Recent Investigations/Modifications on the ISS
LIGO internal note

Hartmut Grote

November 27, 2008

1 Context

This document tries to summarise the investigations and changes done on the ISS electronics at Livingston during October and November 2008. The work was triggered by the ISS#115 which went to an oscillatory state on 10/29/2008, from which we could not easily recover it.

2 The very latest history after the move to eLIGO

With the installation of the enhanced LIGO laser, the laser power actuator changed from the current shunt to AOM actuation. The AOM uses a RF driver, which needs a bias to set the operating point of the AOM. The choice was to add this bias at the output of the ISS. This was implemented by Stefan Ballmer on LHO (and later at LLO) and documented on April/30/2008 in the LHO elog.

At that time the open loop transfer function of the ISS was like shown in Figure 1, red and green trace (assuming a flat actuator response).

2.1 Loop shape

A bit later there was the implementation of somewhat more gain in the ISS servo loop in the 100 Hz region, to make sure that the loop would not be gain limited there. (Having in mind that the low-frequency laser power noise is particularly important for the DC readout. So certainly the noise should be sensor limited.) The blue/purple traces in Figure 1 show the modified servo, also not taking the actuator transfer function into account. This work was also done and documented by Stefan. Here is the excerpt of the LLO elog entry from Aug/22/2008, describing the electronics changes on SN#115:

```
Detailed electronics changes:
ISS SN 115:
 - R11,R13,R38,R35,R27,R32,R34,R20,R61,R240,R281,R247,R278,
   R262,R269, R274,R254,R245 to 1kOhm metal film
```

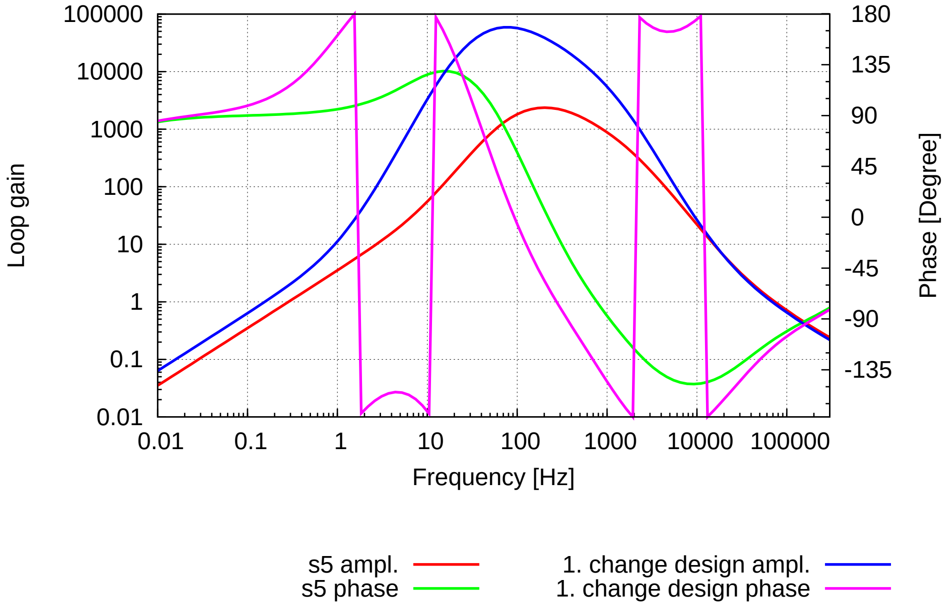

Figure 1: Initial ISS loop design and modifications from Aug/22/2008

- R18,R24,R31 to 510Ohm metal film
- R7 open
- Left R16 at 402Ohm (instead of 2k). This bring 5x more gain than the LHO unit.
- Additional 2.1 kHz pole:Added C=150nF in parallel to R31(499Ohm)
- Lower AC coupling pole by 2: C25 --> 2uF
- Move pole:zero pair to 10x lower frequency (30Hz:0.8Hz):
  C2 --> 10 uF
- Add 20Hz:2Hz pole:zero pair: C1 --> 47uF, R1 --> 169Ohm,
  (R21 stays at 1.54k)
- Add 870Hz:8.6kHz pole:zero pair: C51 --> 330nF, R51 --> 56.2Ohm,
  (R58 stays at 499 Ohm)
- By-pass U22 and add passive offset network at the output
  (see picture below).
  This gives an offset adjust between 0.44 V and 0.64 V.

```
TP13 --- 422 Ohm ---x---0 to 500 Ohm---1 kOhm---+15V---4.7uF---GND
                    |
                    \------ to 50 Ohm load (AOM driver)
```

Besides the increase of gain these changes (and others) also addressed the 1/f flicker noise from resistors which see a significant DC voltage drop.

The unit SN#115 was working at LLO since then, until Oct/29/2008, when it went into an oscillatory state without any obvious outside reason, in the middle of the night.

3 Recent investigations and modifications

3.1 Loop shape

The ISS could not be recovered from the faulty state by any gain setting. Testing the actuator chain (RF drive input to laser power drop) showed no particular problem at the time. The DC laser power drop for 500 mV input to the RF drive, was around 3 %. There was an intermittend state in time, on which the power drop seemed much less, but this state had somewhat disappeared the other day. (A month later we had this state again for 1-2 days. There is a spare AOM at LLO by now, such that this problem can be investigated a bit more relaxed, once this problem with the actuator shows up again. M. Zucker proposed to measure the RF-impedance of the AOM in its setup, yielding information to compare potential broken states from nominal ones.) However, even when the actuator seemed working fine again, there was a low-frequency oscillation around 2 Hz of the servo, which frequently saturated the loop. When taking into account that the AOM actuator chain has actually a frequency response containing a real zero at 2 kHz and a pole at 13 kHz, it looks reasonable that the loop tends to go unstable at the lower frequency end, for states with too low gain etc.

Figure 2 shows the loop shape of that time (before the fix), including the actuator response (blue and purple). The red and green trace are again the initial ISS design for comparison. The addition of the actuator respons made the loop unconditionally stable at the upper frequency end, but at the lower end, the gain rises rather steep, resulting in a higher UGF, and thus less phase margin.

The modification we then implemented was to shift one of the zero-pole pairs at the lower frequency end from 0.8 and 30 Hz, to 4 and 150 Hz, respectively. This fixed the ISS at the time. Later one of the poles at 1 kHz was moved to 5 kHz, which in part compensates for the actuator response, while keeping increased phase margin at the upper end. It makes the gain shape more symmetric again such that the overall gain can be increased more, before running into oscillations at the upper frequency end. Both changes combined are shown in Figure 3, which is now implemented on both units at LLO (115 and 111).

Also included in the new loop revision is the removal of the zero-pole pair at 0.8 MHz and 3 MHz, respectively. According to Rana, this was originally put in to compensate for a too high finesse of the PMC. With the recent move to a lower finesse, this is not needed any more, but also is its phase influence around 100 kHz rather small.

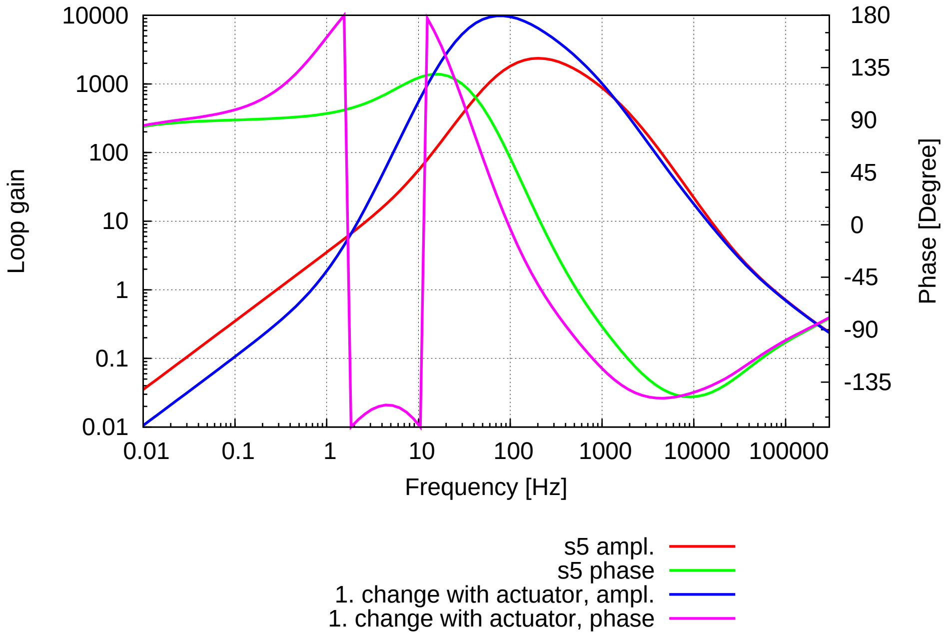

Figure 2: Comparison of s5 loop shape with loop shape as of October 2008 (simulated). The AOM/YAG amplifier chain adds differentiation from 2 kHz to 13 kHz, which makes the servo rather shallow at this end. As a result, the overall gain cannot be increased sufficiently, to get good stability at the lower frequency end.

3.2 Resistor matching of the AD829 stages

The AD829 features a relatively large 3 μA of bias current. Therefore, matching of the DC-impedances seen by the inverting and non-inverting inputs is essential to obtain low offsets, and thus low offset drifts. While in the original design, it was well taken care of this, the offset performance degraded somewhat with the adding of gain in the first AC-coupled stage (R16 (SN115) was lowered from 2k to 400 Ohm). This has now been corrected by changing R23 from 2k to 360 Ohm, and changing C25 from 2 μF to 10 μF to keep the pole frequency roughly the same. All other stages look about right in their resistor matching.

3.3 Oscillations of the AD829 stages around 100MHz

The AD829 Opamp is not stable for gains (at the high frequency end) below 20. The standard technique used throughout the circuit to make the AD829 stages stable, is to use a compensation capacitor at pin 5 of the chip. For circuits with a gain of 1, the datasheet recommends a capacity of 68 μF. On both ISS units, some of the stages were found oscillating around 100MHz with amplitudes varying from few 10 mVpp up to 500 mVpp. Changed compensation capacitor (C26, stage before

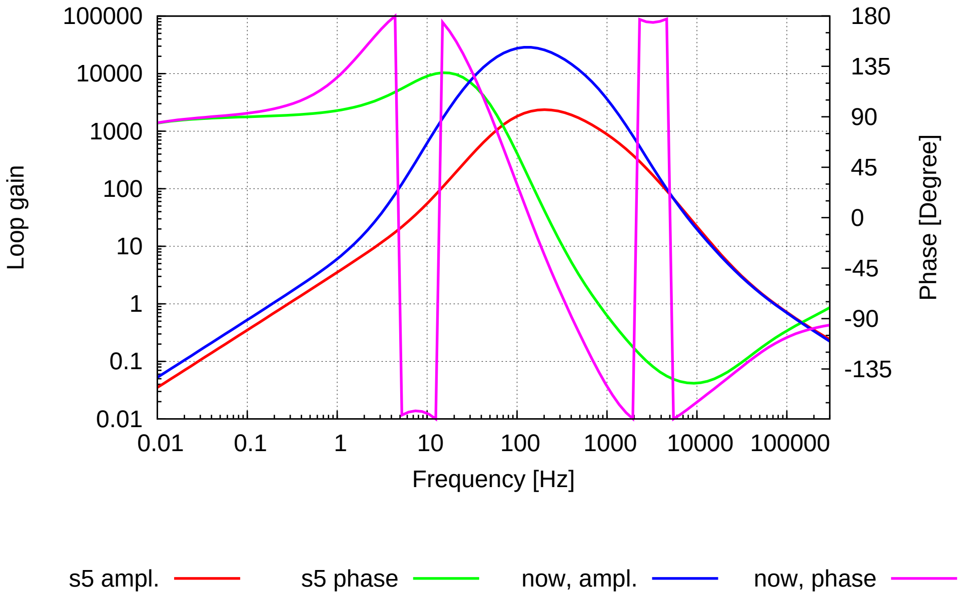

Figure 3: New (actual) loop shape of ISS 115 and 111 (including actuator response function), compared to s5 loop shape.

AC-coupling) from 27 pF to 68 pF, changed compensation capacitor (C23, stage after AC-coupling) from 47 pF to 68 pF, and changed compensation capacitor (C22, 2. stage after AC-coupling) from 3.9 pF to 10 pF. Also changed compensation capacitor on input stage to 68 pF. This stopped all oscillations. This might be very conservative, but on the other hand I think there is not much of a penalty. The slew rate goes down to 16V/μs, but that is still much more than needed. Phase delays are also no problem, in particular at the low-gain stages. There had been an earlier assessment of the oscillation problem by others, but perhaps the changes made were stable in the workshop, and then conditions might have changed under long-term operation, or with recent component changes. Just look out for these oscillations and increase compensation capacitors as necessary.

3.4 Offset adjusting potentiometers of AD829 stages

The offset adjusting potentiometers of the AD829 stages have their tap connected to +Vss in the board layout. The nominal point (according to the data sheet) is -Vss however. They do work at +Vss, but their tuning range is 80 times larger, which makes them more susceptible to drift and noise. I removed all offset adjusting potentiometers from the first differential receiver stages of all 4 PD inputs. Further removed all potentiometers from the main loop chain, except the one on the second stage after the AC-coupling (R2). The reasoning is, that offset trim before the AC coupling does not really matter, in particular as we only look at less than mV here. After the AC-coupling, offsets accumulate to contribute to the bias of the RF drive, which could be (before modifications) up to 100mV at the level of the drive, thus changing gain and operation point substantially. It seemed prudent to remove the offset pot. at the first stage after AC-coupling, as there any drifts from the potentiometer would be most amplified in the strages beyond. The second stage after the AC-coupling can potentially produce the largest offset, as it features the largest resistors at its inputs, and also a gain of order 100 is to come in the this and the following stage. So I left the potentiometer here, but its tap is connected to -Vss now. The third stage then will not substantially add offset any more, as the resistors are smaller again, and its offset is only amplified by factor 10. So for the offset adjustment it seems fine to tune the remaining potentiometer for zero offset at the output of the third stage (after the AC-coupling). With all the above changes, I have not seen any significant offset or offset drift on the operating units.

3.5 DAQS monitor output channels

When Josh and I looked at the whitened and unwhitened DAQS monitor channels (for sens- and monitor PD), we found them in some strange excess-noise state. While we first thought the 1 MHz on the whitened channels of several 100 mV would be a problem for the DAQS AA filters, it turned out that they are ok. Nevertheless I changed the pole in the whitened path from 50 kHz to 20 kHz, in order to lower the 1 MHz signal somewhat. (The 1 MHz originate from relaxation oscillations with the noise eater off. We wanted to make sure that the channels would work fine regardless of the noise eater state.) The main problem however was oscillations of the LT1124/25 opamps driving the long cables to the electronics bay. The series resistors in the outputs of these opamps were 20 Ohm, which was not sufficient to decouple the capacitive cable load. We increased those resistors to 200 Ohm. (I saw occasions in GEO, where even 50 Ohm were not enough to prevent oscillations.) The offset of the whitened stages has to be adjusted accurately, as the gain is high. Another change had to be made to the unwhitened channels of ISS 111. The Rev D-00 does not have pads to attenuate this signal by factor 10, as required for the DAQS. So I implemented voltage dividers at these outputs, consisting of 1 k and 110 Ohm in series.

3.6 RF drive bias

I set the biases to 500 mV on both units. (Compare to Stefans measurement of the actuator response in Figure 4). Recently we measured a power drop of 4 % for this setting. It might be that the Hanford RF driver has a different gain, however.

An offset drift of the order 1 V in the circuit would have shifted the operating point from (say) 500 mV to 400 mV, thus significantly changing gain and range. However, this should not happen anymore now. If you wish to reduce the laser power drop, it might be the right thing (as Rana proposed) to attenuate the RF,

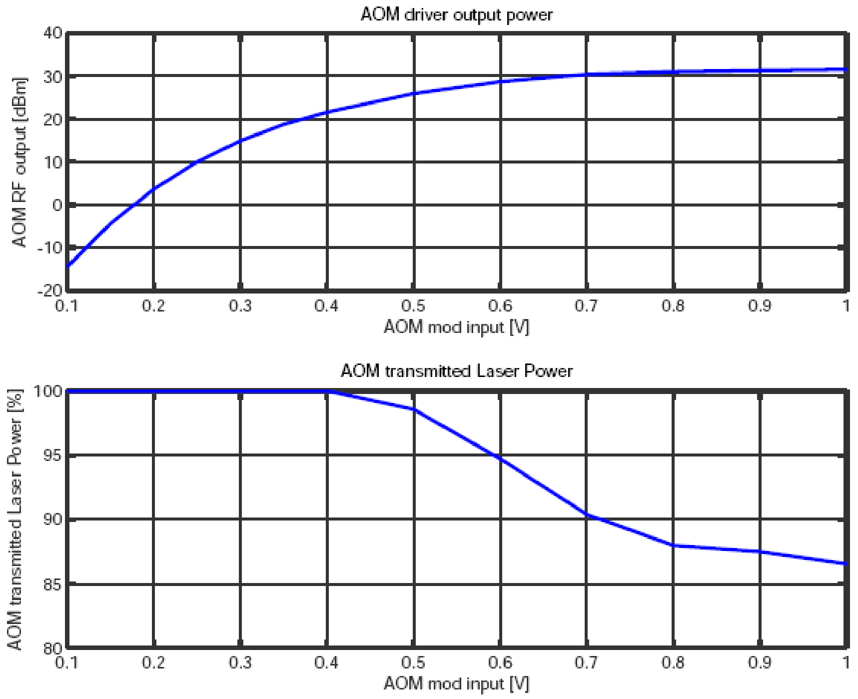

Figure 4: Transfer function from RF drive input to laser power drop (S.Ballmer)

instead of lowereing the bias. There might also be the possibility to adjust the gain of the RF driver just by a trimp pot. on the driver, which can be accessed from the front.

4 Summary

Both ISS serial numbers 115 and 111 are working now. The offset at the output of the third stage after the AC-coupling point (where the highest DC gain has accumulated) was always less than 10 mV upon recent investigations. There is no more a big offset change during warmup of the board, or when going from open loop with no PD connected, to closed loop condition. An offset of 10 mV results in a change of the bias (recently 500 mV) of only about 1 mV. So this looks very stable now. I did not sort out the individual effects quantitatively, as that would have taken too many iteration steps and long-term observations. In hindsight, it seems likely to me that the resistor matching of the 1. stage after the AC-coupling had the largest effect on the offset drift, at least for the warm-up phase of the circuit. However, the trim-pot and oscillations removal also reduced offset-drift. All four DAQS channels for whitened/unwhitened signals of in-loop sensor PD and monitor PD have been tested and work well now. Consistent RIN in- and out-of-loop spectra can be obtained from them. The epics readbacks are in an overall bad state still. This needs more investigation if people want to draw any conclusions from them. The current best diagnosis of the ISS, is to look at the photodiode signals via the DAQ channels.

Table 1 gives a list of the changes done within this work. Mike Fyffe, Carl Adams, and Peter King helped a lot with unit 111 and its documentation.

5 Further things to do

- On unit 111: The resistors in the PD signal input parts of the circuit (up to the AC-coupling) are mainly not low-noise types yet. Might well be this dominates the out-of-loop noise at low frequencies for this unit.

- Rana suggested to move the 2kHz pole from the first AC-coupled stage to some point later in the chain (perhaps close to the RF drive), in order to facilitate open loop TF measurements.

- It would be better to have the offset correction potentiometers in the whitening DAQS channels also connected to -Vss. The gain of these stages is 100, the resistors are not matched, and the potentiometer has too large range, such that the offset may drift out of the DAQS range.

- The Epics monitor channel labelled ’AOM drive (V)’ on the Epics screen is not working. It shows permanently 0.98 V, regardless of the true signal. I traced the signal on the board and it looks ok on both units. So I guess the problem is somewhere downstream of the ISS box. Having this monitor running would be very nice, as it would give a direct measurement of the actual offset. Also, the Epics saturation monitor seems not working properly (at least on unit 111). It sometimes shows saturation (4 V), although the unit works fine.

SN 115 rev. D02 component	SN 111 rev. D00 component	former value	new value	comment
C2	C2	10 μF	2 μF	shifts zero-pole structure in frequency
R28	R30	1.58 k	300	shifts pole from 1 kHz to 5 kHz
R65	R66	475	remove	remove zero-pole at 0.8-3 MHz
C60	C69	100 pF	remove	remove zero-pole at 0.8-3 MHz
R23	R24	2 k	360	R-matching at 1. stage after AC-coupl.
C25	C25	2 μF	10 μF	R-matching at 1. stage after AC-coupl.
C23	C23	15/47 pF	68 pF	make OPamp loop stable
C22	C22	3.9 pF	10 pF	make OPamp loop stable
R10	R11	20 k	remove	less noise/drift at no penalty
R246	R232	20 k	remove	“
R67	R70	20 k	remove	“
R293	R279	20 k	remove	“
R5	R5	20 k	remove	“
R4	R4	20 k	remove	“
R6	R7	20 k	remove	“
R59	R60	20 k	remove	“
R2	R2	tap at +Vss	tap at -Vss	“
C144	C144	1 nF	2.7 nF	pole from 50 kHz to 20 kHz
C189	C187	1 nF	2.7 nF	pole from 50 kHz to 20 kHz
R190	R188	20	200	make line drive stable
R235	R230	20	200	“
R189	-	20	200	“
R234	-	20	200	“
R242	R235	20	200	“
R277	R267	20	200	“
R241	-	20	200	“
R276	-	20	200	“
-	R187	20	1k+110 to gnd	attenuate outputs by 20 dB
-	R229	20	1k+110 to gnd	“
-	R234	20	1k+110 to gnd	“
-	R266	20	1k+110 to gnd	“
R230	R226	20	200	make line drive stable
R191	R189	20	200	“
R231	R227	20	200	“
R192	R190	20	200	“

Table 1: Detailed list of changes