Quantum locking of mirrors in Gravitational Interferometers

J.M. Courty
A. Heidmann
M. Pinard

Laboratoire Kastler Brossel (Paris)

U.P.M.C. E.N.S. C.N.R.S.
Quantum noise in length measurement

- Length measurement with phase shift
- Mirror motion due to fluctuating radiation pressure
Sensitivity of measurement

- Phase noise: error in measurement
- Intensity noise: back action
Sensitivity of measurement

- **Phase noise**: error in measurement
  \[ \alpha \frac{1}{I_{in}} \]

- **Intensity noise**: back action
  \[ \alpha \frac{I_{in}}{(\Omega^2)^2} \]
Sensitivity of measurement

- **Standard Quantum Limit**

\[ \delta X_{\text{sql}} = \sqrt{\frac{\hbar}{M_\text{m} \Omega^2}} \]

Outline

- Quantum noise reduction
- Control of mirror motion
- Back action cancellation
Description with quadrature operators

Light in coherent state: \[ \langle \delta a_1^2 \rangle = \langle \delta a_1^2 \rangle = 1 \]

\[ \delta I = \sqrt{I} \delta a_1 \]
\[ \delta \varphi = \frac{1}{2\sqrt{I}} \delta a_2 \]
Measurement in phase space

- Output phase:
- Optomechanical coupling

\[ a_{2}^{\text{out}} = 2\xi_{a}X_{\text{sig}} + a_{2}^{\text{in}} - \frac{2\hbar\xi_{a}^{2}}{M\Omega^{2}}a_{1}^{\text{in}} \]

\[ \xi_{a} = 4k_{0}\frac{F_{a}}{\pi}\sqrt{T_{\text{in}}}. \]
Measurement in phase space

- Output phase:

- Optomechanical coupling

- Signal estimator

\[
\hat{X}_{\text{sig}} = \frac{1}{2\xi_a} a_{2\text{out}} = \frac{1}{2\xi_a} a_{2\text{out}} = \frac{1}{2\xi_a} a_{2\text{in}} - \frac{2\hbar \xi_a^2}{M \Omega^2} a_{1\text{in}}
\]

\[
\xi_a = 4k_0 \frac{J_a}{\pi} \sqrt{I_{\text{in}}}
\]

\[
a_{2\text{out}} = 2\xi_a X_{\text{sig}} + a_{2\text{in}} - \frac{2\hbar \xi_a^2}{M \Omega^2} a_{1\text{in}}
\]
Squeezing input noise

- Intensity – phase correlation
- Correlation depends on frequency

Signal estimator

\[ \hat{X}_{\text{sig}} = \frac{1}{2\xi_a} a_{\text{out}}^2 = X_{\text{sig}} + \frac{1}{2\xi_a} a_{\text{in}}^2 - \frac{2h\xi_a}{M\Omega^2} a_{\text{in}}^2 \]
Squeezing input noise

- Intensity – phase correlation by squeezing
Squeezing input noise

- Intensity – phase correlation by squeezing
- New limit: Ultimate Quantum Limit

Squeezing by radiation pressure

- At the Standard Quantum Limit squeezing is 60%
At the Standard Quantum Limit squeezing is 60%.

Measurement of adapted quadrature

\[ \hat{X}_m = -\frac{1}{2\xi_b \sin \theta} a_{\theta}^{\text{out}} = X_m - \frac{1}{2\xi_b} a_2^{\text{in}} - \left( \cot \theta \frac{\hbar \xi_b}{2\xi_b - \frac{\hbar \xi_b}{M_r \Omega^2}} \right) a_1^{\text{in}} \]

Optimal quadradure depends on frequency
Noise reduction in real instruments

Noise control on the whole spectrum

- Use of already existing squeezing
  - Design of interferometer
  - Adapted detection scheme
- Injection of squeezed light
- Active control of radiation pressure noise
Control of thermal noise

- **Measurement of mirror motion**
- **Correction with active feedback**
- **Analysis of quantum regime**
Quantum locking of mirror motion

Freezing mirror motion by quantum locking

- Quantum feedback loop
- Motion of reference mirror
- Measurement strategy
Sensitivity of free interferometer

Interferometer:
Finesse : 600
Input: 20 Watt
Measurement with an auxiliary cavity

Reference cavity:
Finesse: 10 000
Input: 5 milliwatt
Control with infinite gain

Interferometer is locked to reference mirror

- Suppression of interferometer radiation pressure noise
- Sensitivity of interferometer is sensitivity of reference cavity
Control with optimal gain

Optimization on whole spectrum with frequency dependent gain

- Reduction of radiation pressure noise
- Increase of interferometer bandwidth

Optimal gain
Optimal detection is achieved on the whole bandwidth.

- Phase shift with detuned cavity
- Measurement of output intensity

Optimal detection is achieved on the whole bandwidth.
Optimal detection

- **Same optomechanical coupling for interferometer and auxiliary cavity**
Optimal detection

- **Same optomechanical coupling for interferometer and auxiliary cavity**
- **The only noises are phase noises**
• Losses in interferometer: no impact on quantum locking
• Losses in detection of 1%:
  back action still reduced by factor 100
Discussion

- **Squeezing is already present**
  in quantum limited interferometers
- **Active techniques allow the control**
  of noise in the whole spectrum

- **Quantum locking**: an alternative method to beat quantum noise

- **Local control compatible with existing designs**

- **Squeezing may be used in a simple system**
Conclusion - References

• Quantum locking of mirrors in interferometers

• Back action cancellation by quantum locking
  J.M. Courty, A. Heidmann, M. Pinard, gr-qc/0301068