Resonant detectors: bars and spheres

Viviana Fafone
INFN-LNF
7 July 2003
NEWS from the detectors

<table>
<thead>
<tr>
<th>ALLEGRO:</th>
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<tbody>
<tr>
<td>After a short run during the LIGO E7 run (2.0 x 10^{-21} Hz^{-1/2} bandwidth = 1 Hz), it was cooled down again and took data for 1 month, with a new transducer and a commercial Quantum Design SQUID amplifier during the LIGO S2 run.</td>
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<table>
<thead>
<tr>
<th>AURIGA:</th>
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<tbody>
<tr>
<td>• New double stage SQUID amplifier: measured noise energy 200 \text{h} at 1.5 K coupled to resonant loads</td>
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<td>• New transducer + amplifier chain: three modes operation (2 mechanical + 1 electrical) to optimize the signal coupling</td>
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<td>• New mechanical suspensions: fully modeled cryogenic stages (attenuation &gt;360 dB @1kHz)</td>
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<td>• FRAMES data format</td>
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<tr>
<td>The cooldown will start in the second half of 2003. The expected strain sensitivity is 6 x 10^{-22} Hz^{-1/2} B=40 Hz @1 x 10^{-21} Hz^{-1/2} Phase I (2003) 2 x 10^{-22} Hz^{-1/2} B=80 Hz @1 x 10^{-21} Hz^{-1/2} Phase II (2004)</td>
</tr>
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<th>EXPLORER:</th>
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<tr>
<td>It is taking data, equipped with the rosette transducer and a commercial Quantum Design dcSQUID. The peak strain sensitivity is 2.5 x 10^{-21} Hz^{-1/2} and the bandwidth 30 Hz @10^{-20} Hz^{-1/2}</td>
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<tr>
<th>NAUTILUS:</th>
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<tr>
<td>New bar tuned at 935 Hz. New bar suspension cable. New transducer and SQUID (the same EXPLORER readout). Third run has started; the bar is at 3.5 K for the time being. The peak strain sensitivity is 2 \times 10^{-21} \text{ Hz}^{-1/2} and the bandwidth 30 \text{ Hz} @10^{-20} \text{ Hz}^{-1/2}</td>
</tr>
</tbody>
</table>
Thermal noise

\[ S_F = M k T \frac{\omega}{Q} \]

Electronic noise

\[ V_n, I_n \quad T_n = \sqrt{V_n^2 I_n^2 / k} \]

The mechanical oscillator

- Mass \( M \)
- Speed of sound \( v_s \)
- Temperature \( T \)
- Quality factor \( Q \)
- Res. frequency \( f_r \)

The transducer

Efficiency \( \beta \)

The amplifier

Noise temperature \( T_n \)
ALLEGRO

After a run during the LIGO E7 run, the system was upgraded. The old transducer had lost coupling on several previous cooldowns (persistent current had declined by half to 6 amps.) An old Maryland transducer was adapted and installed, coupled to a QD dc SQUID.
• Sensor gap reduced from LSU transducer by factor of ~5, from ~125 mm to ~25 mm
• Current increased by 2.5, from 6 A to 16 A
• Doubled area (pickup coils on both sides)
• Improved coupling

Talk by W. Johnson
• About one month of good data, covering the second half of S2.
• Data for three orientations during run.
  – At start (15 March) ~ 63° W of N (~ parallel to IGEC)
  – Rotated to ~18° W of N on 28 March (~ LLO y-axis)
  – Rotated to ~108° W of N on 9 April (~LLO x-axis)
Plans for the short term …

- Helium leak
- Mechanical Q. (low by factor of 3 or 4)
- Amplifier (noise high by factor of ~2)
- New calibrator (calibrator mode interfering with detection modes)

New run in October (S3)
...and mid term (about 1 year)

- Design a two-mode transducer
- Integrate a 2-stage SQUID (AURIGA-QD design)
AURIGA II run (mid 2003)

- Al2081 holder
- LHe4 vessel
- Main Attenuator
- Electronics wiring support
- Sensitive bar
- Thermal Shield
- Compression Spring
- Transducer

Talk by L. Taffarello
AURIGA II run *(mid 2003)*: upgrades

**new mechanical suspensions:**
- attenuation > 360 dB at 1 kHz
- FEM modelled

**new capacitive transducer and s.c. transformer**
- two-modes (1 mechanical+1 electrical)
- optimized mass

**new amplifier:**
- double stage SQUID
- 200  \( \hbar \) energy resolution

**new data analysis:**
- C++ object oriented code
- frame data format
AURIGA II run (mid 2003): upgrades

- Single stage SQUID amplifier
- Double stage SQUID amplifier

Two-stage SQUID: $T_n(h) = 97 + 78T(K)$
Single stage SQUID: $T_n(h) = 1280 + 300T(K)$

Achieved same performances of SQUID amplifier after integration with the capacitive transducer

Talk by J. Zendri
Experimental flux noise spectral density

$\Phi_n (\Phi_0 \sqrt{\text{Hz}})$

- $T=0.9 \text{ K}$
- $\xi = 5.5 \hbar$

- $T=4.2 \text{ K}$
- $\xi = 28 \hbar$

Carelli et al. (‘98) ROG coll.
EXPLORER has been on the air since May 2000 with:
- new, 10 µm gap transducer
- new, high coupling SQUID

The noise temperature is < 3 mK (h=4.4 \times 10^{-19}) for 84% of the time.

Bandwidth: the detector has a sensitivity better than 10^{-20} Hz^{-1/2} on a band larger than 30 Hz

Talk by M. Visco
For ~ 80% of time the sensitivity to short gw bursts is better than $h=4.4 \cdot 10^{-19}$
NAUTILUS 2003

- $\nu_a = 935$ Hz
- new antenna suspension cable
- new capacitive transducer
- Quantum Design dc SQUID

The bar was cooled down to 3.5 K in April. Data taking is under way. Performances can be improved with system optimization.

Talk by M. Visco
NAUTILUS April 2001

Teff (K) - hourly averages

T\textsubscript{bar} = 1.5 K

3 mK

NAUTILUS 28-29 June 2003

Teff (K) - 1 minute averages

T\textsubscript{bar} = 3.5 K

3 mK

T\textsubscript{eff} (keV/in)

3 mK

2001

2003

1.3 mK
NAUTILUS spectral density at 3.5 K
June 2003

Expected spectral density at 0.15 K
Present Spherical Detectors Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Material</td>
<td>CuAl6%</td>
</tr>
<tr>
<td>Density $\rho$</td>
<td>8000 kg/m$^3$</td>
</tr>
<tr>
<td>Diameter $\Phi$</td>
<td>0.65 m</td>
</tr>
<tr>
<td>Mass $M$</td>
<td>1150 kg</td>
</tr>
<tr>
<td>Sound velocity $v$</td>
<td>4000 m/s</td>
</tr>
<tr>
<td>Resonant freq. $f$</td>
<td>3160 Hz</td>
</tr>
<tr>
<td>Short cool-down time</td>
<td></td>
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</table>
Advantages of a sphere

- Larger cross-section than a bar of the same frequency
- Omni-directional
- Determination of direction and polarization
All the "heavy" parts (cryogenic chambers, antenna vibration isolation system, and the antenna itself) are already assembled.

A couple of weeks ago: first cool down to 4.2 K failed due to a leak.

In the first cool the Q measurement of the antenna will be performed.
Two-mode parametric transducer with an oscillator phase noise = -131dBc @ 3.2kHz from the 10.21 GHz carrier. electrical Q ~ 1k mechanical Q ~ 1M at the moment intermediate mass = 53 g last mass = 0.01g HEMT pre-amplifiers. Expected sensitivity with this system = $10^{(-21)}$ Hz$^(-1/2)$ in a 50Hz bandwidth
Minimum temperatures:
\[ T_{\text{sphere}} = 80 \text{ mK} \]
\[ T_{\text{mc}} = 20 \text{ mK} \]

Heat leak: \( 45 \, \mu\text{W} \) from sphere

Time dependent heat leak due to ortho-para conversion of \( \text{H}_2 \) confined in micro-bubbles in the sphere (~50 ppm)

Expected temperature \( \sim 20 \text{ mK} \)
3-mode inductive transducer

- Flat, superconducting Niobium coil
- 2 stage SQUID
- In collaboration with Twente Univ.

Q > 1 million each, I₀ ~ 4 Amp, 170 hbar @ 4K

www.minigrail.nl
Talk by L. Gottardi
Sensitivity - 3 mode inductive transducer

Expected sensitivity \( h \sim 10^{-20} \)

Mass ratio – \( 10^{-3} \)

SQUID - quantum limit

\( T = 20 \) mK

\( Q = 10^7 \)
capacitive transducer

electrode

electrode support

resonator
capacitive transducer

Mass ratio – $10^{-3}$
SQUID - 700 hbar
$T = 20$ mK
$Q = 10^6$
Bursts

- ROG Coll.: Class. Quant. Grav. 18, 243 (2001)

Continuous signals

- ALLEGRO Coll.: Proc. 2nd E. Amaldi Conference 1997

Stochastic Background


Search for correlation with GRB’s


Effect of cosmic rays

ON times for the various detectors 1997-2003

- NIOBE: 200 d
- AURIGA: 221 d
- ALLEGRO: 852 d
- NAUTILUS: 831 d
- EXPLORER: 1036 d

Upgrade
Relocation
Upgrade
Upgrade
Upgrade
Network of the 5 bar detectors almost parallel

ALLEGRO NFS-LSU http://gravity.phys.lsu.edu
AURIGA INFN-LNL http://www.auriga.infn.it
NIOBE ARC-UWA http://www.gravity.pd.uwa.edu.au
EXPLORER INFN-CERN http://www.roma1.infn.it/rog/rogmain.html
NAUTILUS INFN-LNF
EXCHANGED PERIODS of OBSERVATION 1997-2000

fraction of time in monthly bins

- $H > 6 \cdot 10^{-21} \text{Hz}^{-1}$
- $3 + 6 \cdot 10^{-21} \text{Hz}^{-1}$
- $H < 3 \cdot 10^{-21} \text{Hz}^{-1}$

exchange threshold

$H$ is Fourier amplitude of burst gw

$h(t) = H \cdot \delta(t - t_0)$

arrival time
**UPPER LIMIT on the RATE of BURST GW from the GALACTIC CENTER DIRECTION**

Upper limit for burst GWs with random arrival time and measured amplitude \( \geq \) search threshold

\[ H \sim 2 \cdot 10^{-21} / \text{Hz} \leftrightarrow 0.02 M_\odot \text{ converted at Galactic Center} \]
EXPLORER-NAUTILUS 2001 data analysis

During 2001 EXPLORER and NAUTILUS were the only two operating resonant detectors, with the best ever reached sensitivity. A new algorithm based on energy compatibility of the event was applied to reduce the “background”

Corr. Coeff. = 0.96
(-0.19 on the 24 hours)

New data are needed for further considerations

Talk by M. Visco

ROG Coll.: CQG 19, 5449 (2002)
E. Coccia ROG Coll.: CQG Proc. Of GWDAW 2002
ROG Coll.: gr-qc/0304004
STOCHASTIC BACKGROUND

12 hours of data $\Delta f = 0.1$ Hz $S_{12} < 1 \times 10^{-44}$ Hz$^{-1}$
$\Omega_{GW}$ (920.2 Hz) < 60

- Will optimize overlapping bandwidth by acting on the bias E field
- Potential common band is $\sim 100$ x that exploited in `97.

With $T_{obs}$ of about 100 days, upper limit on $\Omega_{GW}$ less than unity can be achieved
Stochastic Background

• The cross-correlation of 6 months of NAUTILUS and AURIGA phase I, would put the limit $\Omega_{gw} \leq 0.1$ @ 935 Hz.

• Joint analyses with VIRGO - NAUTILUS and VIRGO - AURIGA II may put limits at the level $\Omega_{gw} \leq 3-5 \times 10^{-3}$ (1y integration $10^{-22}$ Hz$^{-1/2}$ @900 Hz for VIRGO)

• LIGO I ($10^{-22}$ Hz$^{-1/2}$ @ 1 kHz) and ALLEGRO ($2 \times 10^{-21}$ Hz$^{-1/2}$): $\Omega_{gw} \leq 0.1$ (1y of data, analysed at periods of 2-3 months).

• LIGO II ($10^{-23}$ Hz$^{-1/2}$ @ 1 kHz) and ALLEGRO ($10^{-22}$ Hz$^{-1/2}$): $\Omega_{gw} \leq 6 \times 10^{-4}$
Continuous waves

- ALLEGRO put upper limits \((4 \times 10^{-23} \text{ over } 1 \text{ Hz band})\) on signals from the GC and 47Tucanae using one month of data.
- Limit for signals in the GC, using 95 days of EXPLORER data \(h_c = 3 \times 10^{-24}\), in the range 921.32 - 921.38 Hz (ROG Coll.: *PRD*, 2002)
Continuous waves

Overall sky search

Phase I ended: 2 days of EXPLORER 1991 data analyzed in collaboration with A. Krolak & Collaborators put an upper limit of $h_c = 2 \times 10^{-23}$.

(10$^8$ points, by choosing spin-down parameter and position randomly) - CQG, proc. GWDAW 2002
Continuous waves

**Phase II ended**: collaboration with Krolak & C. and the Virgo Project Group in Rome. Two-day stretch of data disjoint from the two-day stretch analysed in the previous search.

Search done using the computers provided by the Virgo Project (March-May 2003). Number of candidates found: 29909.

Highest SNRS:
- Northern Sky=8.15
- Southern Sky=7.83

(99% confidence threshold is 8.3, none of the candidates exceeded this thrs.)

Comparison of candidates found in the two searches is now in progress.

The results of the search will be compared with those of an analysis done using the hierarchical search procedure, developed by the Virgo group of Rome, in collaboration with the ROG group (this work is now in progress). The aim is to analyze at least 1 year of data of EXPLORER and NAUTILUS.

**Phase III**: 2 more days of EXPLORER data is in progress.

[www.astro.uni.torun.pl/=kb/all-sky](http://www.astro.uni.torun.pl/=kb/all-sky) and [www.roma1.infn.it/rog](http://www.roma1.infn.it/rog)
Agreement between ROG and AEI Max Planck in Golm for the coherent analysis of data selected from 1 year of data of Nautilus 2001.
The data base of FFTs (17193 FFTs, 28 minutes each, in the format used by GEO/LIGO in their analysis) has been produced and is now in the cluster in Golm.
The procedures to veto the data is under studying.
Searches pointing at Globular Clusters, Galactic Plane...are in schedule.
Effect of cosmic rays

\[ h = 3 \times 10^{-22} \text{ Hz}^{-1/2} \]
\[ h_{\text{pulse}} = \Delta L/L = 4 \times 10^{-19} \]
\[ \Delta E = 2 \text{ mK} = 0.3 \mu\text{eV} \]

**Nautilus is equipped with 7 layers** (3 above the cryostat - area 36 m²/each - and 4 below - area 16.5 m²/each) **of Streamer tubes.**

<table>
<thead>
<tr>
<th>Period</th>
<th>NAUTILUS temperature (K)</th>
<th>Duration (hours)</th>
<th>nc</th>
<th>n</th>
<th>Rate(ev/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept-Dec 1998</td>
<td>0.14</td>
<td>2002</td>
<td>12</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Feb-July 2000</td>
<td>0.14</td>
<td>707</td>
<td>9</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>2709</td>
<td>21</td>
<td>0.89</td>
<td>0.178</td>
</tr>
<tr>
<td>Aug-Dec 2000</td>
<td>1.1</td>
<td>118</td>
<td>0</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Mar-Sept 2001</td>
<td>1.5</td>
<td>2003</td>
<td>1</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>2121</td>
<td>1</td>
<td>0.45</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Effect of cosmic rays

Talk by G. Mazzitelli
2 nested resonant masses
measure the differential deformation between the lowest quadrupolar modes

Talk by M. Bonaldi

- gw signals add
- back action noises subtract
2 nested resonant masses

Sensitive in a kHz-wide frequency band

Mo Dual
16.4 ton  height 2.3 m  Ø 0.94m
SiC Dual
62.2 ton  height 3 m   Ø 2.9m

T~0.1 K, Standard Quantum Limit

readout:
selects quadrupolar deformations
averages over a wide area

⇒ flat sensitivity in a wide band
The End
The displacement of the secondary oscillator modulates a dc electric or magnetic field or the frequency of a s.c. cavity.

\[ x_m = \sqrt{\frac{M}{m}} x_M \]
The rosette capacitive transducer; gap=$9\mu$m
Quantum technology

dc-SQUID

- superconducting loop with inductance $L$
- 2 Josephson junctions: critical current $I_o$, shunt resistance $R$, capacitance $C$
- Input inductance $L_{in}$, coupling $\alpha$
Eliminating the Vibration Noise in Continuously Filled 1 K Pots

A. Raccanelli, L. A. Reichertz, E. Kreysa

Max-Planck-Institut für Radioastronomie, auf dem Hugel 69, D-53121 Bonn, Germany

Abstract. We present a study on the origin of the vibrational noise originating from pumped helium chambers (1 K pots) that are continuously replenished from a main bath at 4.2 K. The vibrations can be eliminated by thermalizing the helium, coming from the main bath, to the pot temperature. Vibrations in 1 K pots are a source of excess noise in cryogenic detectors and therefore have detrimental consequences on their performance.

INTRODUCTION

1 K pots are small pumped helium chambers continuously replenished from a main bath at 4.2 K through a flow impedance. 1 K pots are often a necessary cooling step in continuously operating 3He-4He dilution refrigerators, that are commonly used to cool many different kinds of sensitive detectors to temperatures of a few mK, e.g., gravitational-wave antennas [1], bolometers for far-infrared radiation or high-resolution energy particle detection [2].

It is known that continuously filled 1 K pots are the source of vibrations that can result in electrical, thermal and mechanical noise [3]. Suggested solutions to the problem of vibrational noise in the 1 K pot include: either mechanical decoupling [2] of the experiment, or regulating the helium flow from the main bath and adjusting the helium level inside the 1 K pot itself [4].

These methods provide only a partial attenuation of the noise and not the elimination of its origin; in some experiments this may not be a sufficient solution.
Plastic scintillators

2 layers of 13 m²

1 layer of 6 m²
TARGET SENSITIVITY OF EXPLORER

- EXPLORER can reach a sensitivity of $T_{\text{eff}} = 150 \mu K \ h = 1 \cdot 10^{-19} \text{ -bandA}$

- New transducer double gap
- New transformer higher elect. Q
- New SQUID lower noise

![Graph showing target sensitivity](image)
Transducer location (TIGA)