PRESENT AND FUTURE OF RESONANT DETECTORS

or

Bars and Spheres : The hardware side

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ABSTRACT
some elementary considerations on:

• BAR DETECTORS: SOME TECHNICAL TERMS
  – Crucial components that make an antenna work
  – Sensitivity: $h$, $S_h(f)$, $T_{\text{eff}}$, $\Delta f$ and all that

• SENSITIVITY and BANDWIDTH: WHERE WE STAND and where can we go?
  – Handles to improve present performances:
    • New amplifiers and/or transducers
    • Colder bars
    • New resonators

• The SPHERICAL WORLD: News from MINIGRAIL
The peak sensitivity depends on $T/MQ$.

The bandwidth depends on the transducer ($\beta$) and amplifier ($T_n$).

We Need to broaden AND deepen the dips in this curve:

$\Rightarrow$ More peak sensitivity

$\Rightarrow$ AND more bandwidth

$$h_{\text{min}} \approx \frac{\tilde{h}(f_a)}{\tau_g \sqrt{\Delta f}}$$

$$\Delta E_{\text{min}} \approx \frac{k_B T}{\tau \Delta f}$$
…Therefore, to improve sensitivity:

- We need to improve the peak spectral sensitivity $\tilde{h}(f_a)$
  - Increase M : large and/or multimode detectors
  - Reduce T/Q : ultra-cryogenics, New materials

- We also need to increase the bandwidth $\Delta f$
  - Increase $\beta$ : transducer w/ tighter coupling
  - Reduce $T_n$ : better amplifier (double SQUIDs)
A DICTIONARY OF ANTENNA TERMS

- **The mechanical oscillator**
  - Mass $M$
  - Speed of sound $v_s$
  - Temperature $T$
  - Quality factor $Q$
  - Res. frequency $f_a$

- **The transducer**
  - Efficiency $\beta$

- **The amplifier**
  - Noise temperature $T_n$

**Thermal noise**

$$S_F = Mk\omega/Q$$

**Amplifier noise**

$$V_n I_n \quad T_n = \sqrt{V_n^2 I_n^2 / k}$$
Minimum detectable energy change

\[ \Delta E_{\text{min}} \equiv k_B T_{\text{eff}} = 2k_B T \sqrt{\frac{\text{wideband noise}}{\text{thermal noise}}} \Delta f \]

A low effective temperature makes the sensitivity higher and the bandwidth larger

\[ \Delta f = \frac{4 f}{Q} \frac{T}{T_{\text{eff}}} \]

strain sensitivity

\[ h_0 = \frac{1}{\tau_g} \sqrt{\frac{S_h(f_o)}{2 \pi \Delta f}} = \frac{L}{2 \nu_s^2 \tau_g} \sqrt{\frac{k_B T_{\text{eff}}}{M}} \]
A resonant transducer with a mass $m = \mu M$ allows us to gain a factor $\mu^{-1}$ in $\beta$.

But it also introduce a bandwidth limitation $\Delta f < f_a \sqrt{\mu}$

(transducer motion noise grows intolerably outside $\Delta f$)

$$\langle x_{th}^2 \rangle = \frac{kT}{m \omega^2}$$
TWO MODE DETECTOR (2)

• So, coupling $\beta$ improves with lighter transducer mass $m_t$

• But bandwidth and thermal noise improve with heavier $m_t$

• An optimum does exist for $m_t$:

\[ m_{opt} = \frac{2\alpha \phi}{\omega^2 \phi_n} \sqrt{\frac{k_BT m_x}{\tau}} \]

As amplifiers improve, transducers can be made more massive
IMPROVING $\beta$ : Better Transducers

• As the coupling grows, the resonant transducer mass can be made larger:

• The largest you can imagine it, it is as massive as the antenna itself:
  two large masses coupled by a readout (looks familiar ?)
  the detector becomes very wide band


• This idea has been recently reexamined by the Auriga group (J.P. Zendri in a few minutes).
IMPROVING TRANSDUCER TECHNOLOGY:

The rosette capacitive transducer; gap=9µm
EXPLORER has been on the air since May 2000 with:
- new, 10 µm gap transducer
- New, high coupling SQUID

The noise temperature is < 5 mK for 84% of the time.

Bandwidth: the detector has a sensitivity better than $10^{-20}$ Hz$^{-1/2}$ on a band larger than 40 Hz before 1999

after 2000
EXPLORER PERFORMANCES

GW spectral amplitude (h/√(Hz))

- **E=5 \times 10^6 V/m**
  - **h = 5 \times 10^{-19}**

- **E=8 \times 10^6 V/m**
  - **h = 2 \times 10^{-19}**
IMPROVING $T_n$ : Better Amplifiers

A SQUID is so good an amplifier that noise from the second stage is usually dominant. The only suitable second stage is another d.c. SQUID.

However the two devices tend to disturb each other !!!

Several efforts underway to produce a reliable amplifier for antenna readouts (see P. Falferi in about 40’).
“Dream” noise spectrum of Roma double SQUID

\[ \Phi_n (\Phi_0 \sqrt{\text{Hz}}) \]

- \( T = 4.2 \text{ K} \)
- \( \varepsilon = 28 \text{ K} \)
- \( T = 0.9 \text{ K} \)
- \( \varepsilon = 5.5 \text{ K} \)

Carelli et al. 98
IMPROVING T/Q : (I)

- New, powerful Dilution Refrigerators
- MINIGRAIL was cooled (Jan 2003) to 80 mK
- Cooling below 30 mK appears possible
- $T_{\text{min}}$ probably limited by ortho-para H conversion.
IMPROVING THE ANTENNA CROSS SECTION (II): SPHERES

(Warren, are you there ?)

• Need a larger mass (larger cross section, or lower thermal noise). This can be achieved with
  – One single huge resonator
  – Distributing the mass over many small detectors

• Besides, the resonator mass can be better exploited by monitoring all the modes that are sensitive to g.w.
  \[\Rightarrow\] use the 5 quadrupole modes of a sphere.
A NEW KID ON THE BLOCK: MINIGRAIL

- The MINIGRAIL Team:
  - G. Frossati, A. de Waald, L. Gottardi

Kammerling-Onnes Laboratories of Leiden Univ. (NL)
A vibrating sphere has two classes of normal modes:

- Toroidal (no radial displacement)
  \[ \bar{\psi}_{lm} = c \psi_l(kr)(\vec{r} \times \vec{\nabla} Y_{lm}) \]
  \[ \psi_l(x) = \left( \frac{1}{x} \frac{d}{dx} \right)^l \left( \frac{\sin x}{x} \right) \]

- Spheroidal (radial and transverse displacement)
  \[ \bar{\psi}_{lm} = \left[ a_l(r) \vec{n} + b_l(r) R \vec{V} \right] Y_{lm} \]

\( a(r) \) and \( b(r) \) are dimensionless radial eigenfunctions.
Extracting the information from the 5 quadrupole modes

- Five degenerate quadrupole modes (described using the basis of the five spherical harmonics $Y_{2m}$; the same basis can be used to express $h_{ij}$)

- Using a metric theory of gravity, such as General Relativity, the direction and polarization of the wave can be inferred from the measured components (and also a possible spin 0 amplitude of the wave, due to a scalar field –Brans and Dicke 1961)

\[ h_x, h_y, H, \delta, h_s \]
• Absorbed energy:

Sphere

\[ \sigma_s = F_n \frac{G}{c^3} M v_s^2 \quad \text{omnidirectional} \]

\[
\begin{align*}
2R &= L \\
\text{Same fundamental frequency} \\
\sigma_s &\approx 18 \sigma_c^{\text{max}} \\
\sigma_s &\approx 70 \bar{\sigma}_c
\end{align*}
\]
\[ \sigma_{2c} \equiv 0 \]

\[ \frac{\sigma_{1c}}{\sigma_{3c}} \approx 9 \]

\[ \frac{\sigma_{1s}}{\sigma_{2s}} \approx 2.6 \]

A single spherical detector constitutes a xylophone in its own
Large cross section

\[ \sigma_n \propto Mv^2 \]

- Due to larger mass \( \rightarrow 17 \times \)
- Due to omni-directionality \( \rightarrow 4 \times \)
- Total \( \rightarrow 70 \times \)
We might eventually have an array of small spherical resonators!

Exploiting the resonant-mass detector technique: the spherical detector

TIGA, PRL 1993
Hollow sphere, PRD 1998
Dual sphere, PRL 2001

MINIGRAIL
Leiden (Netherlands)

MARIO SHENBERG
Sao Paulo (Brasil)

SFERA
Frascati (Italy)

CuAl(6%) sphere
Dia= 65 cm
Frequency = 3 kHz
Mass = 1 ton
SPHERES AROUND THE WORLD
## MiniGRAIL properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CuAl6%</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho = 8000 \text{ kg/m}^3$</td>
</tr>
<tr>
<td>Diameter</td>
<td>$\Phi = 0.65 \text{ m}$</td>
</tr>
<tr>
<td>Mass</td>
<td>$M = 1150 \text{ kg}$</td>
</tr>
<tr>
<td>Sound velocity</td>
<td>$v = 4000 \text{ m/s}$</td>
</tr>
<tr>
<td>Resonant freq.</td>
<td>$f = 3160 \text{ Hz}$</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>~ 20 mK</td>
</tr>
</tbody>
</table>
Spectral Amplitude compared to LIGO 2 M

Xylophone of spherical detectors

\[ \Delta f \sim 10\% f \]

From 1 – 3 kHz:
10 detectors with \( \downarrow = 0.65 \rightarrow 2 \text{ meters} \)
Cooldown time MiniGRAIL – Run 2

New results on Forced Helium Flow

N₂

Copper tube

Nitrogen Dewar

Roots 1200

Roots 250
COOLING MINIGRAIL (II)
COOLING MINIGRAIL (III)

Temperature (K)

Time (days)

Nautilus

MiniGRAIL

T (mK)

Time (Days)
IMPROVING THE ANTENNA CROSS SECTION (I): New materials

\[ \sigma_n \propto Mv^2 \]

Several spheres at 2 kHz

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (m)</th>
<th>Density (kg/m²)</th>
<th>Sound velocity (m/s)</th>
<th>Cross section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al5056</td>
<td>1.38</td>
<td>2500</td>
<td>5400</td>
<td>1</td>
</tr>
<tr>
<td>CuAl6%</td>
<td>1.02</td>
<td>8000</td>
<td>4000</td>
<td>0.7</td>
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<tr>
<td>CuBe5%</td>
<td>1.19</td>
<td>7516</td>
<td>4668</td>
<td>1.4</td>
</tr>
<tr>
<td>CuBe10%</td>
<td>1.38</td>
<td>6537</td>
<td>5400</td>
<td>2.6</td>
</tr>
<tr>
<td>Be</td>
<td>3.06</td>
<td>1800</td>
<td>12000</td>
<td>38.8</td>
</tr>
</tbody>
</table>
That’s all folks!
Typical condition
\( h = 4 \cdot 10^{-19} \)

decreasing electronic noise

increasing Q and decreasing electronic noise
\( h \sim 1 \cdot 10^{-19} \)

Calibration peak
BANDWIDTH IN A RESONANT DETECTOR

• Why are we sensitive only around resonance?

• Why can we be sensitive in a region $\Delta f \gg f/Q$?
Maximum deformation at two times differing by half a period induced by the six polarization states of a metric wave incoming along the vertical axis: a) $\Phi_{22}$; b) $\Psi_2$; c) Re $\Psi_4$; d) Im $\Psi_4$; e) Re $\Psi_3$; f) Im $\Psi_3$
• Absorbed energy:

\[ \Delta E = \int_{\Delta \omega} d \omega \phi(\omega) \sigma(\omega) \]

Cylindrical bar

GW flux

Cross section

The cross section depends on the wave propagation direction and polarization

\[ \sigma_c = \frac{8}{\pi} \frac{G}{c^3} M v^2 s^2 \left[ \sin^4(\theta) \cos^2(2 \phi) \right] \]