DECIGO and DECIGO Pathfiner

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National Astronomical Observatory of Japan
on behalf of DECIGO Working Group

GWADW2011 in Isola d’Elba, Italy (24 May 2011)
Contents

1. DECIGO
2. DECIGO Pathfinder (DPF)
3. Summary

Some of the viewgraphs are owing to S. Kawamura, M. Ando, and other members of DECIGO Working Group.
Roadmap to GW astronomy of Japan

Detecting GW
International network

Opening a new window
(after LISA)
1. DECIGO

2. DECIGO Pathfinder (DPF)

3. Summary
Deci-hertz interferometer gravitational-wave observatory

- "bridge" the gap between LISA and terrestrial detectors
- Observation band: 0.1~10Hz
- Space GW antenna

![Graph showing frequency and strain levels for DECIGO and other detectors.](image)
**Design (pre-conceptual)**

- **Interferometer Unit**
  - **Differential Fabry-Perot interferometer**
    - Baseline length: 1000 km
    - 3 S/Cs formation flight
    - 3 FPs (finesse: ~10)
    - Drag-free control

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm length</td>
<td>1000 km</td>
</tr>
<tr>
<td>Finesse</td>
<td>10</td>
</tr>
<tr>
<td>Mirror diameter</td>
<td>1 m</td>
</tr>
<tr>
<td>Mirror mass</td>
<td>100 kg</td>
</tr>
<tr>
<td>Laser power</td>
<td>10 W</td>
</tr>
<tr>
<td>Laser wavelength</td>
<td>532 nm</td>
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</table>
**Orbit and constellation**

- **Candidate Orbit**
  - Record disk around the sun

- **Constellation**
  - 4 interferometer units
    - 2 overlapped units → Cross correlation
    - 2 separated units → angular resolution
Science by DECIGO

Verification of inflation

- Correlation (3 years)
- Inflation ($\Omega_{GW} \sim 2 \times 10^{-16}$)
- BH binary (1000 $M_\odot$ $z=1$) Coalescence
- NS binary ($z=1$) Coalescence
- 5 years
- 3 months
- 1 cluster

Strain [Hz$^{-1/2}$]

Frequency [Hz]

- Strain $\approx 10^{-3}$ to $10^{-24}$
- Frequency $10^{-3}$ to $10^3$

- Mini-black hole $\downarrow$ Dark matter
- Brans Dicke parameter
- Acceleration of Universe $\downarrow$ Dark energy

- Formation of super-massive BH
- Verification of inflation

GWADW2011 in Isola d’Elba (24 May 2011)
Requirements

Sensor Noise
- Shot noise: $3 \times 10^{-18} \text{ m/Hz}^{1/2}$ (0.1 Hz)
- $\Rightarrow x 10$ of LCGT in phase noise

Other noises should be well below the shot noise
- Laser freq. noise: $1 \text{ Hz/Hz}^{1/2}$ (1 Hz)
- Stab. Gain $10^5$, CMRR $10^5$

Acceleration Noise
- Force noise: $4 \times 10^{-17} \text{ N/Hz}^{1/2}$ (0.1 Hz)
- $\Rightarrow x 1/50$ of LISA

External force sources
- Fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.
## Roadmap

<table>
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<tr>
<th>Mission</th>
<th>Objective</th>
<th>Design</th>
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<tbody>
<tr>
<td>R&amp;D Fabrication</td>
<td>Space test of key tech. GW observation</td>
<td>Single small satellite</td>
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<tr>
<td></td>
<td></td>
<td>Short FP interferometer</td>
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<tr>
<td>R&amp;D Fabrication</td>
<td>Detect GW with min. spec FP between S/C</td>
<td>3 S/C</td>
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<tr>
<td></td>
<td></td>
<td>1 interferometer unit</td>
</tr>
<tr>
<td>R&amp;D Fabrication</td>
<td>GW astronomy</td>
<td>3 S/C</td>
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<tr>
<td></td>
<td></td>
<td>x 3-4 units</td>
</tr>
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</table>

### Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>2010</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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<th>28</th>
<th>29</th>
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<tr>
<td>SDS-1/ SWIM</td>
<td>DECIGO Pathfinder (DPF)</td>
<td>Pre-DECIGO</td>
<td>DECIGO</td>
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**DECIGO Pathfinder (DPF)**

**Pre-DECIGO**

**DECIGO**
DECIGO interim organization

**PI:** Kawamura (NAOJ/ICRR)
**Deputy:** Ando (Kyoto)

**Executive Committee**
Kawamura (NAOJ/ICRR), Ando (Kyoto), Seto (Kyoto), Nakamura (Kyoto), Tsubono (Tokyo), Sato (Hosei), Tanaka (Kyoto), Funaki (JAXA/ISAS), Numata (Maryland), Kanda (Osaka City), Ioka (KEK), Takashima (JAXA/ISAS), Yokoyama (Tokyo)

**Pre-DECIGO**
- **Detector**
  - Sato (Hosei)
- **Science & Data**
  - Tanaka (Kyoto)
  - Seto (Kyoto)
  - Kanda (Osaka City)

**Spacecraft**
- Funaki (JAXA/ISAS)

**Mission Phase**
- **DECIGO Pathfinder**
  - Leader: Ando (Kyoto)
- **Detector**
  - Sato (Hosei)
  - A. Ueda (NAOJ)
  - Aso (Tokyo)
- **Laser**
  - Musha (E.C.)
  - K. Ueda (E.C.)
- **Drag-free**
  - Moriwaki (Tokyo)
  - Sakai (JAXA/ISAS)
- **Thruster**
  - Funaki (JAXA/ISAS)
- **Signal Process**
  - Akutsu (NAOJ)
- **Bus**
  - Takashima (JAXA/ISAS)
- **Data**
  - Kanda (Osaka City)
Collaborations and supports

- Supports from LISA
  - Technical advices from LISA/LPF experiences
  - Support Letter for DECIGO/DPF, Joint workshop (2008.11)

- Stanford univ. group
  - Discharge system for DPF, other R&D for DECIGO

- NASA
  - Fiber laser, Joint observation with GRACE

- JAXA Navigation-control section
  - Formation flight of DECIGO, DPF drag-free control

- Research Center for the Early Universe (RESCEU), Univ. of Tokyo
  - supports DECIGO as one of main projects (2009.4-)

- Geo-gravity field group (Kyoto, ERI, UEC, NAOJ)
  - Geophysics by DPF obs. data

- Advanced Technology Center (ATC) of NAOJ
Calculating the sensitivity

- Arm length: 1,000 km
- Laser power: 10 W
- Laser wavelength: 532 nm
- Mirror diameter: 1.0 m
- Mirror mass: 100 kg
- Mirror reflectivity: 77.3%
- Cavity g-param: 0.1

To detect stochastic GWs and observe the early universe, we should clean off any “foreground GW sources.”

Tune the parameters a little bit to improve the sensitivity more (~ 3 times more) in the obs. freq. band.

Preliminary!!

GWADW2011 in Isola d’Elba (24 May 2011)
Considering “Conceptual design”

- Arm length: 1,500 km
- Laser power: 30 W
- Laser wavelength: 532 nm
- Mirror diameter: 1.5 m
- Mirror mass: 100 kg
- Mirror reflectivity: 77.3%
- Cavity g-param: 0.1

This is the first step to considering the conceptual design.

Next:
⇒ Confirm the calculations.
⇒ Find the realistic way to realize this!

Parameters tuned

Strain Sensitivity [Hz^{-1/2}]

Frequency [Hz]

CGI Program by Numata
1. DECIGO

2. DECIGO Pathfinder (DPF)

3. Summary
### DECIGO Pathfinder in the roadmap

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<td>Detect GW with min. spec FP between S/C</td>
<td>3 S/C 1 interferometer unit</td>
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<td>2012</td>
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<td>GW astronomy</td>
<td>3 S/C x 3-4 units</td>
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<tr>
<td>2013</td>
<td>DECIGO</td>
<td></td>
<td></td>
<td>R&amp;D Fabrication</td>
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</table>
DECIGO Pathfinder (DPF)

First milestone mission for DECIGO
Shrink arm cavity
DECIGO 1000km → DPF 30cm

Single satellite
(Payload ~1m³, 350kg)
Low-earth orbit
(Altitude 500km, sun synchronous)

30cm FP cavity with 2 test masses
Stabilized laser source
Drag-free control
**DPF Satellite design**

**DPF Payload**
- Size: 950mm cube
- Weight: 150kg
- Power: 130W
- Data Rate: 800kbps
- Mission thruster x12

**Power Supply**
- SpW Comm.

**Satellite Bus**
- ('Standard bus' system)
- Size: 950x950x1100mm
- Weight: 200kg
- SAP: 960W
- Battery: 50AH
- Downlink: 2Mpbs
- DR: 1GByte
- 3N Thrusters x 4
DPF mission payload

Mission weight: ~150kg
Mission space: ~95 x 95 x 90 cm

Drag-free control
Local sensor signal
→ Feedback to thrusters

Laser source
Yb:YAG laser (1030nm)
Power: 25mW
Freq. stab. by Iodine abs. line

Fabry-Perot interferometer
Finesse: 100
Length: 30cm
Test mass: ~a few kg
Signal extraction by PDH

Fig. by Ando
DPF sensitivity

- Noise level: $h \sim 2 \times 10^{-15}$ strain/rtHz
- Limited by laser frequency noise and acceleration noise

Parameters are preliminary.

- Cavity length: 30 cm
- Laser: 1030 nm, 25 mW
- Finesse: 100
- Mirror mass: 1 kg
- Q-value of a mirror: $10^6$
DPF Requirements

Sensor Noise
- Disp. noise: $6 \times 10^{-16} \text{ m/Hz}^{1/2}$ (0.1 Hz)
- x 200 of DECIGO in disp. noise

Other noises
- Laser freq. noise: $0.5 \text{ Hz/Hz}^{1/2}$ (1Hz)

Acceleration Noise
- Force noise: $1 \times 10^{-15} \text{ m/s}^2/\text{Hz}^{1/2}$ (0.1 Hz)
- x 250 of DECIGO

Satellite motion
- Disp. noise: $1 \times 10^{-9} \text{ m/Hz}^{1/2}$ (0.1 Hz)

External force sources: Residual gas damping, fluctuation of magnetic field, electric field, gravitational field, temperature, pressure, etc.
Blackholes events in our galaxy

**IMBH inspiral and merger**

\[ h \sim 10^{-15}, f \sim 4 \text{ Hz} \]

Distance 10kpc, \( m = 10^3 M_{\text{sun}} \)

Obs. Duration (~1000 sec)

**BH QNM**

\[ h \sim 10^{-15}, f \sim 0.3 \text{ Hz} \]

Distance 1Mpc, \( m = 10^5 M_{\text{sun}} \)

Observable range covers our Galaxy (SNR~5)

Hard to access by others → Original observation
Measure gravity field of the Earth from Satellite Orbits, and gravity-gradiometer

An example.

GPS satellite

Determine global gravity field
$\rightarrow$ Density distribution

Monitor of change in time
Ground water motion
Strains in crusts by earthquakes and volcanoes

By Araya and Fukuda

NASA’s mission
GRACE FO (2016-2021?)

$\Rightarrow$ DPF contribution (2017?) in international network
R&D for DPF subsystems

- Frequency-stabilized laser
- Electrostatic sensor/actuator
- Test mass module
- Laser sensor
- Interferometer (monolithic optics)
- Drag-free model
- Signal processing and control in space
- Low noise thruster

Photo by JAXA
Test mass module (Inertial sensor)

Subsystem of Interferometer module

Prototype experiment of individual functions

- Req. of local sensor noise (capacitive sensor)

Controlling motions of a suspended test-mass with electrostatic actuators

Design & Analysis

- FEM analysis (electrostatic)

To meet the requirements of:
Noise of Capacitive sensors, Range of Electrostatic Actuators, and Electrostatic Stiffness

Design

Manufacture & Functional test

Figs by Ejiri

Figs by R. Suzuki
Interferometer module

❖ Monolithic optics
   (as input optics)

Why monolithic?
➡ To survive the shocks during launch.
➡ To prevent optical path from fluctuating in space
➡ etc...

Demonstration:
➡ With the optics,
   a FP cavity can be in operation
   (30cm long, same as DPF’s)

Fig by Michimura
Interferometer module (contd.)

Structure

Assemble every component to one module

- Components: test-mass modules, optics, electronics, optical fibers and metal wires, dynamic mechanisms, robust chassis,...
**SWIM**\(\mu\nu\) --- *Mission Successfully Completed!!*

- **SWIM**\(\mu\nu\): tiny **space GW sensor** (torsion type)
- **SWIM** (one of the missions of JAXA’s **Small Demonstration Satellite-1**) = **SWIM**\(\mu\nu\) + **new satellite technology**
  - space-qualified computers, signal processing systems etc.
- **Design sensitivity:** \(1e^{-6} \text{ rad/rtHz (0.1-1Hz) in space}\)

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**TAM:** Torsion Antenna Module with free-falling test mass
(Size: 80mm cube, Weight: \(~500g\))

**Test mass**
- \(~47g\) Aluminum, Surface polished
- Small magnets for position control

**Photo sensor**
- Reflective-type optical displacement sensor
- Separation to mass \(~1\text{mm}\)
- Sensitivity \(~10^{-9}\ \text{m/Hz}^{1/2}\)
- 6 PSs to monitor mass motion

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Launch photo on January 23, 2009

*photo by JAXA*
Taking data together with terrestrial detectors

Now data analysis is ongoing!!

Details:
Ando’s talk tomorrow (May 25)
Funding status of DPF

DPF: One of the candidate of JAXA’s **small satellite series**

- At least 3 satellites in 5 years with **Standard Bus** + M-V follow-on rocket
- 1st mission (2012): SPRINT-A/EXCEED
- 2nd mission (~2013/14): ERG
- DPF survived until final two
- 3rd mission (2016/17?): TBD

**DPF is one of the strongest candidates of the 3rd mission**
1. DECIGO

2. DECIGO Pathfinder (DPF)

3. Summary
DECIGO: Fruitful Sciences

Very beginning of the Universe
Dark energy
Galaxy formation

DECIGO Pathfinder

Important milestone for DECIGO
Strong candidate of JAXA’s satellite series

SWIM – Mission successfully completed!!
first precursor to space!
END