TAMA beam centering system

Gerhard Heinzel, TAMA Project, NAO Mitaka

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1 Introduction

This document describes the beam centering system developed for the TAMA 300 gravitational wave detector.

It is based on a similar system used in the GEO 600 project which had been developped by G. Heinzel and (mainly) H. Grote in Germany. This previous work is used with kind permission of the GEO project.

The purpose of the system is to keep a moving laser beam centered on a quadrant photodetector. The quadrant photodetector has two kinds of output signals, RF and DC. The RF signal is used for the automatic beam alignment of the interferometer with the "differential wavefront sensing" method (see e.g. [Morrison94, MPQ243, Grote99]). One condition for this method to work optimally is that the beam must be kept centered on the quadrant diode, with a bandwidth that is higher than the bandwidth of the main alignment loop (a few 10 Hz). This is achieved by the system described here.

The DC output signals of the quadrant detector are used to obtain error signals which are fed back to the actuators (two galvanometer scanners mounted orthogonally, each of which is used to rotate a small mirror).

This document describes the circuit, referring to the 5-page circuit diagram. It also gives some hints for initial testing of the circuit and adjustments.

2 Input stage

The four signals from the four quadrants are connected to input ports Y1 ... Y4 on page 5. These are the DC outputs of the quadrant detector, which may have a range of up to ±10 Volts. Actually it is usually best to increase the feedback resistor in the photodiode front end current-to-voltage converter as much as possible, i.e. such that the maximum signal is indeed near 10 Volt (see [MPQ243, Appendix B.1.1]).

The polarity of the input signals can be either positive or negative, and their bandwidth should be at least 10 kHz. In particular, no significant phase shift should occur up to 2 kHz.

The input signals are buffered by op-amps N56 and N57 (page 5). This is in order to ensure a constant and very low driving impedance to the next stage (difference amplifier).

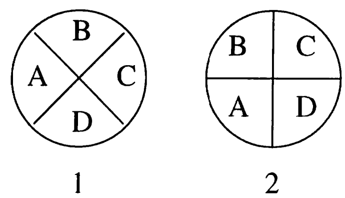

Figure 1: Two configurations to mount a quadrant diode.

There are two possibilities to mount a quadrant photodiode, called '1' and '2' in Figure 1. Although configuration '2' is generally preferable, the present TAMA photodiodes use configuration '1', and the circuit described here can handle both cases.

The error signals describing the offset of the beam's center from the photodiode's center are found as follows:

configuration '1'

$$-\Delta x = A - C,$$
$$\Delta y = B - D.$$

configuration '2'

$$-\Delta x = A + B - C - D,$$
$$\Delta y = B + C - A - D.$$

These signals are computed with op-amp N58 (page 5). The resistors used should be well matched (0.1% or better) for good common-mode rejection. On the present board design integrated resistor networks (RN51 ... RN54) are used, which could, however, be replaced by individual resistors if necessary. The absolute value of the resistors is uncritical; anything in the range 3 kΩ ... 10 kΩ should work. Good matching is only necessary between the 3 resistors of each network.

If the four jumpers J1 ... J4 are installed, the signals are computed for configuration '2', whereas configuration '1' can be accomodated by opening all four jumpers.

Test: The input stage can be tested by connecting an input signal to one of the inputs Y1 ... Y4 and measuring the transfer function from the input to the testpoints

X200 and X201, which should be one of 0, 1 or -1 according to the above equation, and repeating the process for all four inputs Y1 ... Y4.

Furthermore the sum (more precisely, inverted average) of all four input signals is formed by op-amp N21A (page 5). Since this signal is used only for normalization and error checking, high precision resistors are not necessary here; 1 % should be sufficient.

This sum signal is further processed by op-amps N21B and N22B (page 2). N21B together with switch S20 form an optional inverter, and N22B amplifies the signal and allows the adding of some offset. The resulting signal is called 'denominator' and is available at X211.

Adjustment/Test : The polarity (switch S20) must be set such that this (X211) signal is positive. The gain (P1) should be set auch that the maximal signal during operation is slightly below 10 Volts (e.g. 8 Volts). The offset (TR23) can then be adjusted that the signal is zero with no laser beam shining on the diode (to compensate for ambient light and other offsets). Note that the offset setting is amplified with a different gain than the signal ($1 + P_1/R_{212}$ instead of P_1/R_{212}) such that the offset should be re-adjusted after a gain change, if it turns out that a huge offset is necessary (maybe not).

Testing can be done by verifying that the transfer function from each of the inputs Y1 ... Y4 is $-1/4$ to X210, and is identical for each of the four inputs input when measured at X211.

3 Normalization

In order to keep the open-loop gain of the beam centering system constant under varying circumstances (in particular during lock acquisition and during initial operation of the main automatic beam alignment system), the error signals Δx and Δy are divided by the sum of all four quadrants before being fed to the loop filter. The effect is that the loop gain becomes independent of the incident light power, and only depends on the size of the beam spot and the geometry of the setup, both of which should remain fairly constant.

In order to ensure proper operation of the divider, the denominator voltage is monitored by comparators N29 and N2A (page 2). The output of N29 goes LOW, and LED8 goes on, if the denominator exceeds 10 V (the maximum denominator input to the divider which ensures proper operation). Resistors R240 and R241 provide a hysteresis of about 10 mV to avoid oscillations and bouncing.

Similarily, the output of N2A goes LOW, and LED7 goes on, if the denominator falls below a limit set by TR24 (e.g. a few 100 mV). The limit should be set such that the denominator in all acceptable operating conditions (when the beam centering should work) is above the limit. On the other hand, if the light power drops below the limit, this indicates some kind of error condition (such as loss of input light to the interferometer or the beam having been moved completely off the quadrant diode).

The two comparator's output are wire-OR'ed by diodes D20 and D21. The resulting signal[1] ERROR\ (X216) is HIGH if the denominator is within its limits, and LOW otherwise. This signal is used in the control logic (see Section 6). Note that a CMOS gate (in this case, N47A) must be used to buffer this signal.

The actual divison takes place in the analog multipliers/dividers N25 and N26 (page 2). They are connected in the 'direct divison mode' as recommended in the datasheet [AD734, Fig. 10], with a bandwidth of more than 1 MHz for denominators above 100 mV. The transfer function is given by

$$W = \frac{(X_1 - X_2) \times Y_1}{U}, \tag{1}$$

where X_1 is the error signal from the previous stage, X_2 an offset that can be adjusted with trimmers TR20/TR21, U is the denominator derived from the sum of the four channels as described above, and Y_1 is a gain-control voltage between 0 and $+10\,V$, the use of which is described below.

3.1 Divider noise

Analog dividers have a reputation for being noisy. The AD734 data sheet specifies an output-referred noise spectral density of $1.0\,\mu\mathrm{V}/\sqrt{\mathrm{Hz}}$ between 100 Hz and 1 MHz. Measurements [Grote] done under the typical operating condition in this circuit ($X_1 - X_2 = 0$, $Y_1 = 10\,\mathrm{V}$, $U = 5\,\mathrm{V}$) are shown in Figure 2 and confirm this specification.

3.2 Divider bypassing

Since the divider noise described in the above Section is expected to be the main source of electronic noise in the circuit, the divider can by bypassed if desired in operation. For that purpose, analog switches N27 and N28 on page 2 are controlled by front-panel switch SW3. An LED lamp (LED6 on page 5) shows the status of this switch.

4 Actuators

Although the actuators are the last part of the system from a signal-flow point of view, their frequency response must be known for the design of the loop filter. Therefore they are discussed here.

[1] in the circuit diagrams drawn with EAGLE, inverted logical signals are identified by a backslash (\) after the signal's name.

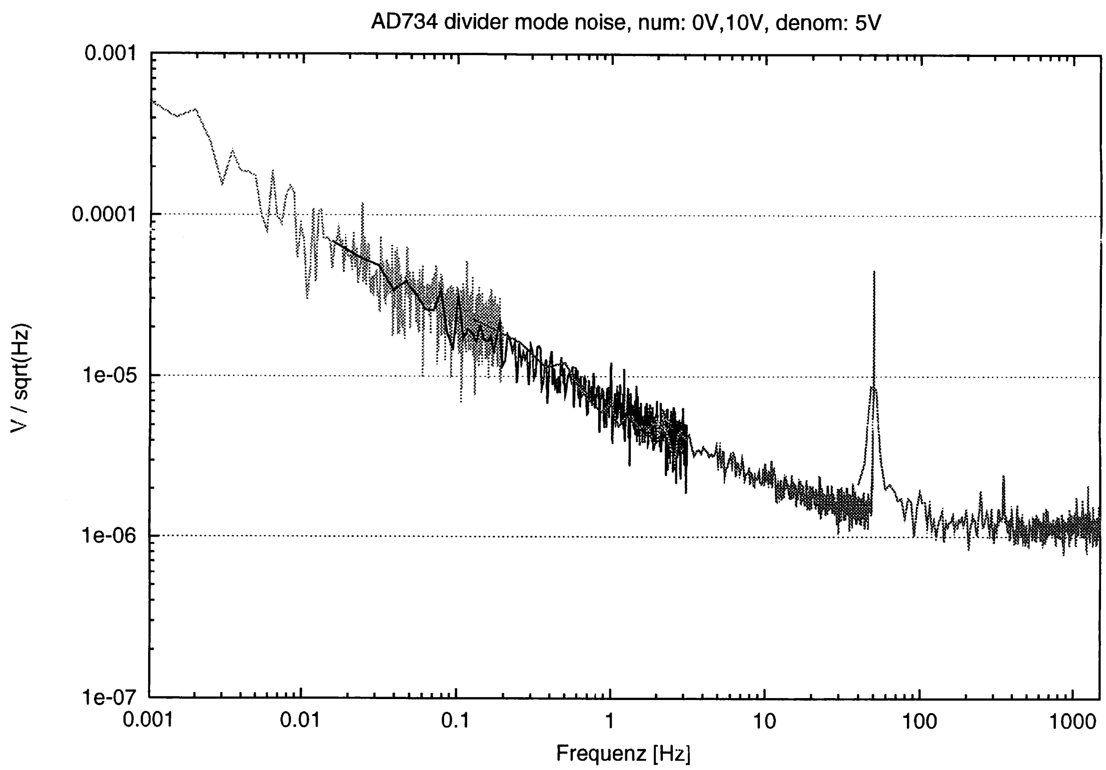

Figure 2: AD734 divider output noise in direct division mode [Grote].

We use galvanometer scanners for the actual deflection of the beam. These are coil-magnet devices with one rotational axis. They have a rather stiff torsional spring which holds the axis in its rest position if no current is applied. The model we chose, G108 from General Scanning, has a maximum excursion of ±8° for a current of approx. 1 A. Each galvanometer scanner has two coils, which can be connected in series or in parallel. We use them connected in series, with the coils connected as follows:

input1 – red–coil–black – green–coil–yellow – input2

We will refer to the series combination as "the galvanometer coil". Its frequency-dependent impedance and its transfer function (current ⟶ angle) depend on the moment of inertia of the attached mirror, as well as on possible mechanical resonances of the system. Hence the following measurements were done with the mirror mount and mirror tha will be used in the beasmsteering system. Measured at 120 Hz, the coil's impedance is approximately 8 Ω and 6 mH. By forming a voltage divider with a resistor and measuring the transfer function, the frequency-dependent impedance can be found. It is shown in Figure 3. An electrical equivalent model is shown in Figure 4.

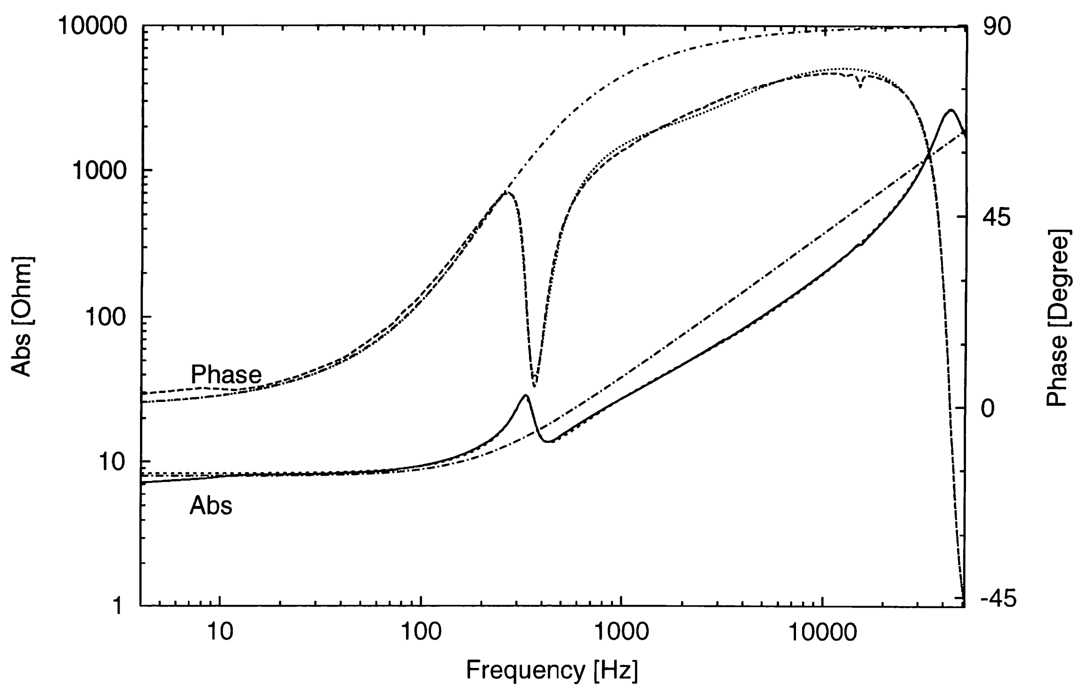

Figure 3: Impedance of the galvanometer coil with mirror attached. Shown are the measured data, the model shown in Figure 4 and the simple model consisting of 8 Ω and 6 mH.

It can be seen that the impedance has a rather complicated structure, such that

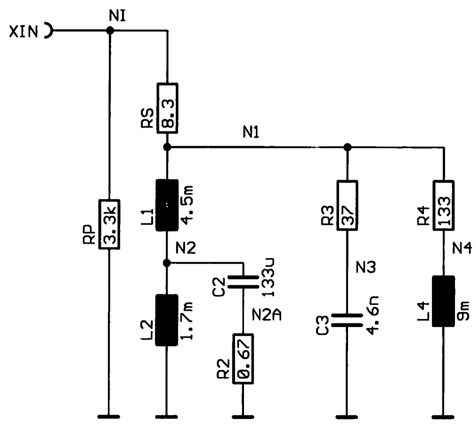

Figure 4: The model for the galvanometer impedance. The mechanical resonator is well described by an equivalent electrical resonator.

the current, when driven from a voltage source, will also have a complicated frequency response. A simpler frequency response can be obtained by driving the coil with a current source. This was adopted in our circuit.

4.1 Current drivers

The current drivers are the op-amps N45 and N46 on page 4. The GEO 600 design uses L165 voltage-feedback power op-amps (by SGS-Thompson), which could, however, not be bought in Japan. Hence they were replaced by EL2099 current-feedback power op-amps (by Elantec). The compensation network ($470\,\Omega - 1\,mu$F) was designed to stabilize the L165. Since the EL2099 turned out to be stable also with this network, it was not changed.

For the current-sensing resistor (R418/R419) the relatively small value of $1\,\Omega$ has been chosen, such as to limit the power dissipation. The resulting dynamic range (10 V at the input $\longrightarrow$ 10 A through the coil is far too large, hence it is limited at the input by the voltage divider R412/R414. The resulting nominal efficiency of the current driver stage is $8°/11\,\text{V} \approx 0.72°/\text{V}$.

4.2 Frequency response

The resulting frequency response of the actuators is shown in Figure 5.

It was measured optically (with the quadrant diode). The fittted curve has the following features (which are used in modelling the open-loop gain):
complex pole at 718 Hz, Q=2.05;
complex pole at 14.7 kHz, Q=26.7;

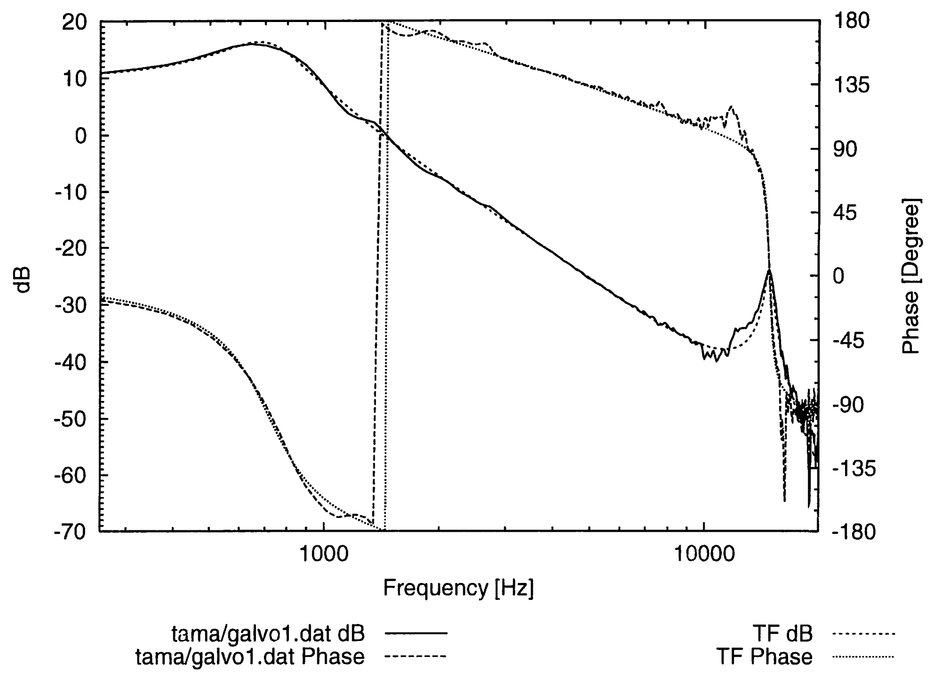

Figure 5: Frequency response of the galvanometer scanner (current driver input ⇒ motion).

real pole at 5.2 kHz;
time delay of 3.5 μs.

While the 700 Hz resonance is due to the interaction of the torsional spring with the mounted mirror mass, the 5.2 kHz pole and some part of the time delay are caused by a early version of the photodetector used for the measurement, which was later improived.

The transfer function depends not only on the details of the mirror and mirror mount that is fixed to the galvanometer (as described above), but also on the signal level that is applied (i.e. the galvanometer behaves nonlinearly). Some measurements are given in [Grote99, Fig. 3.2]. In practice this means that the open-loop gain should be designed conservatively, such that the loop remains stable even the actuators frequency response varies a bit. With the loop closed (and hence very small signals) the main resonance was measured to be at 676 Hz with a Q of 6.5.

4.3 Limiters

In oderer to prevent the beam from running off the photodiode, there are limiter stages before the current driver. They consist of op-amps N41 and N42 (page 4), the diode network and associated resistors. The upper and lower limits can be set by trimmers

P4 ... P7 available on the front panel.

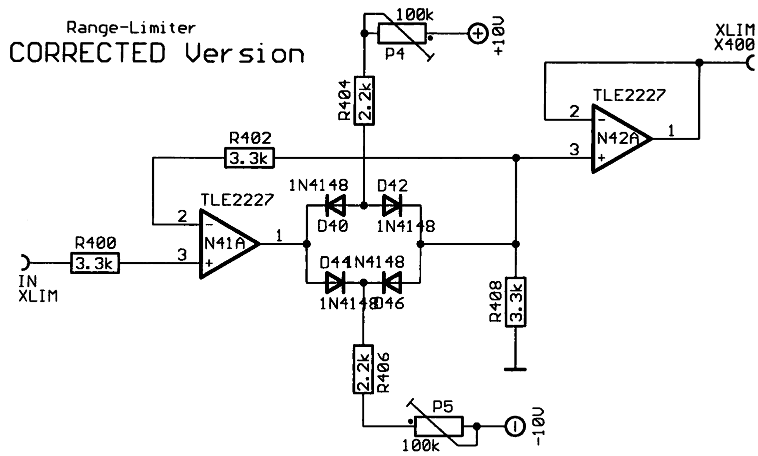

Figure 6: Limiter stage (**corrected** circuit).

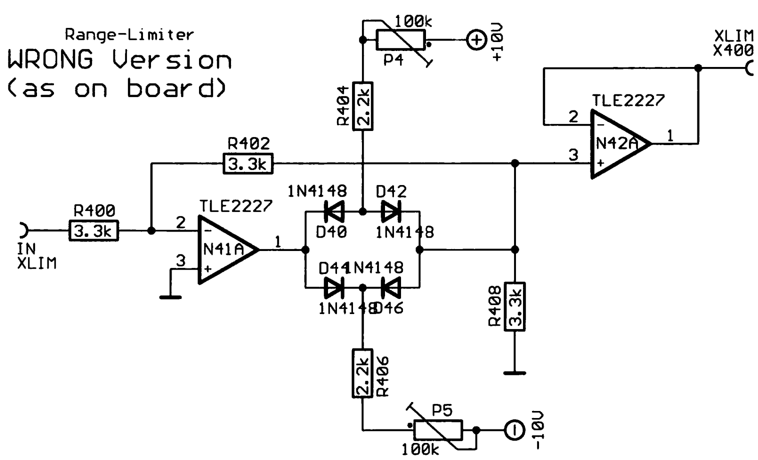

Figure 7: Limiter stage (**wrong** circuit as implemented on the board).

The circuit diagram of the limiter stage is given in Figure 6. Unfortunately, the original curcuit diagram as well as the manufactured board contain a mistake with the wrong circuit (as on the board) shown in Figure 7. **This circuit must be manually changed into the circuit of Figure 6 for each of the 7 boards.**

The principle of operation of the limiters, as shown in Figure 6, is that of a current-limited voltage follower which operates into a load resistor (R408). The diode bridge's output follows approximately its input (pin 1 of N41A). However, no current can flow directly from N41A to the diode bridge's output. All current must come from the +10 V (or -10 V) supply, and the available current is limited by the adjustable resistors.

In the non-limiting operation (for small enough input signals), the op-amp N41 works as a voltage follower and enforces its input voltage to appear across the load R408, where it is again buffered by N42. In this mode, any errors caused by differences in the diode offset voltages, variations in the ± 10 V supply etc. are suppressed by the op-amp's open-loop gain.

For positive signals, the limit is set by P4. The maximum voltage across R408 is given by

$$U_{\mathrm{lim}} = (U_{\mathrm{ref}} - U_{\mathrm{diode}}) \frac{R_{408}}{P + R_{408}}. \tag{2}$$

where $U_{\mathrm{ref}} = 10\,\mathrm{V}$, $U_{\mathrm{diode}} \approx 0.6\,\mathrm{V}$ and $P = P_4 + R_{404}$. The negative limit is accordingly set by $P = P_5 + R_{406}$. With the values given in Figure 6, these limits can be adjusted between 0.29 V and 5.6 V.

For the adjustment of the limiters, the input signal to the limiters can by switched to either $+10$ V or -10 V with switches SW4, SW5 and SW6. For stability of operation it is recommended that the limiters are set to the narrowest possible range, i.e. such that even a huge error signal will not cause the beam to wander off the photodiode. Since the mechanical mount of the beamsteerer should be adjusted such that the coil current in the normal operating point is zero, the limiters should be adjusted after this mechanical alignment and will then be limiting more or less symmetrical.

5 Loop filter

The loop filter is used to create a useful open-loop gain frequency response using the actuator's frequency response. The designed open-loop gain is shown in Figure 8.

Apart from the actuator's frequency response (discussed in Section 4.2), it consists of:

a real pole at 72 mHz,
a real zero at 645 Hz (i.e. an integrator between 72 mHz and 645 Hz),
a real zero at 645 Hz,
a real pole at 22 kHz (i.e. a differentiator between 72 mHz and 645 Hz),
a complex pole at 7.14 kHz ($Q = 1.6$).

The 7 kHz low-pass filter serves to suppress the 14 kHz resonance. The unity-gain frequency is around 2 kHz, with a phase margin of about 25° and infinite gain margin (i.e. the loop is stable with any gain factor ≤ 1).

The filter is realized by op-amps N31, N34 and N35 on page 3. Switches N32 and N33 serve to discharge the integration capacitor in the "loop off" mode (see below),

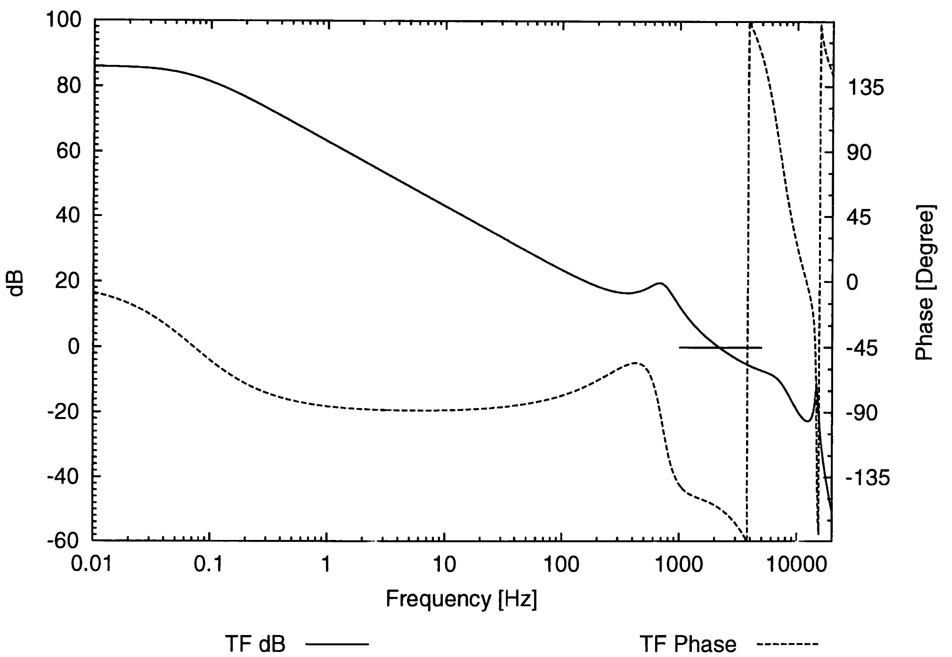

Figure 8: Open loop gain (design).

while differentiator N34 can also be configured as $f^{1/2}$ filter, if desired (see [MPQ243, Appendix B.4]).

The overall loop gain is controlled by op-amps N36, with a gain range of 0 to 100 ($-\infty$ dB to +40 dB). The gain as a function of the potentiometer setting is shown in Figure 9. It is roughly linear in dB in the central range of the gain potentiometer.

The next stages, N37 and N38 serve as optional inverter (to set the sign of the feedback) and as adders to feed in external test signals.

One particularly useful application of the adder is to determine the open-loop gain of the loop in operation (see e.g.[Heinzel95, section 3.2.2]). If a test signal (typically from a network analyzer) is added at the port called "ADD_IN" and the closed-loop transfer function (called $H_{\rm cl}$) is measured from that port to the one called "ADD_OUT", then the open-loop gain $H_{\rm ol}$ of the whole loop can be found as

$$H_{\rm ol} = 1 - \frac{1}{H_{\rm cl}}. \tag{3}$$

Figure 10 shows the result of such a measurement for a prototype (with slightly different loop filters), which shows that a unity-gain frequency of more than 3 kHz can indeed be obtained.

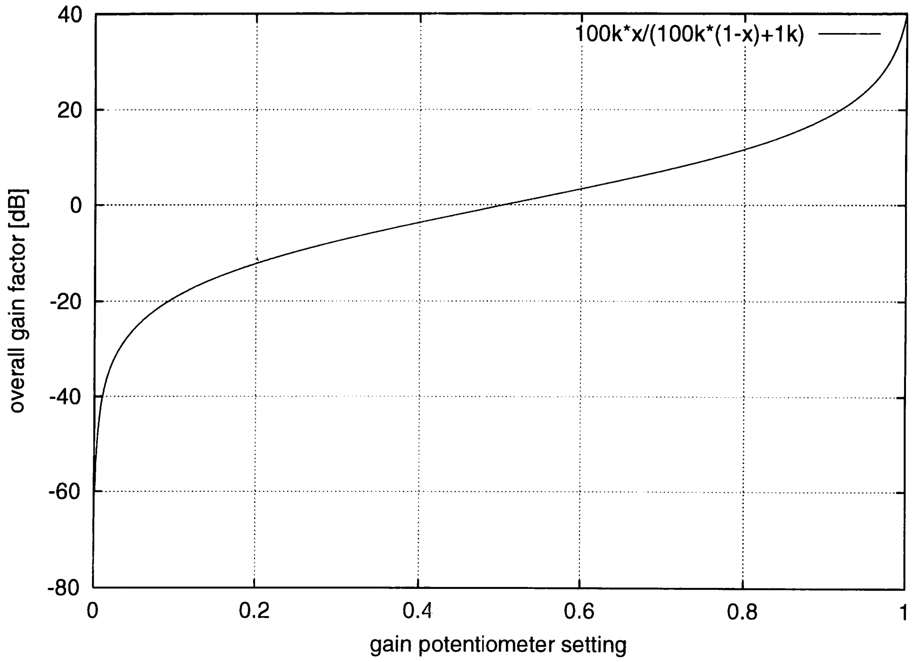

Figure 9: Overall gain as function of potentiometer setting.

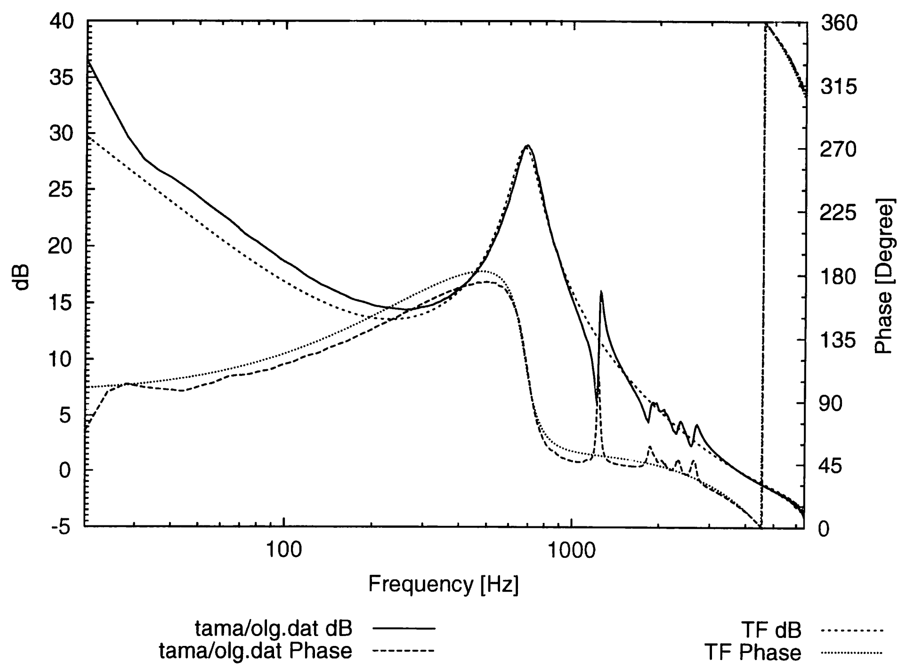

Figure 10: Measured open-loop gain of a prototype.

6 Control logic

The purpose of the control logic is to switch off the loop when
- the detected beam is too weak or too strong,
- the beam moves off the photodiode, or
- the operator wishes to switch it off.

Furthermore, it provides a "soft start" when loop is switched on. This was found necessary in the German prototype to prevent some nonlinear oscillation modes of the system [Grote].

The signal called ERROR\ (X216 on page 2) is HIGH if the denominator is within its limits, and LOW otherwise, as described in Section 3.

The NAND gates N74A ... N74D on page 4 combine this signal with the ytwo switches "Auto on/off" and "Loop on/off" to form the "LOOP_ON" signal as follows:

loop on (SW2)	auto on (SW1)	LOOP_ON (output)
LOW	LOW	LOW=OFF
LOW	HIGH	LOW=OFF
HIGH	LOW	HIGH=ON
HIGH	HIGH	LOOP_ON = ERROR\

The state of the LOOP_ON signal is displayed by the yellow LED lamp LED5 (page 4). The signal controls:
- switches N43/N44 (page 4) which disconnect the current driver inputs,
- switches N32/N33 (page 3) which reset the integrator, and
- switch N24 on page 2 which controls the gain.

The latter switch provides the soft-start operation together with op-amp N22 and the multipliers. According to equation 1, the gain is proportional to the voltage Y1 (output of N22). When switch N24 is closed (loop off), capacitor C21 is discharged and the voltage Y1 is zero. When the loop is switched on, Y1 rises up to 10 Volt with a time constant of $RC = 10\,\mathrm{k}\Omega \times 1\mu\mathrm{F} = 22\,\mathrm{ms}$. The precise value can be trimmed by TR22 for unity gain in the multipliers.

7 Circuit noise

(to be continued...)

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