High Resolution Optical Thermometer

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  - Fiber-Coupled Thermometer
Background—Project Motivation

- The STAR spacecraft will search for variations in the speed of light at the level $\delta c/c \sim 10^{-17}$

- Requires $\delta l/l < 10^{-17}$ for ULE cavities, or a cavity temp. stability of $10^{-8}$ Kpp [*]

- Targets extraordinary precision of $10^{-12}$ in $\delta f/f$ through narrow band measurement (data average over a year)

Fig. ULE optical cavity block with two sets of orthogonal fiber-coupled cavities (courtesy Ball Aerospace).

[*] J. A. Lipa, et al. Prospects for an advanced Kennedy-Thorndike experiment in low Earth orbit Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA.
Background—Project Motivation

Fig. Six-layer thermal enclosure cutaway showing the ULE optical cavity block [*]

Fig. Results from thermal modeling the 6-stage passive thermal enclosure in the left fig [*]

[*] J. A. Lipa, et al. Prospects for an advanced Kennedy-Thorndike experiment in low Earth orbit Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA.
Optical Thermometer Conceptual Diagram

Fiber Coupled Laser Source

Cavity 1 (Reference, low CTE)
Capped with end mirrors, resonant frequency at $f_1$

Frequency Shifter

Feedback control to maintain laser light resonance as rod lengths change

Cavity 2 (Signal, high CTE)
Capped with end mirrors, resonant frequency at $f_2$

Frequency Comparator

Beat Signal $\Delta f$
System Limitation Outline

- Signal Calculation

- Noise Sources
  - Refractive index change
    - Due to pressure fluctuation $\Delta P$
  - EOM driver noise

- Corresponding Solution

- Thermal noise
  - Mirrors, substrate, etc
  - Power buildup in optical cavity

- Mechanical noise
  - Vibration
  - Orientation
System Limitation (Noise Calculation)

- For small cavity length change $\Delta L$, the corresponding frequency shift (hence temperature change) is

$$\frac{\Delta f_T}{f} = \frac{\Delta L}{L} = \alpha \Delta T \quad \Rightarrow \quad \Delta f_T = f \alpha \Delta T = \frac{c}{\lambda} \alpha \Delta T$$

Where $\lambda = 780nm$, $\alpha$ is the CTE of the cavity material

- For detection of $\Delta T = 10nK$ with steel cavity

$$\Delta f_T = 61.6Hz$$
Noise Calculation

- **EOM/AOM driver noise**
  - Frequency stability of commercial driver (SG380): $< 1 \times 10^{-11}$ (1s Allan variance) out of 2GHz, viz:
    \[ \Delta f / f < 1 \times 10^{-11} \rightarrow \Delta f < 0.02Hz \]

- **Thermal noise of cavity components**
  - Noise limitation at 1Hz:
    \[ \sim 0.1Hz / \sqrt{Hz} \]

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Fig. Measurement of frequency noise of a 30MHz EOM driver

Fig. Thermal induced frequency noise vs. frequency[*]

Noise Calculation

- Mechanical Noise
  - Vibration
  - Cavity orientation in the presence of gravitational force

-- Fig. Freq/Accel sensitivity vs Mounting[*]

- Sub-Hertz laser linewidth can be achieved through noise cancellation based on symmetry

[*] John Lipa, “Why another Isotropy Experiment?” presentation slide 29
Summary For 10nK Resolution Requirement

Resolution $\Delta T = 10 \text{ nK} \rightarrow \Delta f_{signal} = 62 \text{ Hz}$

<table>
<thead>
<tr>
<th>Approximate Magnitude</th>
<th>System requirement</th>
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<tbody>
<tr>
<td>Noise due to $\Delta P$</td>
<td>Differential pressure fluctuation $\leq 10^{-7} \text{ torr}$</td>
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<tr>
<td>EOM driver noise</td>
<td>Frequency stability of commercial driver</td>
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<td></td>
<td>(SG380)</td>
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<td>Thermal noise</td>
<td>Proper cavity design</td>
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<tr>
<td>Mechanical noise</td>
<td>Proper mechanical design</td>
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</table>

Table. System requirement for 10nK resolution
Fiber-coupled Interferometer

- Fiber-free space transmission through grin lens systems

Plot by courtesy of Grant Culter

- Optical layout design into a 3-stage vacuum compatible thermal enclosure with micro-Kelvin temperature stability (under development of Grant Culter)
Future Work

- Fiber-free space transmission through grin lenses
- Cavity design
- Vacuum system Design
- Optical layout in thermal cavity
- Beat signal analysis

Plot by courtesy of Grant Culter
Questions

THE END