The current status of contribution activities in Japan for LISA

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LISA is a space gravitational-wave mission that will open the unexplored gravitational-wave frequency window at around millihertz, shedding light on the study of supermassive black holes and the nature of gravity. The LISA project has been propelled by international collaboration in order to maximize the scientific outcome. With the aim of making scientifically important contributions to LISA, instrument and science groups were newly formed in Japan. This article summarizes the current status of the contribution activities conducted by each group to date, highlighting a few selected topics including the development of photoreceivers and theoretical studies on compact binaries and extreme mass ratio inspirals.
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Subject Index   E02, F30, F31

1. Introduction

LISA (Laser Interferometer Space Antenna) is an international full-scale space gravitational-wave (GW) mission led by ESA [1]. LISA is going to explore the gravitational Universe by observing gravitational waves radiated from astrophysical and cosmological sources which would not easily be accessed by either electromagnetic wave observations or ground-based gravitational wave observations. LISA is expected to provide new insights into the origin of supermassive black holes and the nature of gravity in the vicinity of black hole horizons and on cosmological scales.

LISA deploys three spacecraft forming an equilateral triangular constellation, where laser signals are exchanged between the spacecraft with a laser link distance of nominally 2.5×10^9 m, in a heliocentric orbit with a retardation from the Earth of $20°$ or so. The launch date is nominally set for the year 2034. The observations will cover the mHz frequency band from 0.1 mHz to 100 mHz, within which a rich variety of gravitational wave sources are expected, including the coalescence of supermassive black holes, inspiraling galactic binaries, extreme mass ratio inspirals (EMRIs), and other cosmological sources [2].

Prior to the proposal of the LISA mission as an ESA L3 mission, the technology demonstration satellite LISA Pathfinder [3] was launched in 2015. LISA Pathfinder demonstrated the validity of a number of key hardware components and functionalities directly relevant to LISA with the achievement of acceleration noise of 1.7 fm s^{-2} Hz$^{-1/2}$ above 2 mHz [4,5], surpassing the requirement for LISA. The success of LISA Pathfinder subsequently allowed the LISA project to focus on other technological studies and developments which had not fully been addressed by LISA PathFinder. Major parts of the developments and studies include the hardware necessary for intersatellite interferometry, astrophysical and cosmological studies, and analysis methodologies.

In response to the call for applications for LISA consortium membership, two groups from Japan began participating in the consortium with the goal of making significant scientific contributions to LISA in 2018. The first group, the *Japan instrument group*, consists of experimentalists aiming to develop and provide a set of hardware relevant to long-range intersatellite interferometry. The other group, the *Japanese working group for LISA science*, consists of theorists chiefly studying compact star binaries and EMRIs. The science group carries out research activities as associate members of the LISA consortium. This article presents an overview and details of the contribution activities conducted by each group to date.

2. Instrument contribution activities

The Japan instrument group initially proposed to contribute to developing and providing flight hardware including the photoreceivers [6] and the low-vibration signal harnesses. In addition, the group recently began considering the possible development of active aperture mechanisms to minimize the tilt-to-length coupling [7]. In this article the focus is particularly on the development of the photoreceivers, which has seen substantial effort in the past year.

2.1. Overview of photoreceivers

The photoreceivers are optoelectronic devices that receive intensity-modulated laser light in the MHz frequency band and subsequently convert it into voltage signals with an amplification gain. They will be used for detecting optical phase variations in the long-arm and other local interferometers. Therefore, the photoreceivers are the heart of the heterodyne interferometry critical for LISA to be able to achieve its scientific goals. In order to preserve a high signal-to-noise ratio, the transimpedance amplifier must be directly attached to the photoreceiving element or the photodiode.

A summary of the characteristics and requirements is shown in Table 1. The photoreceiving unit, an InGaAs PIN photodiode, has to be segmented into four pieces because the photoreceivers are required to have two sensing functionalities: heterodyne interferometry for the optical phase, and differential wavefront sensing [8,9].

The requirement on the frequency response comes directly from the fact that the distances between the spacecraft vary by typically 1% [10]. Such variations consequently shift the heterodyne frequency via the Doppler effect, requiring the photoreceivers to be able to respond in the wide frequency range

Table 1. Summary of the characteristics and requirements for the photoreceivers. The numbers displayed here may change as the mission and instrument designs become more concrete and precise.

Parameter	Characteristic or requirement
Laser wavelength	1064 nm
Photoreceiving element	InGaAs PIN diode, four-segmented
Size of active area	1 mm in diameter or larger
Frequency response	5–25 MHz, flat in magnitude
Input-referred current noise	2 pA Hz$^{-1/2}$ at 5–25 MHz
Power consumption	Less than 50 mW per segment

from 5 to 25 MHz. A stringent requirement of 2 pA Hz$^{-1/2}$ is set on the input-referred current noise to make the readout electronic noise subdominant against the optical shot noise from laser light of 100 μW [6]. Finally, the requirement on the power consumption is placed in order not to introduce a large amount of heat to the optical bench because it must serve as a stable platform against possible thermal deformation.

2.2. Development of photoreceivers

A major challenge in the development is to satisfy the requirements on the frequency response and current noise at the same time. In general, a segment of the four-segmented photodiode is connected to an active transimpedance amplifier such as those consisting of op-amps and transistors [11,12]. On the other hand, the designers have to take great care over noise introduced by the active components. The most vexing noise contribution for high-frequency applications is the one sometimes referred to as $e_n C$ noise [13], which arises due to the input voltage noise of the amplifier being converted to current noise via the junction capacitance of the photodiode, C_d. Its contribution to the input-referred current noise can be estimated as

$$i_n^{(e_n)} = \mathrm{i}\,\omega C_d e_n, \tag{1}$$

where ω is the Fourier angular frequency and e_n represents the input voltage noise of the amplifier. For white voltage noise, the resultant noise spectral density monotonically increases in proportion to the frequency ω. Substituting a voltage noise of 2 nV Hz$^{-1/2}$, a typical value for good op-amps, into e_n, one finds the current noise to be too high at $i_n^{(e_n)} = 5$ pA Hz$^{-1/2}$ at 25 MHz for a junction capacitance of 15 pF. In order to reduce the contribution of the $e_n C$ noise, two independent approaches are possible according to Eq. (1): reduction of C_d and reduction of e_n.

For this reason, the Japan instrument group has split the development program into two. One part is to pursue the development of an InGaAs PIN photodide with a low junction capacitance, preferably lower than 10 pF. The other is to design a low-noise amplifier that meets the bandwidth and noise requirements simultaneously. Note that reducing the size of the active area below 1 mm in diameter will also reduce C_d, but this solution is not preferred because it would make the design and implementation of the optical bench challenging in terms of minimizing the tilt-to-length coupling.

2.3. Current status and prospects

A research and development program in collaboration with Hamamatsu Photonics K.K. has begun to investigate the possible production of InGaAs PIN photodiodes with a low capacitance while
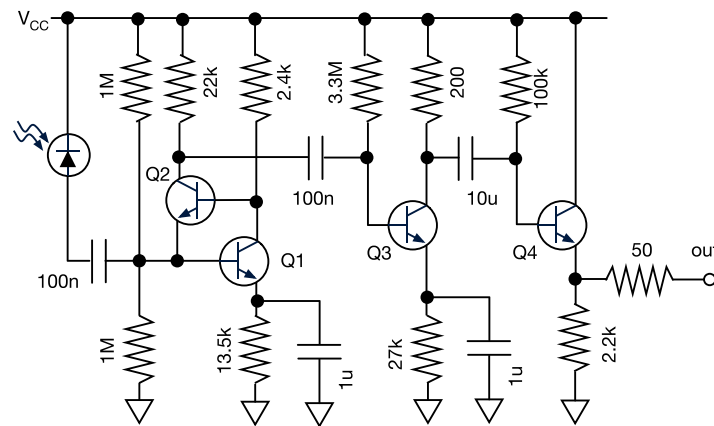
Fig. 1. First design of the prototype transimpedance amplifier. The transistors Q_1 through Q_4 are BFP842ESDs. The supply voltage is set to $V_{cc} = 5$ V, which also serves as a bias voltage across the photodiode.

maintaining a large active area. At the same time, a design study and development has been initiated for a low-noise transimpedance amplifier based on a printed circuit board (PCB) populated with discrete electronic components.

A batch of the first InGaAs test samples was produced using a high-purity semiconductor wafer as a first step. The diameter of the active area was set to 1 mm and the InGaAs element was accommodated in a TO-5 package without a window. An antireflection coating was applied to the surface of the photodiodes to reduce the reflection loss for 1064 nm.

A measurement of the junction capacitance with the first samples showed a successful reduction of the junction capacitance by 1–2 pF for each segment compared with commercially available products. However, this is not sufficient to achieve a junction capacitance of 10 pF or below for a diameter of 1 mm or larger. Therefore, the adoption of alternative solutions is currently being considered, such as the use of a thick intrinsic layer [14] in addition to high-purity wafers.

In parallel to the InGaAs development, a first prototype of a transimpedance amplifier based on a PCB was built. A schematic of the circuit is sketched in Fig. 1. The circuit employs BFP842ESDs [15], a SiGe:C heterojunction bipolar transistor, inspired by the previous work by Barranco et al. [16]. Our circuit design features the use of a regulated cascode (RGC) [13] as the first amplifier stage in order to isolate the junction capacitance from the rest of the circuit. The RGC stage is then followed by a common-emitter stage with a voltage gain of approximately 0 dB, and is finally followed by an emitter follower to convert the output impedance to 50 Ω with 0 dB amplification gain. Figure 2 shows the preliminary result for the frequency response measurement, successfully achieving the required bandwidth. The measurement was performed with voltage signals injected into the input of the transimpedance amplifier, with an extra capacitance of 15 pF deliberately inserted at the input to simulate the effect of the junction capacitance (not shown in Fig. 1). The bandwidth is primarily limited by the capacitance associated with the collector of the Q_2 transistor, forming an RC low-pass filter together with the 22 kΩ resistor.

The noise measurement of the transimpedance amplifier, on the other hand, has been suffering from undesired oscillations at around 50 MHz, which presumably agitates the operating points of the transistors and thus prevents us from making repeatable measurements. This issue is currently being followed up by building another circuit with the same topology in order to identify the cause of the oscillation. Additionally, a shortcoming of the circuit topology was identified to be the poor
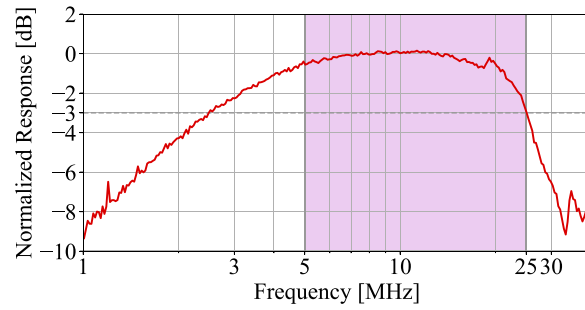
Fig. 2. Preliminary results of the response measurement with the first prototype. The area shaded in magenta indicates the required frequency band. The measurement was performed with voltage signals injected into the input of the transimpedance amplifier, with a capacitance of 15 pF inserted at the input. The cause of the small resonance at around 20 MHz is not fully understood at the moment.
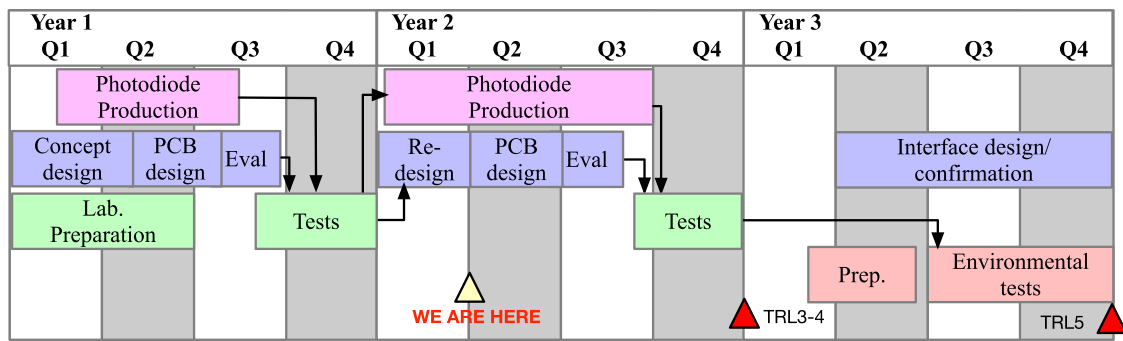

Fig. 3. The development schedule for the photoreceivers. The boxes are arranged from the top in the order of photodiode development, transimpendance amplifier development, laboratory experiments, and environmental tests. The red triangles indicate the goal milestones.

stability of the amplification gain in the second and last amplification stages because they rely on the transistor's gain or h_{fe}. Our plan is to provide a feedback path connected to the Q_2's collector [17] such that the transimpedance gain depends much less on the transistors' gains.

The development of the photoreceivers was proposed as a three-year project. The schedule is sketched in Fig. 3. The project has already completed the first year and is currently at the end of the first quarter of the second year. In the second year, the production of a second InGaAs test sample is expected to be conducted in collaboration with Hamamatsu Photonics. In the meantime, the development of the transimpedance amplifier continues, with the goal of reaching a technical readiness level (TRL) of 3 or 4 by the end of the year. The third year is planned to be dedicated to a set of environmental tests, including vibration, irradiation, and thermal cycles.

3.   Science contribution activities

In the Astro2020 white paper for the LISA mission [18], eight science objectives (SOs) are shown:

- SO1: Study of the formation and evolution of compact binary stars in the Milky Way
- SO2: Trace the origin, growth, and merger history of massive black holes
- SO3: Probe the dynamics of dense nuclear clusters using EMRIs
- SO4: Understand the astrophysics of stellar-origin black holes
- SO5: Explore the fundamental nature of gravity and black holes
- SO6: Probe the rate of expansion of the Universe

- ○ SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- ○ SO8: Search for GW bursts and unforeseen sources.

The activity of the Japan working group for LISA science as an associate member will contribute mainly to SO1, SO3, and SO4.

3.1.   *Study of Galactic/extra-Galactic compact binaries*

Compact binaries consisting of stellar-mass compact objects (like white dwarfs or neutron stars) with orbital periods of $\lesssim 1$ hr, so-called "ultra-compact binaries (UCBs)" emit gravitational waves in the mHz frequency band [19]. Several UCBs have already been found in the Galaxy by electromagnetic observations [20]. Extrapolation of these binaries predicts that there are tens of thousands of UCBs in the Galaxy. During LISAs observation, $O(10^4)$ UCBs above ~ 1 mHz are expected to be resolved individually [21]. Measurement of the masses, orbital parameters, and locations of the resolvable binaries will provide insights into the formation and evolution of compact binaries. Multi-messenger observation with electromagnetic telescopes (e.g. the Square Kilometre Array) will provide more information to gain a deeper understanding of compact binaries [22].

On the other hand, most UCBs are unresolvable and form confusion noise below ~ 1 mHz. Even the confusion noise can provide information on the spatial distribution of UCBs because the orientational dependence of the LISA sensitivity induces an annual modulation of the confusion noise level [19].

Compact binaries with stellar-mass black holes outside the Galaxy are also important sources for LISA. Such binaries will be observed in the kHz band by ground-based detectors a few years after they are found in the mHz band by LISA. Multi-band observation will enable us to forecast GW events for observation in the kHz band and to improve the parameter estimation of the binaries [23].

3.2.   *Development of model and waveform for EMRIs*

An EMRI is a phenomenon where a stellar-mass compact object (1–$100\,M_\odot$) orbits a massive black hole in the central nucleus of a galaxy and is eventually drawn into the hole. The general orbit of an EMRI is very complicated due to several general relativistic effects, such as orbital precessions, spin–orbit and spin–spin couplings, and gravitational radiation. The complication results in a rich structure of gravitational waveforms characterized by three fundamental frequencies. Since EMRIs last dor a long time in the mHz band, tens of thousands of wave cycles will be observed during the LISA mission, which will enable us to measure the spacetime structure near black holes and to test general relativity.

To reach this objective, we need to predict the theoretical waveforms from EMRIs accurately. Black hole perturbation theory is suitable for investigating the dynamics of EMRIs and the gravitational waves emitted, because of the extreme mass ratio. In the framework of this theory, an EMRI is modeled as a particle moving in black hole spacetime. To accurately predict the gravitational waves from the system, we need to know the motion of the particle accurately, including the effect of the "gravitational self-force." Some groups have studied the orbital evolution of EMRIs with the self-force effect since the early 1990s; their work is summarized in Refs. [24] and [25]. Our recent progress is shown in Refs. [26–40] (and see also the BHPC website [41]).

Based on the achievements so far, the modelling of EMRI waveforms is under development. We forecast that the important future milestones will consist of three steps:

Step 1: Adiabatic waveforms for seeking EMRI events

The self-force effects at the leading order in mass ratio drive the dominant part of the secular orbital evolution of EMRIs. The waveforms calculated by taking the secular evolution into account, the so-called "adiabatic waveforms," are considered useful in the search for signals from EMRIs in observed data, although they are not sufficient for accurate parameter estimation. In our previous works, the secular evolution of EMRIs has become calculable both numerically [26] and analytically [38] in the framework of the black hole perturbation scheme. Adiabatic orbital evolution can be calculated, once we know the long-term-averaged change rates of the three "constants of motion," which consist of the energy, the azimuthal angular momentum, and Carter's constant. The breakthrough was the development of a method to evaluate the change rate of Carter's constant [42] based on the earlier work [43]. Here, the self-force due to the time-symmetric part of the self-field, i.e. the half-retarded plus half-advanced field, is unnecessary. The divergence in the self-field that requires an appropriate regularization is concentrated in this symmetric part. Only the radiative field, i.e. the half-retarded minus half-advanced field, is sufficient to compute the leading-order effects, and hence we do not have to implement the complicated regularization of self-force. Nevertheless, it still remains to develop numerical code to calculate the adiabatic waveforms at realistic computational cost applicable to the actual data analyses.

Step 2: Taking account of resonance effects on the waveform

The next-to-leading-order effects in the mass ratio arise from the resonance contribution. The inspiraling orbit occasionally crosses a resonant point, where the ratio of the oscillation frequencies of the orbital radius and the elevation angle is rational. At a resonant point the evolution of the "constants of motion" is modified, and as a result the succeeding phase evolution changes. The correction to the orbital phase due to the passage of a resonant point scales like $\eta^{-1/2}$, where η is the mass ratio. This is much smaller than the total orbital phase that evolves in the radiation reaction timescale, which scales like η^{-1}, but it can still be larger than unity for EMRIs. The method for computing the resonant contribution was formally established in Ref. [35]. The dominant part of the resonant effects might be evaluated by using the radiative field only, but there also exists a contribution from the symmetric field to the radiation reaction to Carter's constant, which was computed only recently for the first time in particular examples [44].

Step 3: Post-adiabatic waveforms for EMRI parameter estimation

It is more challenging to include the next-order corrections in mass ratio, which scale like η^0 in terms of the gravitational wave phase. There have been some studies on formulating this post-adiabatic evolution of the orbit [45–50], though there is currently no implementation to calculate the long-term orbital evolution with the post-adiabatic effects. For the purpose of obtaining waveforms with sufficient accuracy for EMRI parameter estimation, it is necessary to develop an efficient method of calculating the long-term evolution with the post-adiabatic effects.

4.   Conclusion

LISA is expected to open the unexplored millihertz gravitational-wave window. The contribution activities in Japan are currently being carried out by two groups: the science and instrument groups. The instrument group has been actively working on the development of hardware critical to long-range intersatellite interferometry. A large amount of effort was put into the development of photoreceivers. The science group is focusing its efforts on the study of compact star binaries, with an emphasis on the study of galactic/extra-galactic compact binaries, and the development of a model and waveforms for extreme mass ratio inspirals. These contribution activities in Japan will

be sustained in the coming years, with the goal of making scientifically important contributions to LISA.

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