Status and Plans for Future Generations of Ground-based Interferometric Gravitational-Wave Antennas

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2. Advanced Technology
   (Seismic Noise and Thermal Noise)
1. Status and Future Plan
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Interferometric GW Detector

LIGO

GEO

VIRGO

EURO

Upgrade

Advanced LIGO

LIGO

AIGO

TAMA

LCGT
Evolution of Interferometric GW Detectors

Current Generation
- Seismic Noise
- Shot Noise
- Thermal Noise

3rd Generation
- Radiation Pressure Noise
- Shot Noise

5th Generation
- Beyond SQL

2nd Generation
- Seismic Noise
- Thermal Noise
- Shot Noise

4th Generation
- Standard Quantum Limit
Significance of Seismic Isolation

Ground

Isolation System

Mirror

Large Motion

Small Motion

Frequency [Hz]

Displacement

0.1 1 10 100

Improve control noise, lock acquisition, and lock stability

Improve seismic noise directly

Ground

Mirror
Examples of Control Noise

Displacement noise level of TAMA300 (June 2, 2001)

- Seismic noise
- Alignment noise
- L-feedback noise
- Detector noise
- Michelson noise
- Frequency noise
- Intensity noise
- L-Filter noise

Control System

Loop Gain

Frequency

More attenuation

Control noise imposed

Control Force (Length/Alignment)

Mirror
More Isolation

More stages

Isolation System

Ground

Mirror

Lower resonant frequencies

Potential Energy

Original

Resultant

Anti-spring

Displacement
Super-attenuator (VIRGO)

Inverted pendulum

Magnetic anti-spring
Performance of Super-attenuator

- Recycled short-Michelson locked
- $10^{-11}$ m/Hz$^{1/2}$ at 2Hz
SAS
(LIGO-TAMA Collaboration)

- 3m FP cavity locked (Takamori et al.)
- To be installed in TAMA in 2004

Geometrical anti-spring
(DeSalvo et al.)
Multiple Pendulum

- Triple Pendulum used for GEO
- Quadruple pendulum developed for LIGO2
Underground Site

Mitaka Site (Ground-based)

Kamioka Site (Underground)

Kamioka

220km

Tokyo (NAOJ)
LISM (20m Prototype in Kamioka) and TAMA300

<table>
<thead>
<tr>
<th></th>
<th>TAMA300</th>
<th>LISM (Sato)</th>
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<tbody>
<tr>
<td>Maximum Continuous Locking</td>
<td>24 hours (summer 2001)</td>
<td>170 hours (Spring 2001)</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>86% (for the 2001 summer run)</td>
<td>99.8% (for the last week of 2001 summer run)</td>
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Thermal-related Noise

Solutions:
- Low Thermal expansion

Thermoelastic noise by Thermodinamic fluctuations
(Braginsky, et al.)

Pendulum thermal noise

Solutions:
- Low-loss material
- Low-loss fabrication
- Cryogenic temperature

Thermoelastic noise by Photothermal fluctuations
(Braginsky, et al.)

Internal mode thermal noise
Monolithic Suspension

Low pendulum thermal noise

- Weld and Silicate bonding used for GEO
  - Low loss in fiber itself
  - Low loss at the release point
Sapphire at Cryogenic Temperature

- **kT-energy**: low
- **Quality factor**: high (Uchiyama, et al.)
- **Thermo-elastic noise**: low (Cerdonio, et al.)
  - Thermal expansion rate: low
- **Thermal lensing**: negligible (Tomaru, et al.)
  - Thermal conductivity: high (20k-30k)
  - $dn/dT$: small
Issues on Cryogenic Technologies

- Seismic Isolation compatible with cryogenic
- Contamination of mirrors (Miyoki, et al.)
- Required cooling time
- Heat link
- Reduction of power dissipation
  - Improve absorption loss
  - Resonant sideband extraction
Resonant Sideband Extraction

Lower power at BS and front mirrors
⇒ Less heat produced

PRFPMI
- High power recycling gain
- Low finesse cavity

RSE
- Low power recycling gain
- High finesse cavity

Signal Extraction Mirror

Detuning possible by shifting SEM
Features of Advanced LIGO

- Reasonable and significant improvement from Initial LIGO on all the aspects
- A large number of scientists working on R&D
- Collaboration with GEO, VIRGO, ACIGA, TAMA
- Most matured among all the advanced detectors
Current Status and Plan of LIGO

- Intensive R&D going on
- Construction funding proposal late 2002
- Could be funded by early 2005
- Installation of new detectors starting in as early as 2006
Features of LCGT

- Cryogenic
- To be located in the Kamioka mine
- Arm length: 3km
- SAS (DeSalvo)
- RSE (Mizuno)
- Suspension-point interferometer (Drever)?
Suspension Point Interferometer

- Reduce vibration caused by the heat link; verified by experiment (Aso, et al.)
- Possibility of implementing low-frequency (lower cavity) and high-frequency (higher cavity) interferometers (Aso)
Aimed Sensitivity of LCGT

![Graph showing the noise budget of LCGT with different noise types including shot noise, radiation pressure noise, thermal noise, and seismic noise. The graph displays the sensitivity versus frequency, with a log-log scale.]
Current Status and Plan of LCGT

- Four-year budget approved for R&D (and observation and modification of TAMA)
- Various R&Ds going on
- Design efforts going on
- Aiming at obtaining the budget in 2005
Test of Technologies for LCGT

- SAS – @ TAMA (with LIGO)
- RSE – @ 40m, Caltech (with LIGO and GEO)
- High Power Laser - @ TAMA? (with ACIGA)
- Cryogenic technology – @ CLIO
CLIO - Prototype for LCGT

100m Cryogenic prototype in Kamioka mine
- Construction to be started very soon
AIGO

- Currently 80m testbed for high power (Collaboration with LIGO) and for advanced suspension with Euler spring and Nb flexures
- Eventually extended to a km-class advanced detector
Upgrade of GEO

- All reflected configuration with Silicon optics (Low-loss diffractive structure, low mechanical loss: to be investigated very soon)
- Initially cooled to 120k? (No thermo-elastic noise because of zero expansion coefficient)
- high-power YAG lasers (200 W)
- Non-classical light sources
- Upgrade takes place in 2006-9
EURO
(European Future Detector)

• Conceptual design being/will be discussed including the following possibilities:
  - Cryogenic at 4K?
  - Underground?
  - SQL limited sensitivity for 1 ton Silicon?
• Input from the results of the current-generation and the 2nd generation of detectors
• Starting not before 2008?
DECIGO
(Deci-hertz Interferometer Gravitational Wave Observatory)

- Candidate for Japanese space antenna project with shorter arm length
- One of the scientific objectives: measure the acceleration of the expansion of the Universe (Seto, et al. PRL)
- DECIGO-WG convened in 2002; currently 80 members

![Graph showing sensitivity comparison between DECIGO, LISA, and Terrestrial Detectors.]

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Strain [Hz]</th>
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<tbody>
<tr>
<td>$10^{-24}$</td>
<td>$10^{-22}$</td>
</tr>
<tr>
<td>$10^{-20}$</td>
<td>$10^{-18}$</td>
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<tr>
<td>$10^{-16}$</td>
<td>$10^{-14}$</td>
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<tr>
<td>$10^{-12}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>$10^{-2}$</td>
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![Diagram illustrating the detection of gravitational waves with DECIGO.]

- Expansion + Acceleration?
- NS-NS (z≈1)
- GW
- Output

Template (No Acceleration)

Real Signal?

Time

Phase Delay≈ 1 sec (10 years)
Conclusions

- Various levels of advanced detectors being developed/studied/considered
- Various kinds of new technologies to reduce noise already developed/being/will be developed
- Various levels of international collaboration going on to aim at international detector network
- These efforts will bring us to the establishment of GW astronomy in the future