme and have shown that it performs as required to cancel quantum backaction noise. Their ENMO is designed for use with optical measurements on a thin oscillating membrane, a device typically used for high-precision sensing of motion or force.

The researchers report that the performance they observed for the ENMO would correspond to a 77% reduction in quantum backaction noise at the membrane-oscillation frequency at which noise cancellation is optimal (hundreds of kilohertz). However, they have not yet carried out the full experiment to demonstrate this performance.

Junker says that the ability to engineer tunable, coherent interactions between optical components should have applications beyond quantum noise cancellation. Such interactions, he says, are central to various aspects of quantum information processing, including "optical quantum memories, where one wants to map, store, and retrieve quantum states of light without adding excess noise."

These are "exciting results in quantum noise evasion," says Eugene Polzik, a specialist in quantum sensing at the University of Copenhagen. "Compared to other methods, their approach is more versatile and less technically challenging." He says the work should lead to applications in fields including gravitational-wave observation, magnetometry, and interferometry.

Quantum optics expert Matthew Woolley of the University of New South Wales in Australia says that another possible application would be in tabletop experiments aiming to detect quantum gravity, which require ultrasensitive, low-noise measurements.

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