Novel All Digital Ring Cavity Locking Servo

Jeffrey T. Baker, David Gallant, Arthur Lucero

Boeing-LTS, Albuquerque, NM

Harold Miller, Jonathon Stohs, Thomas Shay

AFRL, KAFB, NM

AMOS CONFERENCE 2009

Abstract

We plan to use this servo in the new 50W 589-nm sodium guidestar laser to be installed in the AMOS facility in July 2010. Though the basic design is unchanged from the successful Hillman/Denman design, numerous improvements are being implemented in order to bring the device even further out of the lab and into the field. The basic building block of the Hillman/Denman design are two low noise master oscillators that are injected into higher power slave oscillators that are locked to the frequencies of the master oscillator cavities. In the previous system a traditional analog Pound-Drever-Hall (PDH) loop was employed to provide the frequency locking. Analog servos work well, in general, but robust locking for a complex set of multiply-interconnected PDH servos in the guidestar challenge existing analog approaches. One of the significant changes demonstrated thus far is the implementation of an all-digital servo using only COTS components and a fast CISC processing architecture for orchestrating the basic PDH loops active within the system. Compared to the traditionally used analog servo loops, an all-digital servo is not only an orders-of-magnitude simpler servo loop to implement but the control loop can be modified by merely changing the computer code. Field conditions are often different from laboratory conditions, requiring subtle algorithm changes, and physical accessibility in the field is generally limited and difficult. Remotely implemented, trimmer-less and solderless servo upgrades are a much welcomed improvement in the field installed guidestar system. Also, OEM replacement of usual benchtop components saves considerable space and weight as well in the locking system. We will report on the details of the servo system and recent experimental results locking a master-slave laser oscillator system using the all-digital Pound-Drever-Hall loop.

1. INTRODUCTION

As many already know, laser guidestars are an essential key ingredient to state-of-the-art Adaptive Optical optical systems whose purposes are to mitigate the effects of the atmosphere by using an artificially-created "guidestar" as a reference [1]. While space-based imaging systems exist, there are numerous practical applications of higher quality imaging directly from the Earth. Nature has conveniently provided us with a high altitude mesospheric sodium layer, which is excitable remotely using a finely tuned narrowband 589nm laser source tuned to the D2a line of sodium. On the other hand, nature has also made this 589nm source difficult to obtain at high optical powers, and much research has been done in this area trying to create one of practical use.

Of the available approaches, the successful FASOR[2,3] approach (Frequency Addition via the Sum of Optical Radiation) uses the more readily available 1064nm and 1319nm photons generated in a traditional YAG laser rod, together with a non-linear optical photon-summing Lithium Triborate (LBO) crystal. In order to generate sufficient 589nm power in a CW beam, high power narrowband frequency stabilized sources must be used. Non-Planar-Ring-Oscillators (NPROs) can generate small amounts (100's of mW) of highly stable, even finely tunable 1064nm and 1319nm light, but much more power is needed. High power laser oscillators can be constructed, but they lack the fine control of wavelength and narrow linewidth required for the task. Fortunately, the gravity wave interferometer projects such as LIGO[4], and others, have a similar need for narrowband YAG laser power. One of their approaches is to use a low power NPRO seed laser to injection lock the high power YAG oscillator. A ring configuration, rather than linear cavity, is most efficient at using the limited NPRO seed power, but the efficient coupling of two cavities requires that the optical path length of either one cavity or the other must be adjusted so that the resonances collide for the scheme to work and generate high power with high quality. This requires the PDH servo control method to be applied to each NPRO source/injection-locked laser.

Assuming one has been successful at generating high power 1064nm (~80Watts) and 1319nm (~60Watts) light, Sum-Frequency Generation (SFG) method must then be employed to get 589nm. A properly cut LBO crystal, when heated to 40-deg C can perform this photon adding operation. In order for this to work efficiently, the power levels of 1064nm and 1319nm must be sufficiently high within the crystal for the non-linear process, but not so high as to optically damage the crystal. A doubly-resonant ring cavity can increase the circulating power within the crystal to the point of high conversion efficiency. This requires another pair of PDH servos to achieve double-resonance.

In addition to high power, frequency-stabilized 1064nm, 1319nm, and now 589nm yellow light generation, one must tune this 589nm radiation carefully to the D2a line. A precision wavemeter is used for adequate measurement, and is key to the control system which must tune the two summed laser sources (usually the 1064nm source) to hit the exact D2a line. Care must be taken to avoid NPRO temperature regions which are known to cause multi-modal operation of these seeding sources.

As can be seen in Fig. 1 [5], there are numerous servos in a working FASOR system, and this is still true in the current FASOR-X ("FASOR-for-the-year-2010") system build which will be very similar to this one.

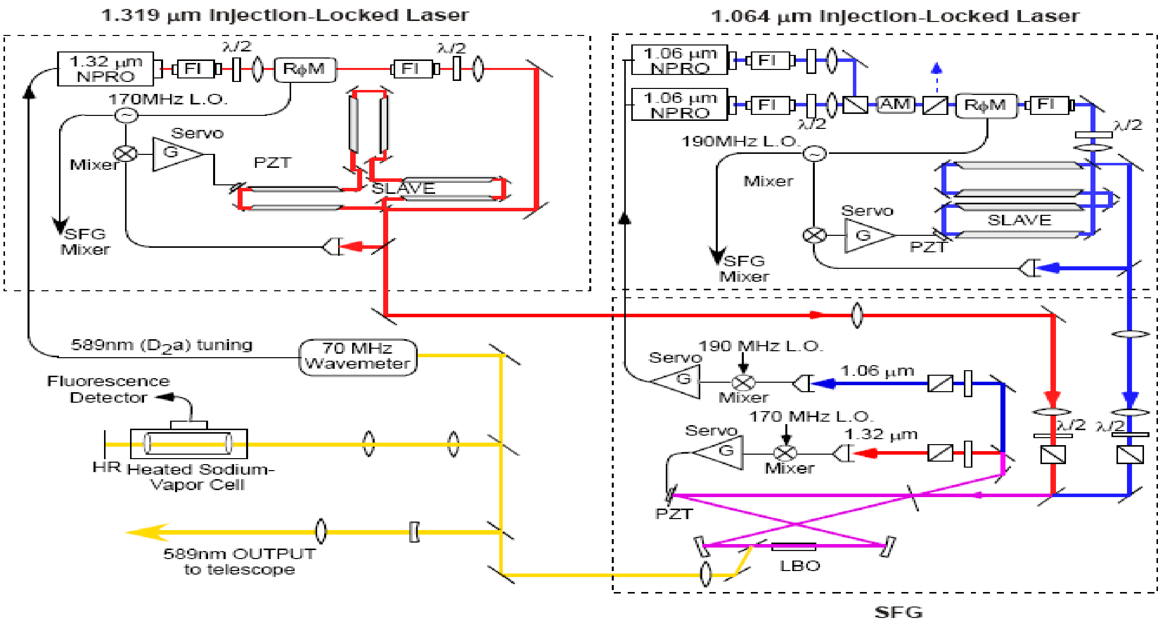

Figure 1 FASOR SYSTEM DIAGRAM

2. THE POUND-DREVER-HALL METHOD

The FASOR-X system under construction requires numerous servo control loops internally, and no less than 4 of these are resonant optical cavity-locking servos based on the Pound-Drever-Hall method[6]. See Fig. 2.

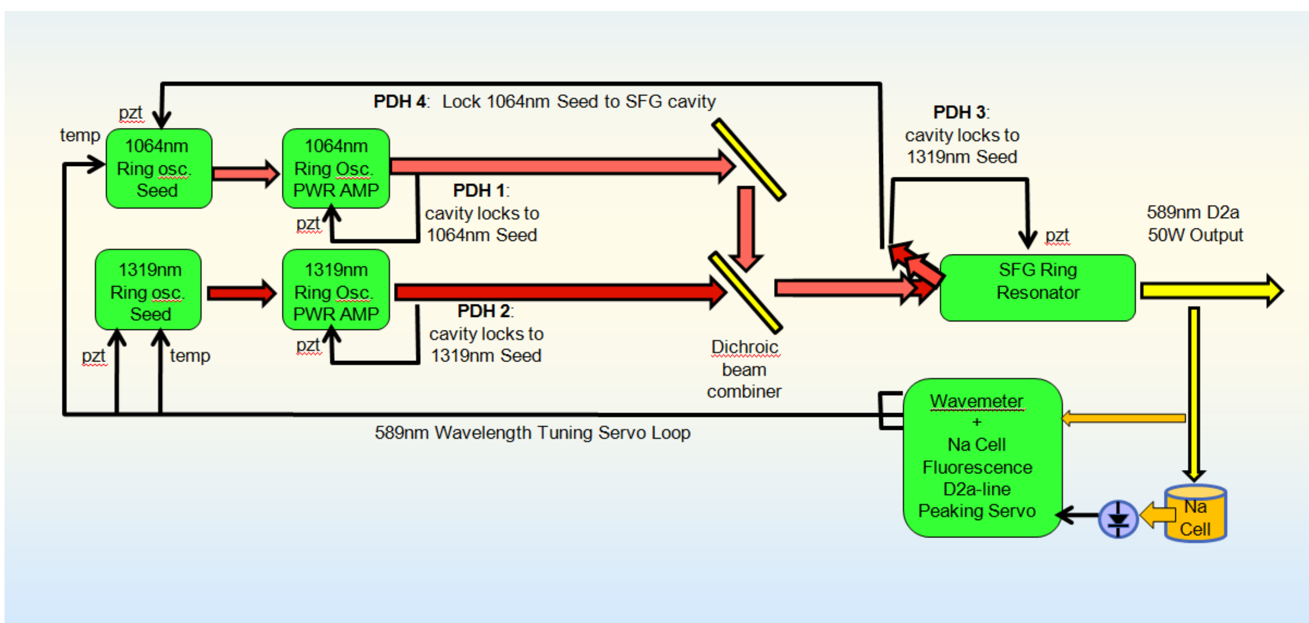

Figure 2 SELECTED CONTROL LOOPS IN A FASOR SYSTEM

If, for example, we focus on only the PDH-1 subsystem control loop details, it looks something like figure 3.

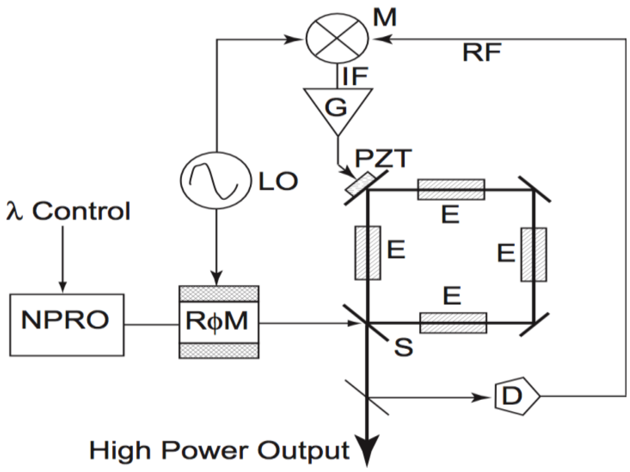

Figure 3 POUND-DREVER-HALL METHOD FOR THE 1064nm SUBSYSTEM

PDH is a means to generate and use an error signal which can then be used to close loop on a cavity spacing to make it resonant with the seed laser. The RΦM is a resonant optical phase modulator driven at a local oscillator frequency, LO. This high frequency optical phase modulation imposes frequency side lobes at +LO and –LO on the narrowband optical signal. Typically, the LO ranges from 20-200MHz, and is based on the free-spectral-range of the ring cavity being locked, and the optical cavity Q (or finesse). The demodulation of the signal coming from photodetector D is achieved in an RF mixer M using the same RF oscillator signal as a reference, with the electrical phase adjusted such that the low-pass-filtered IF error signal looks like the derivative of the optical transmission function for the cavity for the incoming modulated light (see Fig. 4 for typical data). A desired *positive-slope zero-crossing* results in the error signal when the optical path difference is scanned along open-loop by the intracavity PZT actuator. Two additional zero-crossings are present in the error signal, but fortunately their slopes are negative. The error signal is too complex for purely analog servos without some help, however.

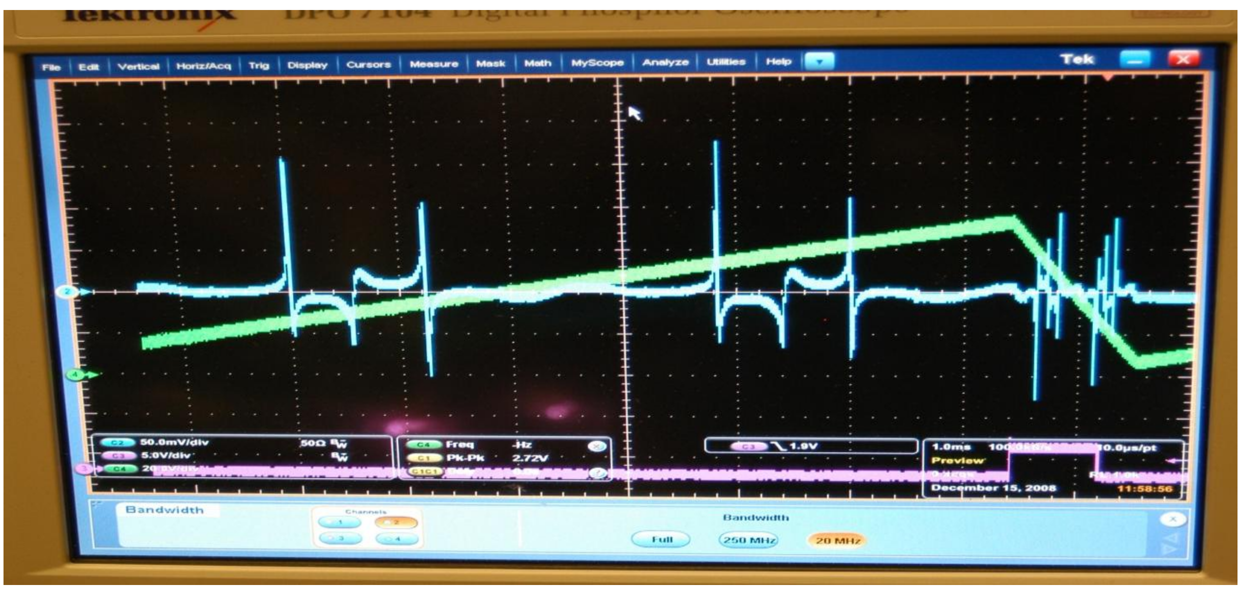

Figure 4 PDH ERROR SIGNAL CAPTURE

Ideally, the error signal for an analog servo would look like the nicely linear green PZT drive trace of Fig. 4. The complexity of the blue trace is the actual PDH error signal, and there is plenty of room for analog confusion when it comes to locking the cavity. The only valid locking points are the sharp positive slope zero crossings. Soft positive slope zero crossings are present half-way in between these, and, therefore, half of the time an analog servo will lock incorrectly due to chance upon power up. There is an additional metric which can be imposed to help out—the ring oscillator only produces forward optical power when properly locked to the correct point. Previous systems use this fact to "kick" the system to the proper lock point. One can repeatedly reset the locking circuitry until the proper lock is verified. The SOR FASOR used a hybrid digitally assisted analog approach, whereby many lock starting positions were tried in sequence before the correct zone was found and verified by a loss of reverse power.

In December 2008, we built the small 1064nm injection-locked ring oscillator shown in Fig. 5 and proceeded to implement the PDH method. This experimental setup in fact produced the PDH signal shown in Fig. 4 above.

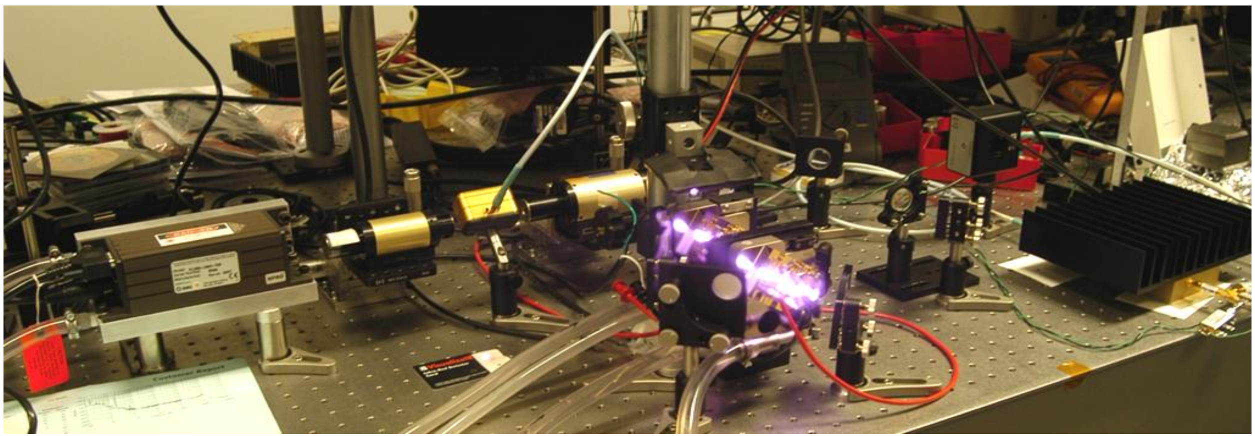

Figure 5 DECEMBER 2008 PDH RISK REDUCTION TEST

We then attempted and subsequently succeeded in implemented the method using an all digital servo. We were thus able to lock to the PDH error signal with ease, but initially we still had the same problem of ambiguous lock points and instability. Coding naivety led to a runaway PZT drive signal when 2pi phase wrapping was added for extended control dynamic range, and when the PZT hit mechanical resonance, the mirror fell off. We solved both problems rather quickly within a few additional lines of code. For example, one can see from Fig. 4 that the erroneous locking points have a much gentler slope and smaller locking range when compared to the correct one. The solution was to add a "kick" voltage transient of suitable sign and size to the locked servo PZT signal every once in a while. If one was in the correct position, the servo would remain locked. If in the erroneous position, the servo would respond by jumping to the correct position within a few milliseconds. This avoided having to verify lock by means of checking another control signal input for the presence of reverse power in the locked ring.

The speed of digital servos had been an issue in the time of the build of the existing installed SOR FASOR, but these speeds have been increasing over time with every new and improved PCI-I/O card, C++ driver, and PC CPU revision. Currently, we can do 100kS/S of multi-channel 16-bit+ control in our all-digital servo done on a CISC host processor approaching hard-realtime specifications. Since it has been experimentally determined that 10kHz analog bandwidths are sufficient, 100kS/S all digital servos should suffice for FASOR-X. FPGA implementations would be even faster, but for now the expense of coding and development infrastructure is unnecessary. Fig. 6 shows the implementation which we will use one shared CISC processor for all simultaneously high speed 4 PDH loops, and another supervisory controller to handle everything else.

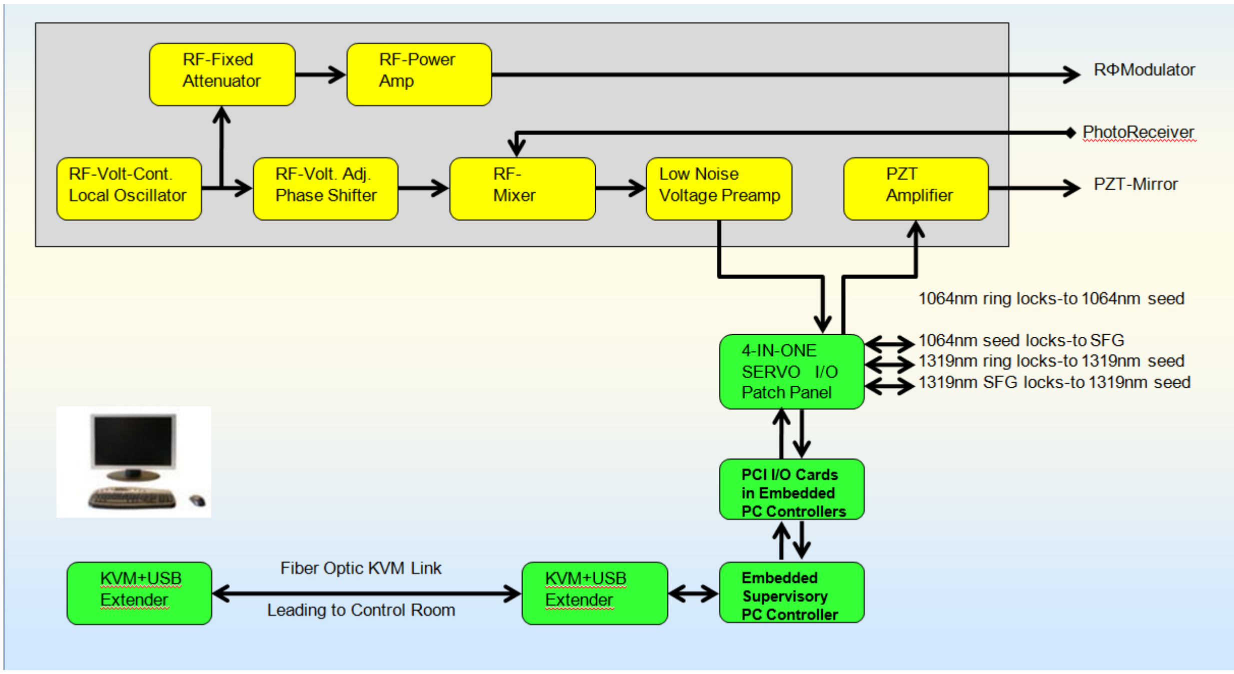

Figure 6 **4-CHANNEL ALL DIGITAL PDH SERVO**

3. BENEFITS of USING ALL DIGITAL SERVOS

There are numerous benefits of being able to demonstrate all digital PDH servos:

a. Space savings—by also choosing miniature OEM-style vs. benchtop-style RF components, in addition to eliminating custom analog boards, we have eliminated the entire on-mount electronics chassis which was integral to the FASOR I while maintaining greater functionality.
b. Power savings—we save electrical power by not having both analog and digital systems working side-by-side. Lower power consumption means we can completely eliminate all cooling fans within the laser, eliminating a significant source of mechanical vibration which might degrade locking. The use of newly available solid state hard drives is a nice complement to the vibration free embedded control system. There is minimal heat released to the delicate telescope optical field.
c. Dev. Time savings—custom circuit boards and interfaces do not have to be designed, built, tested, modified, etc. Replacement of parts is easier. Duplication is also easier and less expensive. Upgrades are done via firmware from the control room as opposed to soldering in-situ "on-the-mount."
d. Accessibility—since there are no custom circuit boards to be adjusted, electronic interfaces can more readily be buried within the laser box, accessible via the GUI.
e. Improved Loops Performance—by controlling all 4 PDH loops in one controller, interoperability and cooperation amongst the loops can be better maintained. This means fewer glitches which ripple through the system, and more rapid and safer re-locks.
f. Improved SNR—the close proximity of key components and elimination of all long signaling cabling and noise-prone electronics will increase the SNR of the PDH signals for better locking under all conditions.
g. Robustness features—an all software system can be programmed to make more frequent and accurate adjustments to account for temperature drifts, ageing of components such as pump diodes, gentle degradations of alignments, etc. We expect greater ease of use and a higher percentage of full power run time before servicing.
h. Self diagnosing—an all software system can be better at diagnosing and predicting internal component failures.

4. CONCLUSIONS

In conclusion, while there is a lot of work left to do, we consider the milestone of demonstrating all digital PDH servos crucial to the success in the FASOR-X 589nm D2a sodium guidestar pump build up for the AMOS facility.

5. REFERENCES

1. Denman, C., Drummond, J., Eickhoff, M., Fugate, R., Hillman, P., Novotny, S., Telle, J. Characteristics of sodium guidestars created by the 50-watt FASOR and first closed-loop AO results at the Starfire Optical Range, Proc. of the SPIE, Vol. 6272, pages 62621L-1 through 62621L-12.
2. Fugate, R., Denman, C., Hillman, P., et. al., Progress toward a 50-Watt facility-class sodium guidestar pump laser, Proceedings of the SPIE Vol. 5490, pages 1010-1020.
3. Denman, C., Hillman, P., Moore, G., Telle, J., et. al., Realization of a 50-Watt facility class sodium guidestar pump laser, Proceedings of the SPIE Vol. 5705, pages 46-49.
4. Advanced LIGO homepage: http://www.ligo.caltech.edu/advLIGO/
5. Richey, J., graphic excerpted from the SOR FASOR Ops Manual, figure 3, page 6, 20-Oct-08 revision.
6. Black, Eric D., An Introduction to Pound-Drever-Hall laser frequency stabilization, Am. J. Phys. 69 (1), January 2001.