THE CO_2 LASER FREQUENCY STABILITY MEASUREMENTS

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In the previous paper, one of the major problems with a laser receiver at synchronous altitude was discussed, that of Doppler shift, which can be as much as plus or minus 700 megahertz. Associated with that is also a maximum rate of Doppler change, which approaches a megahertz per second. I might add that the 10.6-micron laser frequency is 28 terahertz.

In addition to the problems imposed on receiver design that relate to maximum Doppler frequency and its rate of change, the stability of the laser is also of primary concern. Up to this date, we have had very little data on actual stability of the lasers in terms of phase noise, and in order to examine the problem and use it as an input into tracking receiver design, we implemented an experiment in the laboratory to measure and evaluate these stability effects.

Figure 1 indicates the objectives of the experiment. Primarily, we want to obtain experimental data on laser stability which affects the phase-lock loop tracking bandwidth, thus imposing minimum-bandwidth considerations. Another consideration is Doppler tracking performance. We would like to make phase-lock loop bandwidths wide for acquisition and tracking purposes; but conversely, we want to make them as narrow as stability will permit for best signal-to-noise ratios. The third effect is on a bit error rate. Our system is a coherent on-off keying system, and for that, the probability of making an error is, in general, one-half the complementary error function of the square root of the signal to four times the

EXPERIMENT OBJECTIVES

1. **OBTAIN EXPERIMENTAL DATA ON LASER STABILITY FOR DESIGN OF 10.6-MICROMETER RECEIVER**

   a) PHASE-LOCK LOOP TRACKING BANDWIDTH

   b) DOPPLER TRACKING PERFORMANCE

   c) EFFECT ON BIT ERROR RATE

   $$P_E = \frac{1}{2} \text{ erfc } \sqrt{\frac{S}{4N} \cos^2 \theta_{rms}}$$

   d) FREQUENCY ACQUISITION

2. **DETERMINE SOURCE OF INSTABILITIES OBSERVED**

Figure 1. Quantitative CO_2 stability data required for receiver terminal design. CO_2 laser phase noise data not available.

noise. However, if there is an inability to reconstruct the carrier, you get a cosine square of theta-rms, which is caused by oscillator instability. Another concern is the problem of frequency acquisition. If it is possible to open your loop bandwidth wide, you can minimize frequency acquisition problems.

The second major purpose of the experiment was to actually look for instabilities in laser power supplies, acoustical vibrations, and other sources of instabilities.

The actual experiment configuration is shown in Figure 2. We used two CO_2 lasers, shown on the left, and with PTZ tuners, we were able to pull the frequencies of each laser until we had a nominal 20-megahertz beat frequency between the two.
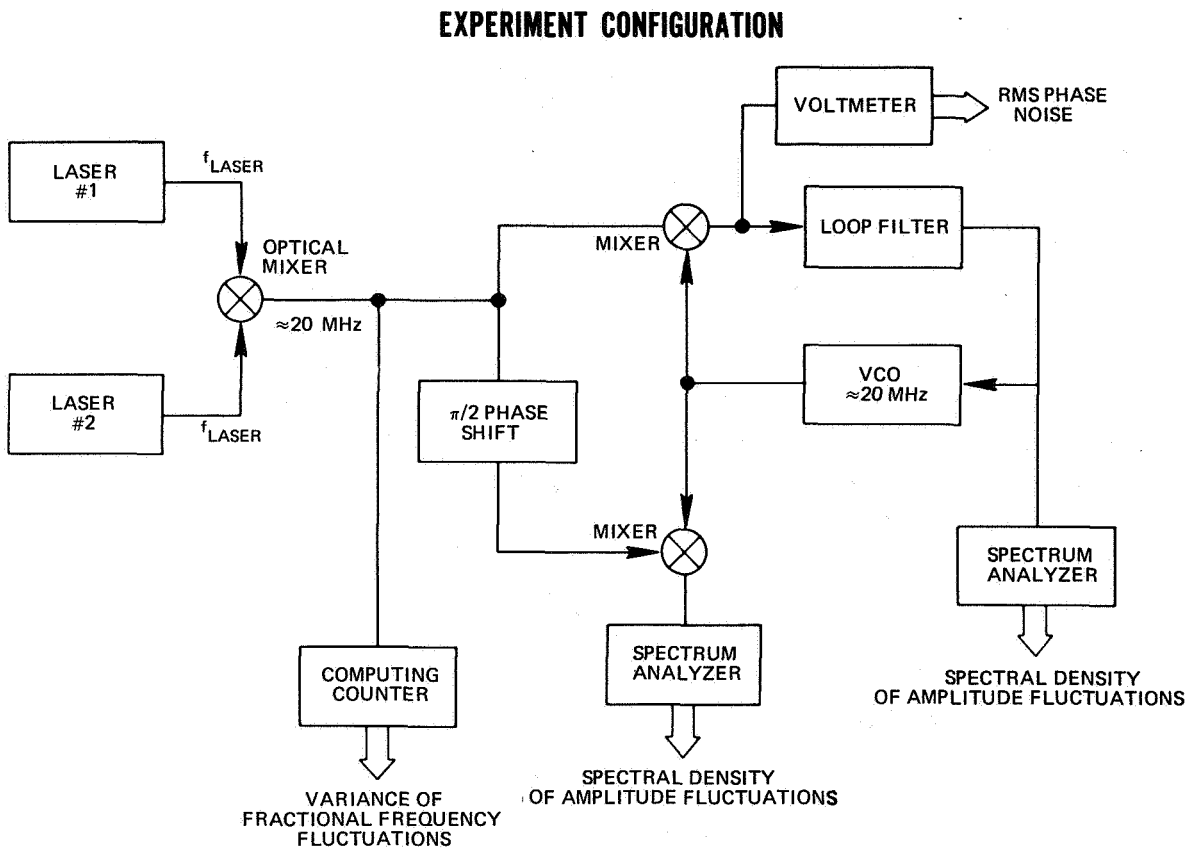
EXPERIMENT CONFIGURATION

Figure 2. Experiment implemented to obtain desired data: spectral density and variance measurement.

This signal emerged from the optical mixer, and was passed to a phase-lock loop tracking receiver. At the output of this receiver, we could measure rms phase noise within a loop bandwidth, and with a spectrum analyzer, we could get a spectral density measurement of the frequency fluctuations.

A third measurement we made was down through a quadrature loop. This would be a coherent demodulation of amplitude fluctuations, and we can get the corresponding spectral density.

A fourth measurement we made was in the time domain, using a computing counter. We actually measured and plotted the variance of the fractional frequency fluctuation. This is a typical signal versus tau plot that you see in the time domain.

The result of what we're after is shown in Figure 3, in which we used the data resulting from the experiment. This plot shows the phase-lock loop tracking error, or your inability to reconstruct the carrier versus the tracking loop bandwidth. The ordinate here is the error in degrees rms versus the phase-lock loop bandwidth in kilohertz. The line running from top left to bottom right is the result of the data from the stability measurements. Basically, it implies that there is a minimum loop bandwidth that you can use.

The horizontal lines — nominally 30 degrees rms phase error — are values where the phase-lock loop will skip cycles and drop out of lock. At 20 degrees' error, some degradation of the data signal-to-noise ratio will occur. These are thus maximum values that we cannot exceed.

PHASE-LOCK LOOP TRACKING ERROR VERSUS LOOP BANDWIDTH
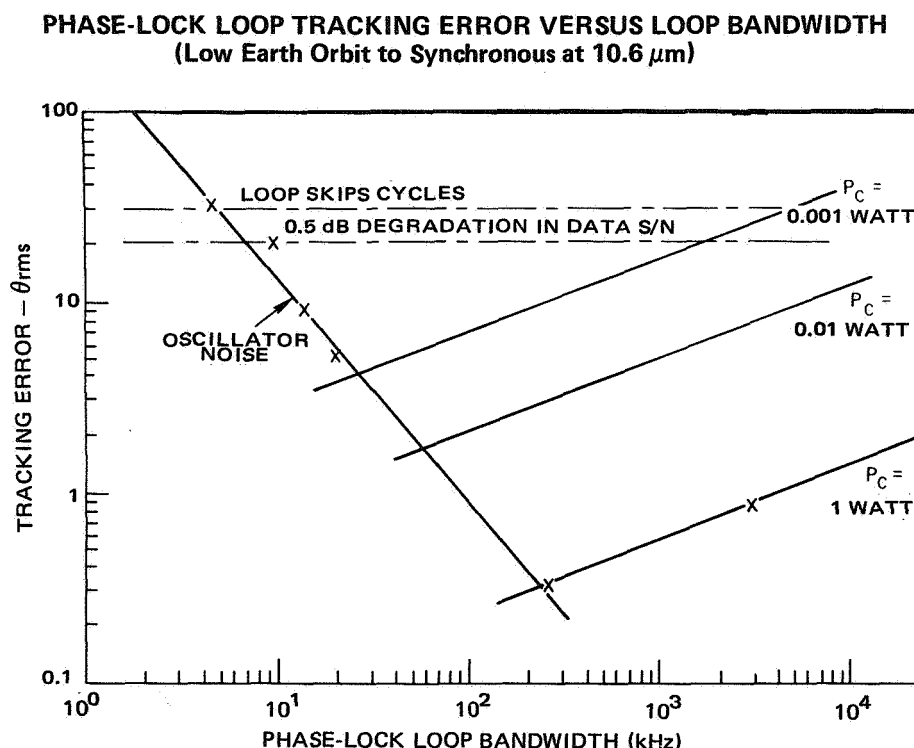**(Low Earth Orbit to Synchronous at 10.6 μm)**

Figure 3. Data used with other receiver parameters. Adequate margin exists in terms of acquisition, Doppler tracking, and bit error rate as they relate to laser stability.

The three sloping lines on the right are for various transmitter powers on an earth orbit satellite up to synchronous altitude. As you can see, for a signal level of, say, a milliwatt in the carrier, there is an optimum loop bandwidth at which we should operate to minimize the phase error.

Corresponding to this bandwidth, there is a maximum Doppler rate associated with it. The basic result is that we have measured the data on the lasers, and there is a margin, as you can see, for these various transmitter powers.