Current Status of TAMA

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@ Caltech

LIGO-G000030-00-M

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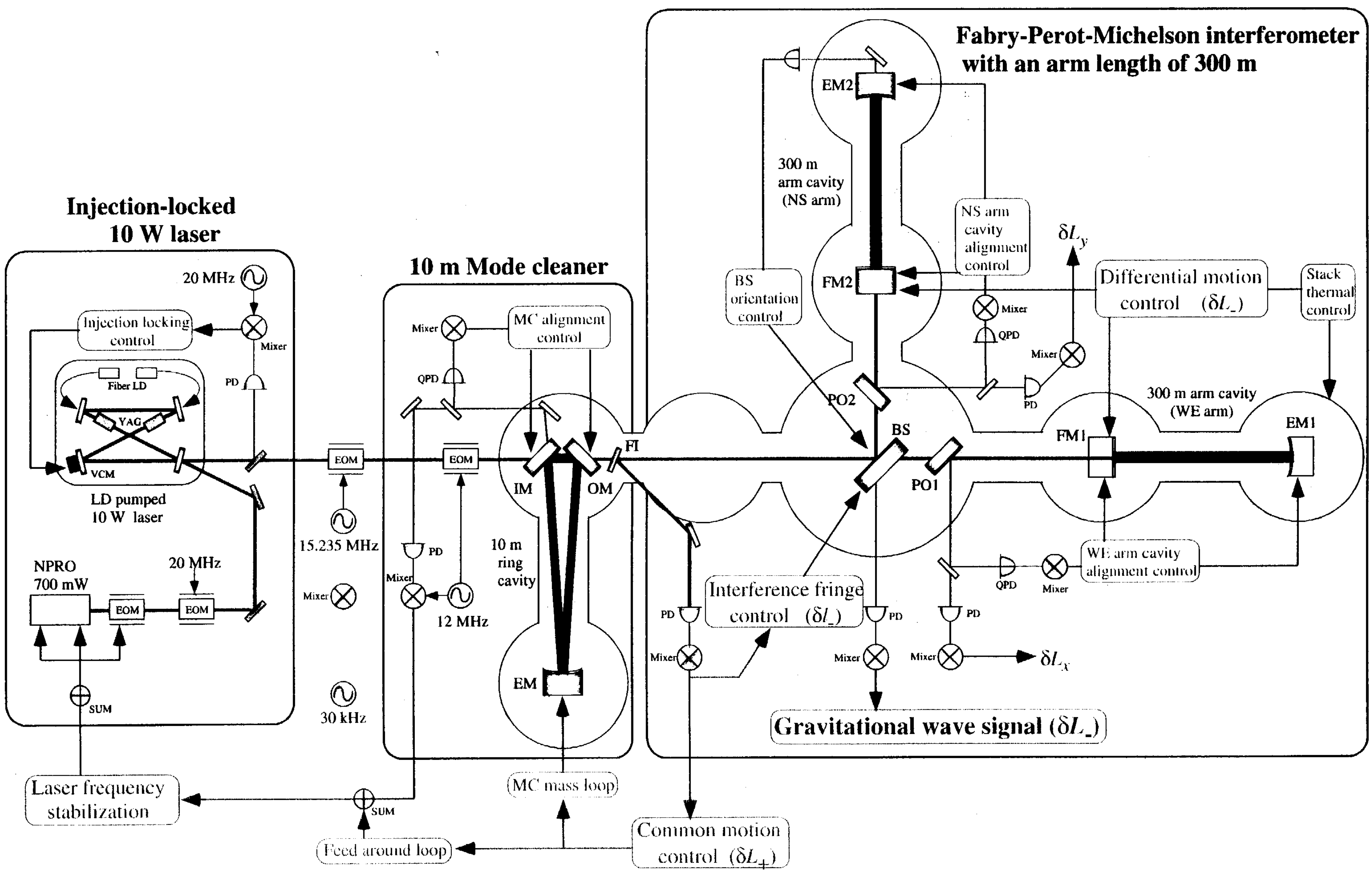
Overview

- Sensitivity ··· 4×10^{-18} m/$\sqrt{\text{Hz}}$
  (600 ~ 1.5 kHz)
- Continuous Locking Time
  ··· about 8 hours
- Calibration Method
  ··· Established

☆ Two-year extension of TAMA:
Formally approved

We are now optimizing the plan.


Injection-locked 10 W laser
20 MHz
Injection locking control
Mixer
PD
Fiber LD
YAG
VCM
LD pumped 10 W laser
NPRO 700 mW
20 MHz
EOM
EOM
SUM
Laser frequency stabilization
EOM
15.235 MHz
Mixer
30 kHz
10 m Mode cleaner
Mixer
MC alignment control
QPD
EOM
PD
Mixer
12 MHz
10 m ring cavity
IM
OM
EM
SUM
Feed around loop
MC mass loop
FI
Fabry-Perot-Michelson interferometer with an arm length of 300 m
EM2
300 m arm cavity (NS arm)
NS arm cavity alignment control
FM2
BS orientation control
Mixer
QPD
δL_y
Differential motion control (δL_)
Stack thermal control
Mixer
PD
PO2
BS
300 m arm cavity (WE arm)
FM1
EM1
PO1
WE arm cavity alignment control
QPD
Mixer
Interference fringe control (δl_)
PD
PD
PD
Mixer
Mixer
Mixer
δL_x
Gravitational wave signal (δL_)
Common motion control (δL_+)

Light Source

Injection-locked 10W Laser

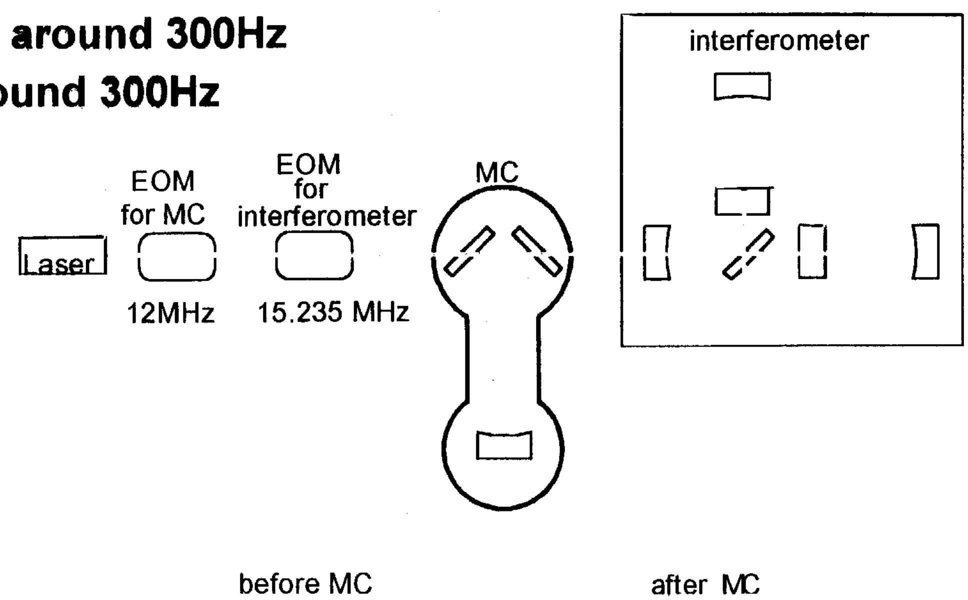
Master Laser : LD-pumped Nd:YAG laser 700mW(NPRO)
Slave Laser : LD(fiber-coupled)-pumped Nd:YAG laser with VCM

10m Ring-type Mode Cleaner

Finesse : 1700
Carrier transmittance : 54%
Sidebands(15.235MHz) transmittance : Excess noise free

Requirement for Stability

Frequency : $\delta\nu < 5 \times 10^{-7}$Hz/rtHz around 300Hz
Intensity : $\delta I/I < 1 \times 10^{-8}$/rtHz around 300Hz



Main Interferometer

Fabry-Perot Michelson Interferometer

- Cavity mirror : Front(flat) R = 99.8%, End(concave) R = 99.99%
- Finesse : 516
- Cut-off frequency : 480Hz

Main Control System

- Length : $\delta l < 5 \times 10^{-12}$ m/rtHz
  - Pre-modulation
- Alignment : $\delta\alpha_{rms} < 5 \times 10^{-7}$ rad
  - Wave-front sensing

Sub-control System

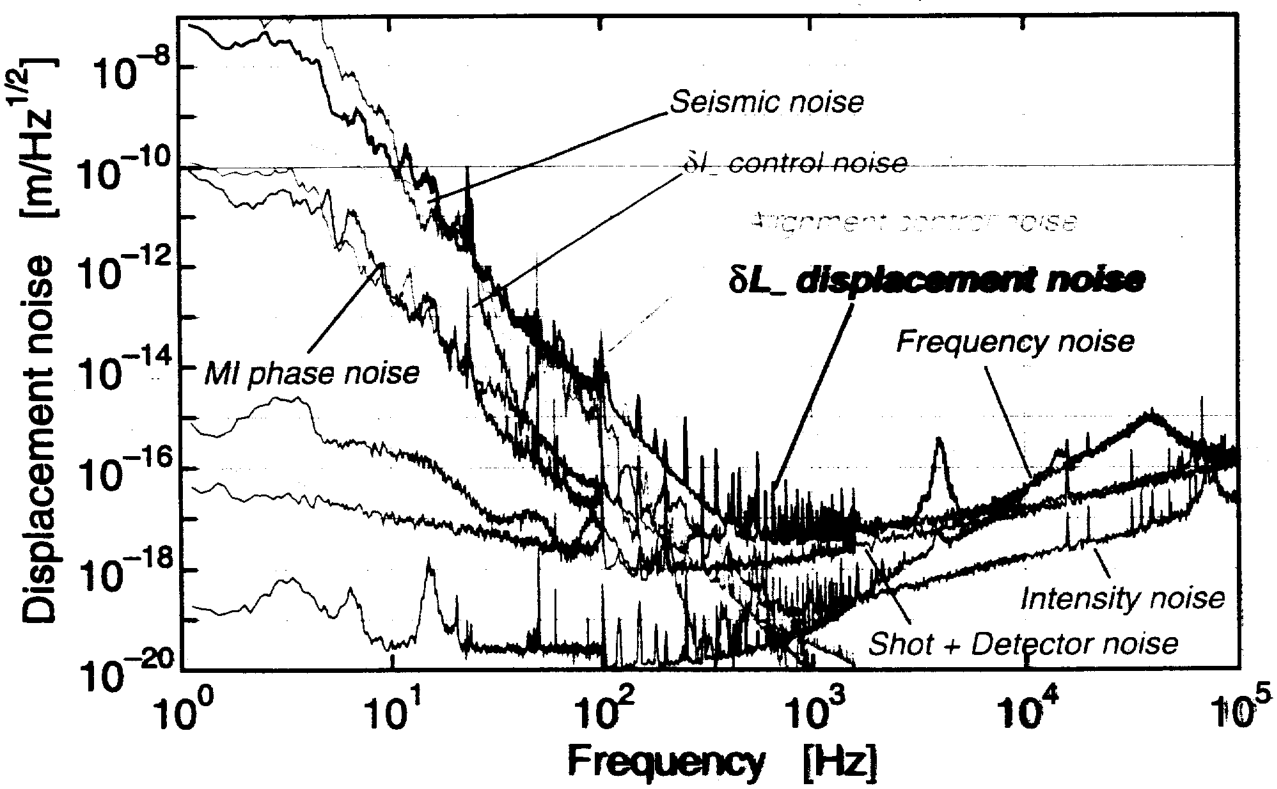
- Beam centering : $\delta d < 0.5$ mm
  - Mechanical modulation
- Length drift : $\delta L < 1$ μm
  - Thermal actuator

Recycling

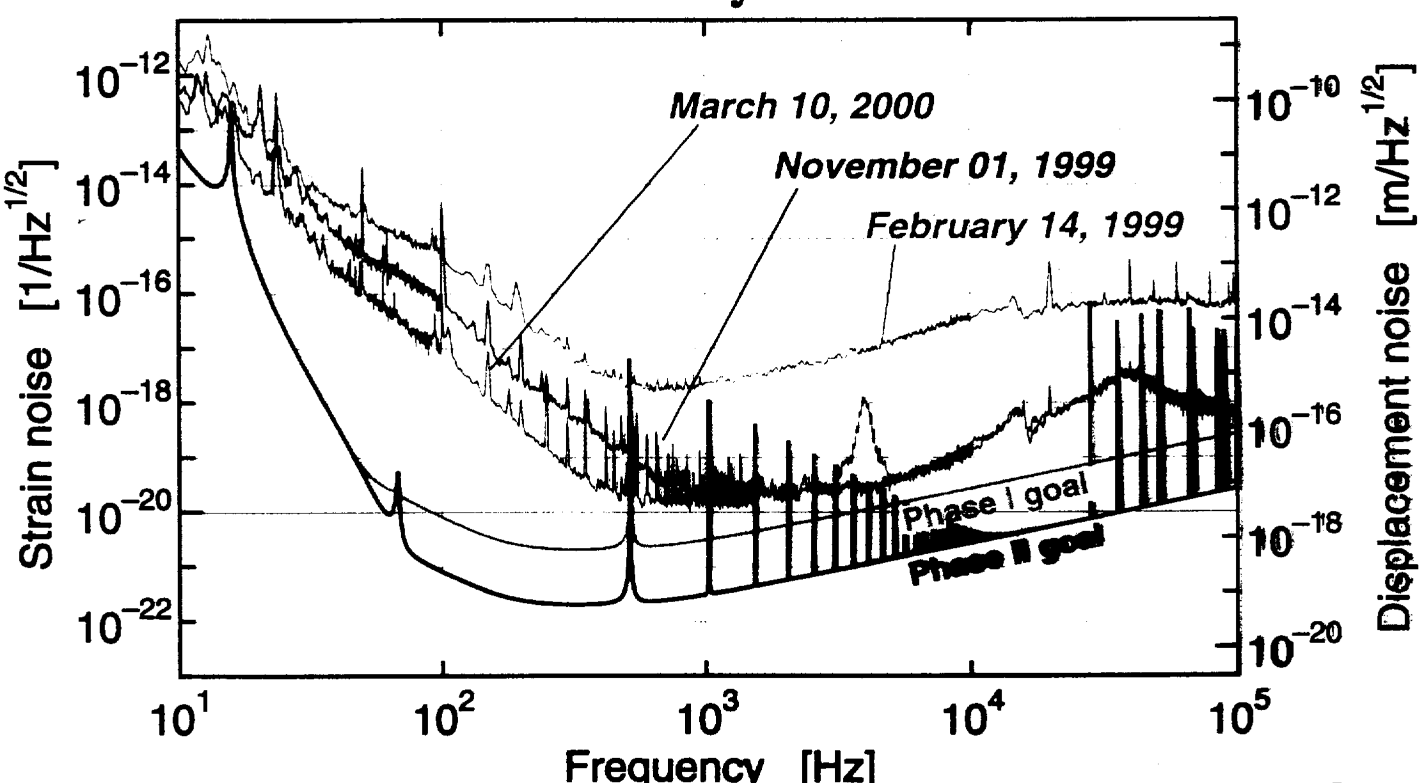
- Gain : 10

Displacement noise level of TAMA300

(March 10, 2000)



Strain sensitivity of TAMA300



Alignment Control Noise I

Pitch motion of test mass at 5Hz

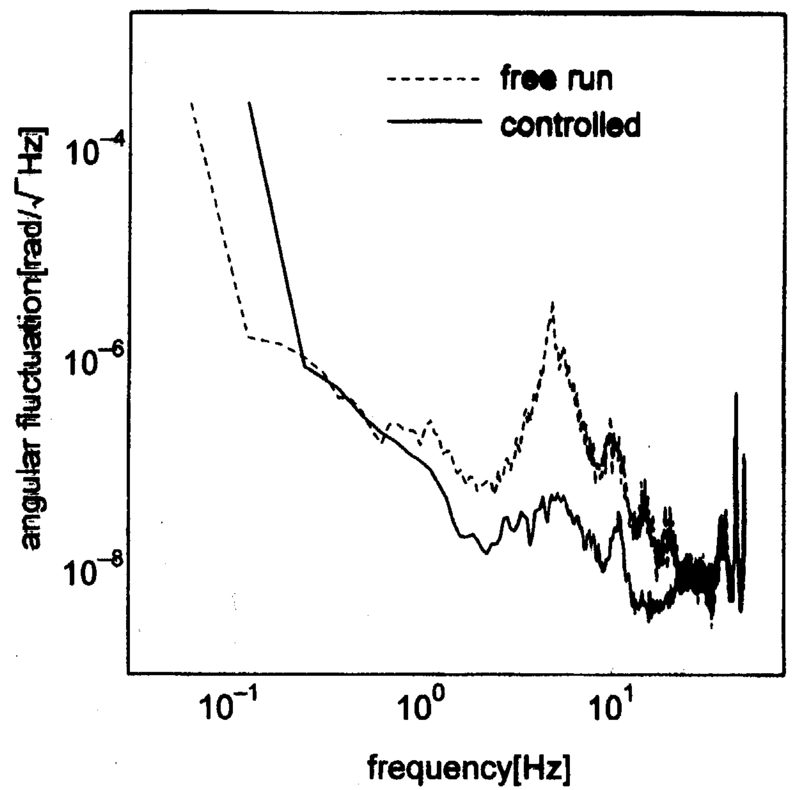
Required angular fluctuation

$\delta\alpha_{rms} < 5 \times 10^{-7}$ rad

Alignment control

Wave-Front Sensing (WFS) is useful.
Large angular fluctuation is damped by WFS servo.
The alignment control noise is dominant in FPMI sensitivity.

angular fluctuation of test mass(EW near:pitch)



Sensitivity of TAMA300 was updated

March 10, 2000

- Modification of QPD Circuit (by G. Heinzel)

  WFS noise was reduced.

- Decreasing of Alignment Control Gain (WE-End-Yaw)
- Adjustment of Mirror Actuator Balance

  Coupling from alignment control was reduced.

- Inserting Blind Plates (with DLC Coating)

  Michelson phase noise was reduced.

- Adjustment of Alignment Offset

  Contrast was improved.

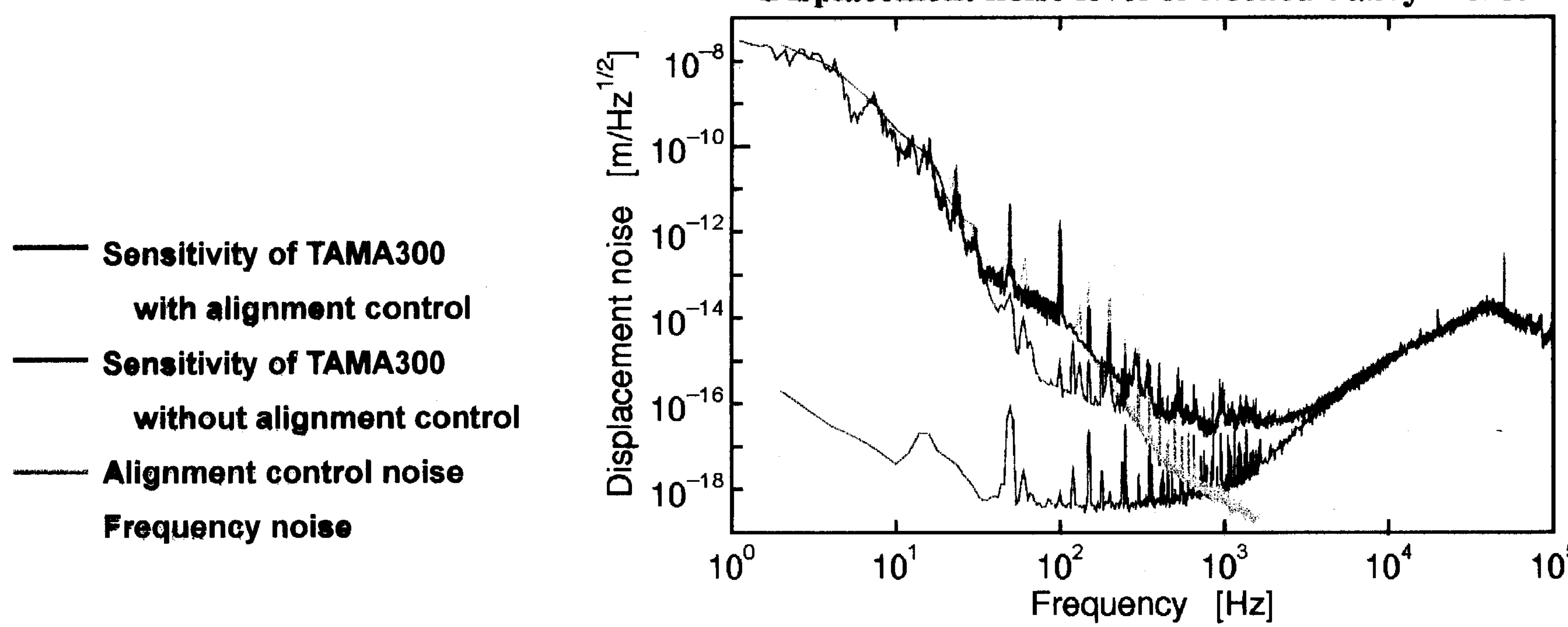
Unknown 4kHz peak was appeared.

Alignment Control Noise II

Solution

Servo circuit with the 10^{th}-order Chebyshev's filter
~~Dynamic Damper tuned to 5Hz~~
Modification of mirror suspension
Active Vibration Isolation

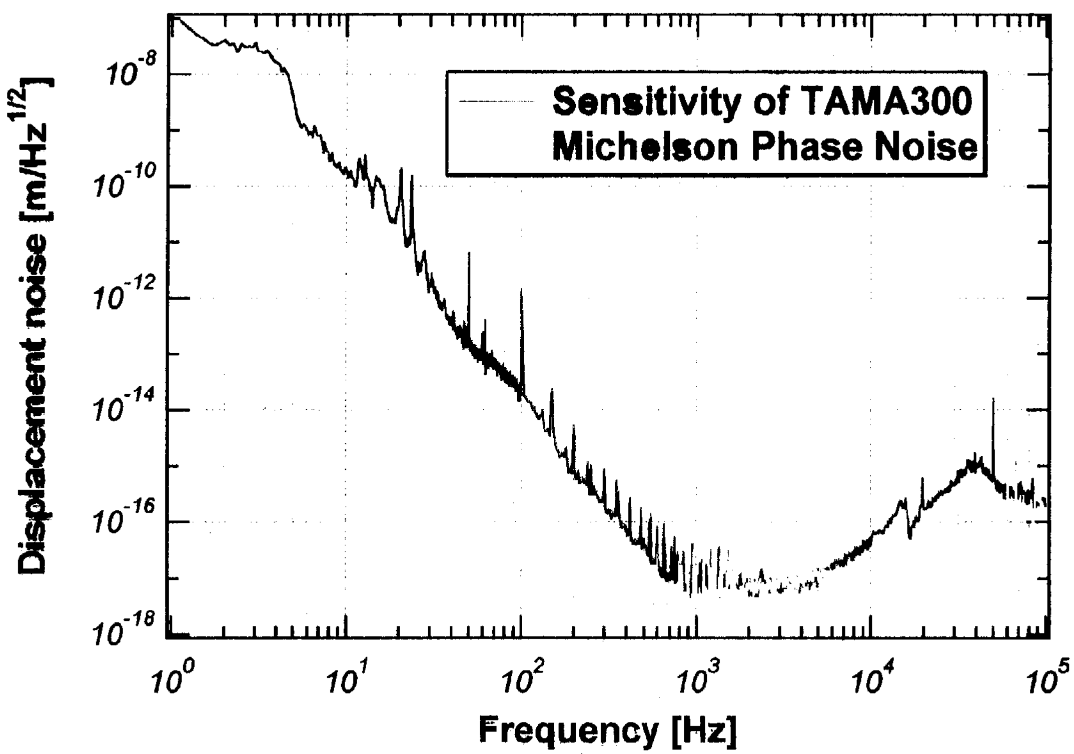
Displacement noise level of Locked Fabry–Perot



Scattered Light Noise I

Phase noise in Michelson Interferometer

Michelson phase noise will appear in FPMI spectrum at the observation band.



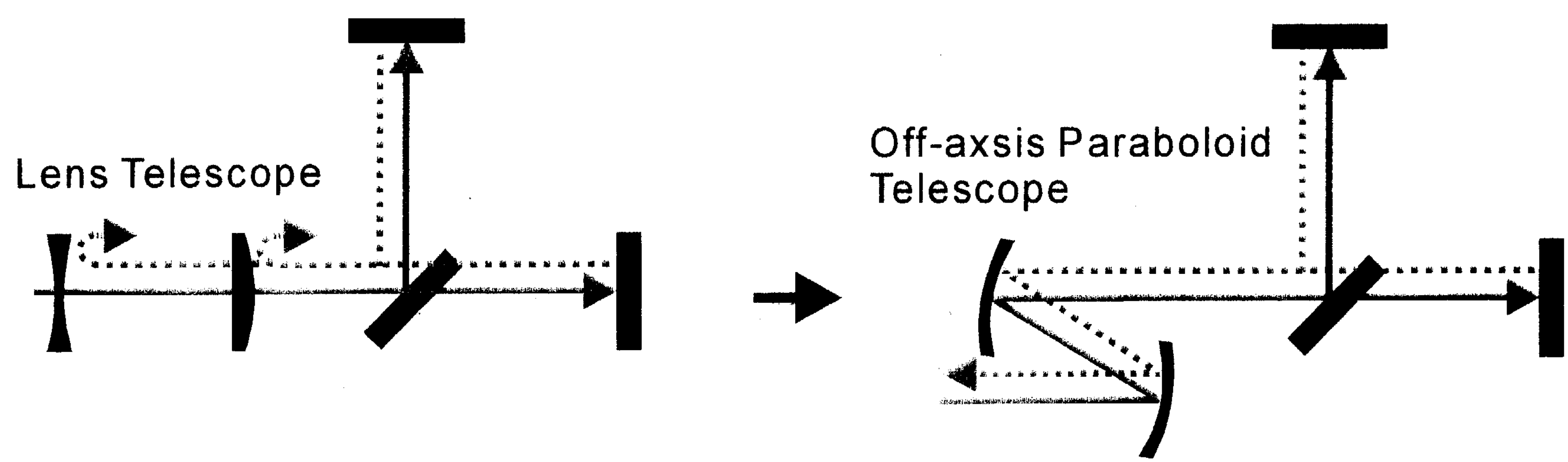
Scattered Light Noise II

Scattering on lens

Reflected beam from Michelson Interferometer returns to the Telescope.
Scattered light by AR surface of lens interfered the incident beam again.

Off-axis Paraboloid Telescope

It has no AR surface.
It is difficult to manufacture high quality paraboloid mirrors.



TAMA alignment

The alignment system had been designed in an early stage of the project.

After years of operation several problems were found:

- no beam centering system
- too much sensor noise
- insufficient signal separation
(front mirror / end mirror)
- insufficient filtering in loop filter

Hence some parts of the alignment system were redesigned:

- beam centering system (new)
- telescope
- quadrant photo detector
- loop filter.

Alignment telescopes

The Guoy phase shifts corresponding to misalignments of the two mirrors are
$\theta_{\text{End}} = 0°$,
$\theta_{\text{Front}} = -54°$.
The new telescope has been designed with additional phase shifts of 180° and +54°, such that the signal contributions of the other mirror vanish.

The measured signal separation was 30 dB, when optimized for one axis.

However, for unknown reasons the beam is elliptical, and the Gouy phase for both axes differs by $\approx 10°$.

Hence the signal separation is only 15 dB.

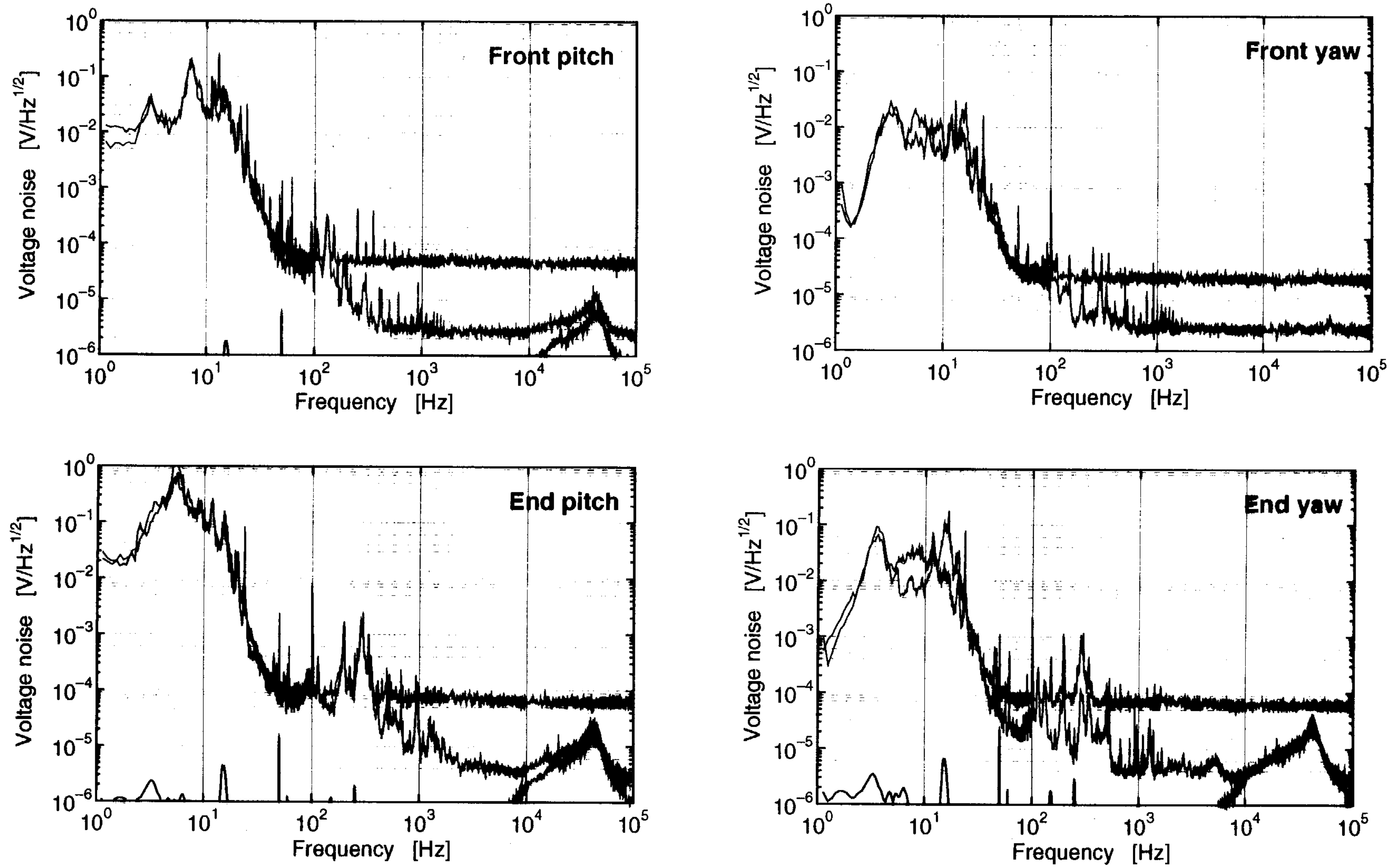
Alignment system: Further work

- Improving signal separation with an analog matrix circuit.

- New loop filters (including a steep low-pass).

- Investigate sensing the cavity alignment at dark and bright Michelson ports instead of using arm cavity pick-off mirrors.

Alignment control error signal (WE arm)



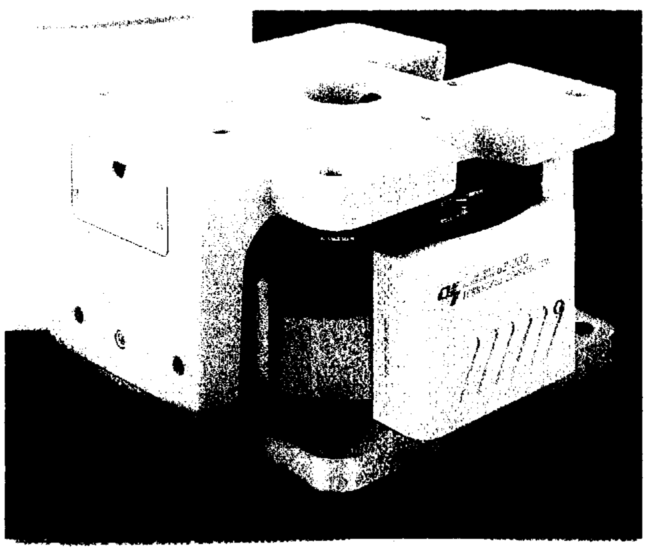
Active Vibration Isolation System

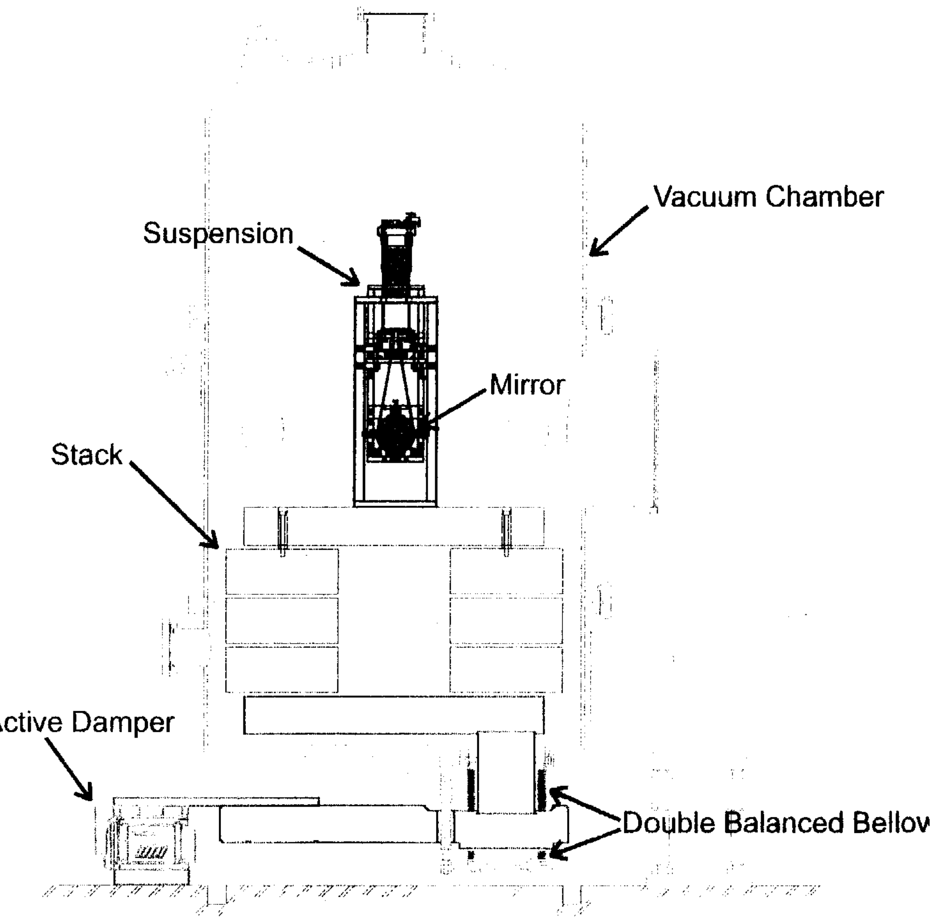
Mechanical Condition

Heavy loaded mass : 1500kg
Double Balanced Bellows

Commercial system

Tokkyokiki Corp. $\alpha 2$
Compact built-in type unit
Pneumatic passive isolation
+ Double active control
Isolation of more than 20dB
at 1-100Hz

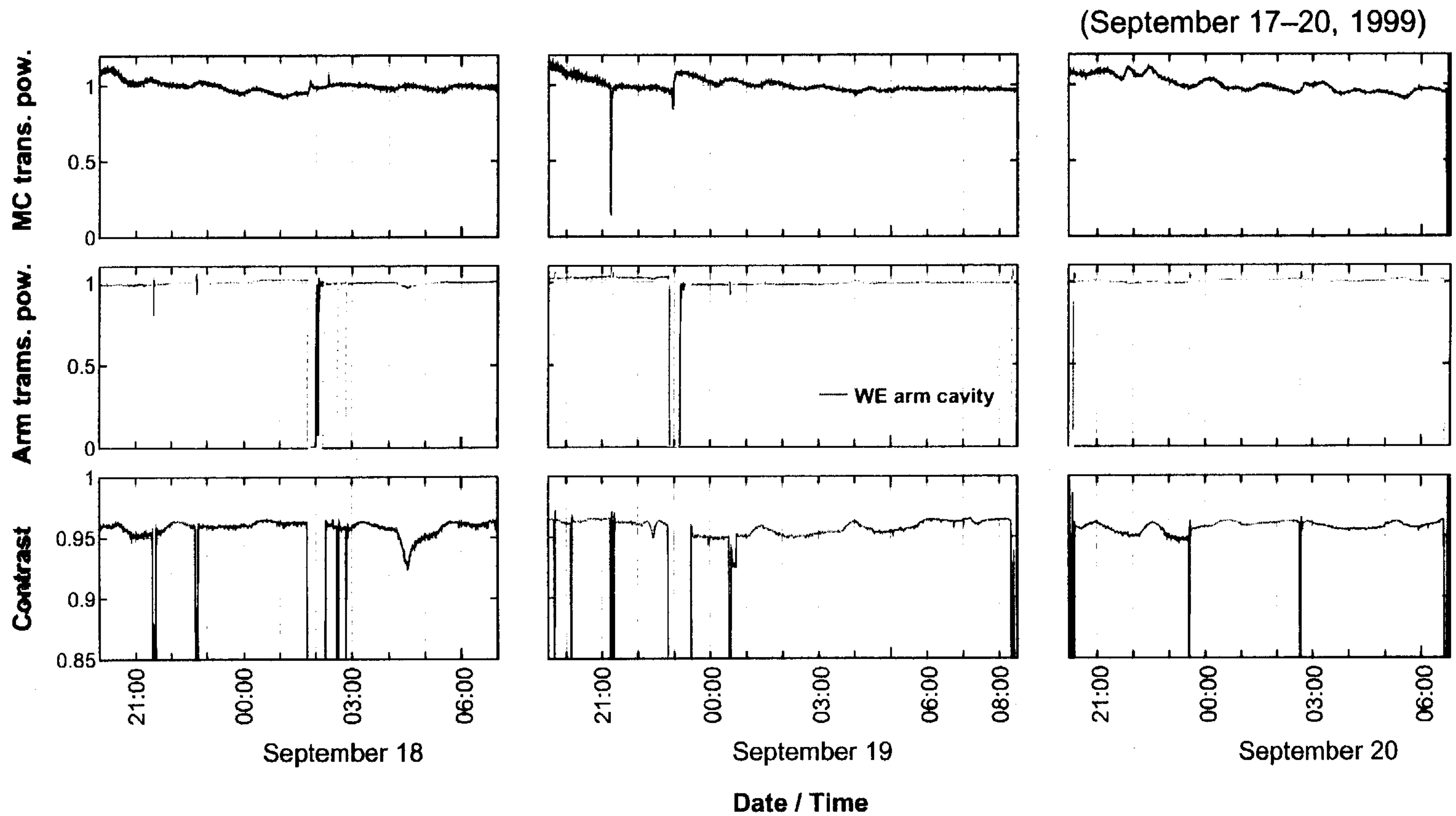




Stability of TAMA300 interferometer (1)

— Long term operation —

- Data taking 2 (September 17 $\sim$ 20).
- Total operation time — about **31 hours**.



Stability of TAMA300 interferometer (2)

— Stability —

- The interferometer is kept lock stably.
  - Total operation time — about 31 hours in 3 nights.
  - Longest locking time — about **7 hours 43 min.**.
- Power fluctuation.
  - Arm cavity transmissivity — fluctuation less than 2%.
  - Contrast — fluctuation between 95% - 97%.
    - Arm cavity alignment control.
    - BS orientation control.
  - Mode cleaner — fluctuation about 10%
    - No alignment control at this time.
- Sensitivity in long term operation
  - Burst-like noise appeared occasionally.

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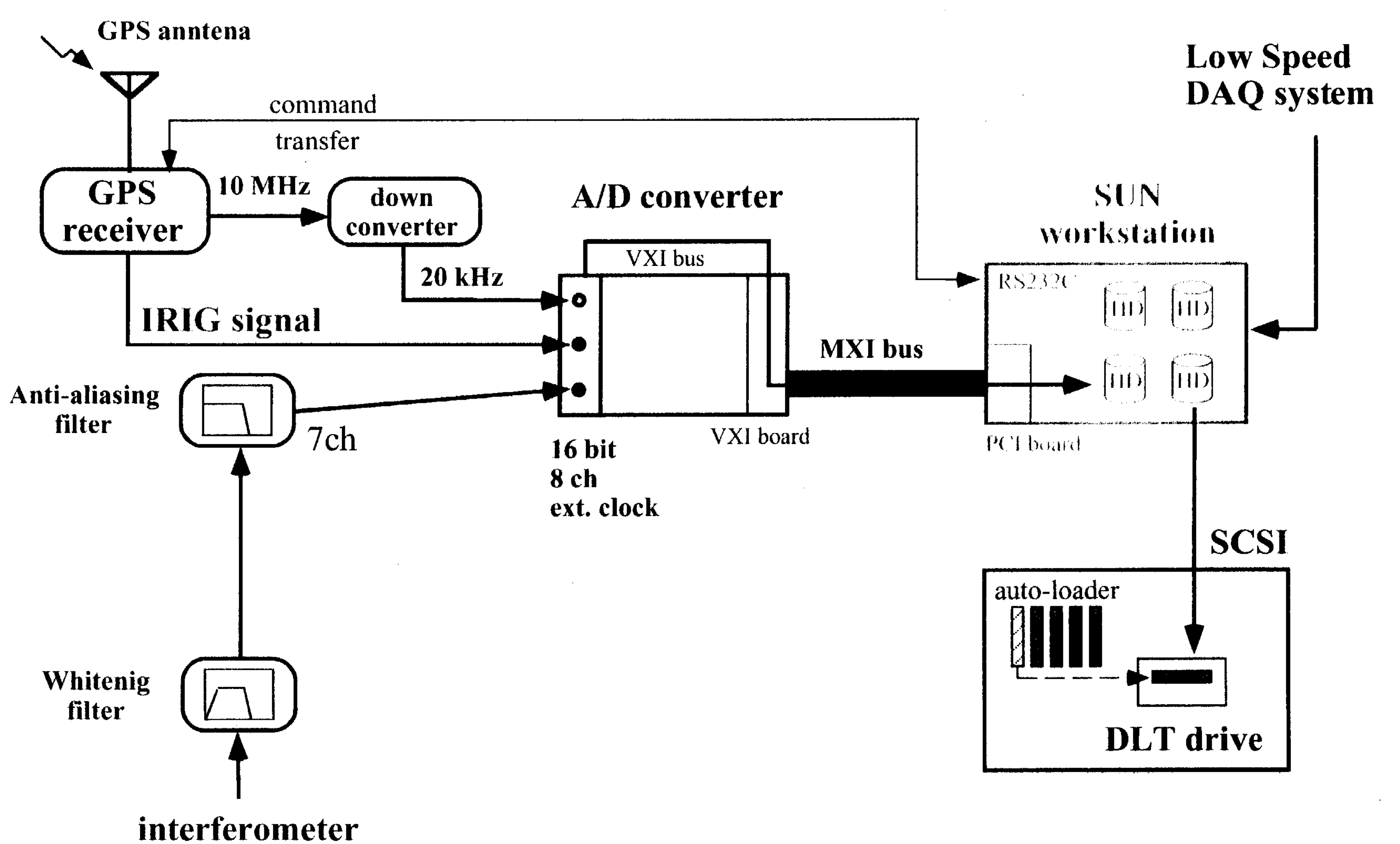
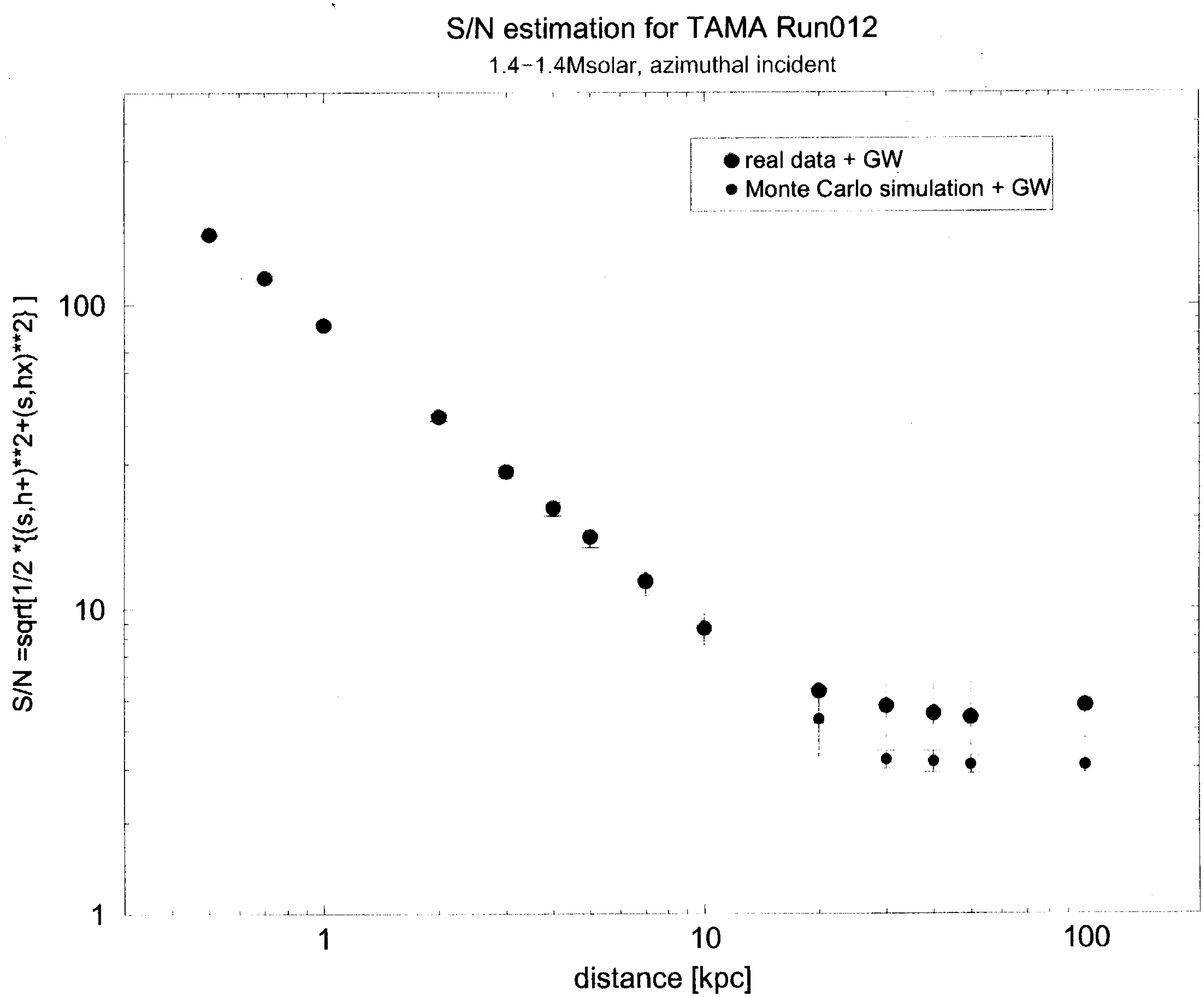
Schematic view of HDAQ

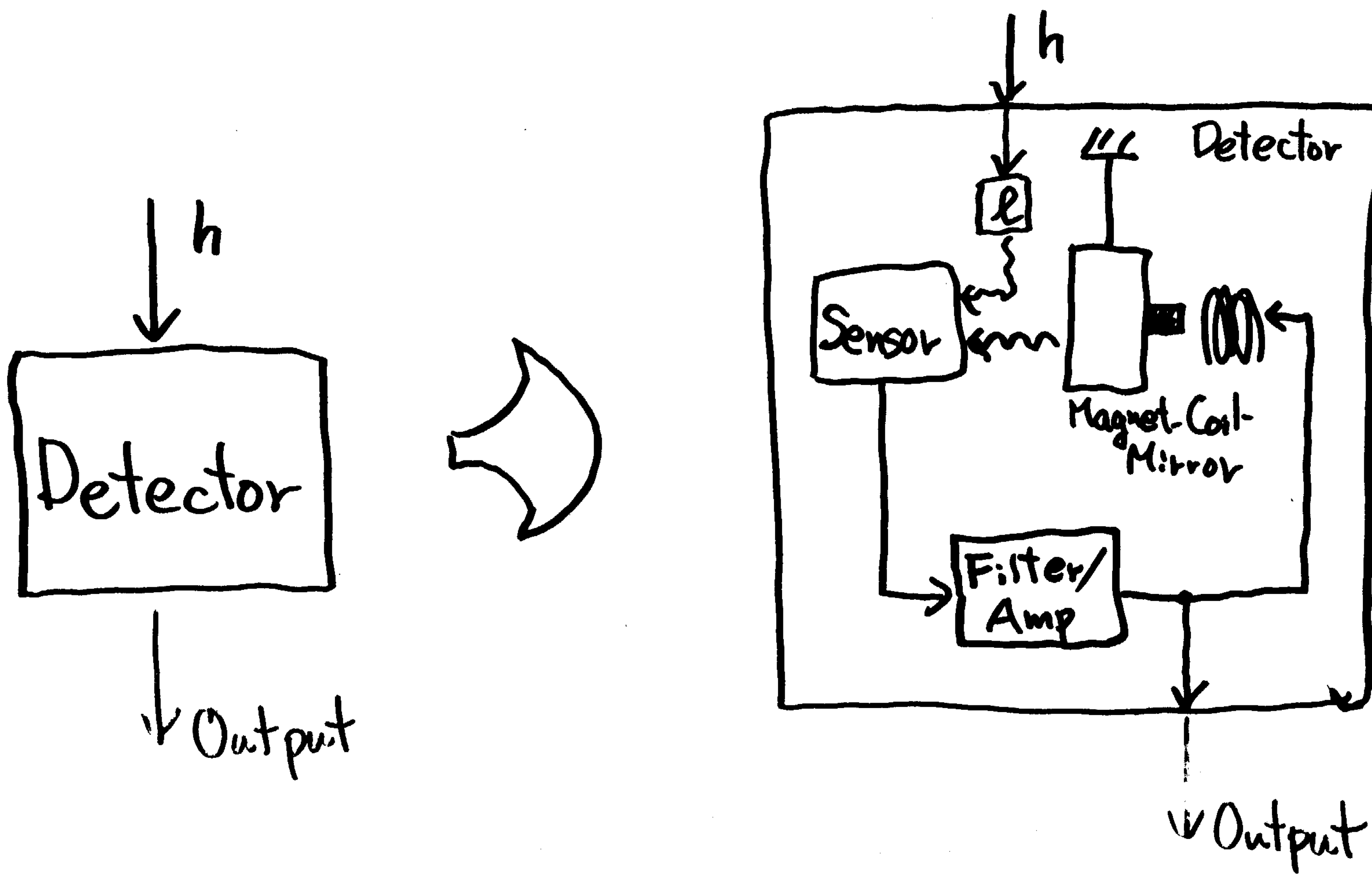




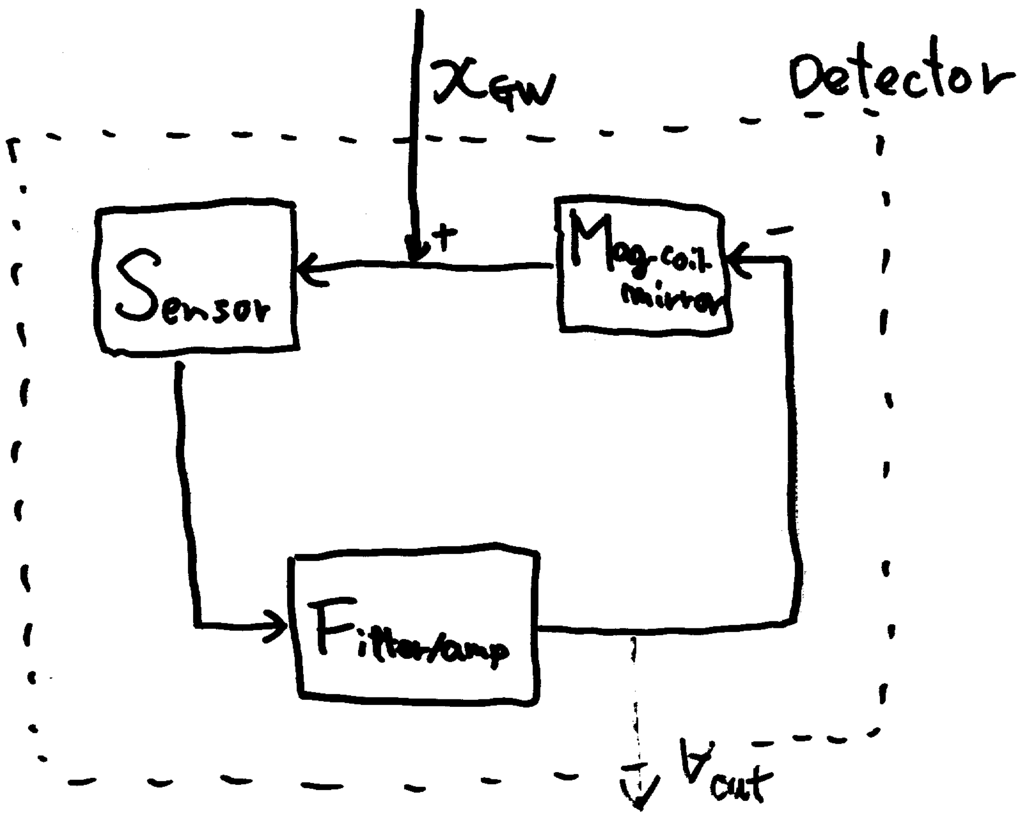
S/N estimation for TAMA Run012
1.4-1.4Msolar, azimuthal incident
real data + GW
Monte Carlo simulation + GW
S/N =sqrt[1/2 *{(s,h+)**2+(s,hx)**2}]
100
10
1
1
10
100
distance [kpc]

Calibration (1)

We have to calibrate the detector response.



Calibration (2)

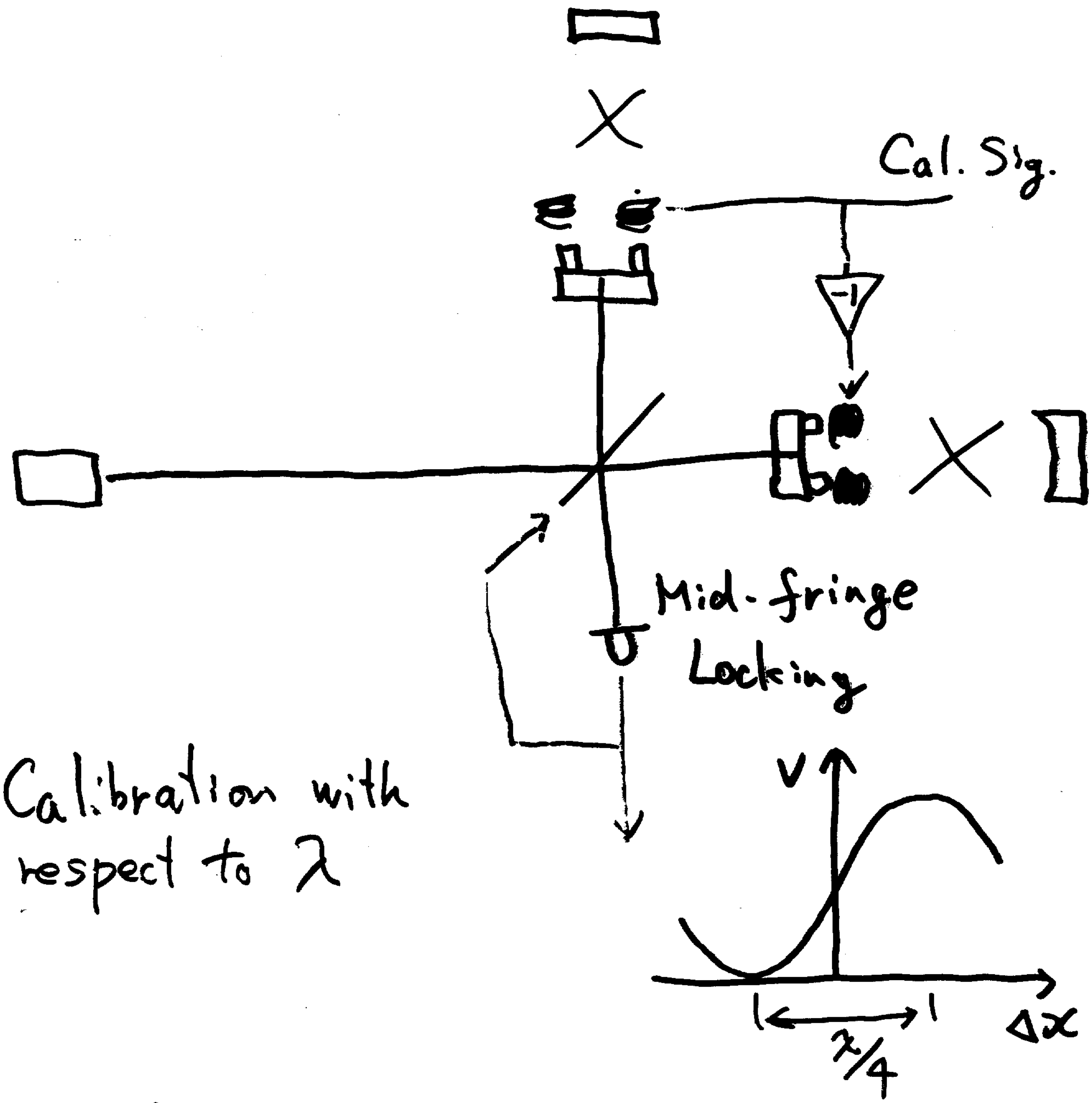


$$\frac{V_{out}}{x_{GW}} = \frac{S \times F}{1 + S \times F \times M}$$

Detector Response

We have to calibrate M and $S \times F$.

Calibration of M



Calibration with respect to λ

Calibrated with an accuracy of ~10%

(to be improved)

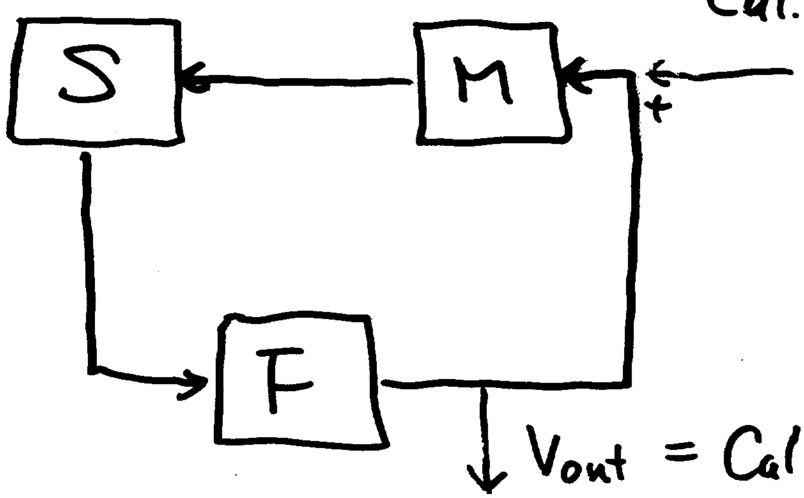
Calibration of $S \times F_{(1)}$

We measure $S \times F$ and assume that only

- DC Gain
- Cavity Pole Frequency

could change in time.

Cal. Sig. ~600Hz
Sinusoidal
Always



$$V_{out} = Cal \times \frac{SFM}{1+SFM}$$

Amplitude · Phase

⇩

DC Gain · Cavity Pole Frequency

Calibration of S×F (2)

Cal. Amplitude : should be

- Large enough to avoid effect of nearby noise
- Small enough to avoid appearence of nearby noise

Cal. Integration Time : should be

- Long enough to avoid effect of neaby noise
- Short enough to avoid large change in S×F

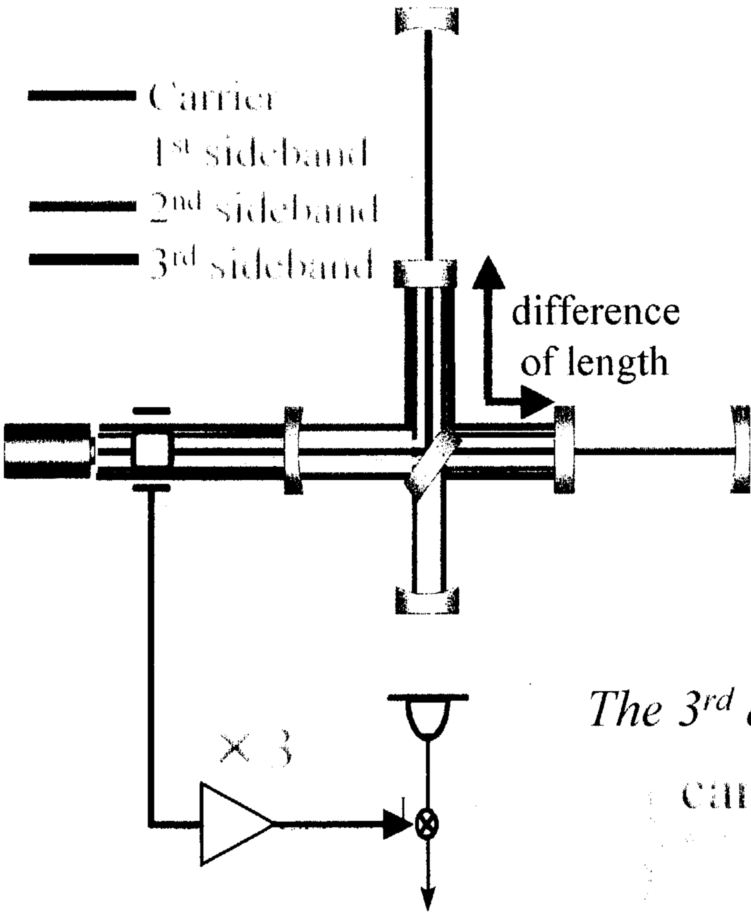
Calibrated with an accuracy of ~5%.

Purpose

To investigate the possibility of TAMA300 and LCGT with narrow-band operation

- Development of a simple signal extraction scheme for a narrow-band interferometer with one modulation
- Demonstration of a narrow-band operation using Resonant Sideband Extraction (RSE) in a bench-top experiment

A new signal extraction method for the SEC with one modulation



- Principle is
  - to make 3rd order sideband at dark condition in the signal port by the difference of the length.
  - to use the 3rd harmonic demodulation

The 3rd demodulation signal is sum of the beat of

carrier and ± 3rd ~~sidebands~~ → arm

and -2nd sidebands
2nd and sidebands } SEC

Extracted signals compared with ls

$\alpha = \pi/3 \left(= \omega_{3m} l_{-} / c\right),\ \beta = \pi$ (: demodulation phase)

Demod.	*L*+	*L*-	*l*+	*l*-	*l*s
1st	0.0027	0	0.080	0	0.015
3rd	0.0027	0	0.080	0	0.015

$\alpha = \pi/3,\ \beta = \pi + 0.01$

Demod.	*L*+	*L*-	*l*+	*l*-	*l*s
1st	0.0026	[redacted]	0.077	[redacted]	0.015
3rd	0.0026	3.9E-6	0.077	0.0015	0.015

$\alpha = \pi/3 + 0.01,\ \beta = \pi + 0.01$

Demod.	*L*+	*L*-	*l*+	*l*-	*l*s
1st	0.0027	[redacted]	0.080	[redacted]	0.016
3rd	0.0026	0.0010	0.079	0.0016	0.016

$\alpha =$ [redacted], $\beta = \pi + 0.01$

Demod.	*L*+	*L*-	*l*+	*l*-	*l*s
1st	3.2E-3	[redacted]	0.091	[redacted]	0.019
3rd	3.2E-3	0.15	0.091	0.0026	0.019

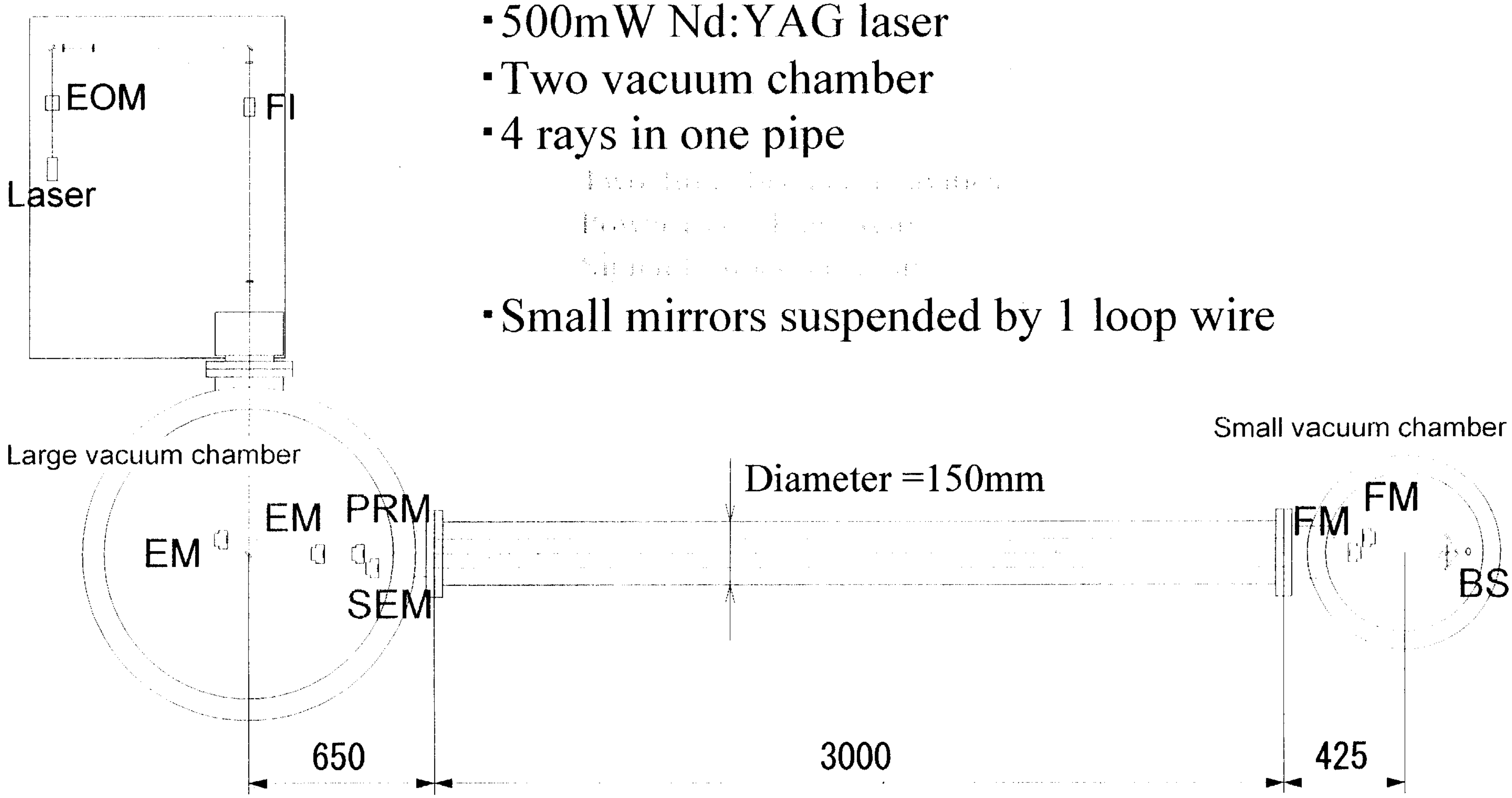
$\alpha = \pi/3 + 0.01,\ \beta =$ [redacted]

Demod.	*L*+	*L*-	*l*+	*l*-	*l*s
1st	9.2E-6	[redacted]	0.0030	[redacted]	0.0010
3rd	1.7E-5	0.011	0.0049	0.0034	0.0013

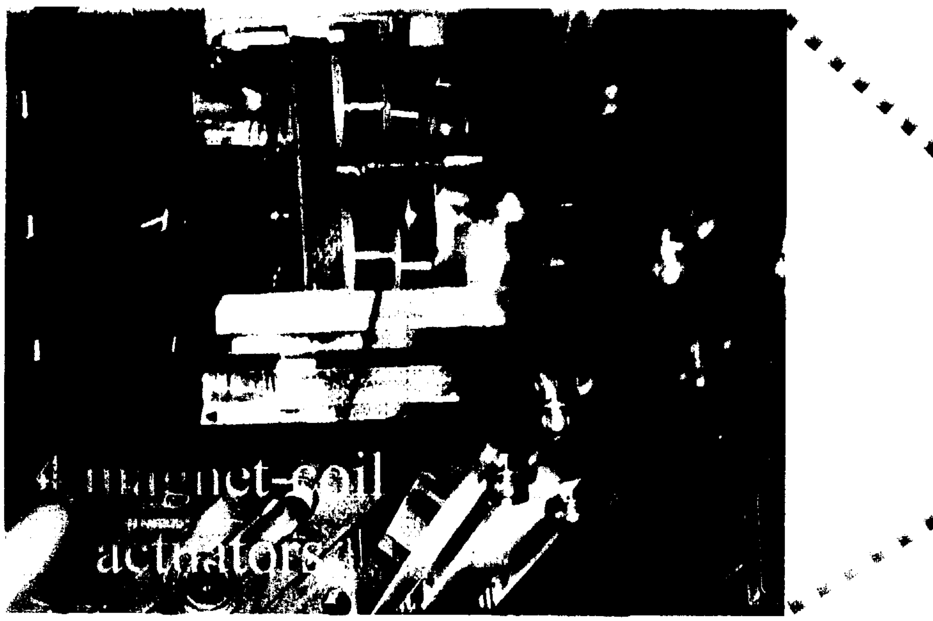
Experimental Instruments

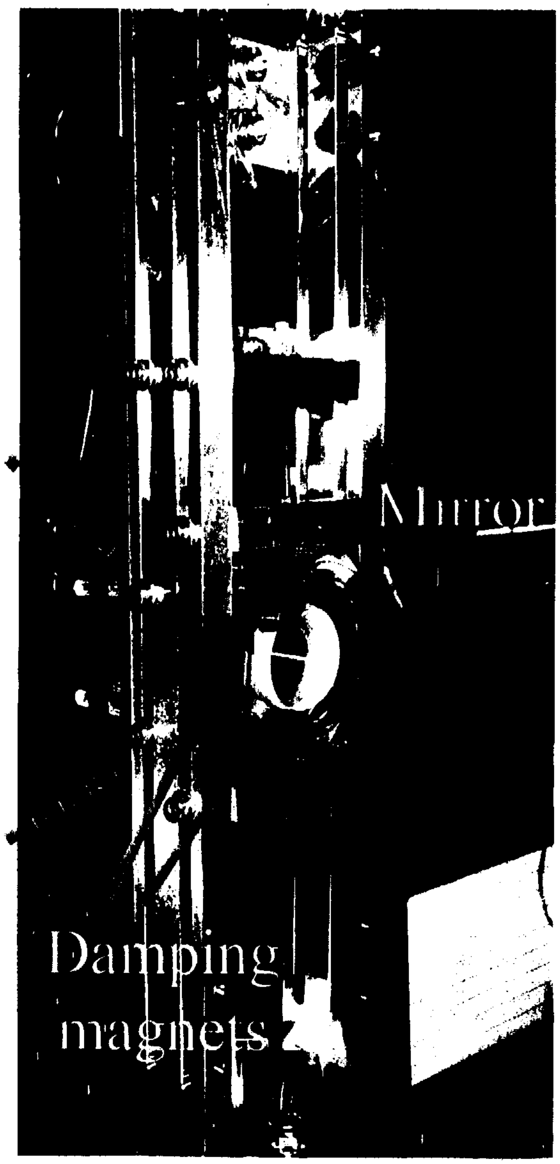
- 500mW Nd:YAG laser
- Two vacuum chamber
- 4 rays in one pipe

- Small mirrors suspended by 1 loop wire



Small Suspension System (SSS)

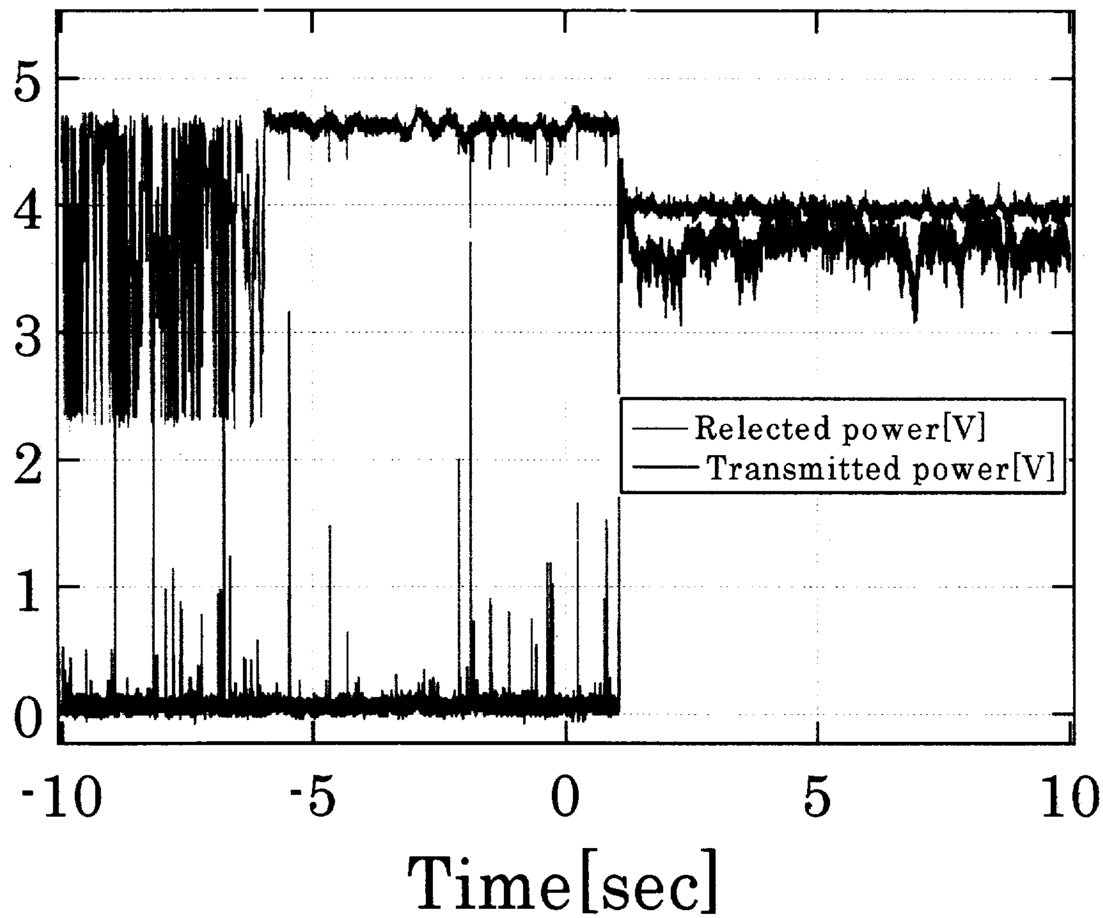




Locking of the 3 mirrors coupled cavity

Sidebands are locked in PRC

Carrier is locked in FP arm and PRC



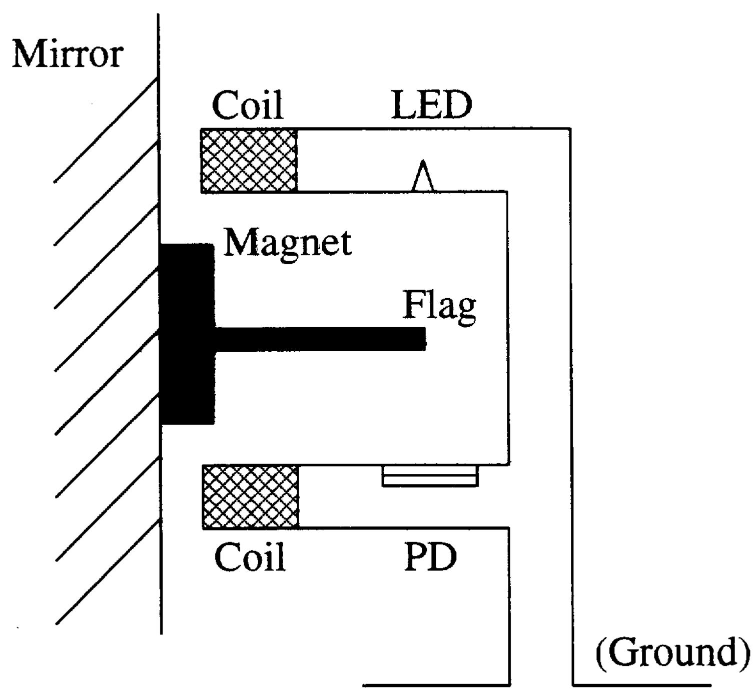
- We have locked the 3 mirror coupled cavity stably with the SSS.

→ Power Recycled gain is still low (1.2) because a reflectance of the PR mirror is 60% and the PR cavity includes a beam splitter.

Pendulum damping

S. Kawamura, H. Tariq, G. Heinzel,
K. Somiya

Conventional shadow sensor:



Some problems:
- many cables
- LED stability
- 1064 nm stray light

New idea

Use coil for sensing and feedback.

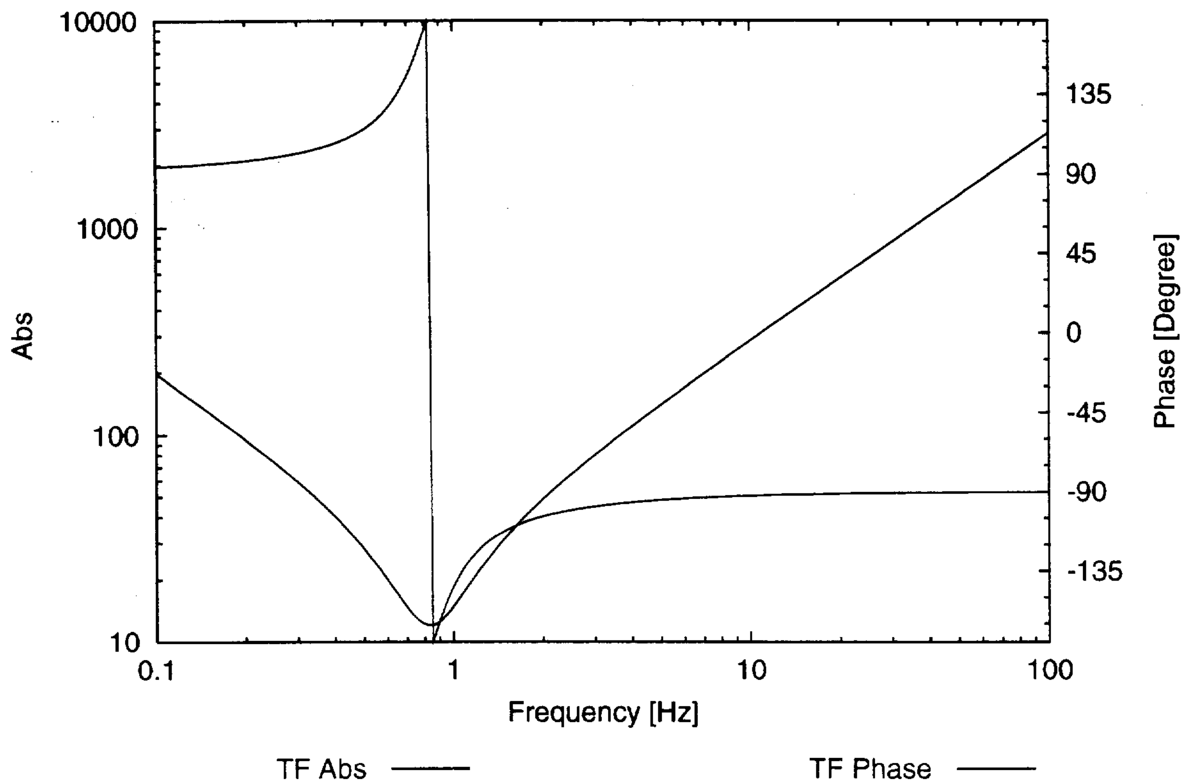
If the coil is shorted, its parasitic ohmic resistance limits the current and the damping effect. Furthermore, the damping is frequency independent and spoils the Q in the measurement band.

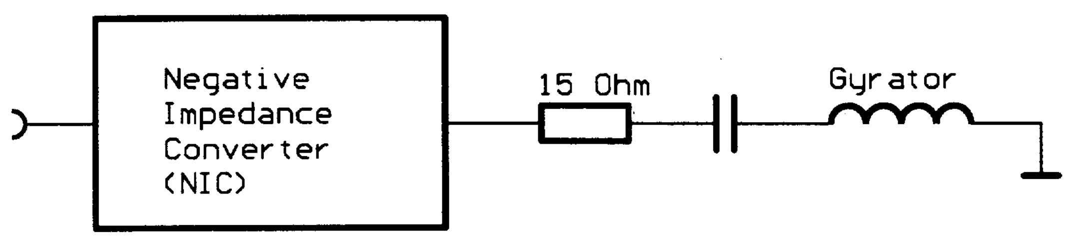
Hence we try to use a
frequency dependent negative impedance

In our simple table-top experiment, $Q \approx 5000$. With the coil shorted ($R = 15\,\Omega$), we get $Q \approx 50$.

By connecting $R = -15\,\Omega$, we obtained
critical damping.

Frequency dependent negative impedance





Problems to be investigated:

- stability
- noise

LISO

Linear Simulation and Optimization
of analog circuits

A program by

Gerhard Heinzel

NAO, Mitaka, Japan,

LISO was written at:
Max-Planck-Institut für Quantenoptik,
Garching, Germany

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Introduction

LISO was written because other common circuit analysis programs cannot:
- correctly predict the noise.
- optimize circuits for our purpose.

The circuit topology is fixed and must be entered by the user.

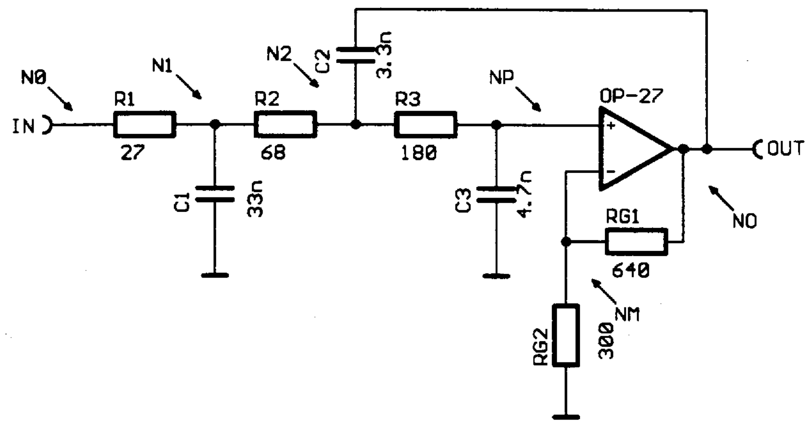
A circuit can consist of resistors, capacitors, inductors, transformers and voltage-feedback op-amps.

LISO performs a **small-signal AC analysis**.

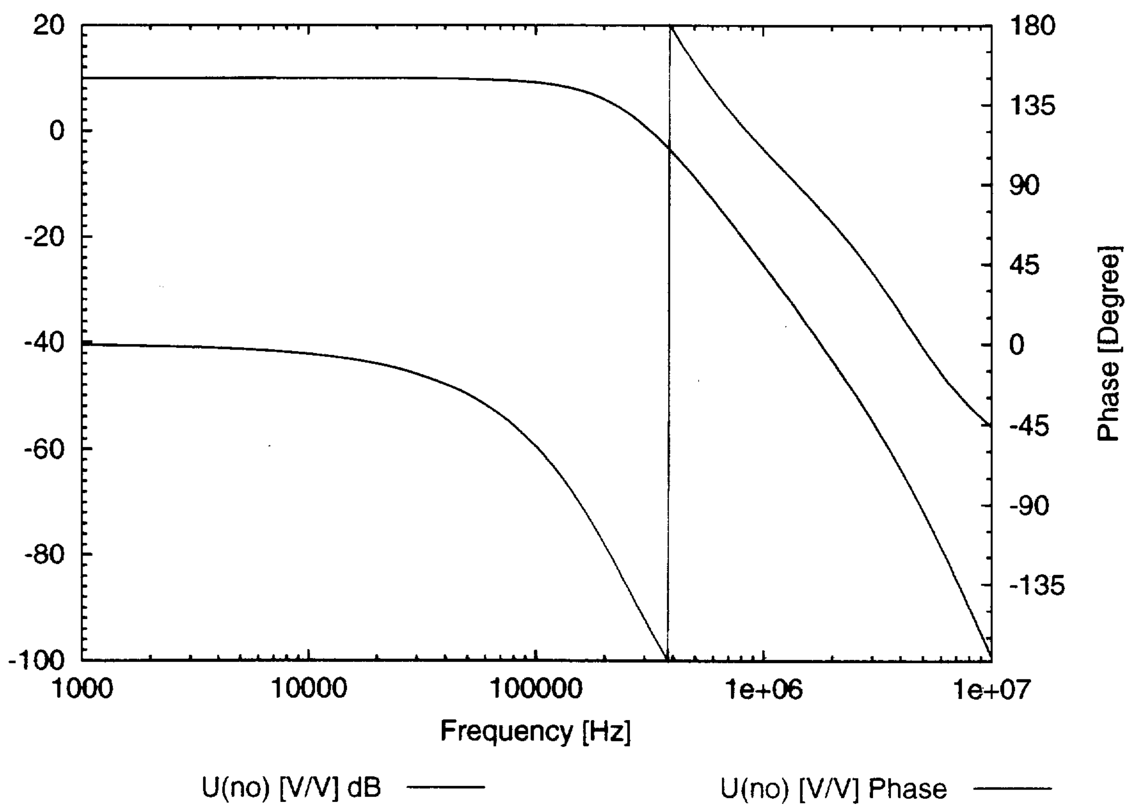
LISO will analyze the circuit in many respects (transfer functions, op-amp stability, noise, input impedance).

In a separate mode of operation ("root mode"), LISO computes transfer functions given by poles and zeroes.

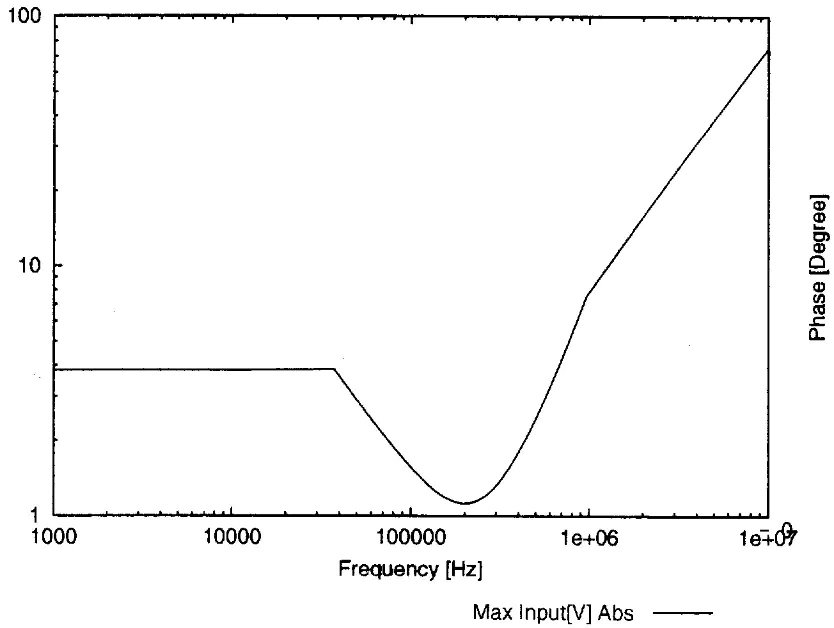
Simulation



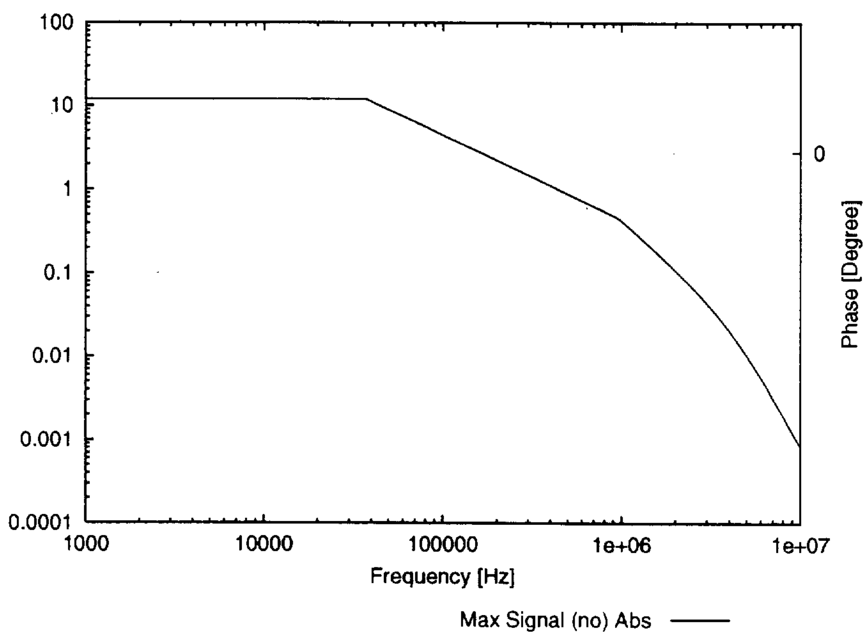
Transfer function:



Signal Range at input and output

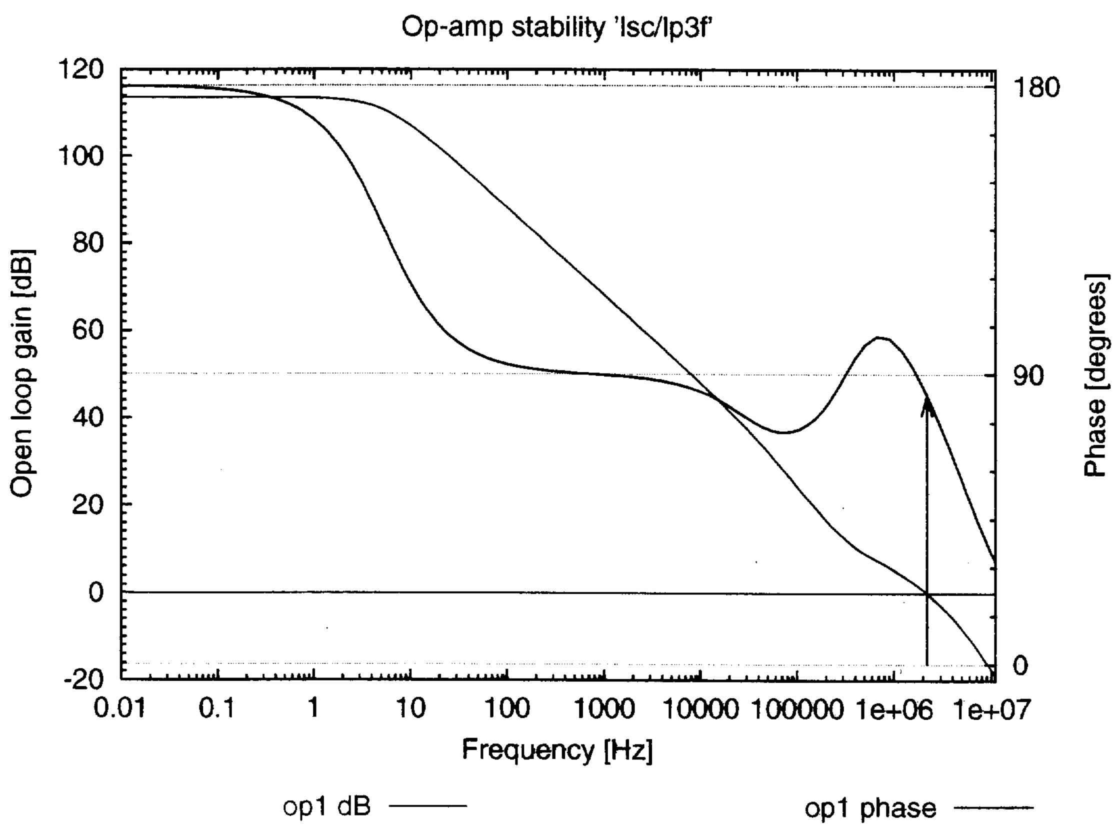



```
from 1000 Hz onwards input is limited by Umax(op1).
from 37.1535 kHz onwards input is limited by SR(op1).
from 977.237 kHz onwards input is limited by Imax(op1).
time used: 0.076 sec
```



Simulation

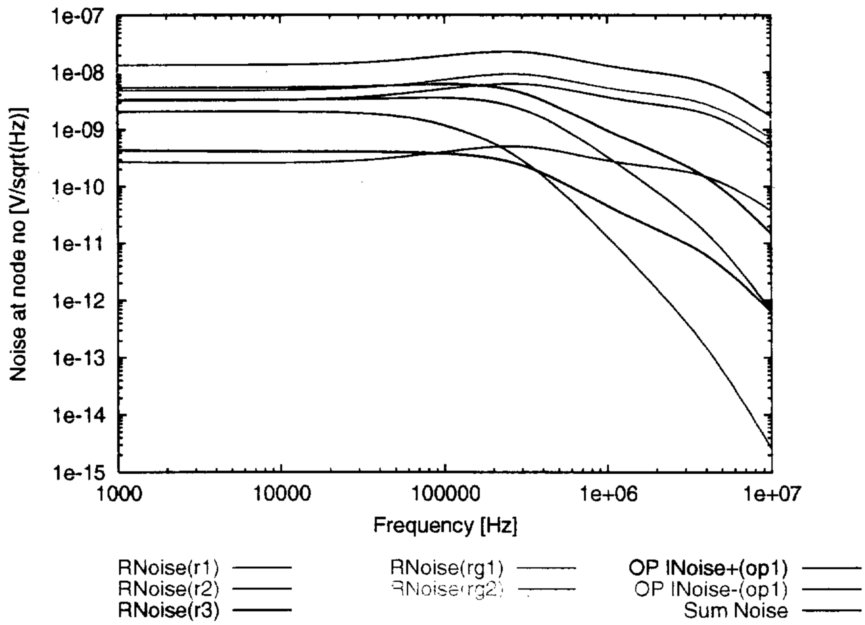
Many more calculations are possible, e.g.:
- current through components,
- opamp differential input voltage,
- input impedance and
- op-amp stability:

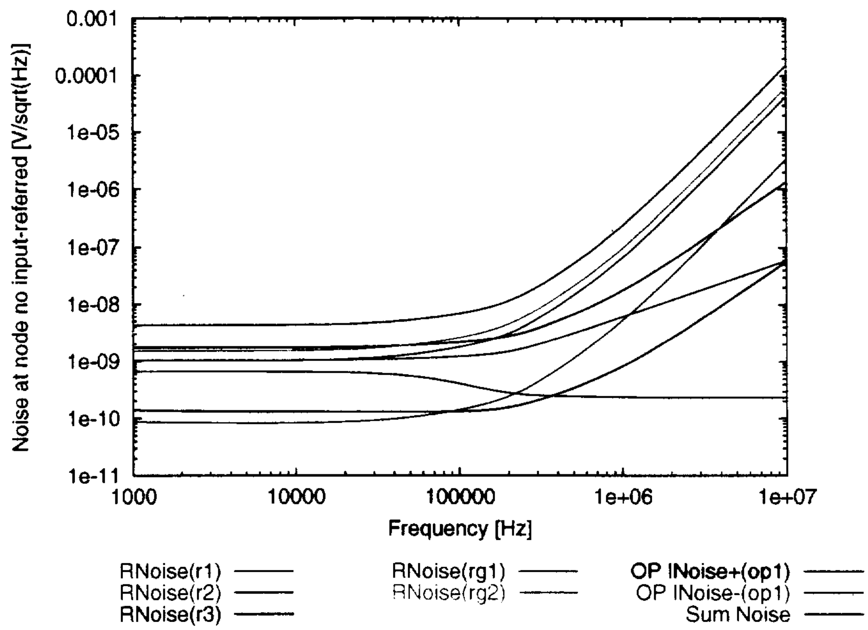


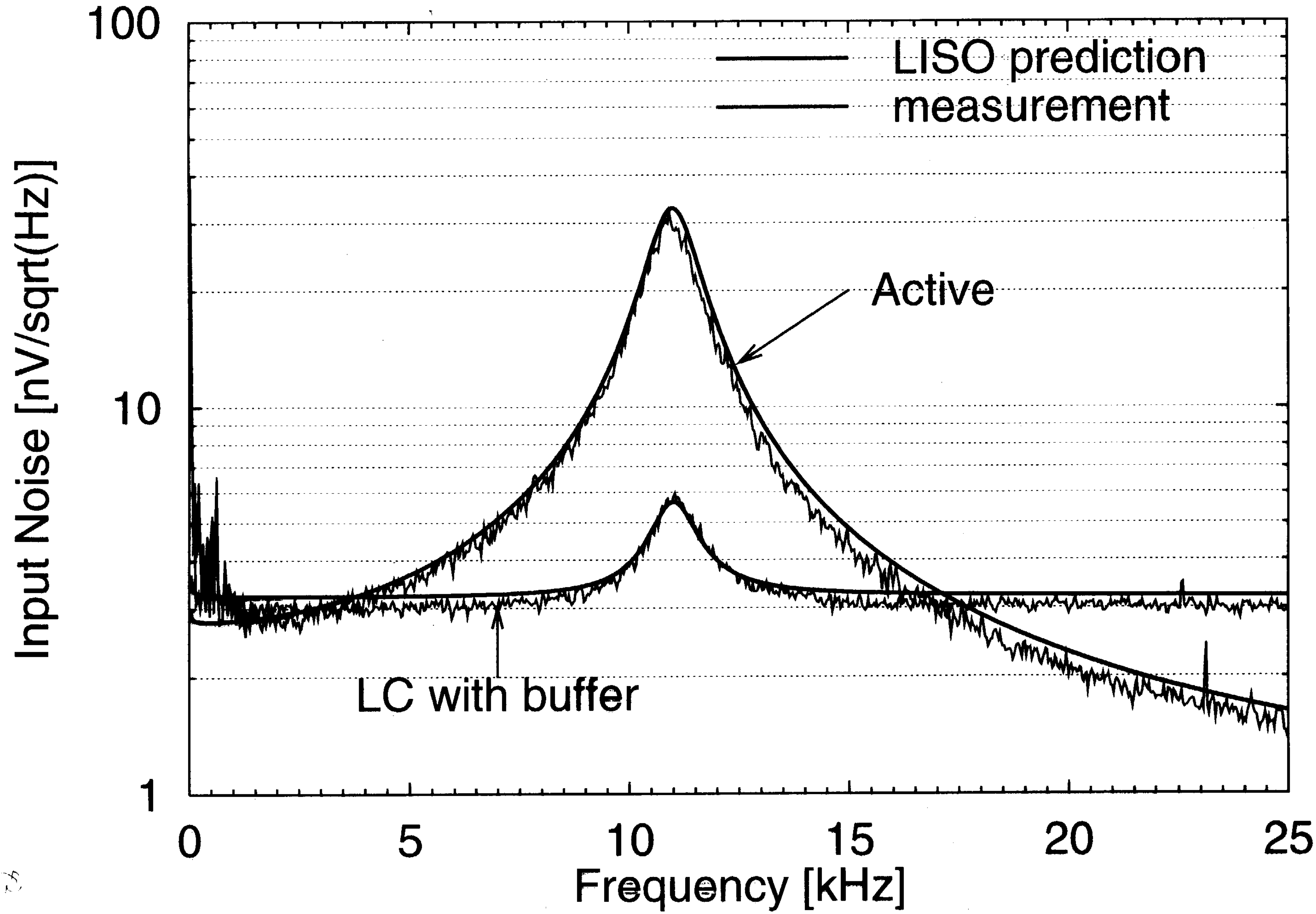
op-amp op1 phase margin +83.49 degrees at 2.18282 MHz

Noise simulation

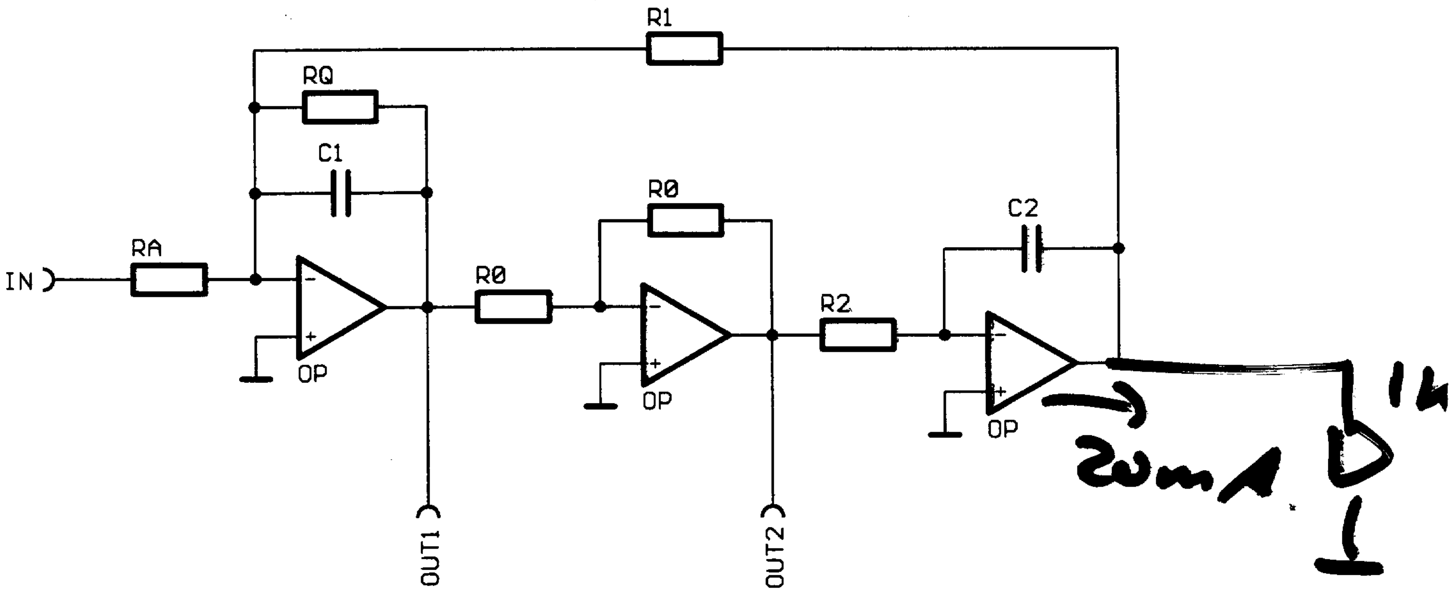
A unique feature of LISO is the precise prediction of circuit noise:

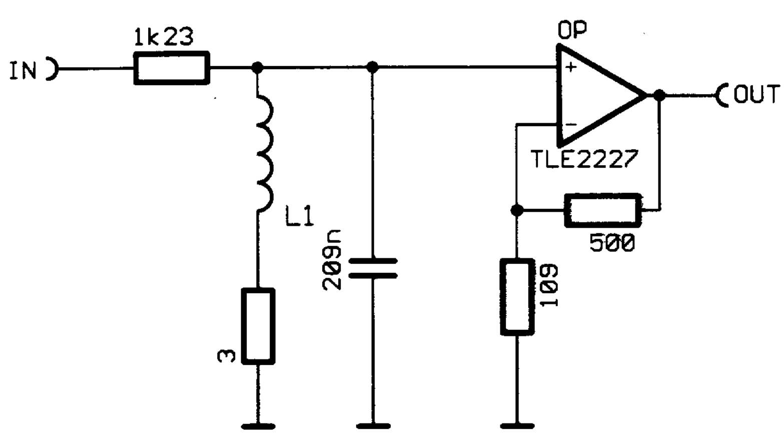





LISO prediction
measurement
Active
LC with buffer
Input Noise [nV/sqrt(Hz)]
100
10
1
0
5
10
15
20
25
Frequency [kHz]

biquadratic
Tow - Thomas





LISO's **fitting function** can optimize component values for a given purpose.

This allows to find components values that yield a given transfer function.

Models for real components with parasitic impedances can be found from measurements and then used in simulations.

With advanced fitting functions, the **dynamic range** of a circuit (i.e. the ratio of maximal signal to noise floor) can be optimized.

LISO was written in **C** on UNIX systems. It is available for Linux, Sun Solaris, IBM AIX and DOS/Windows.

The program and manual can be found at:

~~ftp://ftp.rzg.mpg.de/pub/grav/ghh/liso~~/

http://130.183.90.63/liso.html

Optimization

Given:
- circuit
- desired frequency response

Unknown:
- component values

Conditions:
- Minimize noise
- require minimum output swing.
- all op-amps must be stable

LISO result:

```
r1 =  26.479923 +- 1.733 (6.55%)
r2 =  67.879593 +- 20.92 (30.8%)
r3 =  186.31192 +- 66.17 (35.5%)
rg1 =  640.51121 +- 2.257 (0.352%)
c1 =  35.019345n +- 1.626n (4.64%)
c2 =  3.8937225n +- 908p (23.3%)
c3 =  4.2353818n +- 1.2n (28.3%)
```

Tentative Future Plan

2000	Apr – Jul	Minor Improvement
	Jul	Data Taking (100 hours)
	Jul – Jan	Intermediate Improvement - Suspension Modification - Installation of Active Isolation - Mode Matching Mirror
2001	Jan – Apr	Data Taking (2 months)
	Apr – Jul	Minor Improvement & Data Taking
	Jul – Jan	Major Impromement Two Options: - Installation of TAMA SAS - Reeycling
2002	Jan – Mar	

Note 1, Linda Turner, 03/29/00 10:53:06 AM
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