The 6th BRICS-AGAC Symposium 2026

Clock Noise Suppression in Space-based Gravitational Wave Detection

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Presentation Outline

1. Research background

2. Research content

2.1 TDI technique for laser frequency noise suppression

2.2 Clock jitter noise suppression (*Main focus*)

- Theoretical study
- Experimental validation

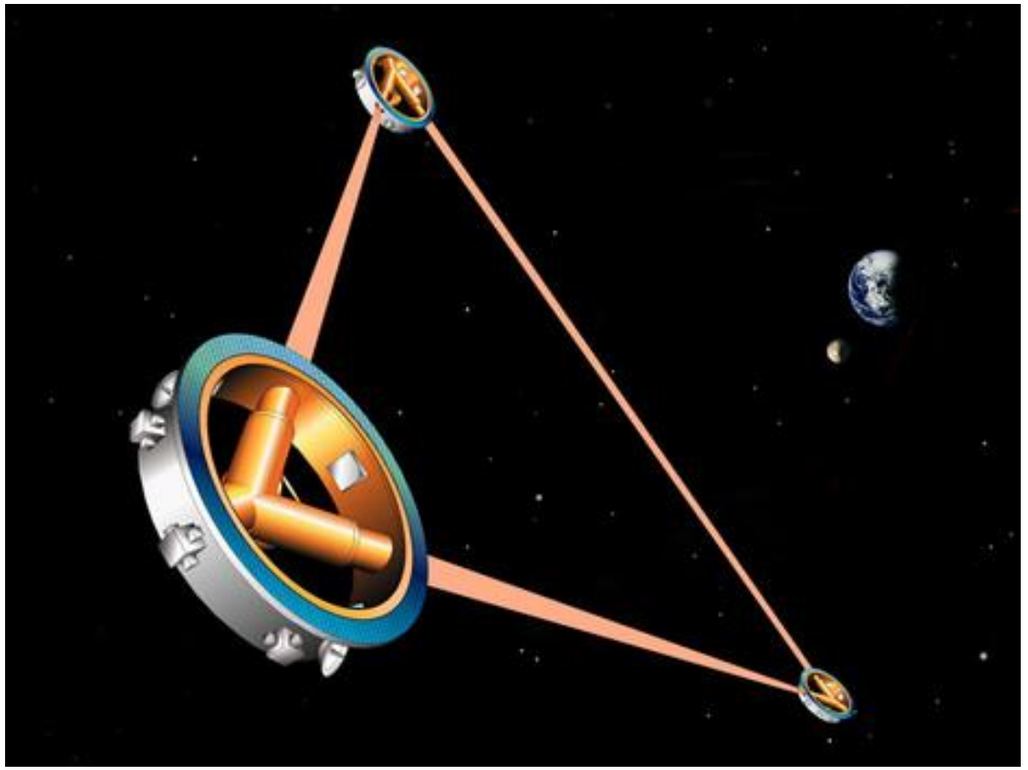
3. Summary and prospects

Significance of Space-based GW Detection

- In 2015, the ground-based GW detector LIGO successfully detected gravitational waves for the first time, opening a new window for observing the universe;
- **Space-based GW detection** enables the observation of low-frequency GW signals and the search for a wider range of sources, advancing the development of physics, astronomy, and cosmology.



Ground-based GW detection

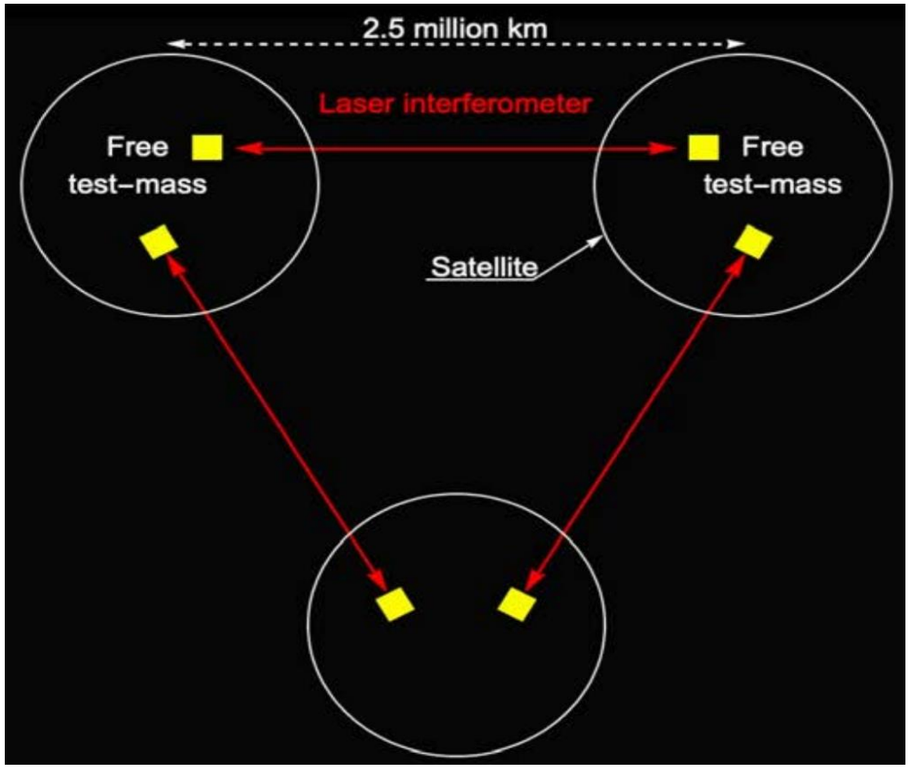


Space-based GW detection

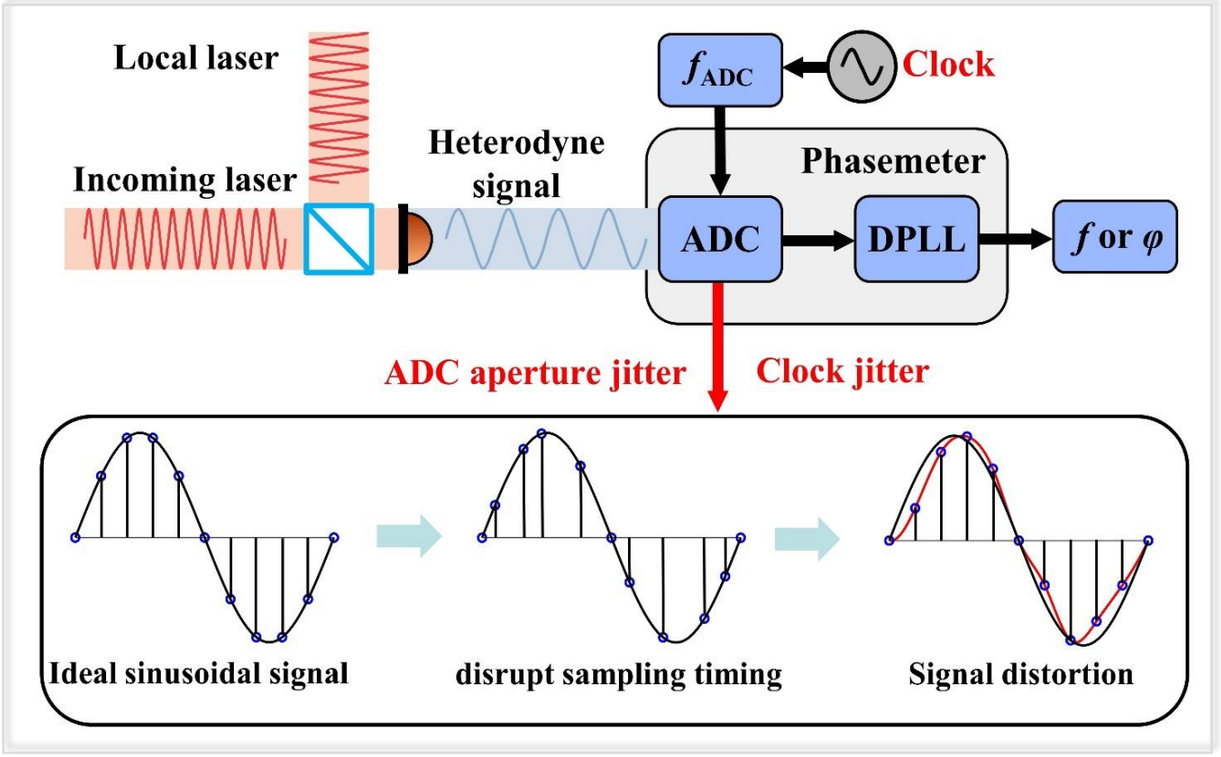
Main Noise Sources in Space-based GW Detection

Interferometric data stream in space-based GW detection mainly consists of:

- GW signal;
- detector fundamental noise—*test-mass noise and interferometric measurement noise*;
- laser frequency noise—*frequency fluctuations of the laser source coupled into the measurement*;
- clock noise—*data sampled by a clock-driven ADC; sampling clock jitter perturbs timing, degrading GW detection*.



GW Detection Architecture Schematic

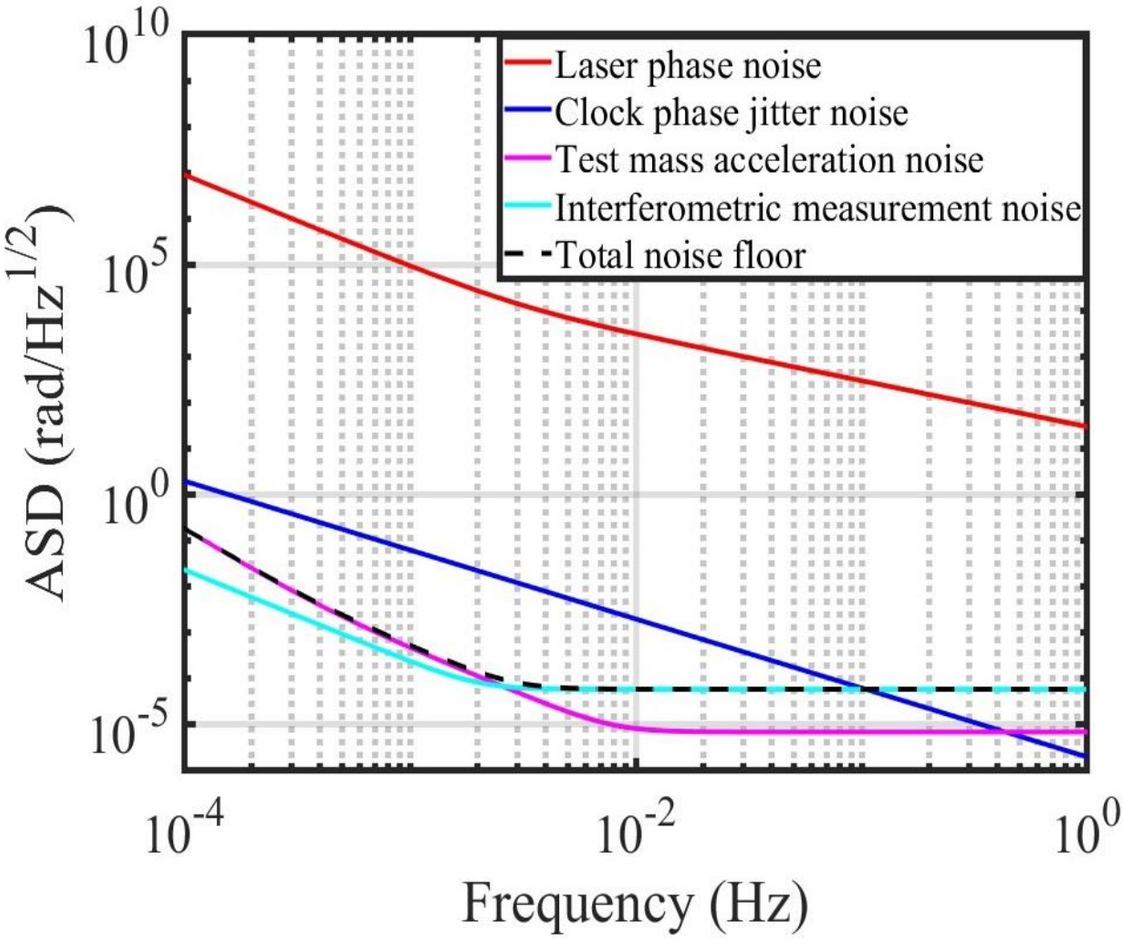


Digitization of interference signals

Main Noise Sources in Space-based GW Detection

- Typical **laser frequency noise** and **clock jitter noise** exceed the detector's fundamental noise by about **8** orders of magnitude and **3** orders of magnitude, respectively.
- These two dominant noises **must be heavily suppressed**; otherwise, they will **overwhelm** the GW signals.

Category	**Item**		**Magnitude @ 3mHz (LISA parameters)**	
Signal	GW signal		$10^{-21}/\sqrt{\text{Hz}}$	
Noise	Detector fundamental Noise	Test mass acceleration noise	$3\ \text{fm/s}^2/\sqrt{\text{Hz}}$	$10^{-21}/\sqrt{\text{Hz}}$
		Interferometric measurement noise	$15\ \text{pm}/\sqrt{\text{Hz}}$	$10^{-21}/\sqrt{\text{Hz}}$
	Other Noise	Laser frequency noise	$30\ \text{Hz}/\sqrt{\text{Hz}}$	$10^{-13}/\sqrt{\text{Hz}}$
		Clock jitter noise	$10^{-11}/\sqrt{\text{Hz}}$	$10^{-18}/\sqrt{\text{Hz}}$
		.....	.....	.....



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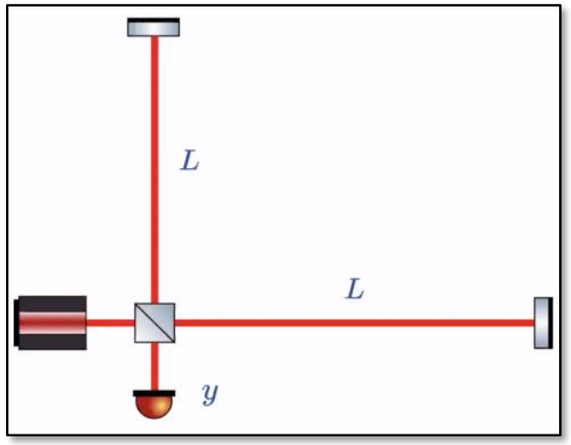
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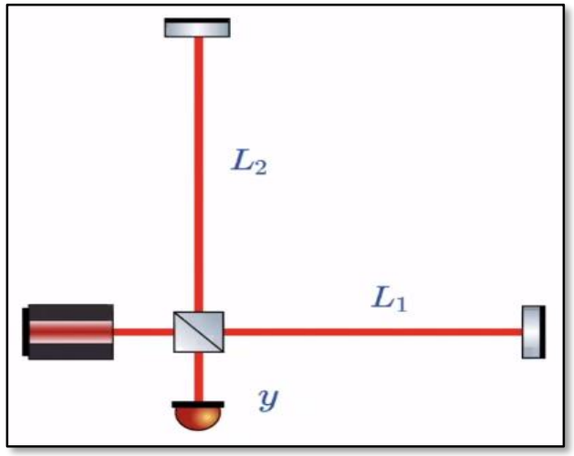
Laser frequency noise cancellation: Equal vs. Unequal arm interferometry

Ideal equal-arm configurations cancel laser noise completely, whereas practical arm-length mismatches leave a dominating residual coupling (arm-length mismatch×laser frequecy or phase noise), masking the GW signals.



Equal-arm Interferometry

- Variables: p = laser phase noise, L = arm length;
- Interferometric phase: $y(t) = p(t-2L) - p(t-2L) = 0$
- Result: Noise (10^{-13}) is **fully canceled**, enabling detection of GWs (10^{-21}).



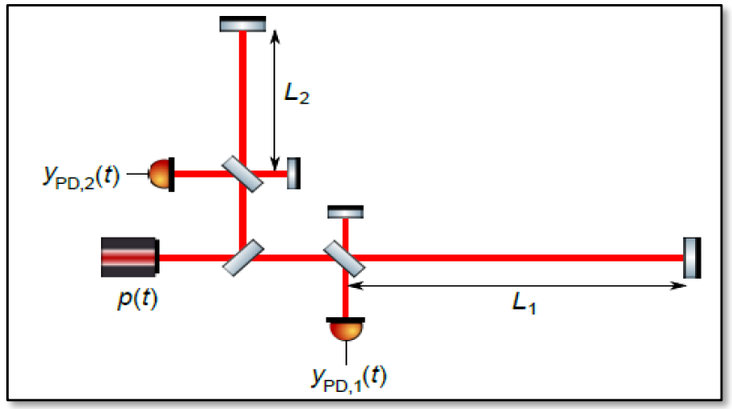
Unequal-arm Interferometry

- Interferometric phase: $y(t) = p(t-2L_1) - p(t-2L_2) \neq 0$
- Noise PSD: $S(\omega) = 4\Delta L^2 \omega^2 S_p(\omega)$

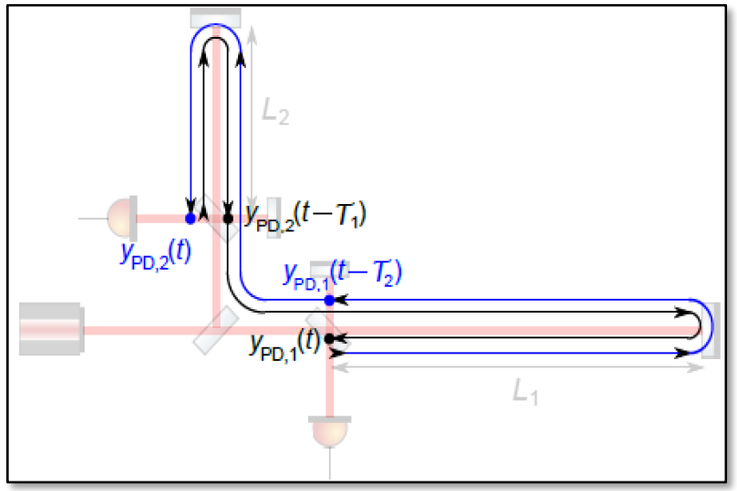
  *Note: ΔL is the arm-length mismatch, leading to a **residual coupling effect**.*
- Result: A 0.2 s mismatch still leaves a residual noise of 10^{-15} at 1 mHz.

Time-delay interferometry (TDI) Principle

Core Idea of TDI: Time-delay and recombine the data streams to synthesize a "**virtual equal-arm interferometer**", thereby canceling laser frequency noise.



Basic Optical Layout ($y_{PD,1}$ and $y_{PD,2}$)



Equivalent virtual interferometry
(**Blue and black paths**)

M. Tinto and J. Armstrong, PRD 59, 102003 (1999)

Step 1: Raw Interferometric Data:

$$y_{PD,1}(t) = p(t-2L_1) - p(t)$$

$$y_{PD,2}(t) = p(t-2L_2) - p(t)$$

Step 2: Direct Differencing

$$y_{PD,1}(t) - y_{PD,2}(t) = p(t-2L_1) - p(t-2L_2)$$

Step 3: Delayed Differencing

$$y_{PD,1}(t-2L_2) - y_{PD,2}(t-2L_1) = p(t-2L_1) - p(t-2L_2)$$

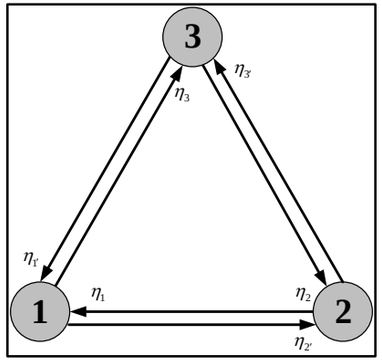
Step 4: TDI Combination

$$x(t) = \underbrace{\left[y_{PD,1}(t-2L_2) + y_{PD,2}(t)\right]}_{\textbf{Blue path}} - \underbrace{\left[y_{PD,2}(t-2L_1) + y_{PD,1}(t)\right]}_{\textbf{Black path}}$$

TDI categories and generations

- Configuration & objective: A three-satellite, six-link constellation generates 6 equivalent interferometric data streams. These are delayed and recombined to suppress 3 independent laser frequency noises.
- High degrees of freedom: Leads to various TDI **Categories** (combinations) and **Generations** (static vs. time-varying arms).
- Selection: Choose the appropriate TDI combinations based on specific **mission requirements**.

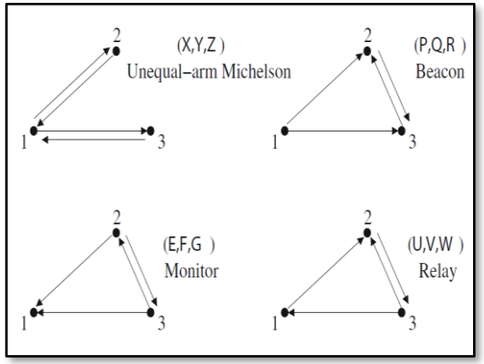
TDI Categories:



3-satellite, 6-link

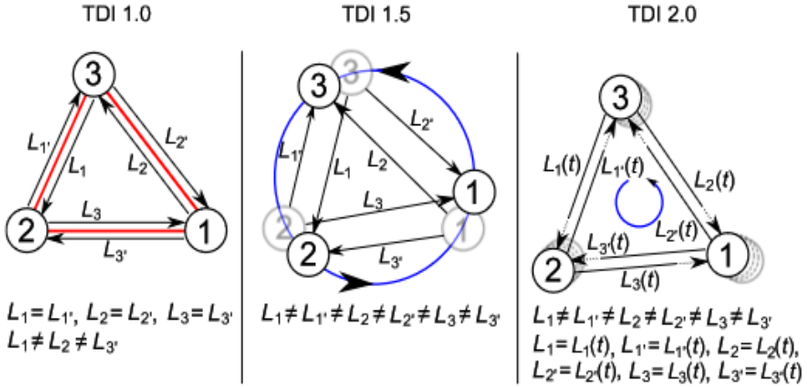
Time-delay combination

$$\text{TDI}=\sum_{i=1,2,3}(P_i\eta_i + P_{i'}\eta_{i'})$$



Michelso,
Sagnac,
fully symmetric Sagnac,
Relay,
Beacon,
Monitor...

TDI Generations:



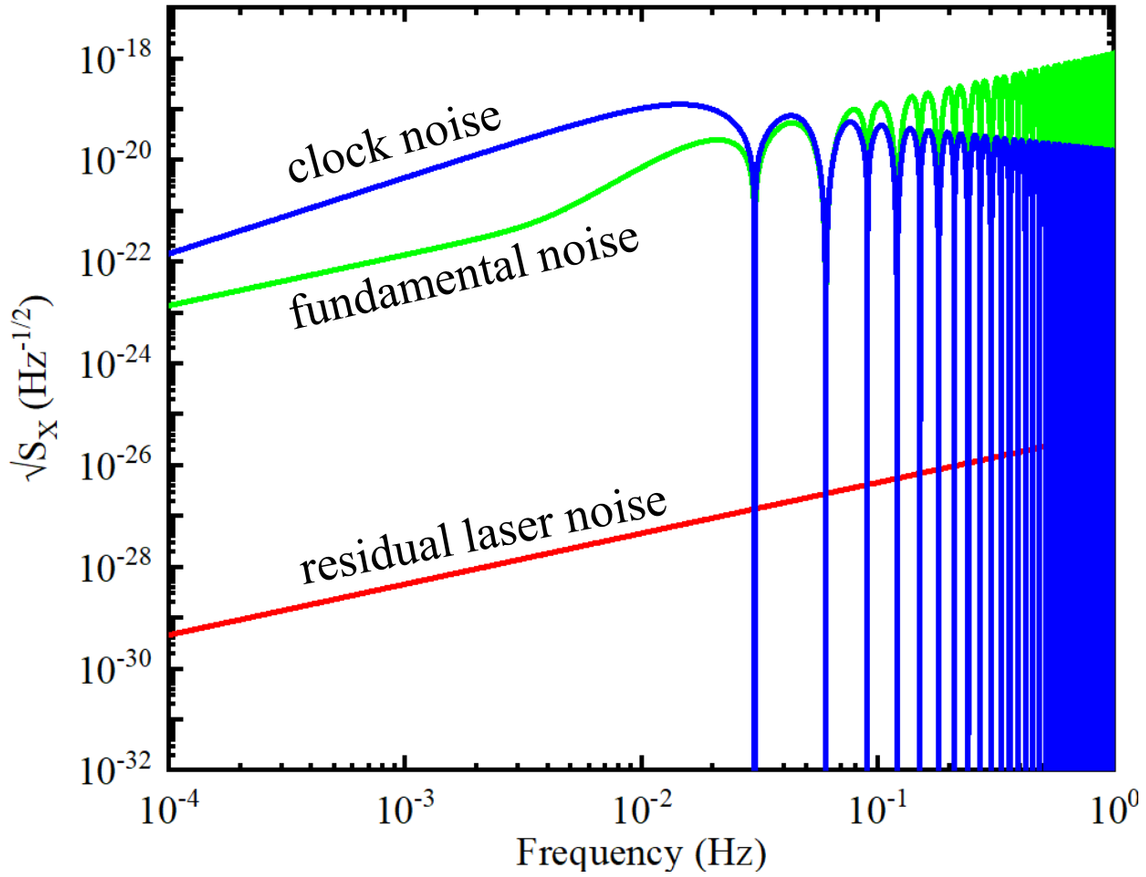
TDI 1.0: $D_1, D_2, D_3, [D_i, D_j] = 0$

TDI 1.5: $D_1, D_2, D_3, D_{1'}, D_{2'}, D_{3'}$
$[D_i, D_j] = 0, [D_{i'}, D_{j'}] = 0, [D_i, D_{j'}] = 0$

TDI 2.0: $D_1, D_2, D_3, D_{1'}, D_{2'}, D_{3'}$
$[D_i, D_j] \neq 0, [D_{i'}, D_{j'}] \neq 0, [D_i, D_{j'}] \neq 0$

Clock noise after TDI processing

- Achievement: TDI combinations effectively suppress laser frequency noise.
- Challenge: TDI simultaneously manipulates clock noise, resulting in highly complex forms. The residual clock noise varies across different TDI combinations.
- **Requirement:** **extend algorithms** based on the existing TDI framework to **further suppress clock noise**.



Example: 2nd-generation Michelson TDI combination

Typical LISA Parameters:

$$L = 2.5\times10^{9}\,\mathrm{m}$$

$$s_a = 3\times10^{-15}\,\frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}$$

$$s_x = 15\times10^{-12}\,\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

$$s_q = \left(\frac{6.32\times10^{-14}}{\mathrm{Hz}^{1/2}}\right)\left(\frac{f}{\mathrm{Hz}}\right)^{-1/2}$$

$$s_p = \frac{30\mathrm{Hz/Hz}^{1/2}}{3\times10^{14}\,\mathrm{Hz}}$$

$$\Delta v = \dot{L}_2 - \dot{L}_3 = 5\mathrm{m/s}$$

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Ultra-Stable Oscillator (USO)-calibrated TDI technique——Principle

- **Step 1: Residual clock noise term after Michelson TDI combination:**

$$X_1^q = [b_{1'}(1-\mathcal{D}_{33'})(1-\mathcal{D}_{2'2}) - a_{1'}(1-\mathcal{D}_{33'}) + a_1(1-\mathcal{D}_{2'2})]\, q_1 + [a_{2'}(1-\mathcal{D}_{2'2})\mathcal{D}_3]\, q_2 - [a_3(1-\mathcal{D}_{33'})\mathcal{D}_{2'}]\, q_3.$$

q_1, q_2, q_3 represent the clock noises in the three satellites.

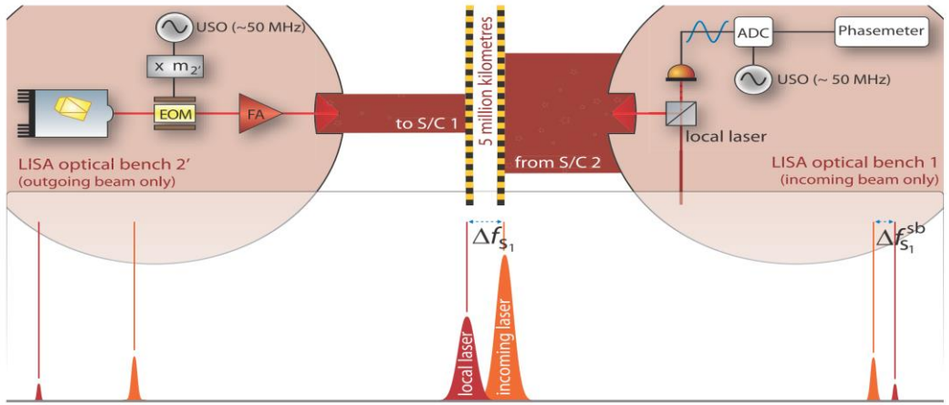
- **Step 2: Construct new measurements mainly containing clock noise:**

carrier (s^c) – sideband (s^{sb}) Data

$$r_i \equiv \frac{s_i^c - s_i^{sb}}{m_{(i+1)'} f_{i+1}}, r_{i'} \equiv \frac{s_{i'}^c - s_{i'}^{sb}}{m_{i-1} f_{i-1}}$$

$$r_i = q_i - \mathcal{D}_{i-1} q_{i+1}, r_{i'} = q_i - \mathcal{D}_{(i+1)'} q_{i-1}$$

six new measurements: (r_1, r_2, r_3, $r_{1'}$, $r_{2'}$, $r_{3'}$)



- **Step 3: Construct the target clock noise form:**

$$K_{X_1} \equiv b_{1'}(I - \mathcal{D}_3\mathcal{D}_{3'})(r_{1'} + \mathcal{D}_{2'} r_3) + a_1(r_{1'} + \mathcal{D}_{2'} r_3) - a_{1'}(r_1 + \mathcal{D}_3 r_{2'}) + a_{2'}[r_{1'} - (I - \mathcal{D}_{2'}\mathcal{D}_2) r_1 + \mathcal{D}_{2'} r_3] - a_3[r_1 - (I - \mathcal{D}_3\mathcal{D}_{3'}) r_{1'} + \mathcal{D}_3 r_{2'}]$$

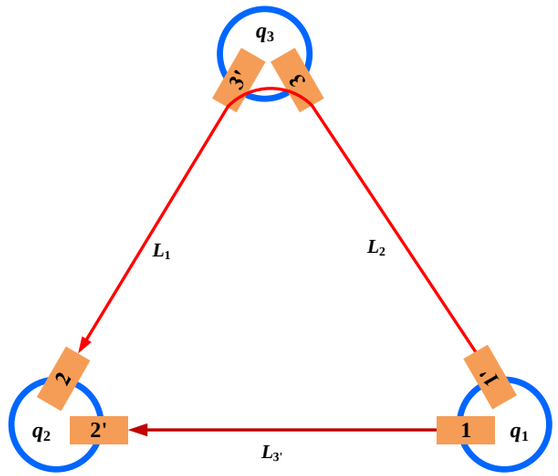
- **Step 4: Suppress clock noise effects:** $X_1^c = X_1^q - K_{X_1} = 0.$

USO-calibrated TDI technique——Algorithm development

Established a mapping between the residual clock noise terms after TDI combinations **and the six new measurements**. We summarized this into a **convenient look-up table** to solve the clock jitter noise suppression problem for typical TDI combinations.

Residual clock noise term after Michelson TDI combination:

$$X_1^q = [b_{1'}(1-\mathcal{D}_{33'})(1-\mathcal{D}_{2'2}) - a_{1'}(1-\mathcal{D}_{33'}) + a_1(1-\mathcal{D}_{2'2})]\,q_1 + [a_{2'}(1-\mathcal{D}_{2'2})\mathcal{D}_3]\,q_2 - [a_3(1-\mathcal{D}_{33'})\mathcal{D}_{2'}]\,q_3$$



$$(\mathcal{D}_{3'} - \mathcal{D}_{12})q_1 = \mathcal{D}_1 r_3 + r_2 - r_{2'}$$

TABLE I. The list of relations between r_i and q_i which does not involve commutators of the delay operators.

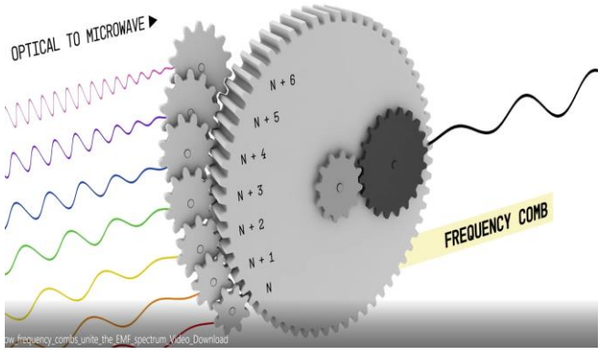
clock terms q_i	independent measurement r_i	clock terms q_i	independent measurement r_i
$(\mathcal{D}_{3'} - \mathcal{D}_{12})q_1$	$\mathcal{D}_1 r_3 + r_2 - r_{2'}$	$(\mathcal{D}_{2'} - \mathcal{D}_{31})\mathcal{D}_2 q_1$	$(\mathcal{D}_3 r_2 + r_1 - r_{1'}) - (\mathcal{D}_{2'} - \mathcal{D}_{31})r_3$
$(\mathcal{D}_2 - \mathcal{D}_{1'3'})\,q_1$	$\mathcal{D}_{1'} r_{2'} - r_3 + r_{3'}$	$(\mathcal{D}_3 - \mathcal{D}_{2'1'})\mathcal{D}_{3'} q_1$	$(\mathcal{D}_{2'} r_{3'} + r_{1'} - r_1) - (\mathcal{D}_3 - \mathcal{D}_{2'1'})r_{2'}$
$(1 - \mathcal{D}_{2'2})\,q_1$	$r_{1'} + \mathcal{D}_{2'} r_3$	$(\mathcal{D}_{1'} - \mathcal{D}_{23})\mathcal{D}_{3'} q_1$	$(\mathcal{D}_2 r_1 + r_3 - r_{3'}) - (\mathcal{D}_{1'} - \mathcal{D}_{23})r_{2'}$
$(1 - \mathcal{D}_{33'})\,q_1$	$r_1 + \mathcal{D}_3 r_{2'}$	$(1 - \mathcal{D}_{22'})\mathcal{D}_2 q_1$	$\mathcal{D}_2(r_{1'} + \mathcal{D}_{2'} r_3)$
$(1 - \mathcal{D}_{312})\,q_1$	$r_1 + \mathcal{D}_3 r_2 + \mathcal{D}_{31} r_3$	$(1 - \mathcal{D}_{3'3})\mathcal{D}_{3'} q_1$	$\mathcal{D}_{3'}(r_1 + \mathcal{D}_3 r_{2'})$
$(1 - \mathcal{D}_{2'1'3'})\,q_1$	$r_{1'} + \mathcal{D}_{2'} r_{3'} + \mathcal{D}_{2'1'} r_{2'}$	$(1 - \mathcal{D}_{1'1})\mathcal{D}_2 q_1$	$(r_{3'} + \mathcal{D}_{1'} r_2) - (1 - \mathcal{D}_{1'1})r_3$
$(\mathcal{D}_1 - \mathcal{D}_{3'2'})\mathcal{D}_2 q_1$	$(\mathcal{D}_{3'} r_{1'} + r_{2'} - r_2) - (\mathcal{D}_1 - \mathcal{D}_{3'2'})r_3$	$(1 - \mathcal{D}_{11'})\mathcal{D}_{3'} q_1$	$(r_2 + \mathcal{D}_1 r_{3'}) - (1 - \mathcal{D}_{11'})r_{2'}$

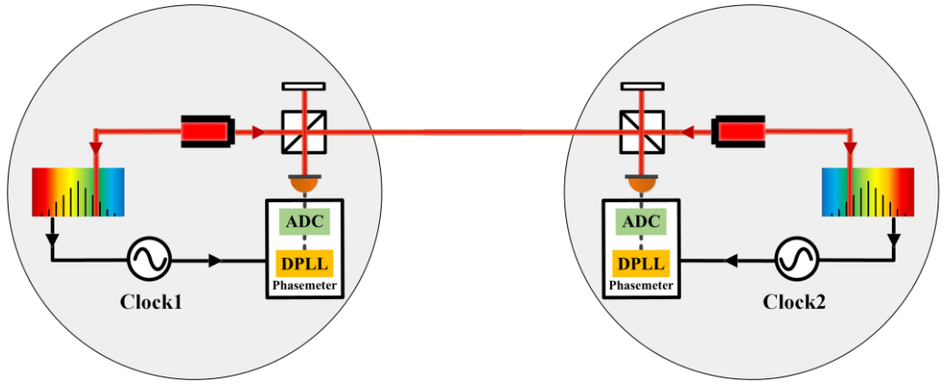
Rule: Only clock noise forming a closed transfer path can be constructed by delay-combining the new measurements!

Refined clock-jitter reduction in the Sagnac-type time-delay interferometry combinations, Physical Review D, 104, 082002 (2021)

Optical comb-based TDI technique——Principle

- **Step 1: Laser and clock share the same source via optical comb down-conversion:**





Correlation between laser frequency noise and clock noise: $q(t) = \frac{f}{\nu} p(t) + \Delta q(t)$

- **Step 2: Data streams under optical comb down-conversion:**

$$\eta_i^{OFC} = H_i + \mathcal{D}_{i-1}\left[1 + b_{i+1}\frac{f_{i+1}}{\nu_{i+1}}\right]p_{i+1} - \left[1 + a_i\frac{f_i}{\nu_i}\right]p_i + 2\pi\nu_{(i+1)'}\vec{n}_{i-1}\cdot[\mathcal{D}_{i-1}\vec{\delta}_{(i+1)'} - \vec{\delta}_i] + N_i$$

$$\eta_{i'}^{OFC} = H_{i'} + \mathcal{D}_{(i+1)'}p_{i-1} - \left[1 + (a_{i'} - b_{i'})\frac{f_i}{\nu_i}\right]p_i + 2\pi\nu_{i-1}\vec{n}_{i+1}\cdot[\vec{\delta}_{i'} - \mathcal{D}_{(i+1)'}\vec{\delta}_{i-1}] + N_{i'}$$

Note: Clock noise can be corrected into the equivalent laser frequency noise

- **Step 3: Find modified TDI combinations to suppress the equivalent laser frequency noise.**

Optical comb-based TDI technique——Algorithm development

Proposed a **delay-operator substitution method**, providing a general and rapid solution to derive the optical comb-based TDI combination for any given standard TDI combination.

Substitution relation:

$$\tilde{\eta}_i \equiv \rho_i^{-1}\eta_i^{\mathrm{OFC}} = \tilde{\mathcal{D}}_{i-1}p_{i+1} - p_i + \dots$$

$$\tilde{\eta}_{i'} \equiv I_{i'}^{-1}\eta_{i'}^{\mathrm{OFC}} = \tilde{\mathcal{D}}_{(i+1)'}p_{i-1} - p_i + \dots$$

$$\tilde{\mathcal{D}}_{i-1} \equiv I_i^{-1}\mathcal{D}_{i-1}, \quad \tilde{\mathcal{D}}_{(i+1)'} \equiv I_{i'}^{-1}\mathcal{D}_{(i+1)'}$$

$$I_i^{-1} = \left(1 + b_{i+1}\frac{f_{i+1}}{\nu_{i+1}}\right)\rho_i^{-1}, \quad I_{i'}^{-1} = \left(1 + (a_{i'} - b_{i'})\frac{f_i}{\nu_i}\right)^{-1}, \quad \rho_i^{-1} = \left(1 + a_i\frac{f_i}{\nu_i}\right)^{-1}$$

Standard TDI

(suppresses laser frequency noise)

$$TDI = \sum_{i=1}^{3} P_i\eta_i + P_{i'}\eta_{i'}$$

Modified TDI

(suppresses **both** laser and clock noise)

$$TDI_M = \sum_{i=1}^{3} \tilde{P}_i\tilde{\eta}_i + \tilde{P}_{i'}\tilde{\eta}_{i'}$$

"...has been generalized to given TDI combinations later by Tan et al." — Yamamoto et al., Phys. Rev. Applied (2026)

Modified time-delay interferometry with an optical frequency comb, Physical Review D, 106, 044010 (2022)

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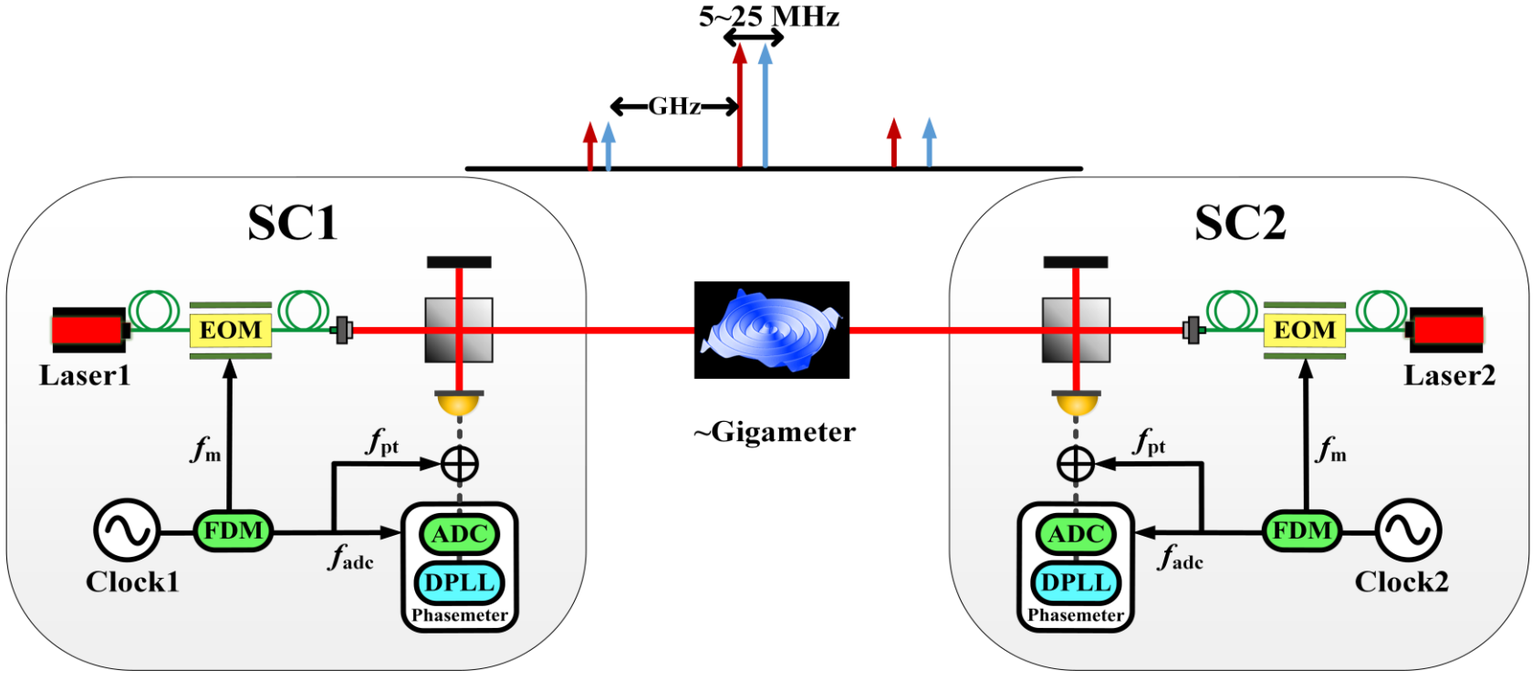
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Clock Noise Suppression Technique——USO-Calibrated TDI

- In hardware, construct **a clock noise transfer and comparison link** with low additional noise (frequency conversion and distribution system FDM + EOM sideband modulation unit);
- In software, develop **clock noise suppression TDI algorithms**.
- Algorithm research is relatively mature, while experimental verification of the effectiveness of the suppression technique needs to be strengthened.

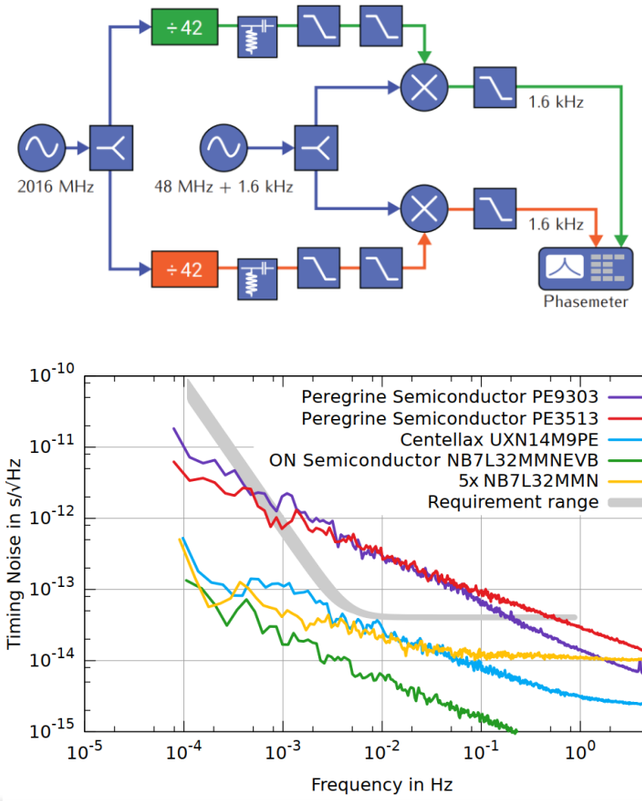


Clock noise transfer and comparison link

Current status of principle verification on USO-Calibrated TDI technique

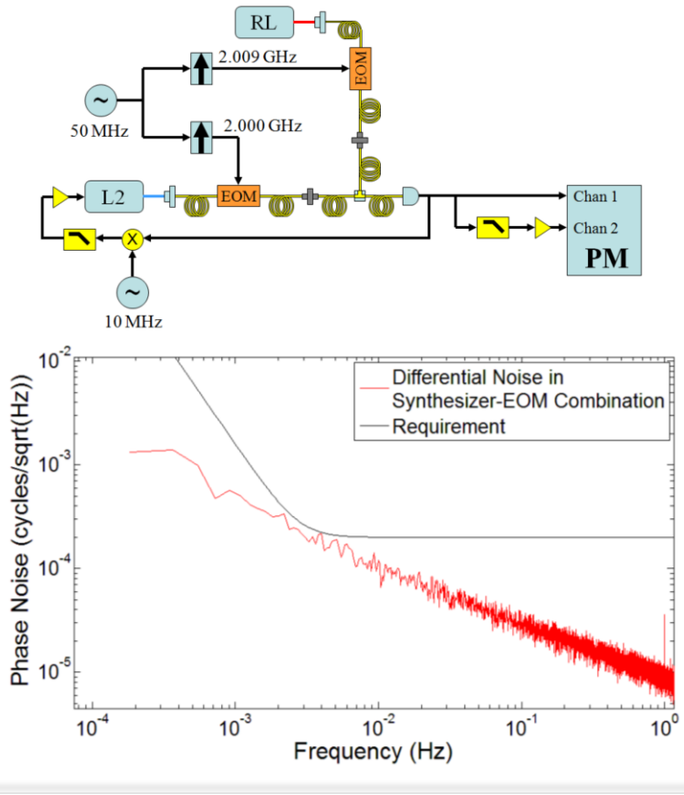
Key component testing: International research teams such as AEI and the University of Florida have tested typical **frequency dividers**, **frequency multipliers**, and **EOM**. The additional noise of some frequency dividers, frequency multipliers (manufactured by Rupptronik), and EOM (with optical power stability) meet the requirements.

AEI：Frequency divider testing



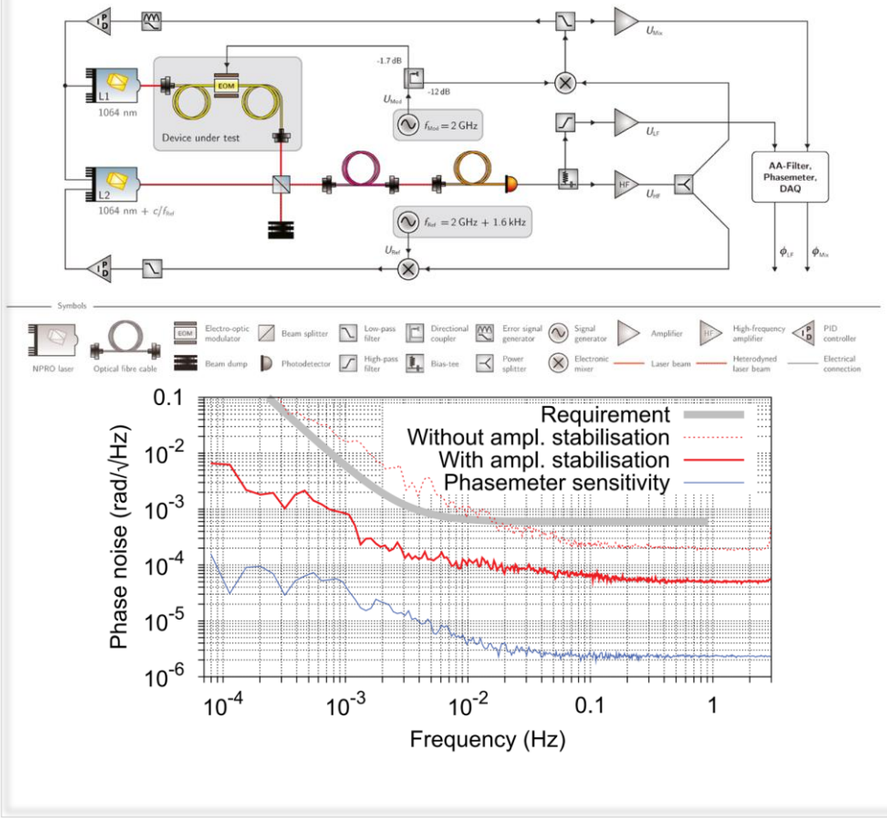
Simon Barke, PHD (2015)

University of Florida:
Frequency multiplier testing



Opt. Express 20, 25603(2012)

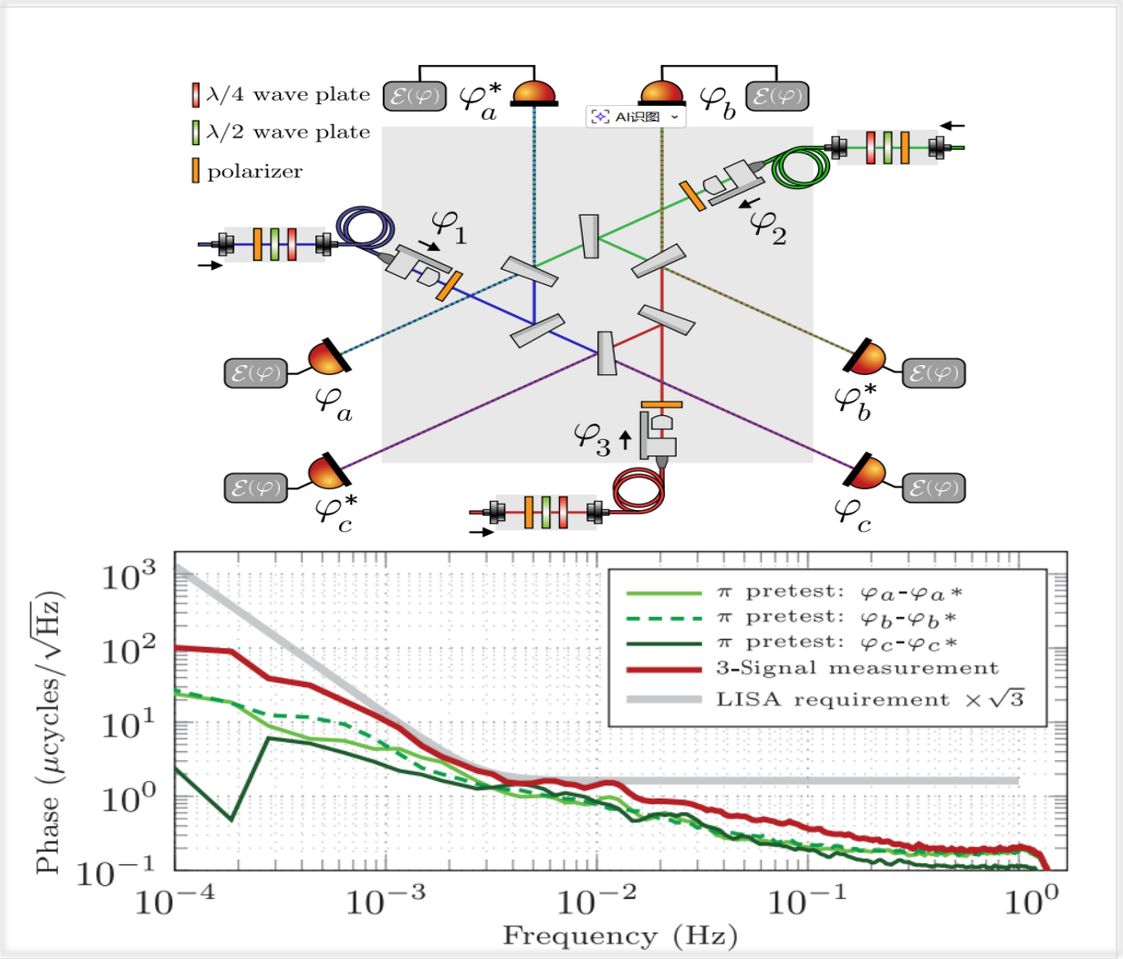
AEI：EOM testing



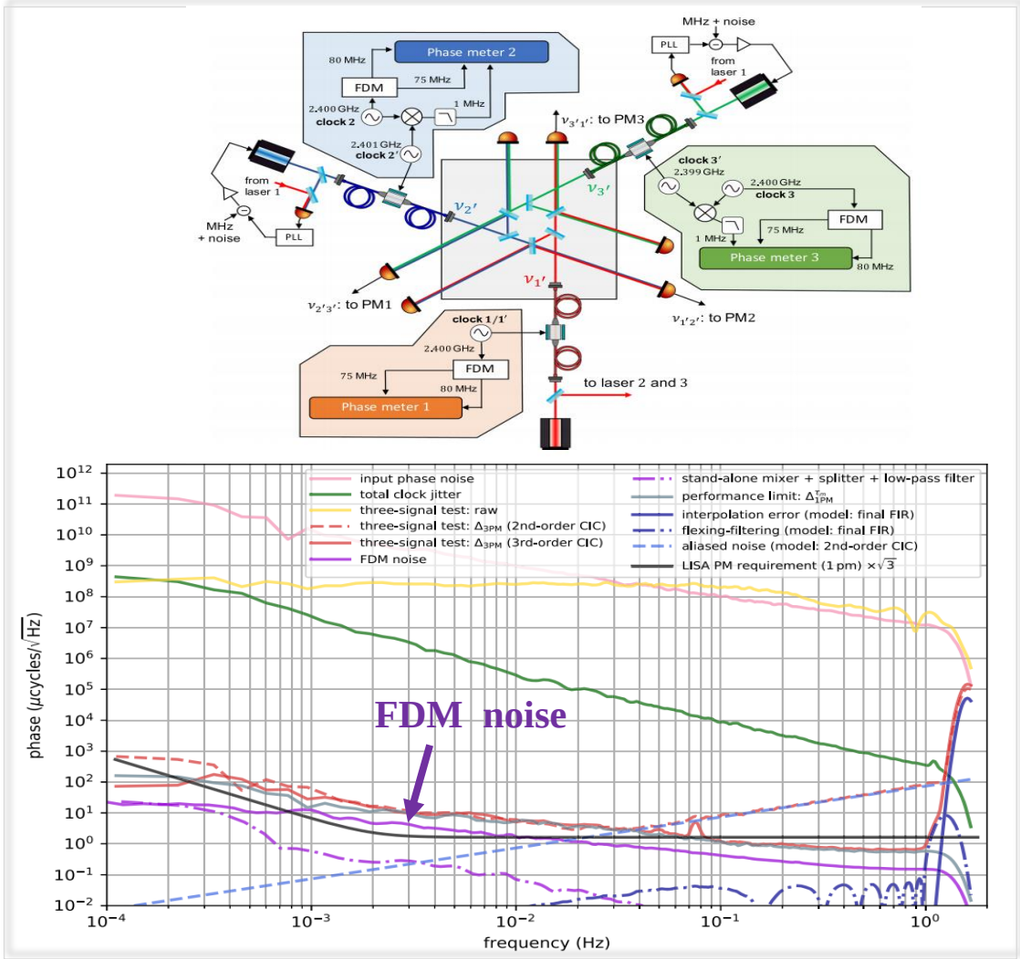
Appl. Phys. B, 98: 33–39 (2010)

Current status of principle verification on USO-Calibrated TDI technique

Clock noise transfer and comparison link testing: AEI team integrated the frequency conversion and distribution system (FDM) and EOM, and based on a hexagonal optical platform, verified the three-spacecraft clock synchronization technology. The residual noise did not reach 1 pm (**FDM noise was slightly higher than 1 pm**).



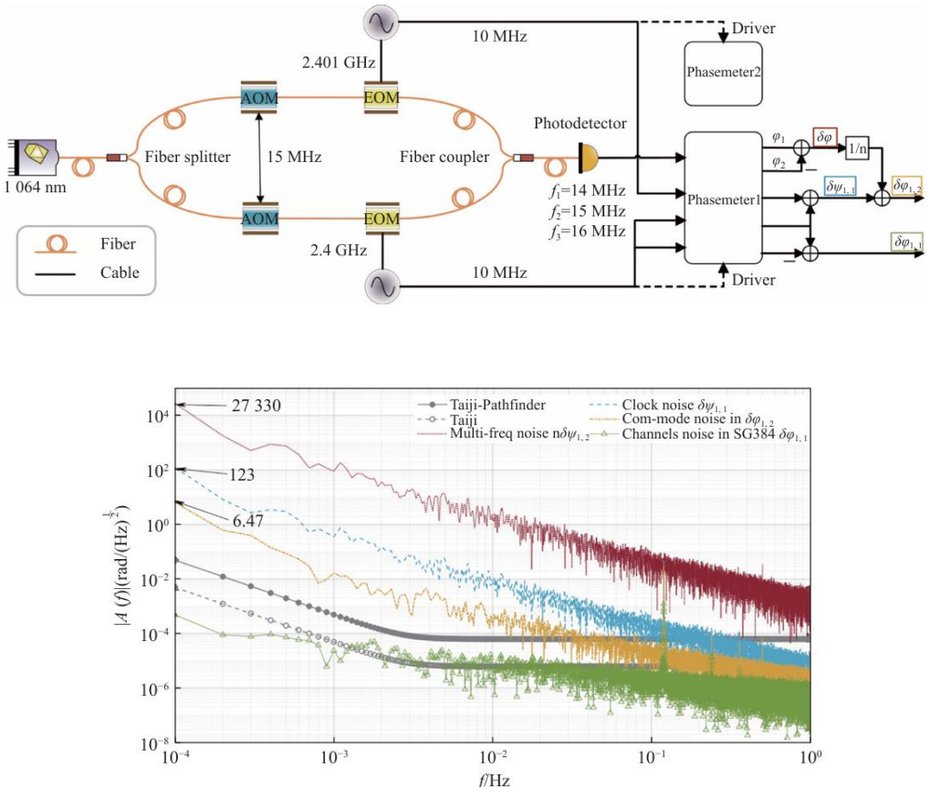
Phys. Rev. Lett., 122, 081104 (2019)



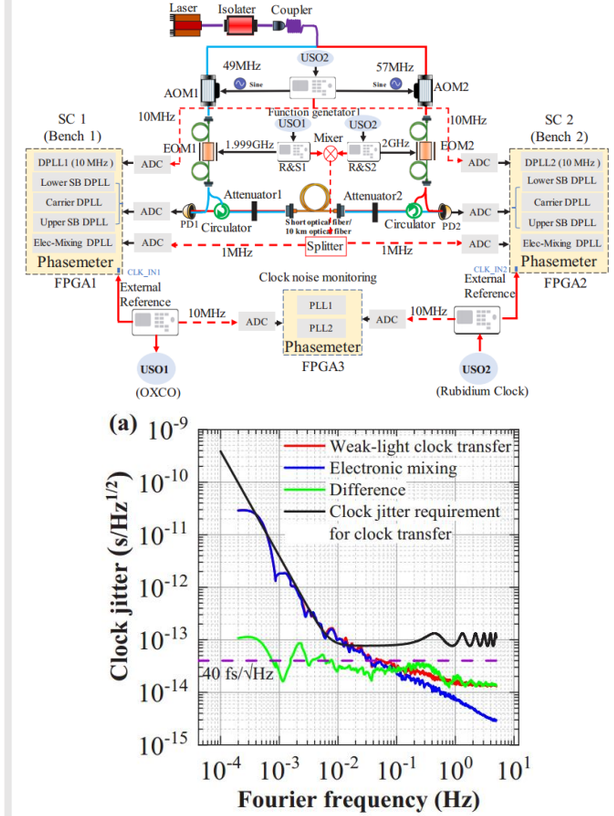
Phys. Rev. D, 105, 042009 (2022)

Current status of principle verification on USO-Calibrated TDI technique

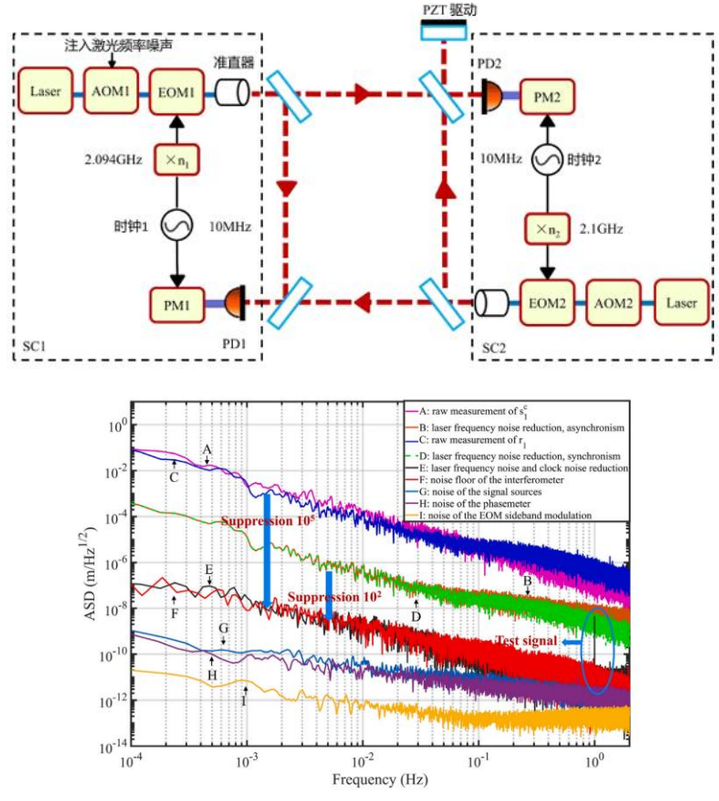
Clock noise transfer and comparison link testing: Chinese Academy of Sciences, HUST and Sun Yat-sen University have all established inter-satellite clock noise transfer and comparison links. **Signal generators are used to replace the FDM**, which does not meet the actual requirements of GW detection.



Chin. Opt., 16 (6): 1394-1403 (2023)



Opt. Express, 31, 34648–34666 (2023)



Res. in Phys., 56, 107221 (2024)

Experimental Aspects

- **Multiple types of clock signals** (USO frequency, ADC sampling clock frequency, pilot tone frequency, modulation frequency) in space-based GW detection;
- Influence on interferometric data is manifested in **time tags** and **clock jitter noise**.

$$t = \tau + \Delta t_0 + \alpha t + \delta\tau$$

fixed time offset; linear time drift

$$\delta\nu(t) = \delta\nu_{\text{laser}}(t) + \nu_{\text{h}}\frac{\delta f}{f_0}(t) + \cdots\cdots$$

Clock asynchronization; Clock jitter noise

① Inter-satellite clock synchronization

Requirements: fixed /linear deviation

Methods: TDIR, clock sideband comparison

② Main onboard clock jitter noise sources

Institution	Clock Noise Source	Reference
University of Glasgow, UK	$\delta f_{\text{pilot}}/f_{\text{pilot}}$	PRD 107 (2023) 083019
AEI Institute	$\delta f_{\text{ADC}}/f_{\text{ADC}}$	CQG 29 (2012) 205003
University of California, USA	$\delta f_{\text{clock}}/f_{\text{clock}}$	PRD 98 (2018) 042003

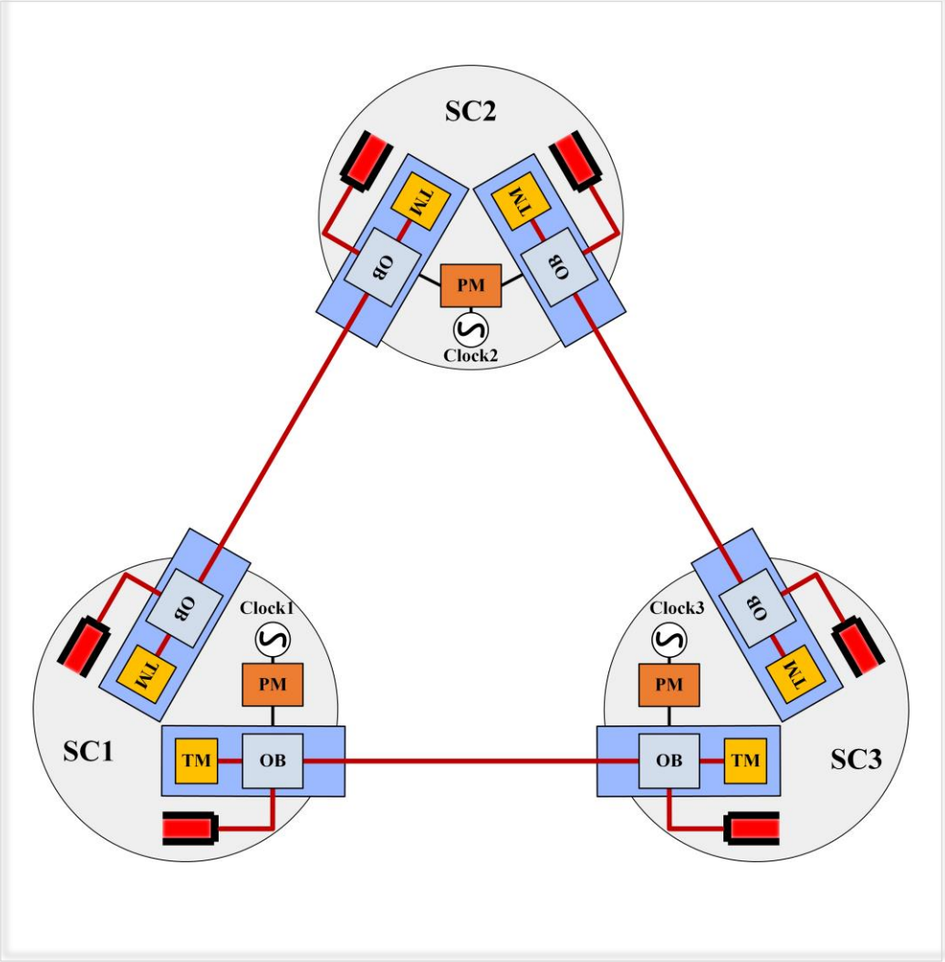
Clarify which clock frequency jitter is suppressed by USO-calibrated TDI

③ Clock jitter noise suppression

Experimental verification of noise reduction effectiveness of clock noise suppression methods

① Inter-Satellite Clock Synchronization——Model & Requirements

Space-based GW detection involves three satellites, each equipped with an independent **ADC clock** for triggering sampling and applying time tags. The **coupling effect of clock asynchronization and noise** must be smaller than the detector's noise floor.



$$f(t_1) = f(t),$$
$$f(t_2) = f(t + t_{2,0} + \alpha_2 t + \delta t_2),$$
$$f(t_3) = f(t + t_{3,0} + \alpha_3 t + \delta t_3),$$

$$f(t) - f(t + t_{2,0} + \alpha_2 t) \to F(\omega) - e^{i\omega t_{2,0}} \frac{1}{1+\alpha_2} F\left(\frac{\omega}{1+\alpha_2}\right)$$
$$\approx -i\omega t_{2,0} F(\omega) + \alpha_2 F(\omega) + \alpha_2 \omega F'(\omega)$$

Clock synchronization requirements:

$$|-i\omega t_{2,0} p(\omega) + \alpha_2 p(\omega) + \alpha_2 \omega p'(\omega)| < |s_x(\omega)|$$

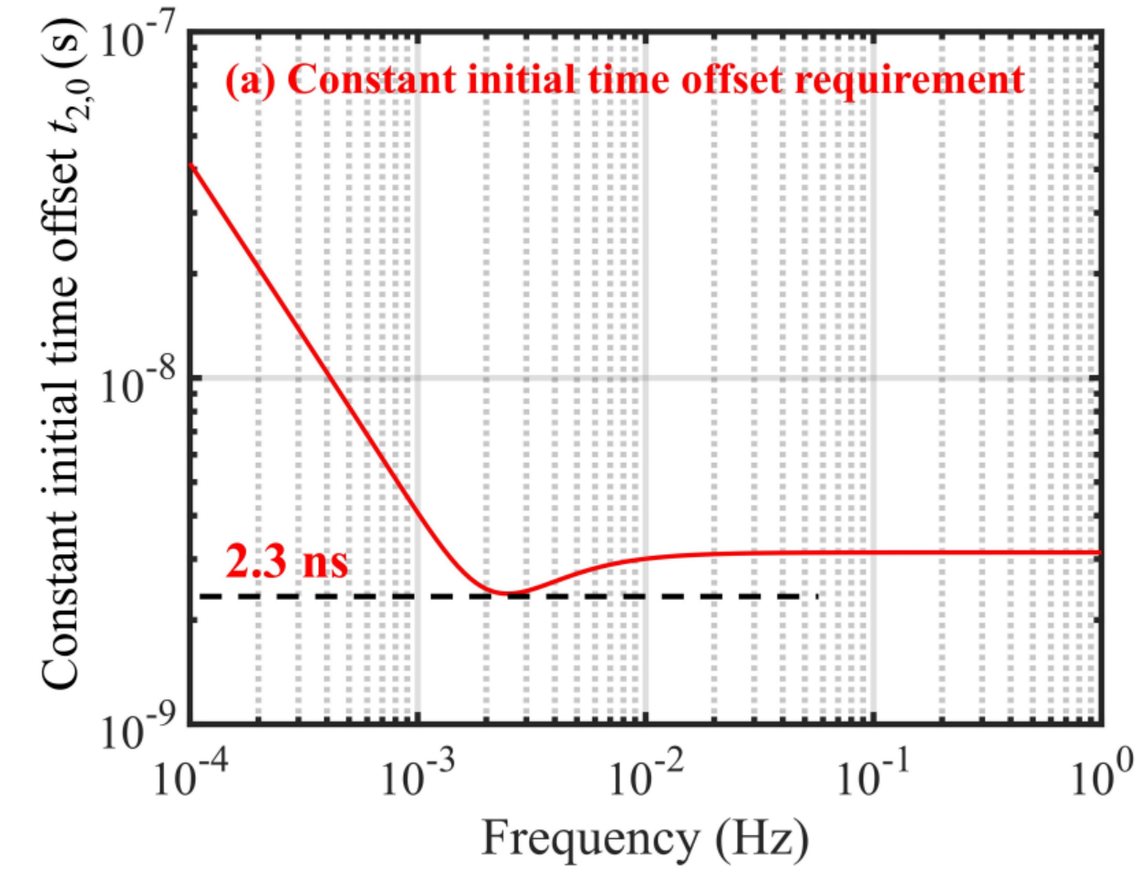
$$|p(\omega)| = 300\sqrt{1 + \left(\frac{3\text{mHz}}{f}\right)^2}\ \text{Hz/Hz}^{1/2}$$

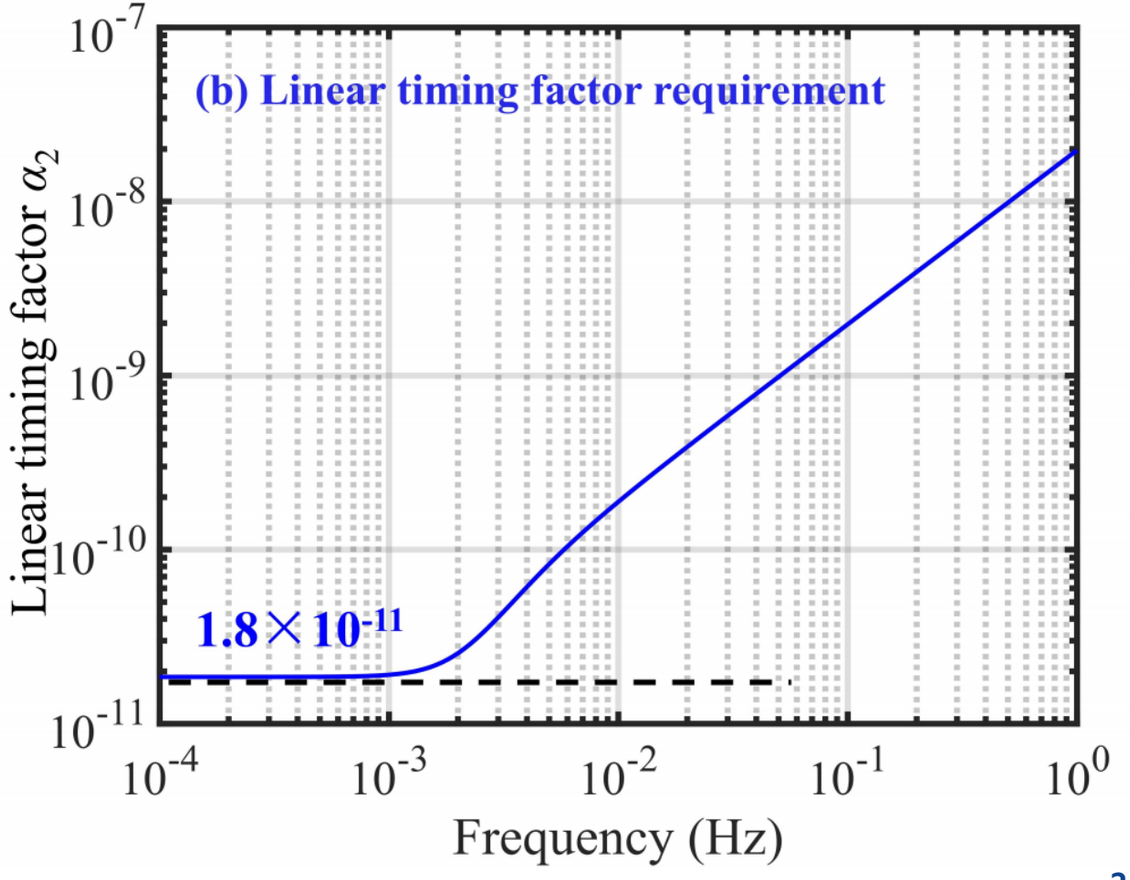
$$|s_x(\omega)| = \frac{2\pi f}{\lambda}\sqrt{1 + \left(\frac{2\text{mHz}}{f}\right)^4}\ 1\ \text{pm/Hz}^{1/2}$$

① Inter-Satellite Clock Synchronization——Model & Requirements

Under the constraint that the coupling contribution of laser frequency noise and clock asynchronization must be below 1 pm, clock synchronization must meet the following requirements:

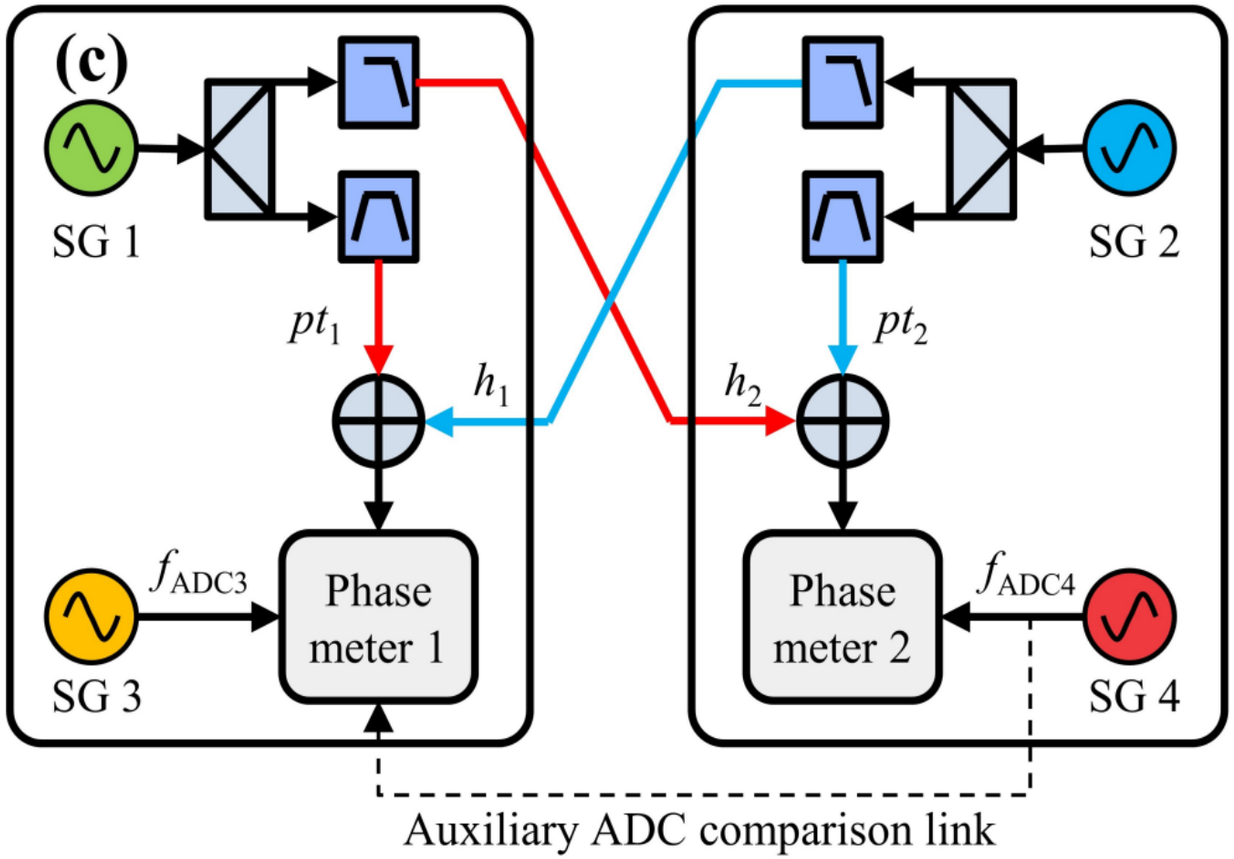
- **Fixed time deviation < 2.3ns**
- **Relative frequency drift rate < 1.8×10^{-11}**





① Inter-Satellite Clock Synchronization——Experimental Verification

Design and build an electrical experimental system based on dual-phasemeter measurements to verify the coupling model of clock asynchronization.



Phasemeter measurement data:

$$h_1(t_3) = 7.667\text{MHz}[q_2(t_3) - q_3(t_3) + q_{\text{ADC3}}]$$
$$pt_1(t_3) = 23.001\text{MHz}[q_1(t_3) - q_3(t_3) + q_{\text{ADC3}}]$$
$$h_2(t_4) = 7.667\text{MHz}[q_1(t_4) - q_4(t_4) + q_{\text{ADC4}}]$$
$$pt_2(t_4) = 23.001\text{MHz}[q_2(t_4) - q_4(t_4) + q_{\text{ADC4}}]$$

Pilot tone correction:

$$\text{cor}_1(t_3) = h_1(t_3) - pt_1(t_3)/3 = 7.667\text{MHz}[q_2(t_3) - q_1(t_3)]$$
$$\text{cor}_2(t_4) = h_2(t_4) - pt_2(t_4)/3 = 7.667\text{MHz}[q_1(t_4) - q_2(t_4)]$$

Combined data: $\text{cor1} + \text{cor2} \xrightarrow{?} 0$

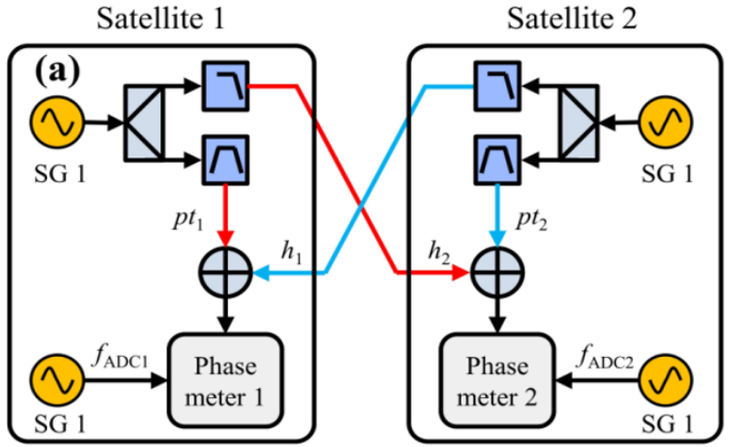
$t_3 = t_4$

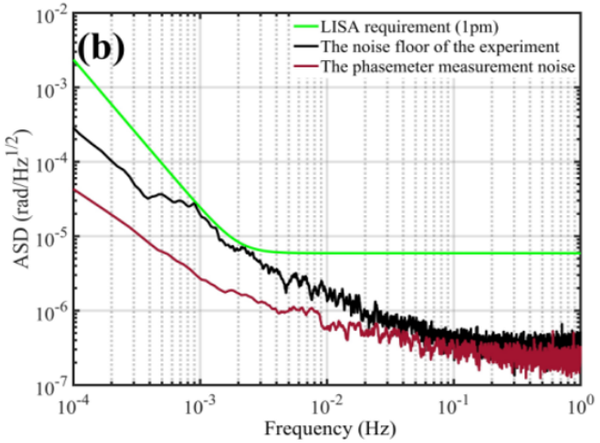
Clock Synchronization

Experimental demonstration of the clock asynchrony model in space-borne gravitational wave detection, Measurement 270, 120900 (2026)

① Inter-Satellite Clock Synchronization——Experimental Verification

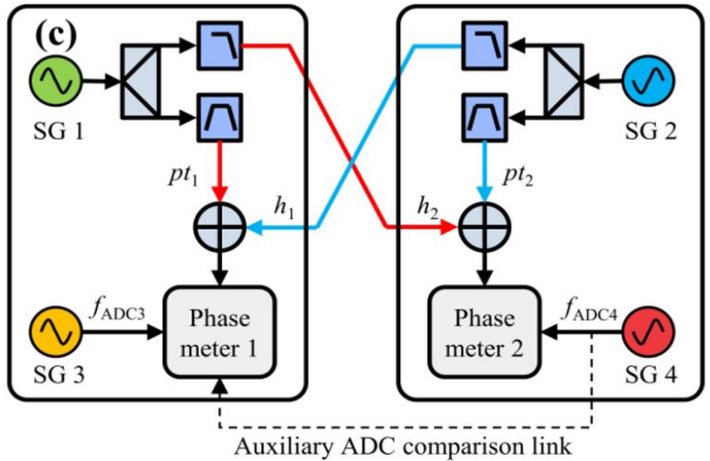
- Need obtain the difference information between the two ADC clocks;
- An ADC clock comparison link (applicable to laboratory settings); The inter-satellite **clock noise transfer and comparison link**, where **ADC frequency is homologous with pilot/modulation frequency** (applicable to space applications).

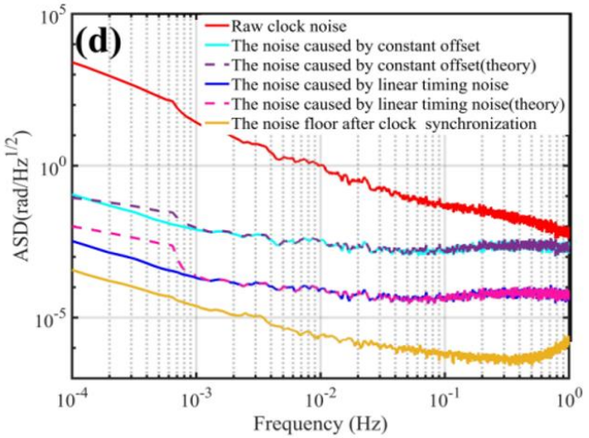




Four clocks homologous:

The measured noise floor is better than the 1 pm requirement.



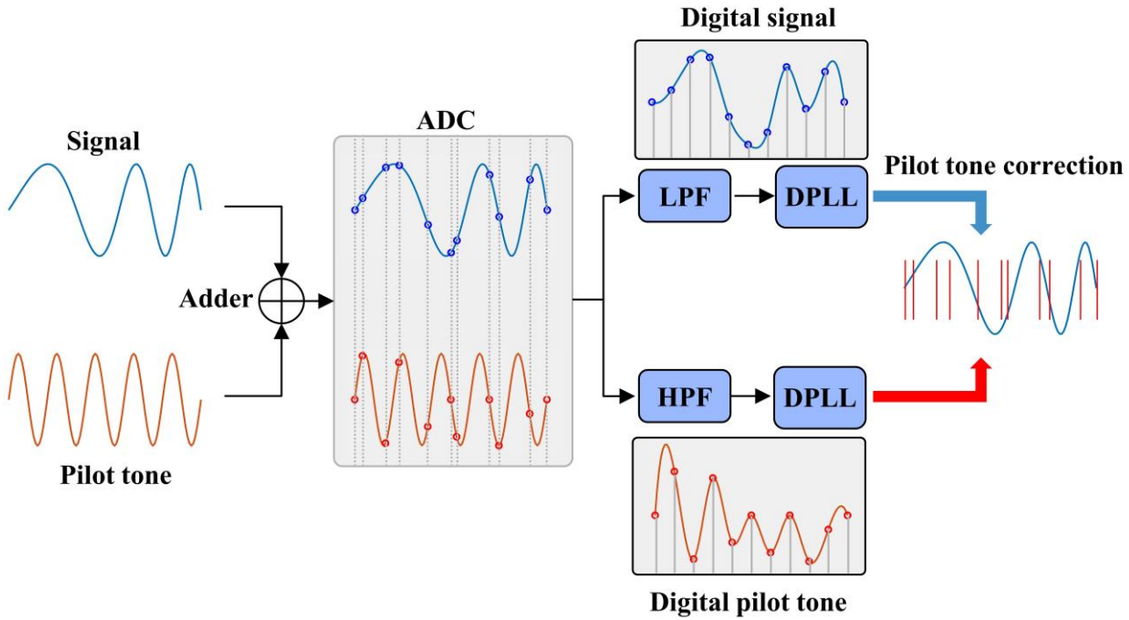


Four clocks non-homologous:

The auxiliary ADC comparison link is used to obtain clock asynchronization information and verify the clock asynchronization mechanism. The experimental results are in good agreement with theory.

② Main Onboard Clock Jitter Noise Sources——Theoretical Analysis

Pilot tone correction effectively suppresses the ADC aperture jitter and sampling clock jitter noise, and the **frequency jitter of the pilot tone becomes the dominant clock noise source**, i.e., the pilot tone serves as the equivalent onboard clock reference.



ADC aperture jitter, Sampling clock jitter

Phase variation to be measured: $\delta\phi_h = 2\pi \times \delta f_h \times t + 2\pi \times f_h \times (\delta t_{adc} + \delta t_{clock})$

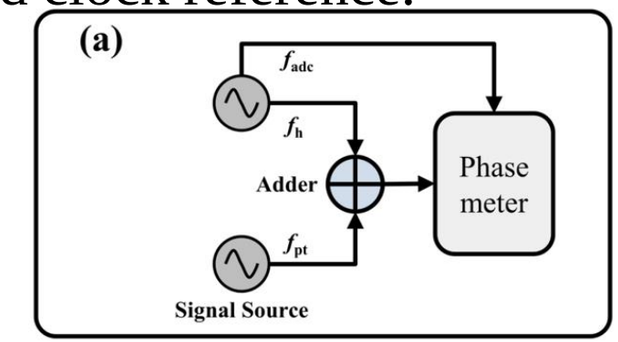
Pilot tone phase variation: $\delta\phi_{pt} = 2\pi \times \delta f_{pt} \times t + 2\pi \times f_{pt} \times (\delta t_{adc} + \delta t_{clock})$

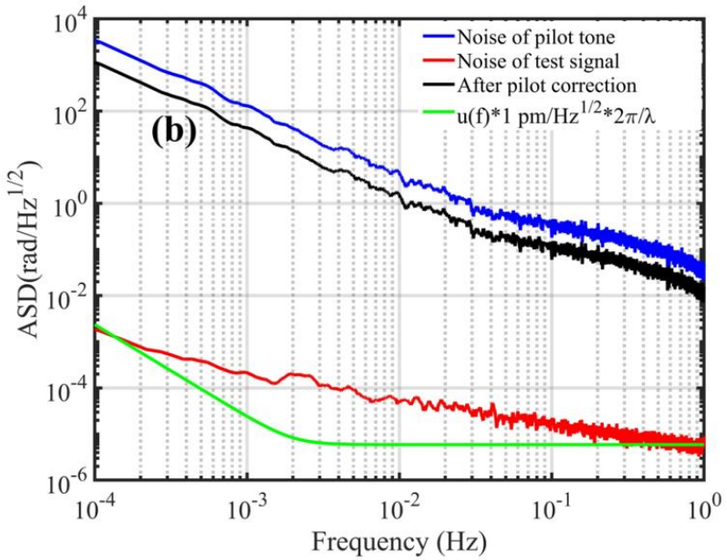
After pilot tone correction: $\delta\phi_{cor} = \delta\phi_h - \frac{f_h}{f_{pt}}\delta\phi_{pt} = 2\pi \times \delta f_h \times t - \frac{f_h}{f_{pt}} \times 2\pi \times \delta f_{pt} \times t$

Pilot tone frequency jitter

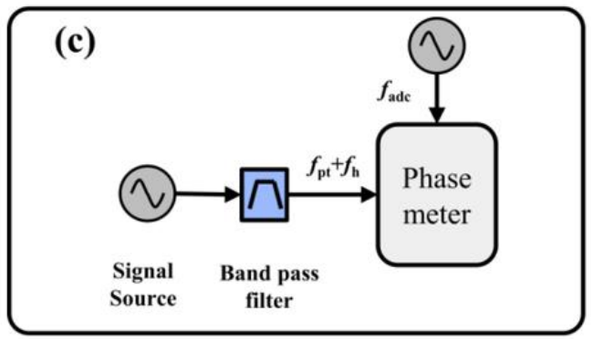
② Main Onboard Clock Jitter Noise Sources——Experimental Verification

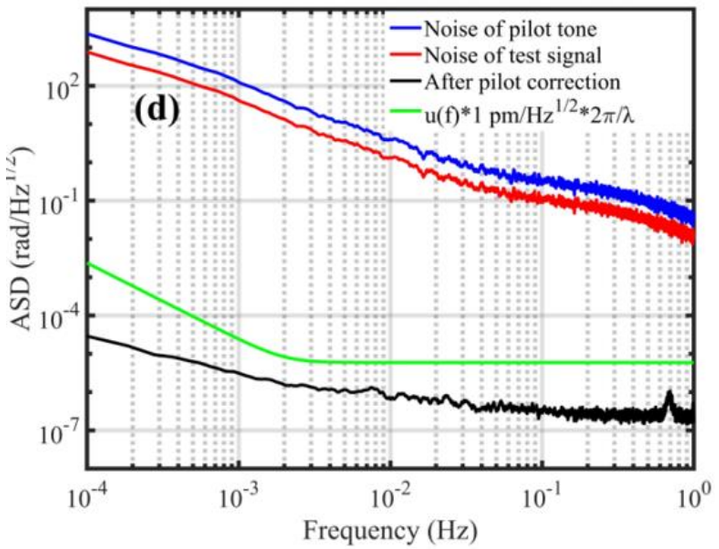
An **electrical experiment combined with frequency homology modulation between the interference signal and the pilot tone** was conducted to experimentally verify the pilot tone becomes the equivalent onboard clock reference.



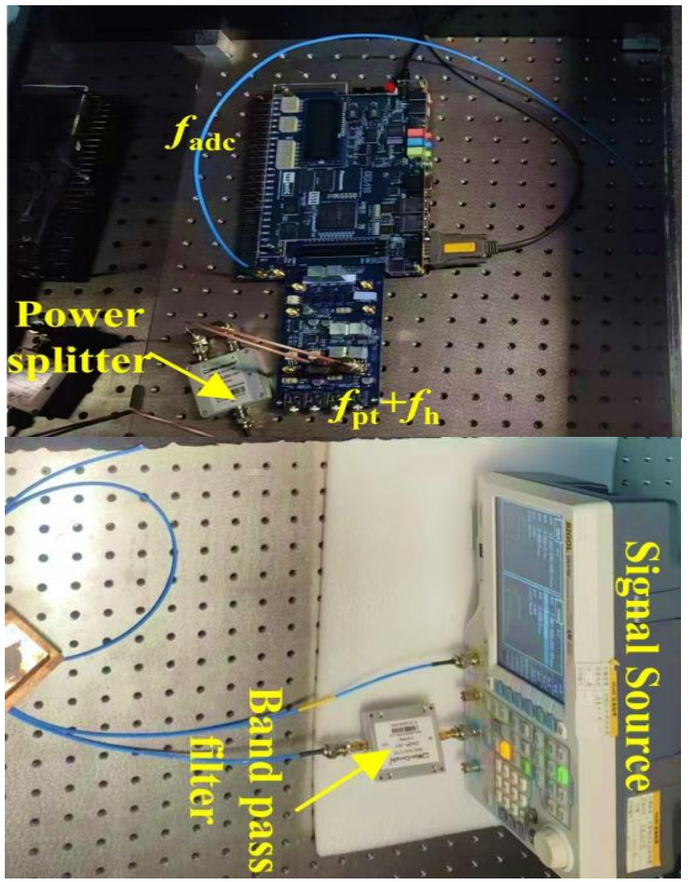


The signal to be measured and the ADC frequency are homologous





The signal to be measured and the pilot tone are homologous

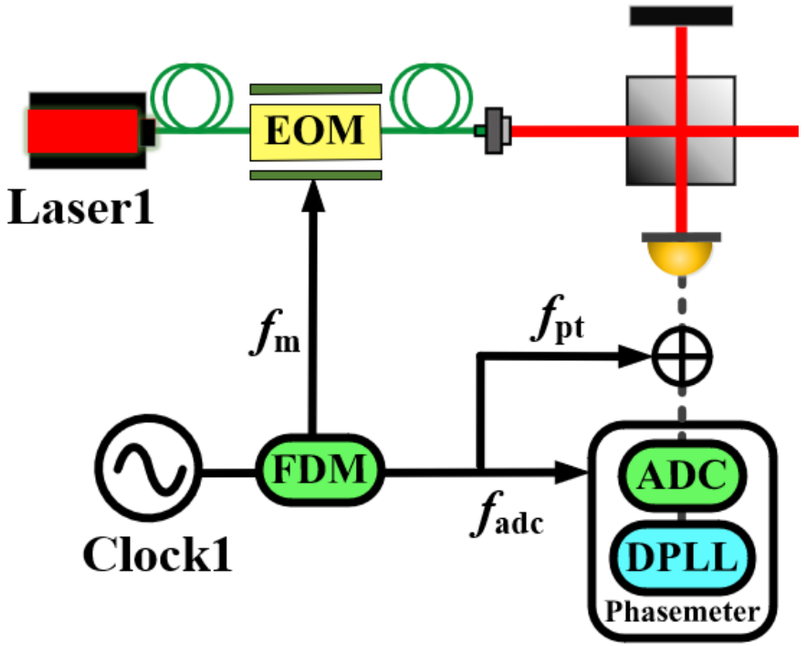


Experimental test setup

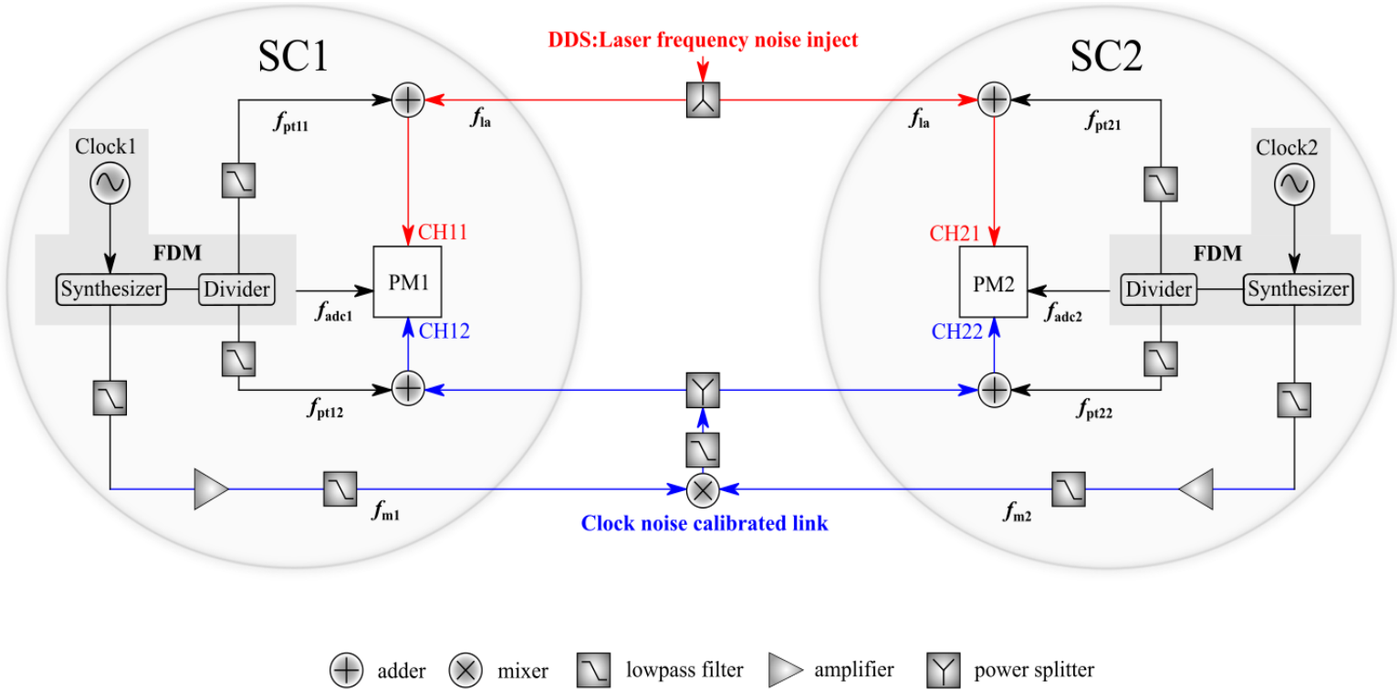
Effective reference clock signal in space-borne gravitational wave detection, Physical Review Applied, 24, 014014 (2025)

③ Clock Jitter Noise Suppression

- **Integrate frequency conversion and distribution system (FDM)**



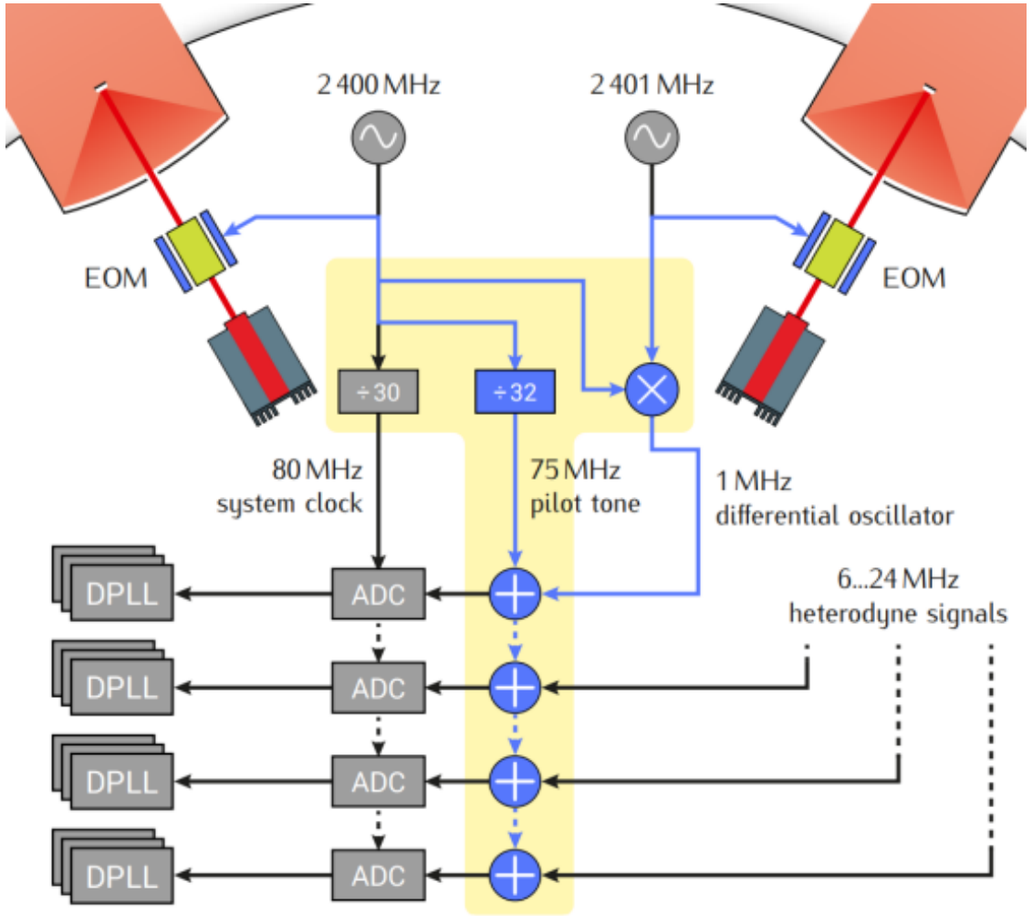
- **Verify clock noise suppression technique**



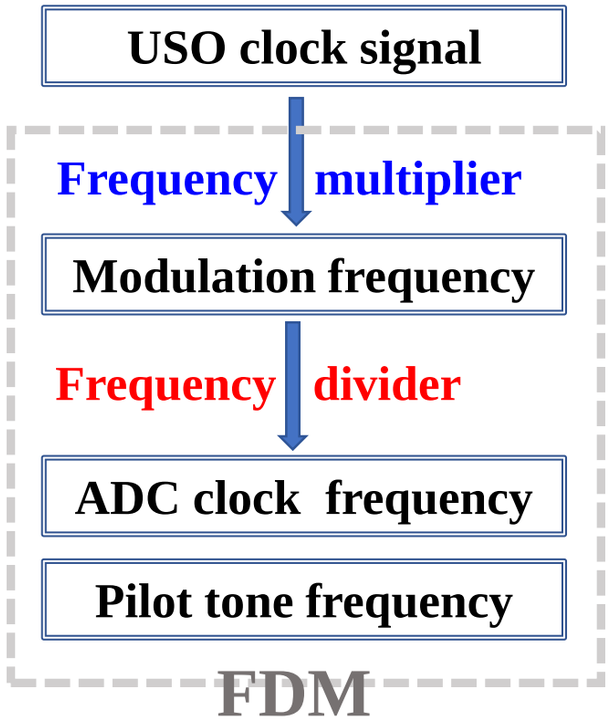
- **Build a high-precision electrical experimental device testing platform for space-based GW detection**

③ Clock Jitter Noise Suppression——FDM Integration

FDM converts the USO clock signal to generate three frequency signals: **EOM modulation frequency**, **ADC clock frequency**, and **pilot tone frequency**. In particular, it must ensure that the pilot tone frequency and the modulation frequency are highly homologous (**additional noise of the frequency divider must be below the 1 pm requirement**).

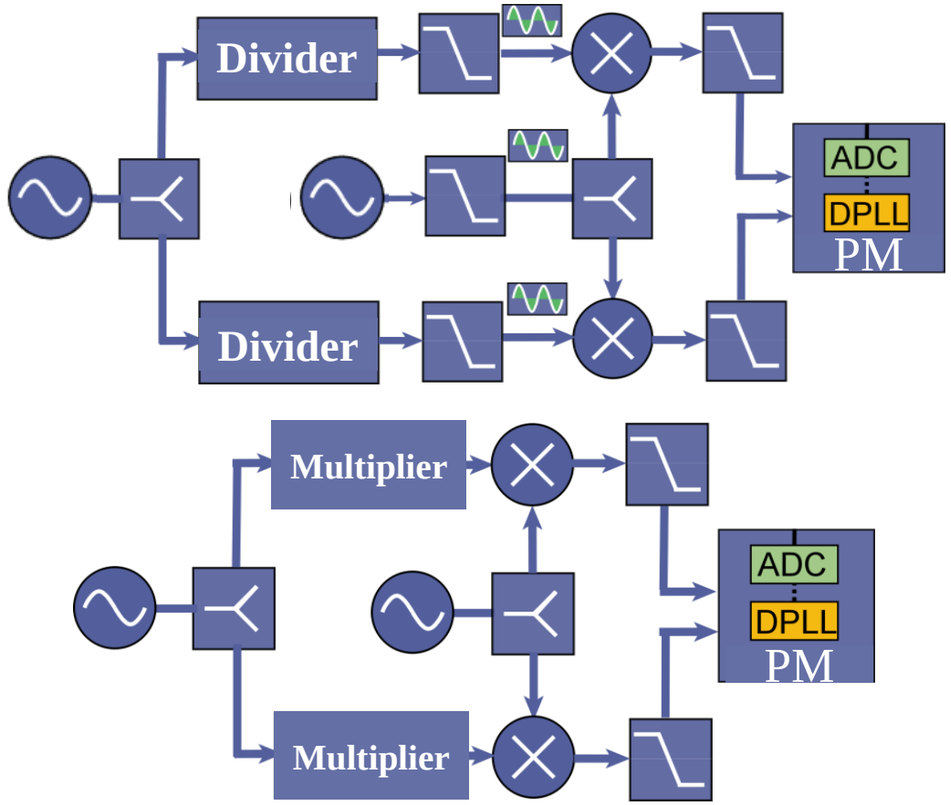


Typical clock signal frequency conversion and distribution system (FDM)

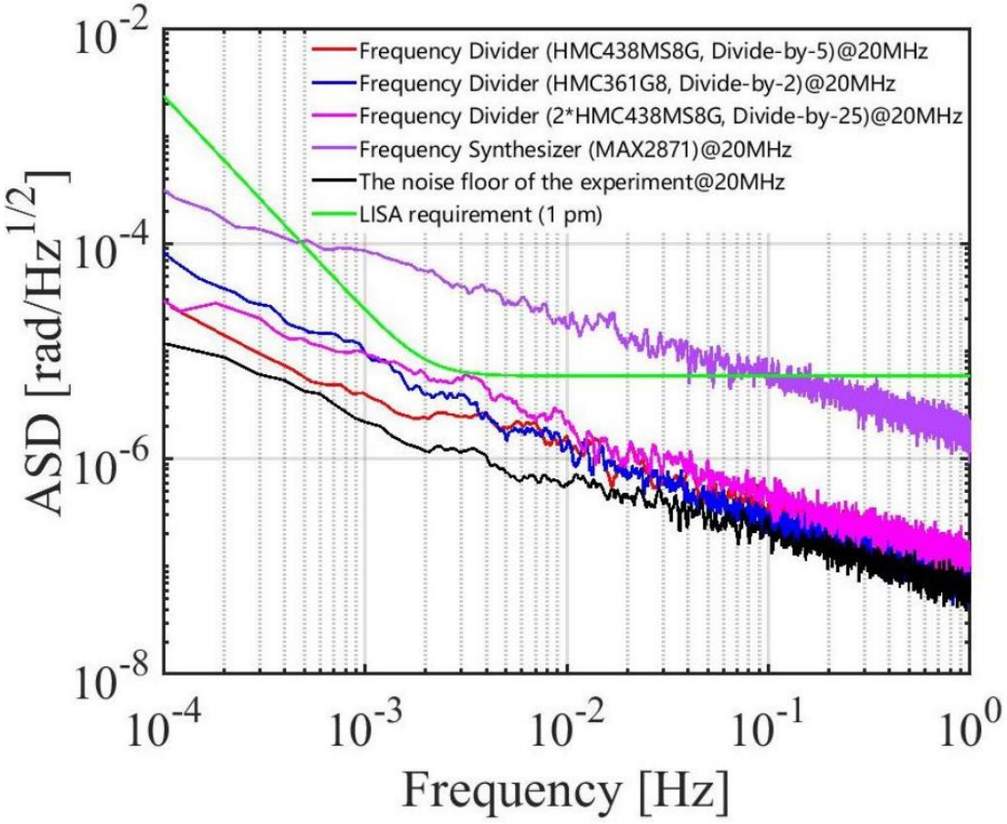


③ Clock Jitter Noise Suppression——FDM Integration

- Differential method was used to measure the additional noise of frequency dividers and multipliers;
- Test results: frequency dividers HMC361G8, HMC438MS8G, and the cascaded divide-by-25 configuration of HMC438MS8G all meet the 1 pm requirement; The additional noise of MAX2871 frequency multiplier is one order of magnitude higher (>1pm@mHz) than that of the frequency dividers;
- **MAX2871 is integrated with the cascaded divide-by-25 configuration to form the FDM**.



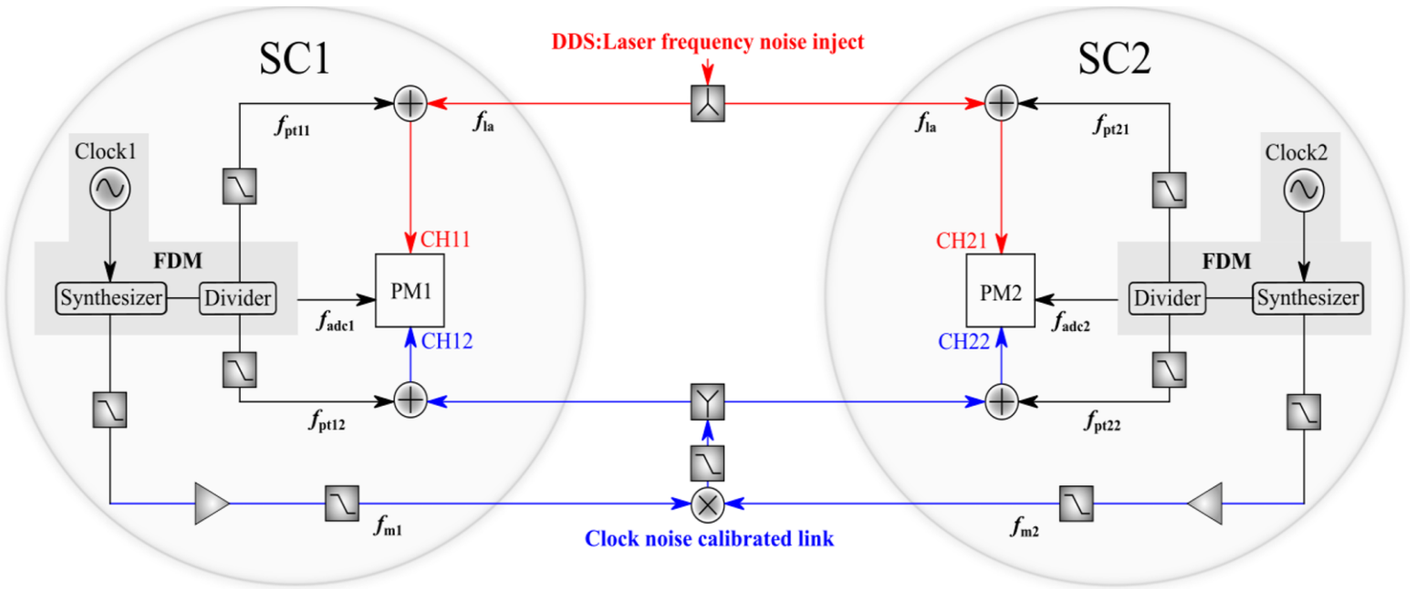
Component noise testing principle (Differential Method)



Component additional noise test results

③ Clock Jitter Noise Suppression——Experimental Verification

Differentially process carrier data to suppress laser frequency noise; combine with auxiliary data to suppress clock noise; **complete clock synchronization before data processing**.





CH11 (satellite 1 carrier interference): $\eta_1(t_1) = \delta\nu_{\text{laser}}(t_1) - a \times \frac{\delta f_{\text{pt1}}}{f_{\text{pt1}}}(t_1)$

CH21 (satellite 2 carrier interference): $\eta_2(t_2) = \delta\nu_{\text{laser}}(t_2) - a \times \frac{\delta f_{\text{pt2}}}{f_{\text{pt2}}}(t_2)$

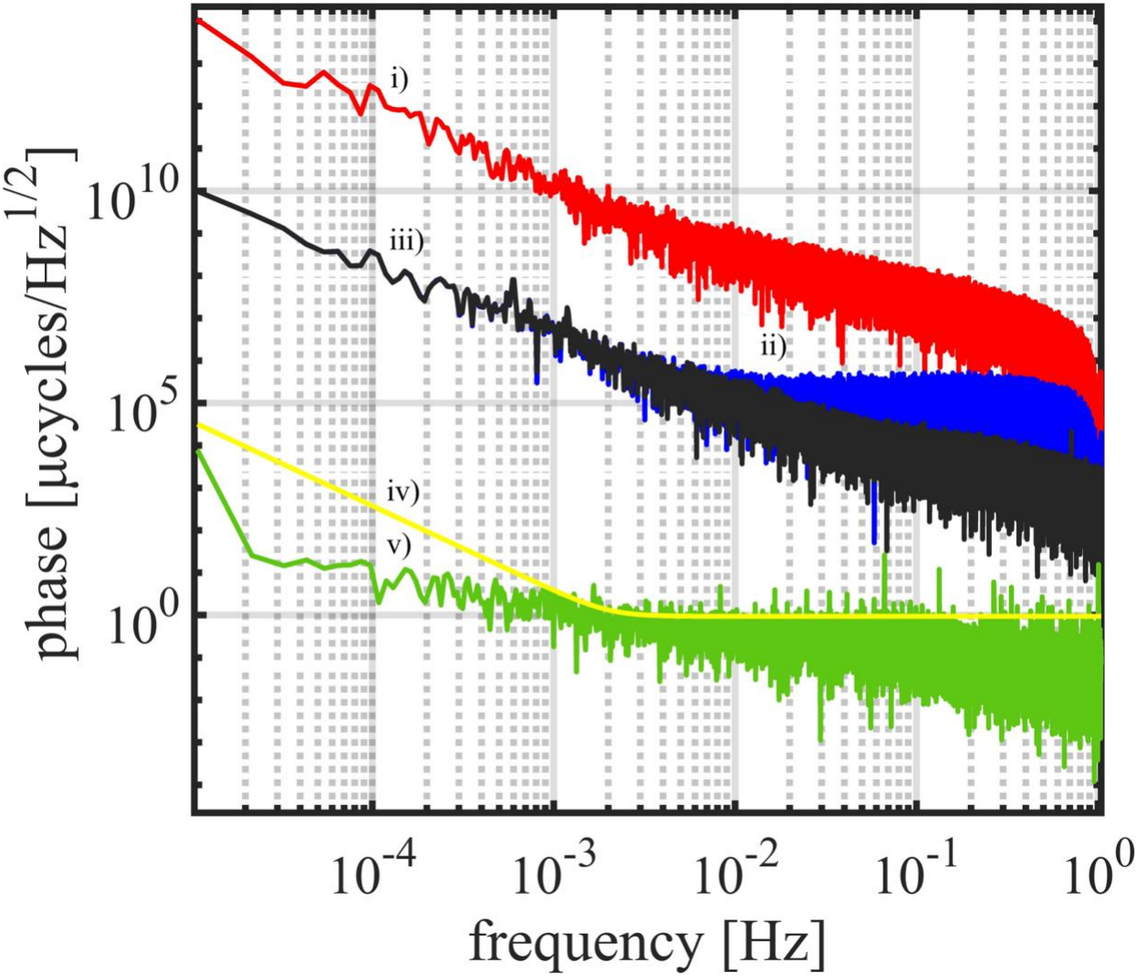
CH22 (satellite 2 auxiliary data): $r_2(t_2) = \delta f_{m1} - \delta f_{m2} - (f_{m1} - f_{m2})\frac{\delta f_{\text{pt2}}}{f_{\text{pt2}}} \approx f_{m1}(\frac{\delta f_{\text{pt1}}}{f_{\text{pt1}}} - \frac{\delta f_{\text{pt2}}}{f_{\text{pt2}}})(t_2)$

CH11-CH21+CH12/f_m*a:

data combination to suppress laser frequency noise and clock noise

③ Clock Jitter Noise Suppression——Experimental Verification

Effectiveness of clock noise suppression technique is verified at a level of 1pm/Hz^(1/2)@3mHz-1Hz, with common-mode suppression of laser frequency noise, inter-satellite clock synchronization, and combination of inter-satellite clock noise comparison data. The experimental results meet the requirements of space-based GW detection across the entire target frequency band.



24-hour measurement results of clock noise suppression experiment.:
(i) raw phase measurement;
(ii)laser frequency noise suppressed by channel data differencing;
(iii) clock asynchronization corrected;
(iv)1 pm requirement;
(v)USO-calibrated TDI-like method applied;
Note: 1μcycle≈1 pm displacement equivalent.

- ✓ **Integrated FDM meets the 1 pm noise suppression requirement;**
- ✓ **Achieve principle verification of clock noise suppression through clock noise comparison.**

Presentation Outline

1. Research background

2. Research content

2.1 TDI technique for laser frequency noise suppression

2.2 Clock jitter noise suppression (*Main focus*)

- Theoretical study
- Experimental validation

3. Summary and prospects

Summary and prospects

Summary:

- **Algorithm & Theory:** Extended the TDI framework (USO-calibrated & Optical comb-based) to simultaneously suppress laser and clock noises in space-based GW detection.
- **Mechanism & System:** Identified pilot tone frequency jitter as the dominant onboard clock noise source; a two-satellite, two-link electrical experimental system (integrated with FDM) was established.
- **Experimental Validation:** Suppression technique verified at a noise level of **1pm/Hz^(1/2)@3mHz-1Hz**, meeting mission requirements across the entire target band. A high-precision electronic testing platform was successfully constructed.

Prospects:

- Conduct additional noise testing of the EOM sideband modulation unit;
- Integrate the EOM, FDM, and noise long time-delay system to build an optical experimental system for clock noise transfer and comparison, and further verify the laser frequency noise and clock noise suppression techniques.

Thanks for your attention!