

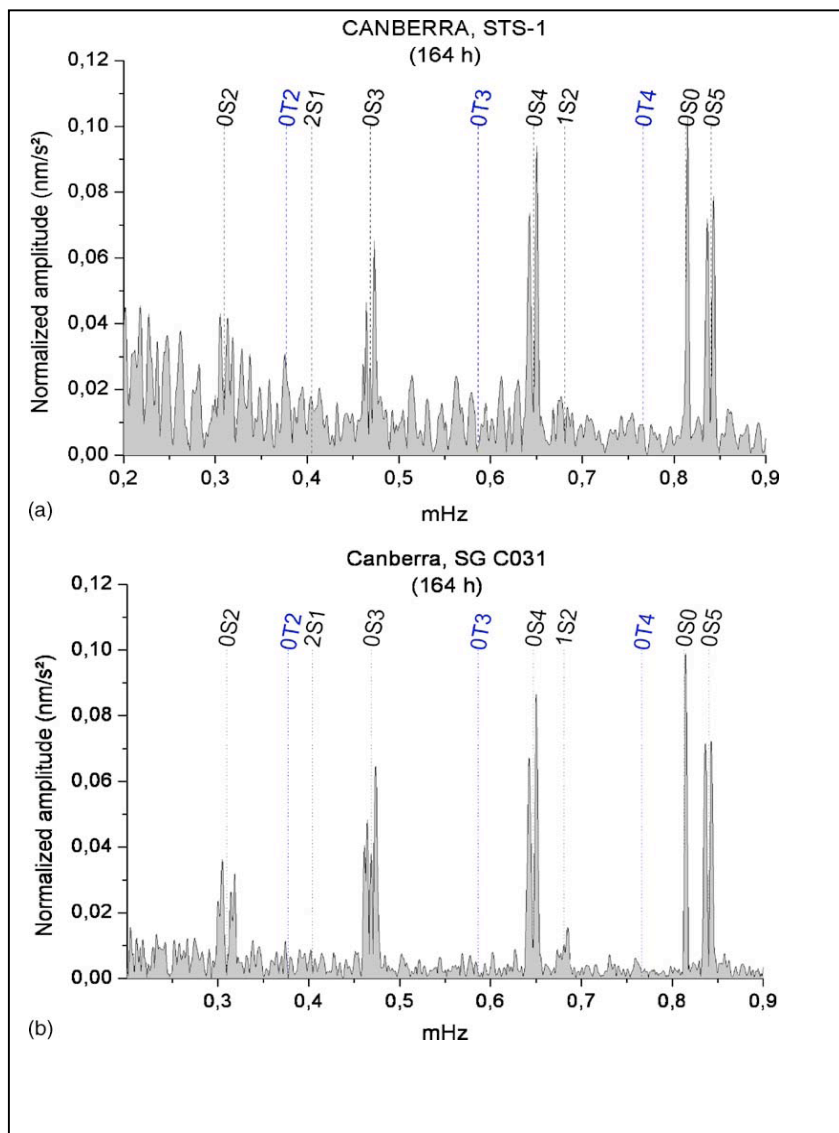
# Potential of a superconducting long-period seismometer

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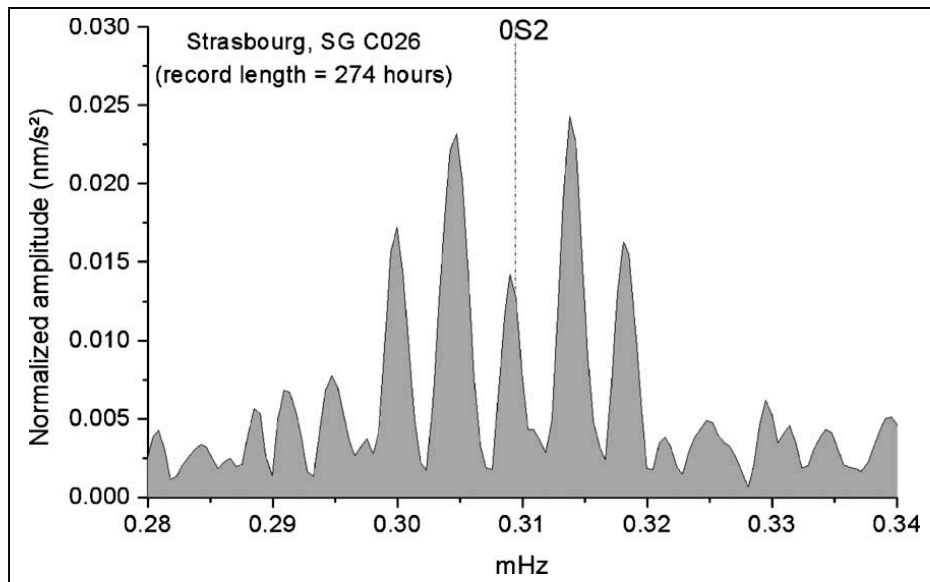
## 1. Current status:

Recent studies have demonstrated that the best superconducting gravimeters (SGs) are less noisy than the STS-1 seismometers for frequencies below 1.0 mHz. Examples include measurement of the torsion modes OT2 to OT4 after the Balleny Islands  $M_w = 8.2$  earthquake on March 25, 1998 (Zürn et al., 2000), and measurement of 1S2 and the splitting of OS2 after the Peru  $M_w = 8.4$  earthquake on June 23, 2001 (Rosat et al., 2003). However, for frequencies above 1.5 mHz, the

STS-1 and ET-19 at BFO are less noisy than SGs. This is confirmed in studies of the hum at Canberra (Australia) where an STS-1 and SG are collocated. In the hum band (2 to 7 mHz) the STS-1 is  $\approx 7$  dB lower and ET-19 is  $\approx 4$  dB lower than the best SGs.



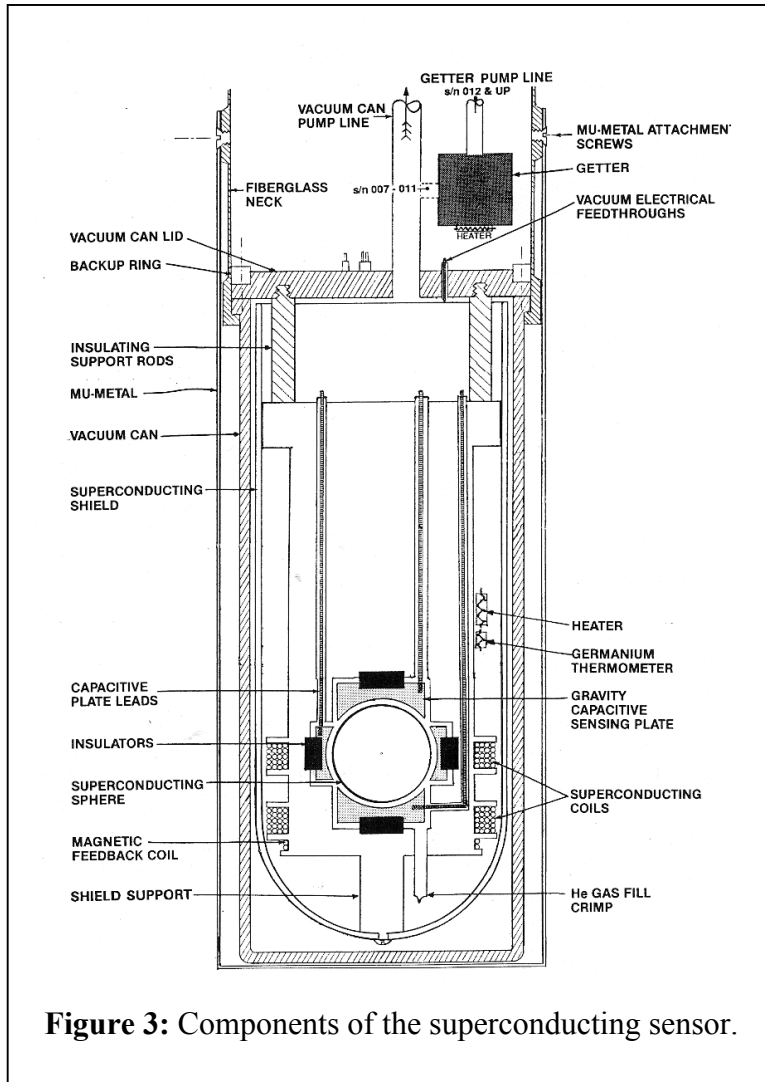
**Figure 1:** Spectra from the 2001 Peru event for which seven SG stations (Canberra, Esashi, Membach, Metsahovi, Strasbourg, Sutherland and Vienna) and the GEOSCOPE STS-1 Canberra station were analyzed (Rosat et al., 2003). In this Figure, only the SG and STS-1 from Canberra are shown. Clearly the SG has a lower noise level than the STS-1 and is superior for recording the longest period normal modes. However, the STS-1 noise continues to decrease and above 1 to 1.5 mHz has a lower noise level than the SG.



**Figure 2:** Observation of the 5 singlets of the fundamental mode 0S2 with the SG C026 at Strasbourg. The spectrum used 274 hours of SG data corrected for tides and atmospheric pressure. The background noise is less than 0.5 nanoGals.

## 2. Description of the Superconducting Gravimeter

J. Goodkind and W. Prothero developed the SG in the late 1960's at the University of California, San Diego (Goodkind, 1999). Their goal was to build a very precise and drift free gravimeter that could be used for measuring vertical movement of the earth's crust. The sensor of the SG, shown in Figure 3, operates at cryogenic temperatures (4.2 degrees Kelvin) and uses two superconducting coils to produce a magnetic field that levitates a spherical superconducting proof mass. The proof mass is one inch in diameter and weighs 4 to 8 grams. This design allows simple adjustment of the vertical magnetic gradient ("spring constant") by adjusting the ratio of the currents in the coils. The currents are applied using a standard current supply operating at room temperature, which is connected to the magnets using a combination of resistive and superconducting wire. After adjustment, heat switches are used to "trap" the currents in each superconducting coil and the power supply connections are removed. The currents remain in the coils as persistent superconducting currents flowing in a completed superconducting circuit. By adjusting the spring constant to be very weak (less than 0.01 N/m), changes in gravity or vertical accelerations produce comparatively large displacements of the sphere. In this way, the SG sensor becomes a low noise gravity amplifier; and conventional phase sensitive detection techniques in conjunction with a capacitance bridge that surrounds the sphere are more than adequate for measuring displacements of the sphere. In operation, the position of the sphere is held fixed by feeding back a current through a small coil in close proximity to the levitation field coils. The magnitude of the current through the feedback coil provides measurement of changes in the gravitational force. The extremely low-noise and low-drift of the SG results from four factors: the very weak and stable magnetic gradient produced by the coils; the inherent stability of persistent currents flowing in a superconductor; the mechanical stability of materials at cryogenic temperatures, and the insensitivity of the SG to environmental effects.

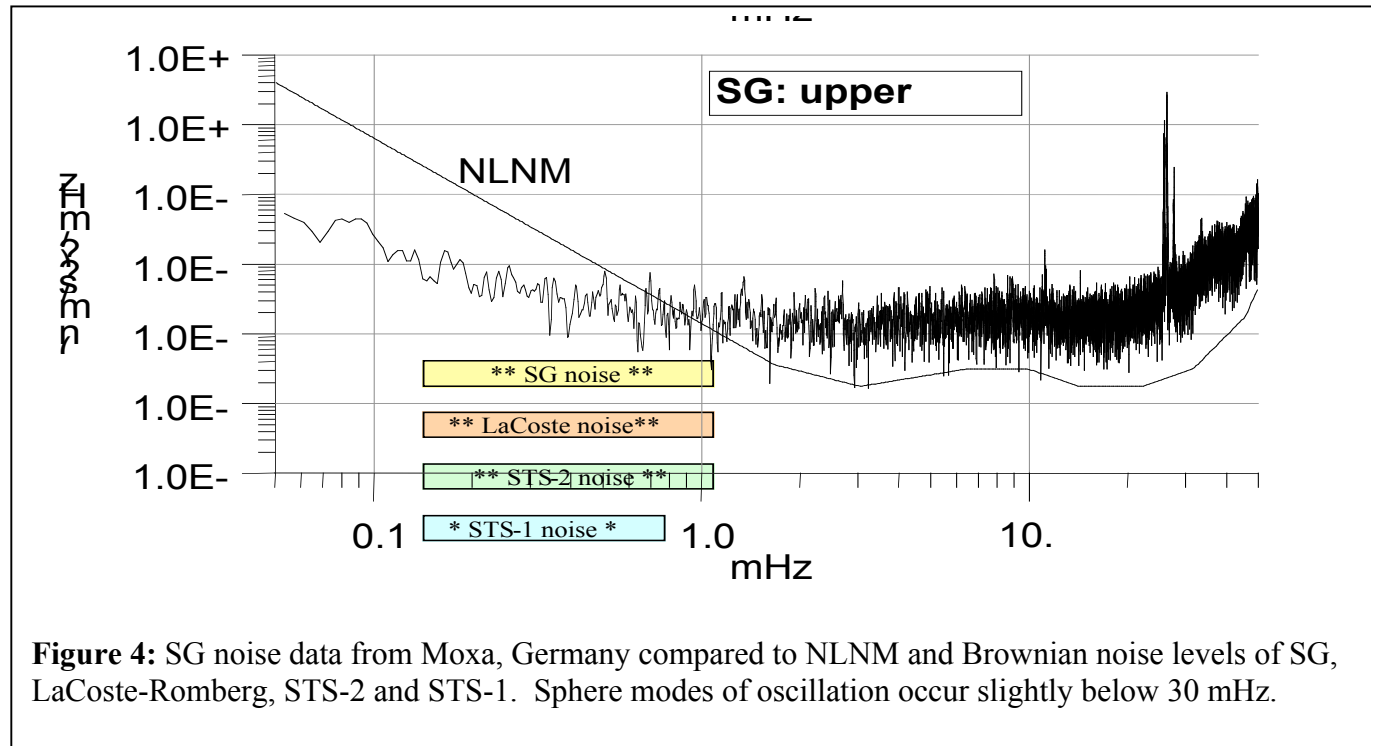


**Figure 3:** Components of the superconducting sensor.

### 3. Noise Limitation for the SG

The spectral acceleration-noise power caused by Brownian motion in a simple mechanical oscillator is given by:  $P_a(f) = 4kTb/m^2$ , where  $k$  is Boltzmann's constant,  $T$  is absolute temperature,  $m$  is the mass,  $T_0$  is the fundamental period,  $Q$  is the quality factor, and  $b = \pi m / (QT_0)$  is the proportionality constant of the velocity dependent damping. Brownian noise (in  $(\text{nm}/\text{s}^2)^2/\text{mHz}$ ) have been calculated for the following instruments: STS-1/Z  $\approx 10^{-6}$ ; STS-2/Z  $\approx 10^{-5}$ ; LaCoste-Romberg ET-19  $\approx 7 \times 10^{-5}$ , and SG  $\approx 5 \times 10^{-4}$  (Richter et al., 1995; Van Camp, 1999). These noise estimates are shown in Figure 4 in comparison to the NLNM and to SG data from Moxa, Germany. Clearly the estimated Brownian noise of the SG is above the NLNM. In addition, its fundamental noise level is likely higher since its test mass has five unconstrained additional degrees of freedom. On the other hand, the STS-1/Z Brownian noise is well below the NLNM measure of earth noise. Nevertheless, from comparison with the SG, it is certain that other sources of instrumental noise dominate the STS-1 signal below 1 mHz.

The Brownian noise advantage of the STS-1 and ET19 is primarily due to their larger masses. The STS-1 uses a 600-gram mass and operates at 383 °K; the LaCoste uses an 80-gram mass controlled at 323 °K; and the SG uses a 5-gram mass controlled at 5 K. Scaling for mass and temperature, one expects the STS-1 noise to be  $\approx 1000$  times less and the ET-19 to be  $\approx 20$  times less than the SG. This is approximately true (within a factor of 4) using the above estimates.



**Figure 4:** SG noise data from Moxa, Germany compared to NLNM and Brownian noise levels of SG, LaCoste-Romberg, STS-2 and STS-1. Sphere modes of oscillation occur slightly below 30 mHz.

#### 4. Proposal to increase the SG mass to 60 to 100 grams

GWR proposes to increase the physical size and mass of the sphere to reduce the SG's instrumental noise level. In particular, we propose to increase the diameter of the sphere to 2 inches and the mass to about 80 grams. The increase in mass will decrease the Brownian noise level by a factor of 100 to 400, so that the SG noise will be well below the NLNM. To levitate an 80-gram mass, the sphere's diameter must be increased to keep the magnetic field strength below the critical field of Nb (1300 Gauss at 4.5 K). From magnetic models, we estimate that the maximum field on the surface of the 1-inch sphere is about 180 gauss. For a constant field, the levitation force  $F$  is proportional to  $R^2$ , where  $R$  is the radius of the sphere. Therefore, 180 gauss can levitate a 2" diameter sphere that is 4 times heavier. In addition, we propose to increase the field strength 4 times to 720 gauss. This will allow levitating a sphere that is 16 times heavier than currently used. At some point, increasing the field strength too close to the critical field will cause instrumental drift and flux motion. Therefore, the field strength must be kept low enough to avoid these problems.

## 5. Is a superconducting seismometer practical?

In early years, SGs operated in very large 200 L liquid helium Dewars. This is no longer true. As cryogenic refrigerators have been integrated with the Dewar, the Dewars have become much smaller and more efficient. GWR's most recent SG sensors operate in 35 L Dewars that are 15 inches in diameter and 44 inches in height. However, even smaller Dewars are possible as shown in Figure 5. In addition, small 4-Kelvin cryogenic coldheads are now available that need



**Figure 5:** SG operating in a small Dewar using a Sumitomo SRDK-101 coldhead and a Sumitomo CA-11C compressor. Dewar is 10 inches in diameter and 36 inches tall

only 1.2 to 1.3 kW single phase 50/60 Hz power. With these coldheads there is no consumption of liquid helium during normal operation. Losses occur only during power failures. It is no longer necessary to transport and transfer liquid helium. To replenish liquid, one simply connects a compressed helium cylinder to the Dewar via a low-pressure regulator and helium is liquefied at a rate of 2 to 3 liters/day. The increase in size of the seismometer sensor will not require a larger Dewar since the sensors are installed through a port in the bottom of the Dewar

## 6. Advantages & disadvantages of SG seismometer

### Advantages:

- Proven technology with extremely low noise below 1 mHz

- Mechanical stability of materials at cryogenic environment
- Insensitivity of sensor to environmental effects
- Simplicity of design should guarantee consistent low noise specifications when manufactured in quantity
- Modest design change to further lower sensor noise level.

#### **Disadvantages:**

- Cost of cryogenic refrigeration alone is  $\approx$  \$ 30,000
- Power requirement of compressor  $\approx$  1.2 to 1.3 kWatt
- Only vertical component available at present
- May need improved methods to raise frequency and damp sphere's free modes of oscillation

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