Simple approach to laser frequency stabilization

Andreas C. Kuhnert, Serge Dubovitsky
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

ABSTRACT

We describe a simple approach to laser frequency stabilization. It was originally developed for the metrology subsystem for NASA's StarLight mission, a space-based separated-spacecraft stellar interferometer. However, it is useful for all applications where modest laser frequency noise suppression is needed. We are using a simple transmit/reflect architecture in which the laser frequency is locked to one side of a Fabry-Perot cavity resonance peak. The frequency stabilization system measures the transmitted light portion of a that cavity and compares it to a stable reference voltage to generate the feedback signal. This signal is controlling the laser frequency using the Nd:YAG laser PZT and crystal temperature actuators, keeping the transmitted light level on the photodetector constant. This is equivalent to keeping the laser frequency stable. Because this system measures the transmitted light level it is sensitive to laser power fluctuations. One remedy to this problem is to monitor the reflected light from the cavity as well and use the ratio transmitted/reflected as the sensor signal. The residual frequency noise in our system was measured with respect to a stabilized laser light that was frequency stabilized using Pound-Drever-Hall stabilization.

Keywords: laser frequency stabilization, StarLight mission, frequency control, laser frequency noise

1. INTRODUCTION

The *StarLight* metrology source frequency stabilization used to be based on the Pound-Drever-Hall(1) (PDH) approach, which is rather complex and requires quite a bit of RF electronics. After the frequency noise requirements for the metrology source were revisited and lowered a trade-study was conducted to chose between several de-scoped approaches. The recommendation was made to use a frequency stabilization system based on the reflected and transmitted light from/through a reference cavity(2). This report summarizes the development of the *StarLight* metrology transmission-lock (TL) stabilization breadboard. It describes the approach that is used for the frequency stabilization system and the methods used for measuring the residual laser frequency noise.

2. EXPERIMENTAL SETUP AND PARAMETERS

The revised frequency noise requirement allows a simpler (compared to the PDH system) approach for the frequency stabilization system. The work reported here deals with that approach. Figure 1 shows an outline of the transmission-lock (TL) technique that was used for the breadboard frequency stabilization. The frequency standard is the same as for the PDH system, an ultra-low-expansion glass (ULE) Fabry-Perot Cavity. However, in this approach comparing the light intensity transmitted through the cavity to a reference level derives the control signals. The lower diagram in Figure 1 shows the transmitted (solid) and reflected (dashed) light levels for a cavity as a function of the laser frequency. If the laser frequency fulfills the resonance condition for the cavity the reflected light level decreases and the transmitted level increases. For a 5 cm long cavity the free spectral range (FSR = c/2L) between the longitudinal modes is about 3 GHz as shown in the diagram. The width $\Delta\nu$ (FWHM) of the resonance peaks is determined by the finesse F of the cavity, in our case F ~ 10,000, and is ~ 300 kHz. If one keeps the light level (lock level) measured on the photo detector constant by comparing the detector output voltage to a reference voltage then the laser frequency (lock point) will be constant too. However, this approach is sensitive to laser output power fluctuations since it measures the light transmitted. If that turns out to be a concern the reflected light (or some portion split of the cavity input light) can be monitored as well and the ratio I_{transm}/I_{refl} used as the sensor signal. According to the data taken with the TL breadboard by sensing the transmitted light only we were not limited by laser amplitude noise.

The first phase of the laser frequency stabilization breadboard was to measure sensor, actuator and cavity gains and design a first-cut feedback loop using an in-air reference cavity. Figure 2 shows the setup for the feedback system. The laser output fiber is connected to an isolator to prevent back-reflections. After a 2x2 coupler (to split the light for the frequency noise measurements, see also figure 4) the light is collimated using a fiber collimator and modematched to the cavity with a telescope. The output from the photo detector that measures the transmitted light power is used as the input to the servo control electronics. The detector output voltage is compared to the reference voltage (lock level) supplied by a quiet power supply. The servo drives any voltage difference toward zero by generating the necessary feedback signals for the laser frequency actuators (PZT and laser crystal temperature T).

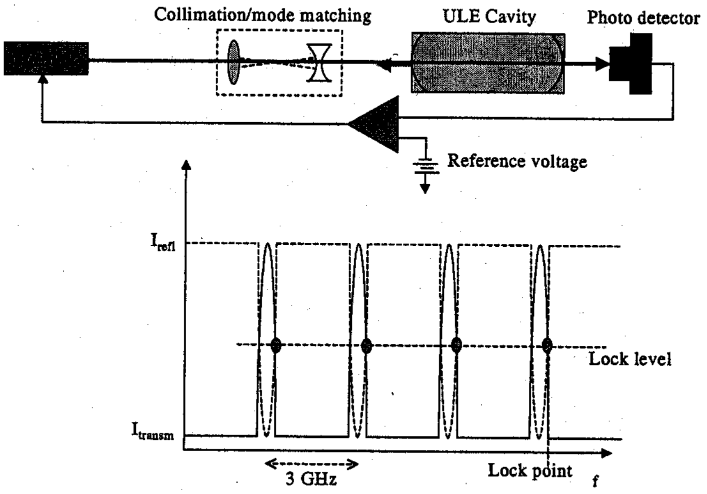


Figure 1: Transmission-lock at a glance

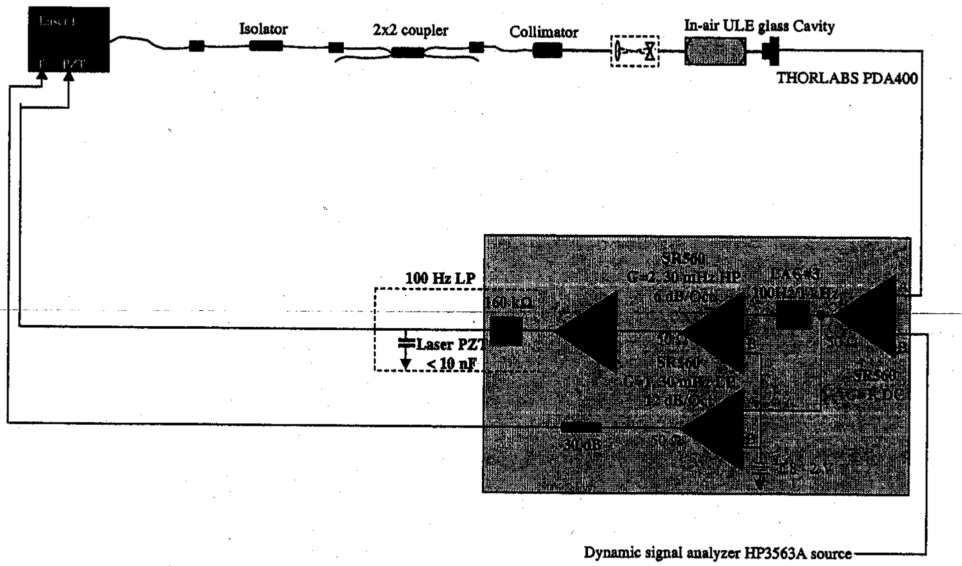


Figure 2: Analog frequency-lock setup (off-the-shelf components

2.1 Cavity Parameters

The cavity is a ULE (Ultra-Low-Expansion-Glass, CTE ~ $3*10^{-8}$) cylinder with two ULE mirrors attached at each end. The cylinder is vented for use in a vacuum. The length of the cavity is d = 5 cm. The radius-of-curvature (ROC) of the mirrors is 10 cm, i.e. ROC > d. This type of cavity is called a spherical mirror Fabry-Perot interferometer. It is rather insensitive to mirror alignment; i.e. it is very stable in terms of the resonating mode. We do not know the exact values for the mirror reflectivity to calculate the finesse. The value of F ~ 10,000 that we used has been measured for the in-air cavity by scanning the laser frequency slowly and measure the width $\Delta\nu$ (FWHM) of the resonance peak on the scope trace. For example a set of mirrors with R(eflectivity) = 250 ppm and L(oss) = 50 ppm would give a finesse of ~ 10,000 and a transmission of 70%.

Free-spectral range (FSR): c/2d ~ 3 GHz
FWHM resonance peak: $\Delta\nu$ ~ 300 kHz
Finesse F = FSR/$\Delta\nu$: F ~ 10,000

2.3 Feedback-loop Design and Parameters

From the metrology system requirements we derived how much open-loop-gain (G_{OL}) is necessary to achieve sufficient suppression of the laser frequency noise. Figure 2a is a generic depiction of the feedback loop shown in figure 1 with d being the disturbance (frequency noise). The feedback loop drives the controlled output y to be equal to the reference voltage (ref), by driving the error signal e to zero. It suppresses the frequency noise d by generating a correction signal c that is equal and opposite to d.

The open loop gain is L*H*G (LHG) and the frequency noise is suppressed by that loop gain (x/d = 1/(1 – LHG)). We will discuss the loop gain measurement in paragraph 2.4 and compare it to the calculated loop gain. Table 1 shows the published gain for the laser actuators and the gain for the cavity-photo detector combination It was determined from the measured cavity finesse, measured transmission peak voltage and lock level voltage (using the known resonance peak shape).

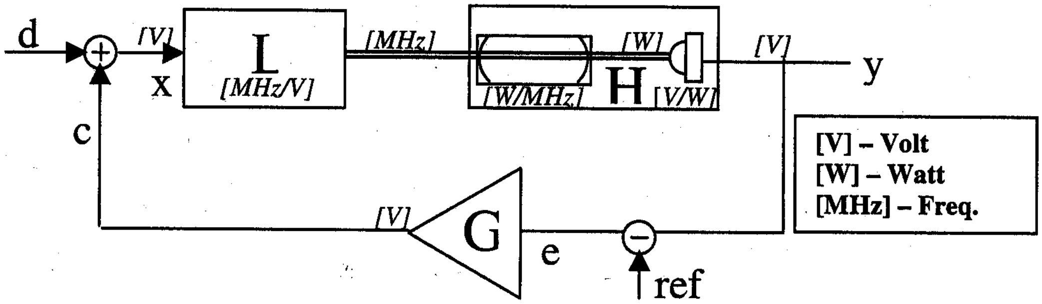


Figure 2a: Generic feedback loop schematic describing our setup.

The suppression factor for the frequency noise equals the ratio x/d. That ratio can be calculated for the closed loop and is $1/(1-G_{OL})$:

$x = c + d$ with $c = LHGx$	$c = Ge = Gy$ with ref=0	$y = e + ref$ with $y = LGHe$
$x = LHGx + d$	and $y = LH(c+d)$	$y = y/LHG + ref$
$x - LHGx = d$	$c = LHG(c+d)$	$y - y/LHG = ref$
$x(1 - LHG) = d$	$c(1-LHG) = LHGd$	$y(1-1/LHG) = ref$
$\mathbf{x/d = 1/(1 - LHG)}$	$\mathbf{c/d = LHG/(1-LHG)}$	$\mathbf{y/ref = 1/(1-1/LHG)}$
		$\mathbf{= (LHG/LHG-1)}$

	Cavity & PD	Σ SR560 1	PZT SR560 2	TEMP SR560 3	HV AMP	LASER II PZT	LASER TEMP.	ATT. SLOW
GAIN	5.3 V/MHz	1	5	1	4.6	> 4 MHz/V	3.8 GHz/V	- 30 dB
FILTER	120 kHz LP 10 MHz LP	DC; 100 Hz/1kHz LAG FILTER	0.03 Hz HP	0.03 Hz LP	100 Hz LP	30 kHz LP	0.1 Hz LP	
ROLL-OFF	6 dB/Oct	N/A	6 dB/Oct	12 dB/Oct	6 dB/Oct	6 dB/Oct	12 dB/Oct	

Table 1: Final loop parameters for transmission lock .

The initial laser actuator and cavity/photo detector gain accounted for a gain of about 46 with the amplifiers set to a gain of 1 (initially we had a cavity transmission peak max. of 5 V and a lock level of 1.8 V ⇒ 11.5 V/MHz * 4 MHz/V= 46).

The feedback loop has to create signals for two actuators with different response times, the PZT actuator with a pole at about 30 kHz and the laser crystal temperature with a pole as low as 10 mHz and a 40 dB/decade gain roll-off, i.e. 180° phase change. The PZT loop ("fast"-servo) is the actual noise suppression loop in the frequency range of interest (1 Hz – 1 kHz) but it has limited dynamic range (~ 30 MHz). That is the reason for the laser temperature loop ("slow"-servo), it increases the feedback loop dynamic range to about 10 GHz allowing the loop to stay locked over a wide temperature range.

The initial loop parameters were determined experimentally, i.e. we tried to make the loop to acquire lock and be robust. Once that was accomplished we were able to characterize the loop components and chose the parameters more carefully. The lag-filter rolls-off the gain faster before the PZT/crystal resonances (around 100 kHz) without reducing the needed phase margin (at unity gain). The final design will use narrow notch-filters to suppress the laser crystal resonances. The following considerations determined the final loop parameters as shown in figure 2b and in table 1:

"FAST" LOOP
- G_{OL} of at least 10 between 1 Hz and 1 kHz
- filter the output of the PZT HV amplifier to reduce output noise
- unity gain frequency of < 70 kHz (well below PZT actuator 100 kHz resonances)
- phase margin(4) 45° and gain margin(4) > 10 dB
- AC-coupled, roll-off at about 50 mHz

"SLOW" LOOP
- Unity gain frequency at about 30 mHz, "slow-fast" crossover at about 10 mHz
  to maintain phase margin 45° and gain margin > 10 dB
  together with a laser temp. pole at about10 mHz at 12 dB/Oct. roll-off.

2.4 Loop detectors and electronics

The breadboard servo electronics was build using commercially available parts: SR560 low noise amplifiers from STANFORD RESEARCH SYSTEMS, additional filters, attenuators, high voltage amplifier (HV-amp) and power supplies. This first stage allowed us to tailor the servo parameters to the problem as well as to take first data of the setup, e.g. to measure mechanical resonances and the open loop gain. Initially, with the frequency servo locking reliably we measured the loop gain and took noise spectra (using the HP3563A spectrum analyzer) from the in-loop photo detector.

We then modified the loop parameters taking into account what we learned from the initial measurements. Figure 3a shows the measured loop gain with the loop parameters set as shown in table 1. The calculated loop gain from table 1 is: 5.3 V/MHz * 1 * 5 * 4.6 * > 4 MHz/V, i.e. a loop gain > 500. Figure 3a shows a measured loop gain of 784 at 1 Hz and a unity gain frequency of ~ 14 kHz. The gain discrepancy could be explained with the uncertainty in the published laser PZT actuator gain.

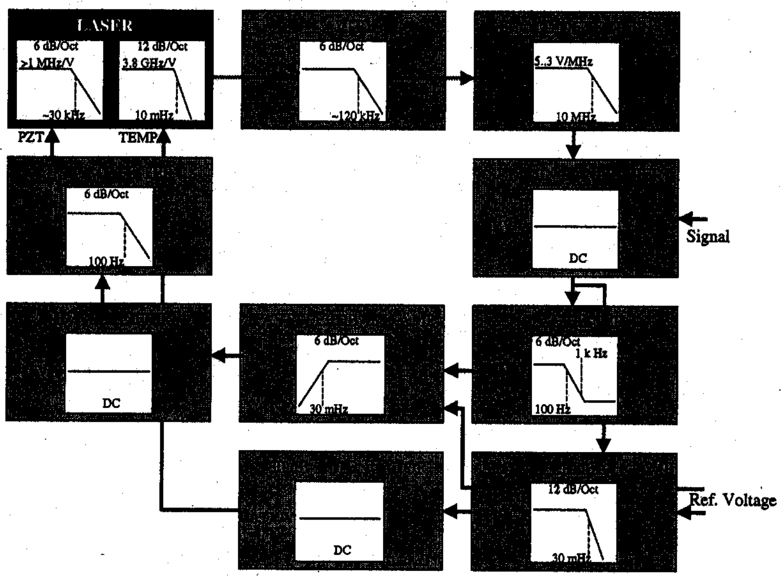


Figure 2b: Analog frequency-lock servo diagram

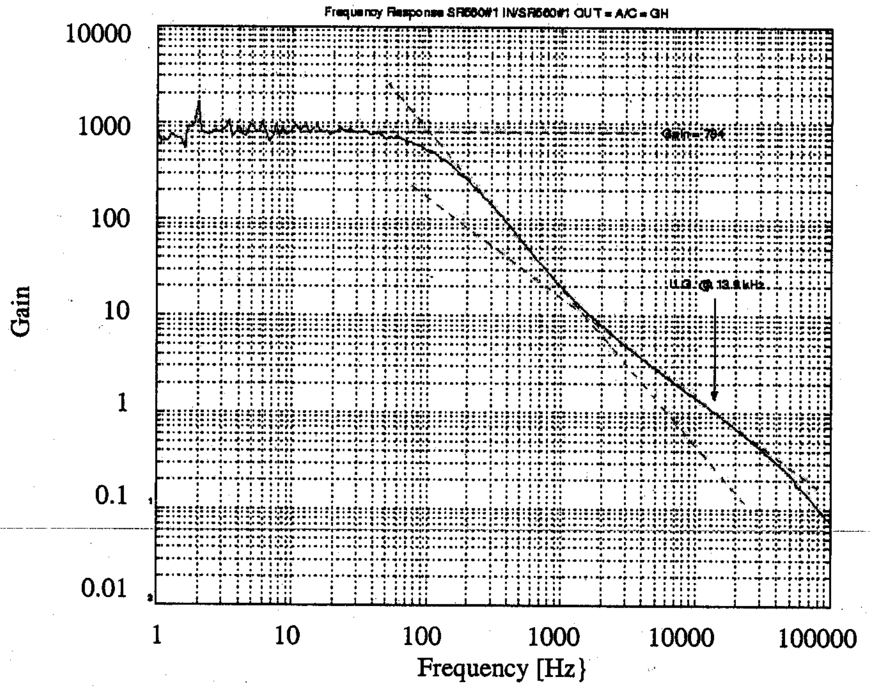


Figure 3a: Measured loop gain between 1 Hz and 100 kHz, loop parameters from table 1.

The measured crossover frequency between the "slow" and "fast" loop is about 15 mHz, the gain at the crossover point is about 100. We did not measure the DC loop gain for the "slow" loop, however, with the parameters in table 1 we expect it to be about 630 (= 5.3 V/MHz * 1 * 3800 MHz/V – 30 dB). In figure 3c the phase is plotted showing sufficient phase and gain margin.

3. FREQUENCY NOISE MEASUREMENT

For the residual frequency noise measurements of the transmission-locked laser we used the setup that is shown in figure 4. In this setup the cavities for both, the transmission-locked and the reference laser, are in a vacuum chamber, well isolated from acoustic noise and temperature changes. The reference laser is locked to its cavity using the Pound-Drever-Hall stabilization method.

The NewFocus 1534 photo detector measures the beat frequency between the two lasers. This beat frequency between the two locked laser depends on the frequencies of the resonances in the two cavities and can be as high as 1.5 GHZ in our case. It was adjusted to a more reasonable value between 5 and 20 MHz using a HP8648A synthesizer and a second mixer to beat down the NewFocus photo detector output frequency.

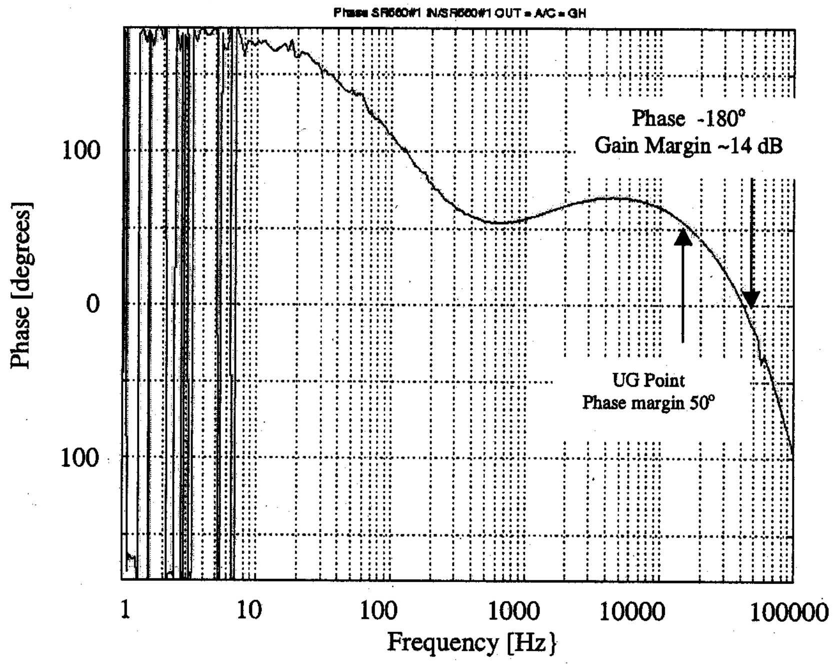


Figure 3b Measured phase between 0.01 Hz and 1 Hz with the parameters from table 1.

3.1 Frequency discriminator

To measure the variation of the beat frequency (due to laser frequency noise) we build a frequency discriminator$^{(3)}$. The discriminator setup is shown in figure 5. The RF photo detector signal is split and one signal is delayed using a ~300 m long RG58 cable to transform frequency noise into phase noise. The two signals are then input into a RF-mixer and the mixer output is low-passed to measure the DC voltage variation with the spectrum analyzer. The output of the mixer was calibrated by using an HP8648A synthesizer as the input to the RF power splitter and stepping the frequency in 10 kHz steps while measuring the mixer DC output variation (figure 6). With the calibration and the recorded peak-to-peak voltage at the mixer output the measured power spectral density V^2/Hz can be expressed as Hz^2/Hz. The mixer output was kept at about 0 V during the frequency noise measurements, i.e. at a known slope of the calibration curve.

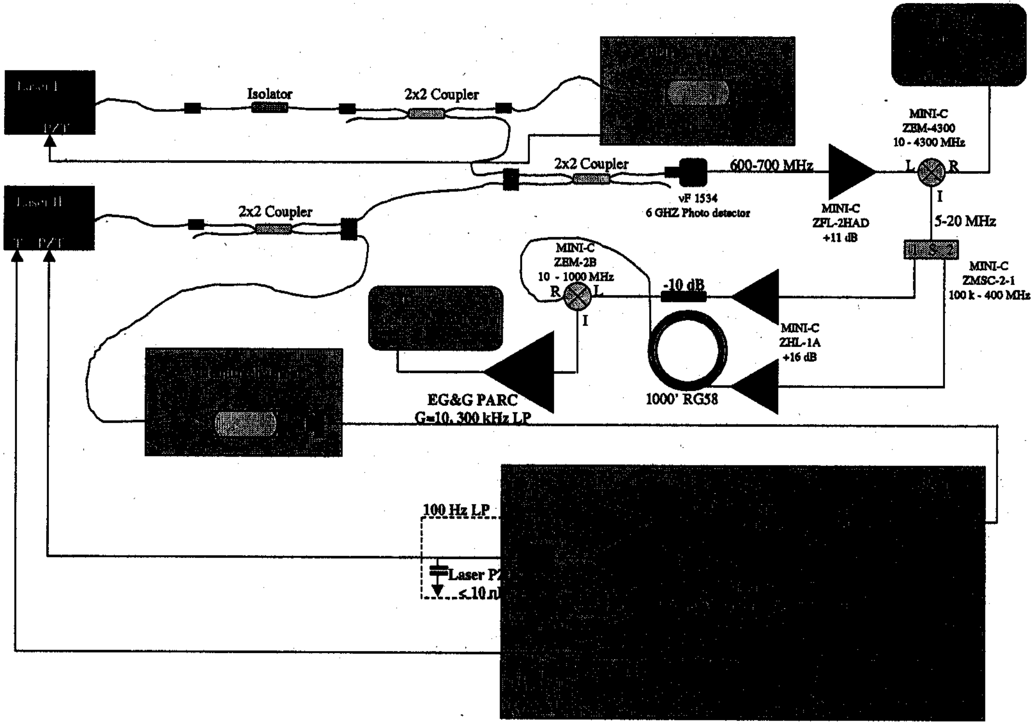
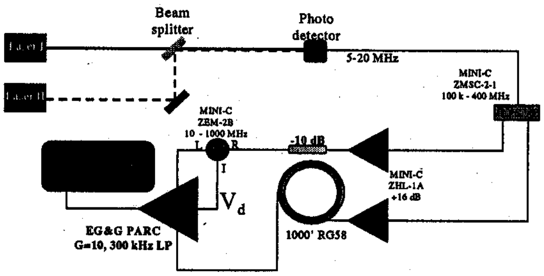


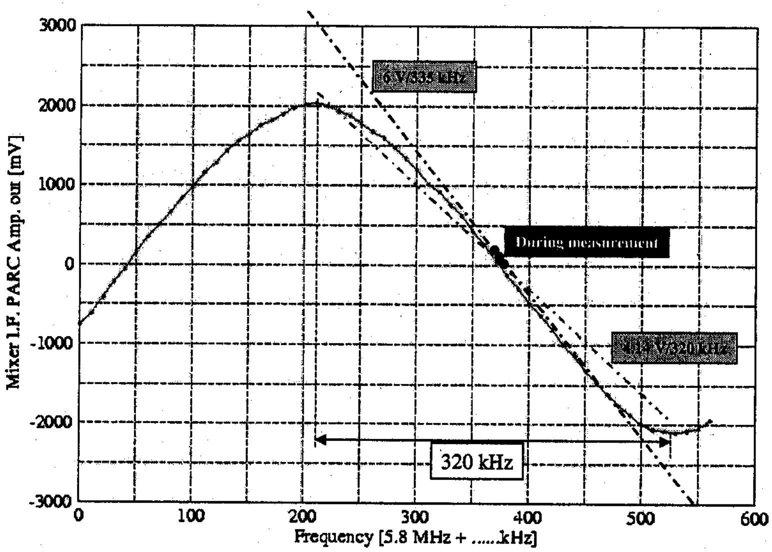
Figure 4: Setup with two lasers to measure the TL laser frequency noise vs. the PDH stabilized reference laser.



$c_{BNC}/L \sim 2*10^8$ m/s/305 m ~ 650 kHz

$V_d = K*\sin(2\pi\tau f_d)$; $K=\varepsilon_1/AB$ w/ A-att. of delay line
B - conv. loss of mixer

Figure 5: Frequency discriminator circuit as used for the frequency noise measurements.



Fri Jul 20 10:42:03 2001

Figure 6: Calibration (V/Hz) for the frequency discriminator circuit. With a 305 m RGA58 cable we expect a 2π phase change about every 650 kHz

3.2 Frequency noise measurement results

The noise power spectral density data taken with this setup are shown in figure 7. It shows to sets of curves: the lower set of curves represents the measurements with one laser locked using the TL system and the other one using the PDH system; the upper curve represents the free-running laser frequency noise of the TL locked test laser. The variation between the lower two curves is caused by different reference laser PDH system parameters. The dashed line is the requirement for the laser frequency noise for 4 nm of error in the *StarLight* metrology system.

3.3 Frequency noise measurement with a Time-Frequency Analyzer

We also used another measurement method using the HP5371A Time-Frequency Analyzer to confirm our residual frequency noise results. The HP5371A measures the beat frequency variation at the output of the first mixer, i.e. the down-converted NewFocus photo detector output. We took data (1000 points each) over 1, 10, 100 μsec and 1, 10, 100 msec. Directly before and after this measurement we took frequency noise data using the setup shown in figure 4 using the delay-line frequency discriminator. The results of these measurements are shown in figure 8. The results for the two different methods of measuring the frequency noise do agree well.

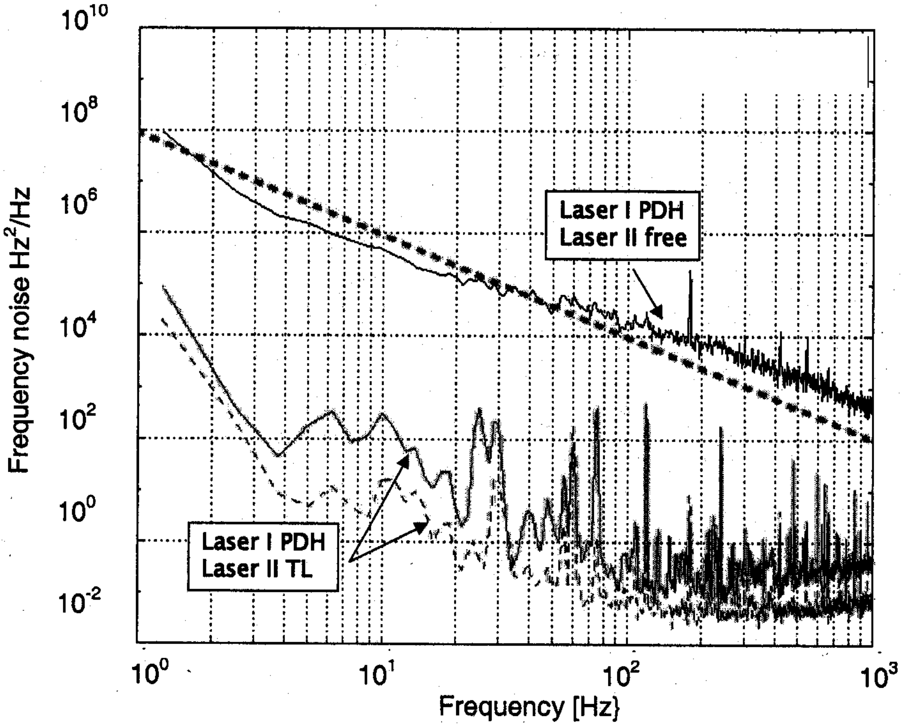


Figure 7: Frequency noise power spectral density of the beat frequency signal between the two lasers.

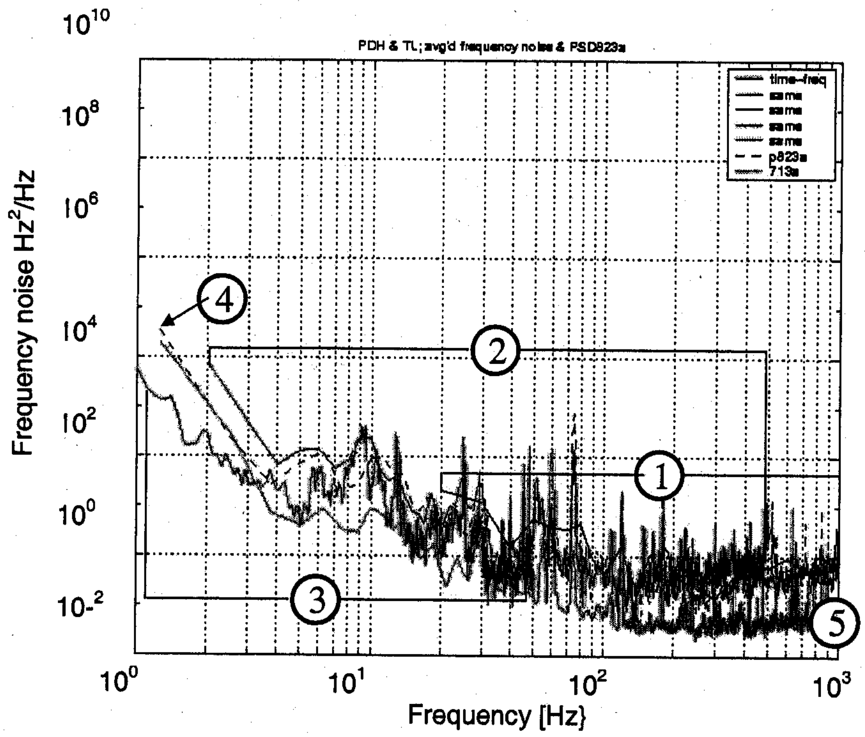


Figure 8: Comparison between frequency noise data measured two different ways:
1. with the HP 5371A Time-Frequency Analyzer ① - sample time = 100 μs
② - " " = 1 ms
③ - " " = 10 ms)
2. ④ and ⑤ - frequency discriminator measurement

SUMMARY

We have demonstrated good frequency noise suppression in the range 1 Hz to 1 kHz for Nd:YAG lasers. A frequency noise suppression of 2-3 orders of magnitude was achieved by using a system that is based on measuring the transmitted light through a stable optical resonator It requires a very limited number of optical components and no RF electronics or laser phase modulation. The system can be tailored for good noise suppression in different frequency ranges as well as for lasers with higher amplitude noise.

ACKNOWLEDGEMENT

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We like to thank Dr. Jim Mason from Lockheed-Martin Corporation (LMC) for his help with the Time-Frequency-Analyzer measurements.

REFERENCES

1. R.W.P. Drever, et al, Applied Physics B 31, 1983, (97-105).
2. T. Day, et al, IEEE J. of Quantum Electronics, Vol. 28, No. 4, April 1992, (1106-1117) and references herein.
3. A. Tykulsky, Proc. of the IEEE, February 1966, p.306.

4. A. Abramovici, J. Chapsky, Feedback Control Systems, Kluwer Academic Publishers, ISBN 0-7923-7935-7