H1 Common-Mode Wavelength Control Overview

LIGO-T020113-00-D
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Several people have approached me asking what the "Common-Mode" wavelength (or frequency[1]) control system does. The following is a brief historical context and a qualitative functional description of the rig recently implemented on the Hanford 4k interferometer (the other two interferometers are fundamentally similar).

The "additive offset" wavelength control topology we have chosen is not new. I first learned about it from Roland Schilling, who implemented it on the Garching 30m interferometer in the early 1980's (Shoemaker et al, *Phys. Rev. D* **38** p. 423, 1988). The Garching group implemented the first mode cleaner, and thus also first encountered the need to control the laser wavelength with high bandwidth while simultaneously keeping it resonant in a transmissive filter cavity (Rudiger et al, *Optica Acta* **28** p. 641, 1981). This is a difficult chicken-and-egg control problem; the interferometer has to control the laser without disturbing the lock of the mode cleaner, which is interposed between them. Later, we expanded and ported the concept to the LIGO 40m interferometer at Caltech (Kawamura et al, *Rev. Sci. Inst.* **68** p. 223, 1997).

The LIGO 4km and 2km design was created by Nergis Mavalvala, Gabriela Gonzalez,Daniel Sigg and Peter Fritschel (*LIGO LSC Final Design,* LIGO-T980068, 1998; Fritschel et al, *Appl. Opt.* **40** p. 4998, 2001). This design has been augmented by Rana Adhikari, along with Mavalvala, Fritschel and Sigg, to accommodate lessons learned during commissioning, notably the "as-built" length and wavelength error fluctuations found at the sites, which in some cases differed substantially from *ab initio* predictions. Finally, the digital implementation by Rolf Bork, including the "generic filter module" software architecture, permits dynamic slewing of filter transfer functions and seamless switching and "freezing" of signal paths in real time. After 20 years of fumbling with pots and relays, this digital functionality finally solves the "chicken and egg" problem in a robust and elegant way.

The term "differential mode" refers to fluctuations in L1 – L2, the difference between the arm lengths. The "common mode" motion is fluctuation in L1 + L2, motions the arms share in common. The name "common mode servo" is a something of a misnomer because the idea is not to touch the mirrors, but to force the laser wavelength to track them. The average of the arm lengths is actually a better absolute reference than the free-

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[1] Laser wavelength □ and frequency are □ are related by □=c/□. Here I generally use wavelength when referring to the laser light, to avoid accidental confusion with audio signal frequency (characteristic of control loop bandwidths, noise and gravitational waves).

running wavelength of the laser, or the reference or mode cleaner cavities. This stands to reason, because we've made the arm cavity mirrors as quiet as we possibly can at all frequencies we care about, and separated them by a large distance.

Casting the mirror motions into "differential" and "common" modes lets us think of the whole interferometer, from the standpoint of the laser and mode cleaner, as one simple cavity with a length equal to the average of the two "real" cavity lengths.

In principle, if the interferometer were perfectly balanced the laser wavelength wouldn't matter; however, small imbalances lead to some leakage into the "differential mode", which is our gravitational wave signal (usually read out as AS_Q). This leakage can be made tolerable by driving wavelength errors as close as possible to zero with a high-gain feedback control loop.

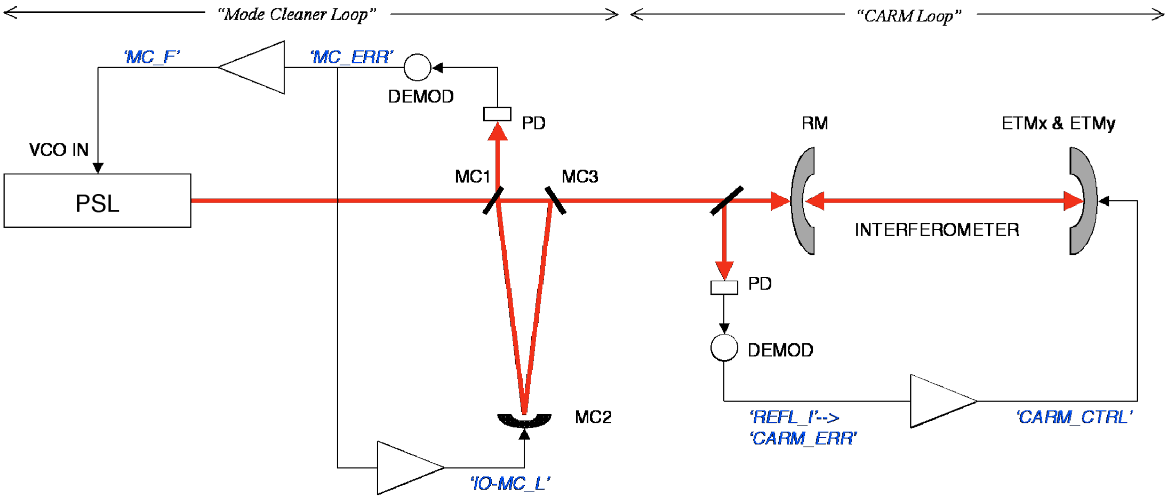

Figure 1 Nominal control arrangement just after acquiring lock. The PSL and mode cleaner form a self-contained unit providing "stabilized" light to the interferometer ("Mode Cleaner Loop"). The interferometer independently adjusts its own common-mode arm length to maintain resonance ("CARM loop"). The interferometer knows better what the wavelength ought to be, but can't talk to the laser.

Referring to **Figure 1**, we start out by locking the laser to the mode cleaner. This gives us a transmitted beam for the main interferometer to work with. In principle, it would be nice to just use the frequency control input on the PSL (VCO IN) and make the PSL track the mode cleaner via signal MC_F. Unfortunately, the mode cleaner is rather noisy at low frequencies due to its suspension and isolation stack modes. This noise exceeds the dynamic range available for the VCO IN port of the laser, so it won't stay locked for very long.

To cure this, we have to send some of the MC error signal at low frequencies (below 50 Hz) to correct the position of mirror MC2 (signal IO_MCL). The PSL is quieter at low frequencies due to its rigid reference cavity, unlike the swinging MC mirrors. This keeps the mode cleaner in lock.

More importantly, it also makes the absolute laser wavelength excursions small enough that the main interferometer can also catch lock by itself (otherwise it's shooting for a "moving target"). The CARM control path does this during the lock acquisition sequence and maintains the overall size of the interferometer as an integral number of half-wavelengths.

Unfortunately, connecting the IO_MCL path also contaminates the mode cleaner length somewhat at high frequencies, where the PSL itself is comparatively noisy. As a result, the overall wavelength jitter is too high for good interferometer sensitivity. Aggressive filtering helps, but we need to cut this link entirely to eliminate PSL noise.

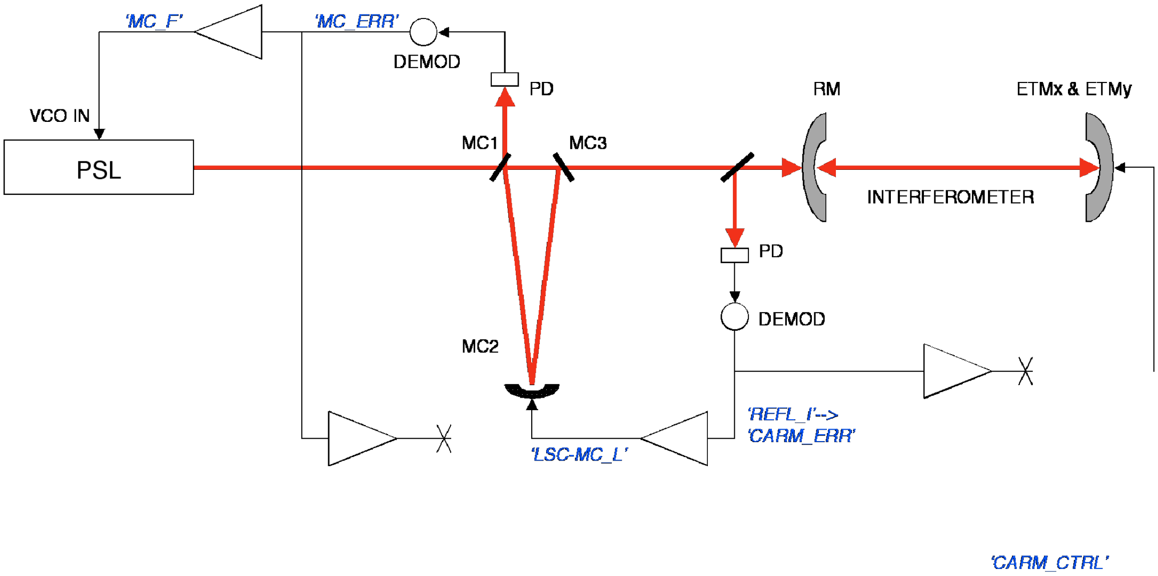

Figure 2 With the common-mode servo engaged, the main interferometer (REFL_I) dictates the laser wavelength by pushing the mode cleaner mirror MC2. The laser tracks the mode cleaner length through the action of the MC servo loop. The IO-MCL path used to calm the mode cleaner at low frequencies is shut off, as is the CARM feedback to the end mirrors of the interferometer.

To accomplish this we turn the CARM_ERR signal around and use it to push MC2 instead, through signal path LSC-MC_L (Figure 2). The handoff involves a brief moment where both IO-MC_L and LSC-MC_L are competing for control of the mode cleaner; the combined system is designed to be stable in a feedback sense, so the main trick is to complete the transition before the intrinsic PSL wavelength and arm cavity wavelength commands have time to wander away from one another.

In this configuration the only signal back to the laser is via the MC_F feedback to the VCO. Whereas previously this control point couldn't support the full range of wavelength deviations between the mode cleaner and PSL, the discrepancies between the quiet interferometer arms and the PSL are now manageable.

With the arms now commanding the mode cleaner length (which, in turn, commands the laser wavelength through MC_F) the CARM_CTRL feedback to the end mirrors is irrelevant and it can be cut off. This isolates the test masses from any differential noise generated by imperfect balance of the common-mode signals sent to ETMx and ETMy.

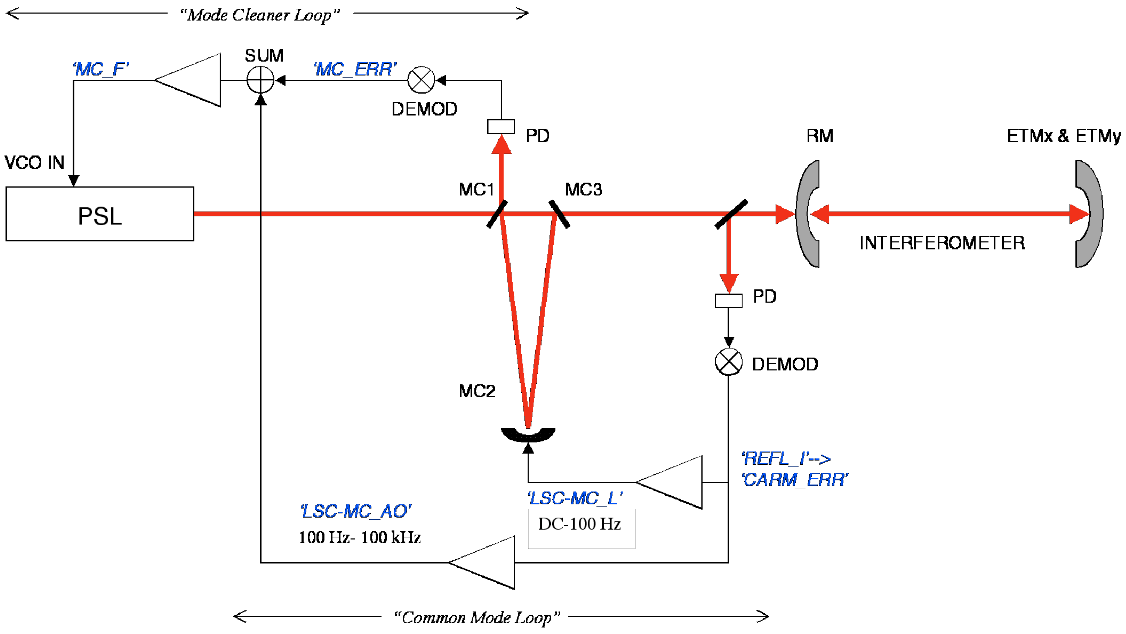

Figure 3 Ultimate wavelength control. The loop bandwidth is augmented by adding a fast trim signal, LSC-MC_AO, directly into the mode cleaner error signal. This "additive offset" corrects fast errors in mode cleaner length and permits a substantial increase in loop gain (and thus, wavelength noise suppression).

The final stage is to increase the bandwidth, and thereby loop gain, of the wavelength correction loop. This is needed to bring wavelength fluctuations down to an acceptable level. Bandwidth would be limited to a few hundred Hz by the limited response of MC2 to its OSEM coil currents; mechanical resonances cause loop instability if the bandwidth is increased further.

To circumvent this limit, we add a filtered, fast correction called LSC-MC_AO directly to the PSL/mode cleaner error signal (Figure 3). This "**A**dditive **O**ffset" could in principle push the laser wavelength off the optical fringe center of the mode cleaner, but restricting its action to high frequencies (well above the stack and suspension frequencies) keeps the total deviation small, so the response stays nearly linear.

The usable bandwidth of the composite LSC-MC_L + LSC-MC_AO actuator, blended by suitable high- and low-pass filters, is in principle very high (probably limited by propagation delays to < 1MHz or so). In practice, however, it is easiest to guarantee robust stability if it is kept below about half the bandwidth of the mode cleaner loop taken by itself. At this writing the MC loop bandwidth is about 30-60 kHz, so the "ultimate" CM loop is limited to about 15-30 kHz bandwidth.

It's worth noting here that the MC loop itself is limited (in much the same way) by the bandwidth of the internal FSS loop within the PSL. Future efforts to increase FSS bandwidth above 1 MHz may allow us to open the MC loop up to > 200 kHz, permitting about a factor of 4 increase in the CM loop bandwidth. Since the gain at kHz frequencies can increase as loop bandwidth squared or cubed in this regime, this could allow a significant further reduction in wavelength fluctuations if it is needed.