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TARGET INDUCED, TURBULENCE-MODULATED SPECKLE NOISE

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Abstract. Many papers on DIAL for remote sensing have been devoted to the averaging properties of speckle noise from diffuse-target returns; *i.e.*, how many (N) return pulses can be averaged before the 1/N reduction in signal variance expected from uncorrelated noise fails. An apparent limit of about 100 pulses or fewer has been the most important factor in determining the accuracy of DIAL measurements using diffusely-scattering targets in the field. The relevant literature is briefly reviewed, and various explanations for the apparent limit are summarized. Recent speckle experiments at LLNL's Site 300 may suggest that the limit of ~100 pulses is not fundamental. The speckle experiments very clearly show that the limit on signal averaging in this data was the result of long-term (~1 minute) drifts in the signal returns rather than of any more subtle statistical properties. The long-term drifts are completely removed to the useful limits of the data sets by working with the log-ratio of adjacent pulses. This procedure is analogous (but not identical) to processing the log-ratios of the powers at different wavelengths in a multi-line DIAL system. We think the Site 300 data therefore suggests that as long as the laser system is constructed to ensure that any long-term drifts are identical among the transmitted wavelengths, the log-ratio of the individual returns will provide a data set that does usefully average over a large number of pulses.

I. Introduction

Speckle noise, generated as atmospheric turbulence modulates the speckle pattern produced by a diffusely-reflecting hard target (see Section II, below), can in many circumstances be the dominant noise source in a differential absorption lidar (DIAL) measurement. As a result, several analyses[1-13] of speckle noise in field experiments have been published, with some discussion of the statistical properties of the noise in the context of how well the averaging of many pulses can reduce the noise. Several good pictorial examples of speckle noise, both for direct and for heterodyne detection, are provided in Reference 5.

That reference[5] also includes an early discussion of an apparent limit to how well signal averaging can reduce speckle noise. Its conclusion is illustrated in Figure 1: as a dataset size increases, the variance of the averages of many such datasets does not decrease as 1/N, where N is the number of points in the individual datasets. Section III below describes in more detail the dataset manipulations that lead to this conclusion.

Reference 8 provides the most detailed mathematical analysis of the signal averaging properties of experimentally-obtained samples of speckle noise. This analysis is based on non-zero correlations ρ_j between return pulses separated in time by j pulse intervals. The reference concludes that, because there are non-zero correlations in the data even for large j (large time separation), the data do not average to give a variance that decreases as 1/N; instead, the relative variance (normalized to the mean) of the datasets appears to approach a limiting value of several percent after fewer than 100 pulses. The nature of the long-term correlations is not explored.

The conclusion that can be reached from this result is most clearly stated in Reference 6, where the authors write (p. 2695): "On the basis of these results it can be seen that, for remote sensing measurements involving reflection from hard targets and taking place over several minutes, one cannot expect signal averaging alone to yield [relative rms] values below ~10% for heterodyne detection or ~2% for direct detection." This conclusion, if generally true, is extremely unpleasant; it clearly implies that the detection of very low concentrations of effluents at long ranges cannot be done.

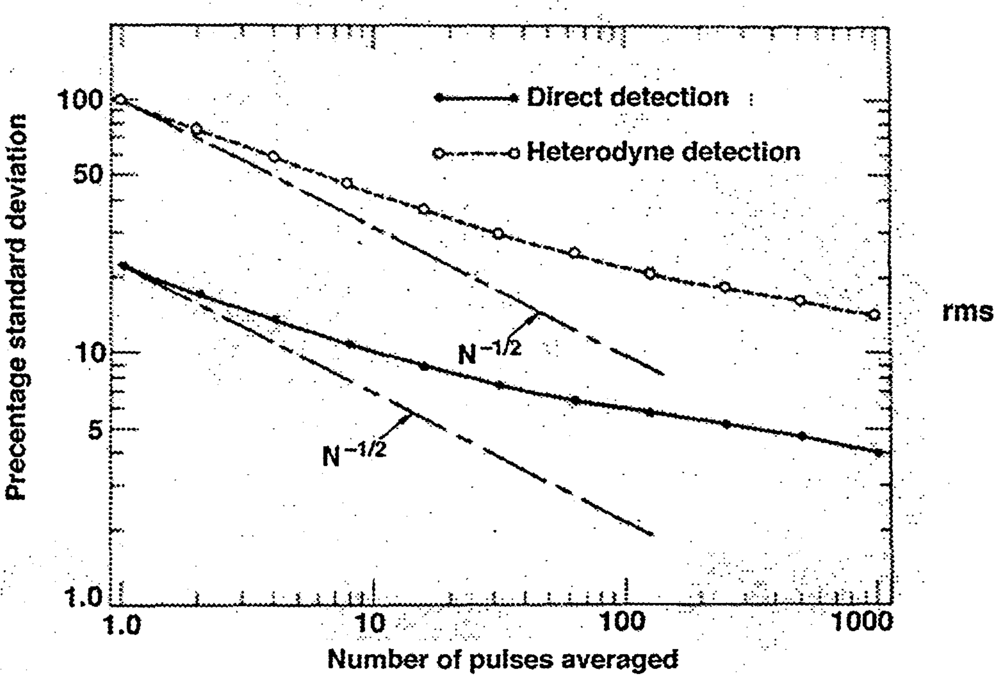

Figure 1. The dependence of r.m.s. of sample averages on sample size N, from Killinger *et al.*[5]

On the other hand, several other papers[9-13] have found that their datasets do average to give variances that decrease as 1/N. In all but one case,[13] the signal returns are from atmospheric (molecular and aerosol) backscatter; in the one exception,[13] the maximum value of N is only 25, so the generality of the result is unclear. One appealing explanation for the differences between the results of these papers and the papers in which variances do not scale as 1/N is provided in Reference 12: "The problems of speckle for hard-target backscatter are to be contrasted with the case for atmospheric backscatter; it has been shown experimentally that the aerosol decorrelation time in the 9-11 μm spectral region is 1-3 μs. Thus, for atmospheric backscatter, the speckle pattern at the receiver for each pulse can be assumed to be totally uncorrelated with those for the other lidar pulses. This independence from pulse to pulse is what allows atmospheric-backscattered signals to be averaged to reduce the standard deviation with an $N^{-1/2}$ dependence, and the lack of same is what inhibits it in the hard-target backscatter case." This interpretation is given additional weight by the fact that this reference found 1/N behavior of the signal variance for >1000 pulse returns.

It was this interpretation, if not this exact quote, that motivated the speckle noise experiments we performed at Site 300 (Section IV, below). The rapid decorrelation of the speckle patterns from aerosol backscattering can also occur from a hard target if the aspect angle of the target is changed between pulses enough to give an independent speckle pattern. A "rotating" target, therefore, should provide speckle noise returns that average as well as aerosol returns. Irrespective of what the atmosphere might be doing, if the speckle pattern returned from a hard target on each pulse is forced to be statistically independent of the other patterns returned on all other pulses, there should be no pulse-to-pulse correlation, and the 1/N behavior of signal variance should be recovered. This conclusion explicitly assumes that the pulse-to-pulse correlations found in References 1-8 were produced by the fixed positioning of the laser, hard target, and receiver; *i.e.*, by a returned speckle pattern that, in the absence of atmospheric turbulence, would be fixed (and hence perfectly correlated).

Results (also described in Section IV) were not as we expected.

II. Speckle noise

DIAL measurements of the concentration of some molecular species in the atmosphere rely on the difference in absorption between laser light at two (or more) slightly different wavelengths. The total path integral of the concentration is proportional to the logarithm of the ratio of the power or energy returned at the two wavelengths. The accuracy with which the concentration path integral can be determined depends on the noise level of the return signals, and on how the signals average.

When DIAL measurements are made by detecting laser light returned by backscatter from a diffusely-scattering hard target, the returned light is broken up spatially into a classical speckle pattern, in which dark and light cells appear randomly across the receiver aperture. The precise amount of light that enters the aperture depends on the details of that random speckle pattern, and has a well-known statistical distribution[14] (over an ensemble of targets with the same average reflectivity but a different set of scatterers) that depends on wavelength, target distance, target spot diameter, and receiver aperture, but is very nearly independent of the details of the surface scattering as long as the surface is rough on the scale of a wavelength.

For fixed laser, target, and receiver geometry, and in the absence of atmospheric effects, the speckle pattern at each of the two DIAL wavelengths would be fixed. The light entering the aperture would be displaced from its ensemble average (the value of interest for concentration determination) by a random value with a variance roughly proportional to 1/M, where M is the number of speckle cells across the receiver aperture. This random displacement would represent a systematic (but very geometry specific) error in the received powers. This random but fixed error is what is meant by the *"Target-Induced... Speckle"* of the title.

The atmosphere turns the systematic error into noise. Turbulence in the atmosphere, with the accompanying fluctuations of index of refraction on a wide range of spatial scales, modulates the speckle patterns both by moving the target spot around and by changing the relative phase relations among the scatterers in the target. The resulting modulation appears as noise in the return signal on timescales greater than a characteristic atmospheric time scale of a few (~5-20) ms. The varying speckle pattern at the receiver produces a random offset from the ensemble average that fluctuates from pulse to pulse. In principle, the only significant difference between the resulting speckle noise and instrument or shot noise is that the magnitude of speckle noise is directly proportional to the magnitude of the return signal. Assuming that atmospheric turbulence is strong enough to completely change the speckle pattern from pulse to pulse, the relative variance of the speckle noise is approximately the 1/M of the previous paragraph.

III. Signal averaging

To examine the statistics of signal averaging, it is useful to start with a very large set N of data points, say N = 20,000. This large data set can be broken up into L smaller sets, each of N' points: *e.g.*, 2 sets of 10,000 points, 3 sets of 6,666 points, 4 sets of 5000 points, ... to 5,000 sets of 4 points each. Each subset of N' points has its own mean, which would correspond to averaging the data collected in N' pulses. For each value of N', there are L means, which are L random variables that have a variance dependent on N'. If the random process producing the data points is stationary, and the pulse-to-pulse noise is uncorrelated, the variance will decrease approximately as 1/N'; the larger the number of points averaged, the smaller is the variance of multiple averages of the same size data sets. For data values x_i, i=1..N, the L averages are

$$\overline{x_j} = \frac{1}{N'} \sum_{i=(j-1)N'+1}^{i=jN'} x_i \qquad j = 1..L \ . \tag{1}$$

The sample variance of the L means is

$$\mathrm{var}(\bar{x}) = \frac{1}{L-1} \sum_{j=1}^{j=L} \left(\bar{x}_j - \langle \bar{x} \rangle \right)^2 , \tag{2}$$

where $\langle \bar{x} \rangle$ is the average of the L means. The sample variance should decrease as 1/N', if the noise is stationary and uncorrelated. The variance in Equation (2) can conveniently be referred to as the variance of the sample averages, or VSA.[15] It is the square root of the VSA (hence the rms of the sample averages, referred to below as the RSA) of the data of Reference 5 that is plotted in Figure 1.

IV. The Site 300 Speckle Experiment

As discussed in Section II, the departures from 1/N' behavior of the VSA for hard-target DIAL signal returns prompted us to put together an experiment to examine the usefulness of a rotating target in decorrelating the speckle returns. The experiment was put together in a pre-existing trailer operated by LLNL's Remote Sensing Group, led by Dennis Slaughter. Laser availability limited operation to 1.064 µm and 532 nm (Nd:YAG fundamental and second harmonic), and to a single wavelength for each set of data. A diffusely-reflecting target (Macor or cardboard) was placed 500 m from the trailer, and illuminated with the Nd:YAG laser operating at 10 Hz. Both the return light and a fraction of the outgoing light were boxcar-integrated over the pulse; the value for the returned pulse energy was then normalized to the outgoing pulse energy by dividing by the measured fraction of the latter. Data was acquired in datasets of about 20,000 pulses at both 1.064 µm and 532 nm, and with either a fixed or "rotating" target.

The "rotating" target actually comprised a diffusely-reflecting target mounted on a stand that could be tilted around two orthogonal axes. The tilting was done in steps of 0.5 milliradians, an angle sufficient to move the returned speckle pattern completely across the receiver telescope aperture; stepping was done after each laser pulse, so that each pulse would provide a statistically independent speckle return. The tilting was done in a square pattern, starting at 6° in both horizontal and vertical away from the target normal, then proceeding horizontally for 150 steps of 0.5 milliradians, moving up 0.5 milliradians vertically, moving back 150 steps horizontally, and so on until the full data set of 20,000 points was acquired.

Figure 2 shows a plot of the normalized returns for a representative 1000-point subset of a 20,000-point dataset taken with a fixed target at 532 nm. The noise in the data is mostly speckle noise, as de-

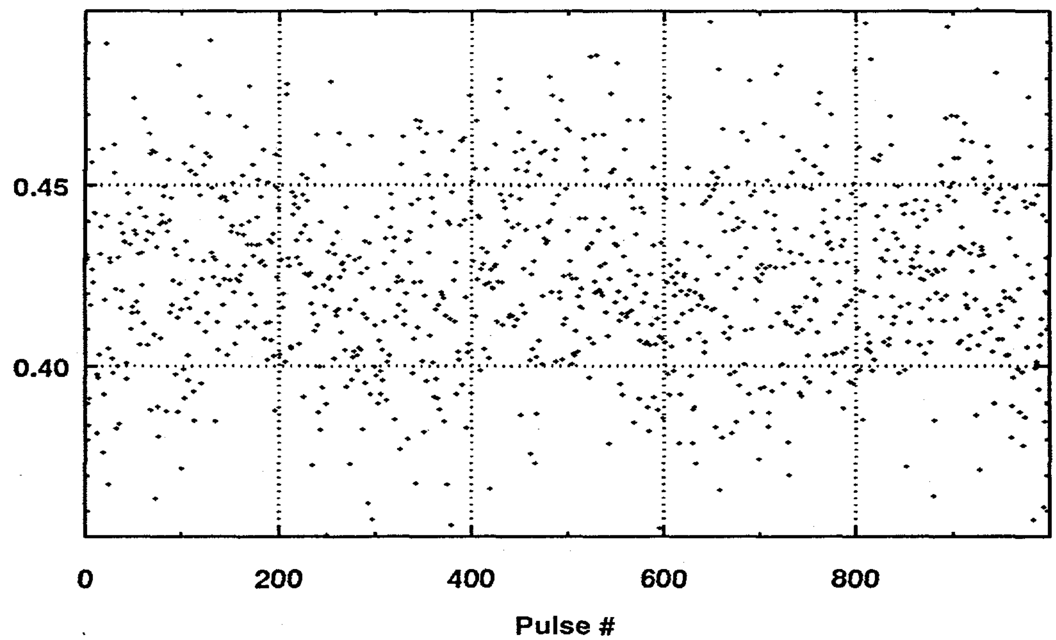

Figure 2. The normalized returns for a representative 1000-point subset of a 20,000-point dataset taken with a fixed target at 532 nm.

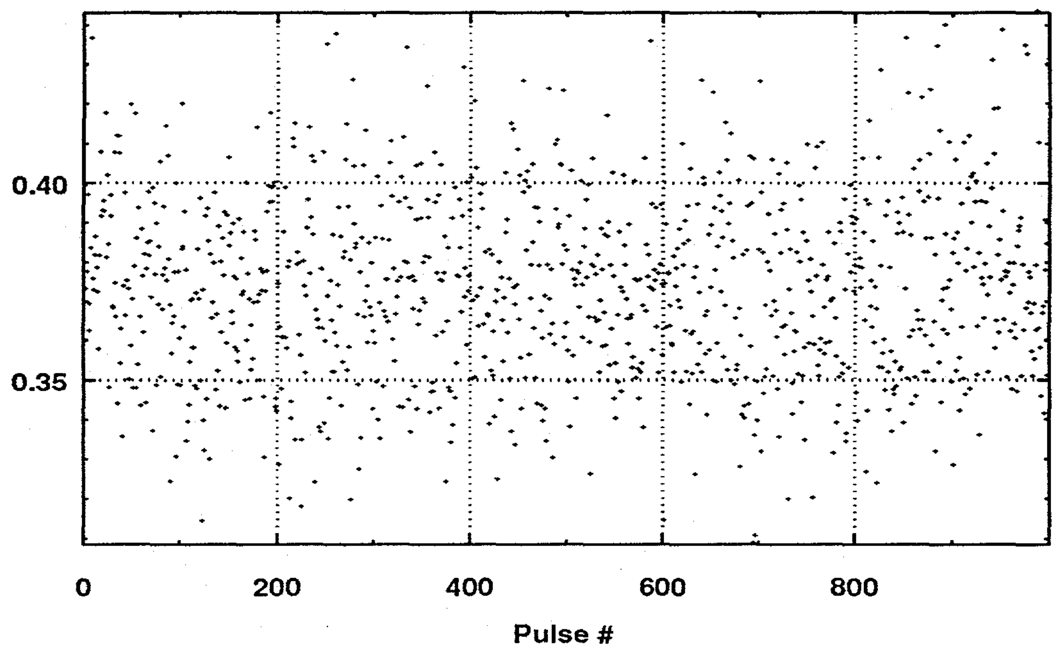

Figure 3. The same as Figure 2, but for a rotating target and at 1.064 μm.

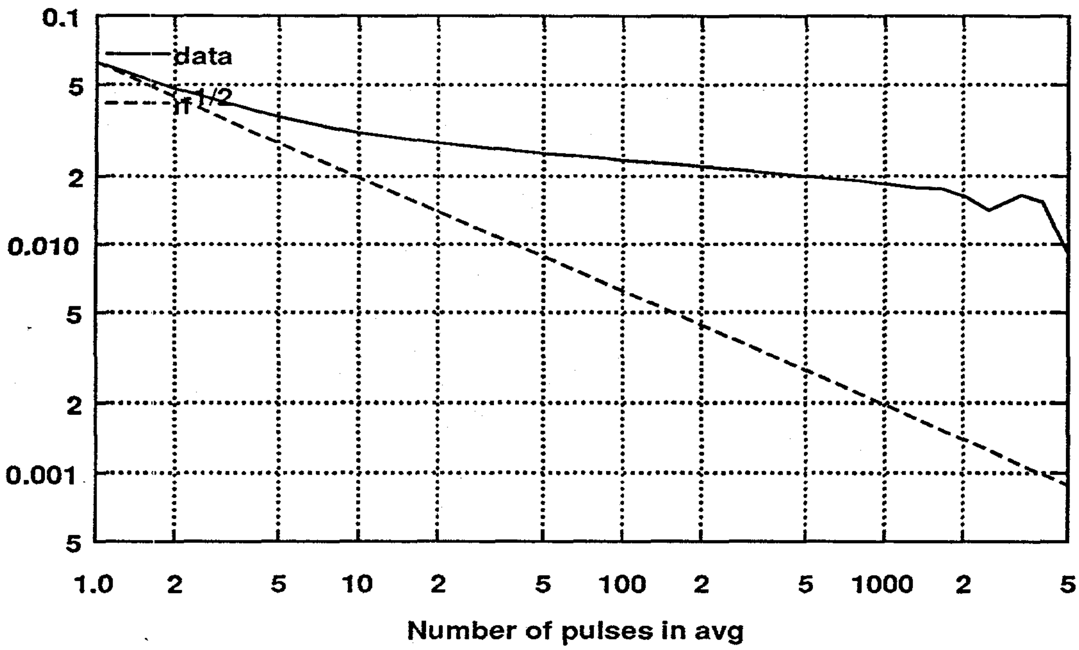

Figure 4. The relative RSA for the full dataset of Figure 2, vs. sample size N'.

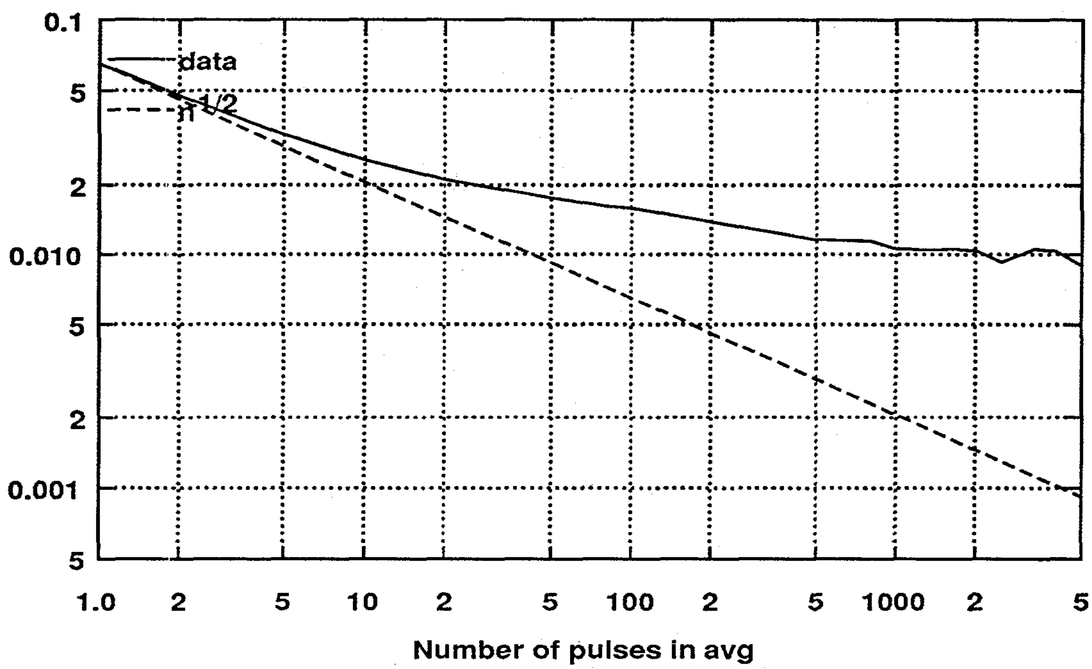

Figure 5. The relative RSA for the full dataset of Figure 3, vs. sample size N'.

scribed in Section II (instrumental and shot noise are below 1%). Figure 3 shows another 1000-point subset, taken this time at 1 μm with a rotating target.

Figures 4 and 5 plot the relative RSA of both datasets vs. the N' of Equation (1). It is immediately apparent that the RSA is not decreasing as $1/\sqrt{N'}$ but is instead decreasing only slightly to an apparent limit of several percent. This behavior is essentially identical to that of the experiments on diffuse-target DIAL returns referenced above.

It is also immediately apparent from Figures 4 and 5 that the departure from 1/N' behavior of the VSA is not improved for the rotating target. The reason is evident from Figure 6, which plots the values of the averages of Equation (1) for L = 100, N' = 200 for the rotating target at 1.064 μm. Plotting these averages shows that there are long-term (~1 min.) drifts in the data that will prevent a reduction of VSA below approximately the square of the relative amplitude of the drifts. These drifts could be caused by drifts in the electronics (the systems that monitor outgoing light and return light use the same photomultiplier tube but separate boxcar integrators and A/D converters) or by changes in atmospheric absorption (*e.g.*, due to puffs of haze drifting across the beam path during a run); the precise origin has not been determined.

The long-term drifts are of course a form of pulse-to-pulse correlation, and their effect on the scaling of the VSA can be treated by the same techniques used in Reference 8. However, the interpretation as instrumental drifts or atmospheric absorption variations raises the possibility that the drifts can be corrected in the data analysis stage. For example, in a two-line DIAL system, if the background absorption and electronics drifts for the two wavelengths are identical, the drifts may be removable by taking the ratio of the normalized return powers, or better yet (to get a closer approximation to an unbiased estimator of absorption), taking the logarithm of that ratio.

With the single wavelength available in the Site 300 data, we can check this suggestion only crudely. Figure 7 illustrates that after taking the log-ratio of the data (*i.e.*, converting the data to N/2 values given by $D_i = \ln[E_{2i-1}/E_{2i}]$, i = 1..N/2, where E_n is the normalized energy returned in the n^{th} pulse) any visible drift has been removed; this figure is the analog of Figure 6, with L = 100 averages of N' = 100 points plotted. Figures 8 and 9 show the results of first, taking the log-ratio of the data, and second, plotting the RSA from the new values. The last two figures show a clear $1/\sqrt{N'}$ reduction of RSA for the D_i out to the useful limits of the data set, *i.e.*, N' ≈ 2000. The drifts of the set of odd points coincide with the drifts of the set of even points and taking their log-ratio removes the effect of the drifts on signal averaging.

V. Conclusions

Our conclusion from the result of Figures 8 and 9 is twofold: (a) all sources of relative drift among the return power at all wavelengths in a multiple-line DIAL system must be controlled to better than the required averaging accuracy, and (b) if this is done, the log-ratios of the return data in wavelength pairs may average with a 1/N' reduction in VSA even for large datasets. The first of the conclusions is obvious, even without knowledge of the data presented here. The second part is by no means obvious, and may be an unwarranted extrapolation of the Site 300 results. That part of our conclusion will be testable when a two-line DIAL system is fielded at Site 300 in the summer of this year (1994).

Similar conclusions about the origin of the correlations in the data of References 1-8 and about the importance of ensuring identical drifts at all wavelengths were reached by the authors of Reference 13.

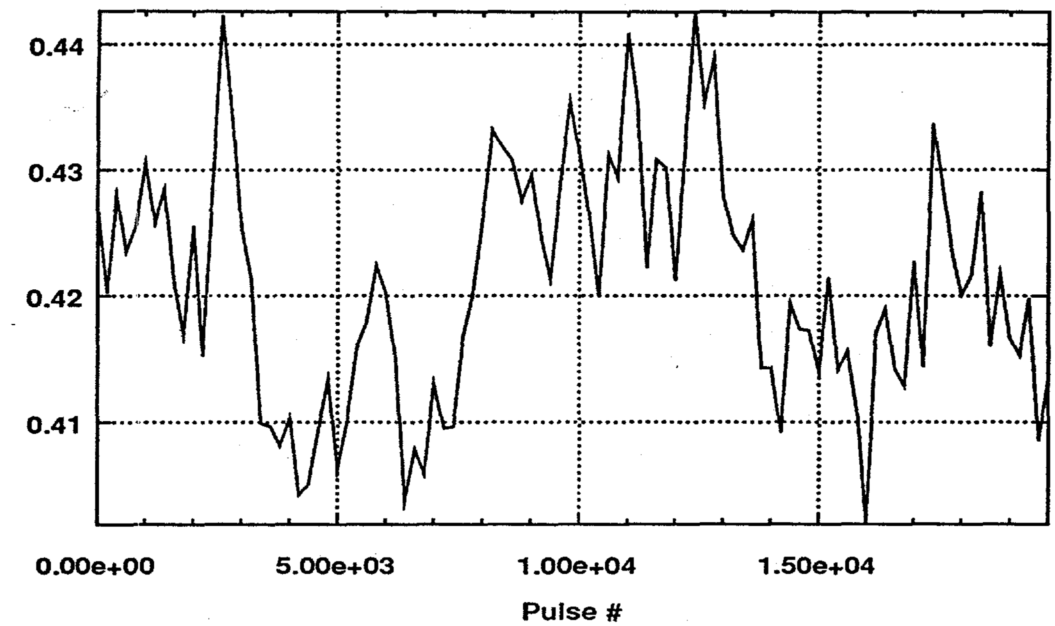

Figure 6. The sample averages for N'=200, for the full dataset of Figure 2.

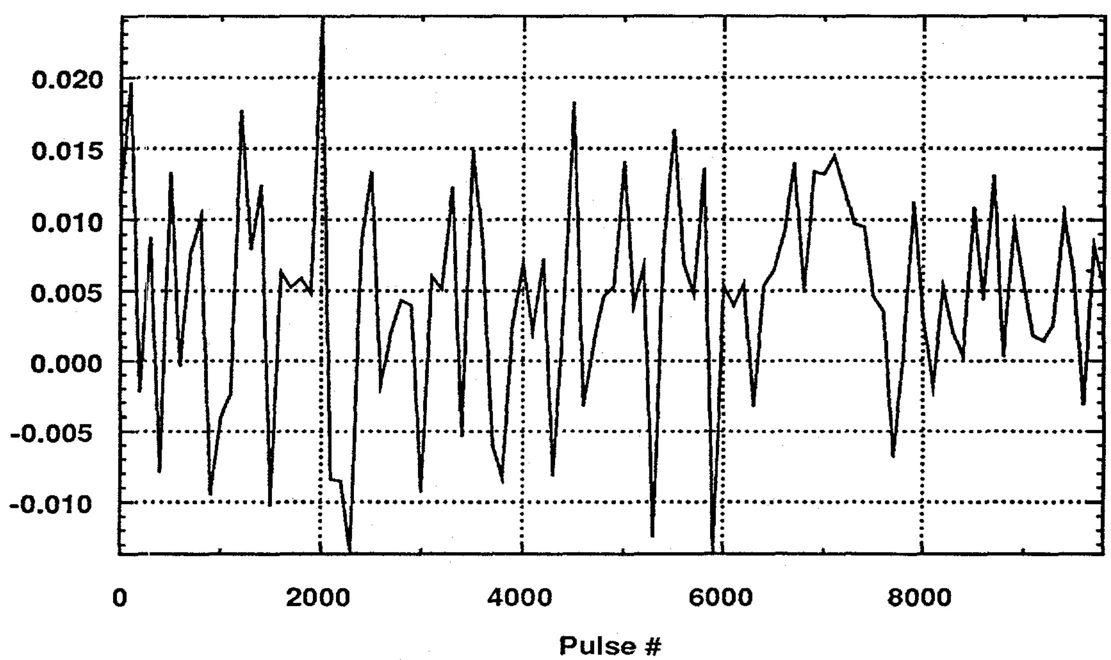

Figure 7. Sample averages for N'=200 for the log-ratio of alternate data points from the dataset of Figure 2.

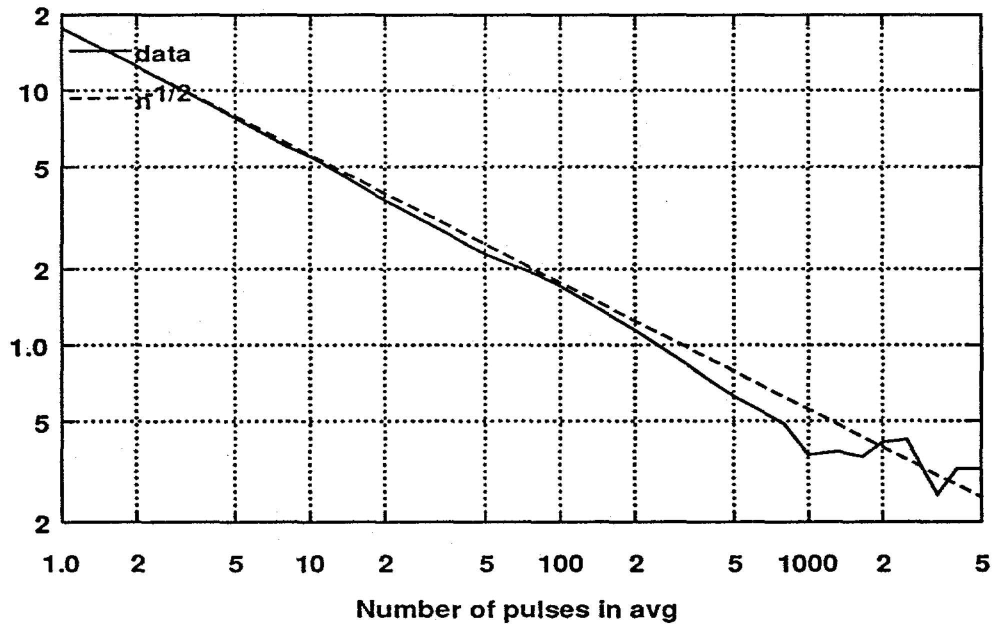

Figure 8. The relative RSA for the log-ratio of alternate points in the full dataset of Figure 2 (fixed target, 532 nm).

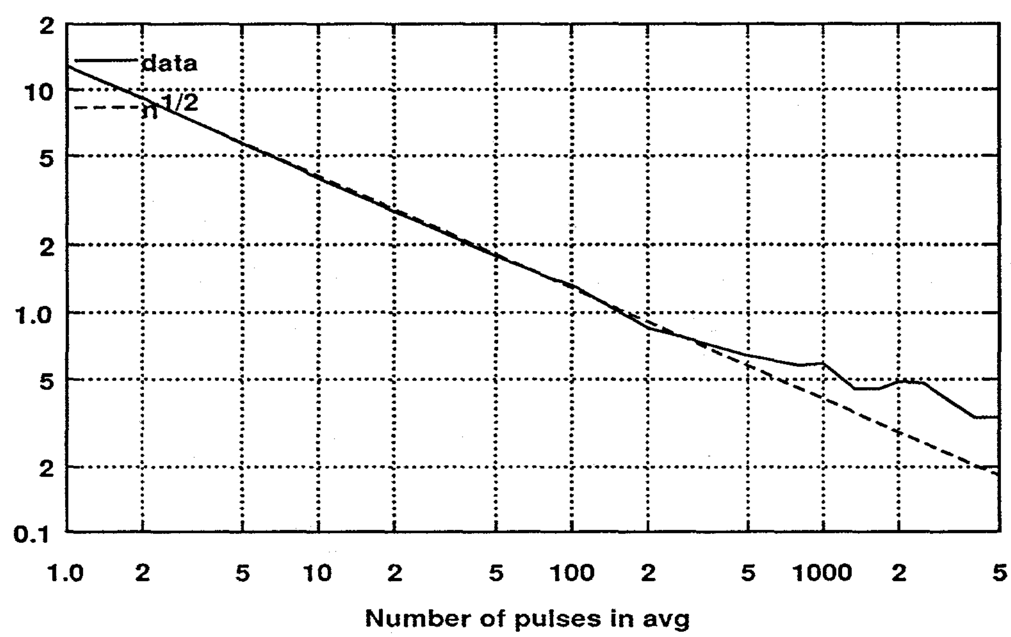

Figure 9. The relative RSA for the log-ratio of alternate points in the full dataset of Figure 3 (rotating target, 1.064 μm).

In the light of the Site 300 data, we also conclude that the idea of using a rotating target to decorrelate the speckle patterns on each pulse was inspired by our misunderstanding of the "correlation" of pulse-to-pulse speckle patterns hypothesized in Section I. This pulse-to-pulse correlation in fact would introduce a systematic error in the averaging – that is, an offset of the final averaged result from a true ensemble average (over an ensemble of diffuse targets) – but would not affect the behavior of the VSA as the number of data points increases. The VSA would still be expected to decrease as 1/N', but the sample averages would approach a value biased from the mean.

Finally, it is interesting to note that the 1/N reduction of the VSA observed in Reference 12, the reference that motivated the "rotating" target for our Site 300 speckle experiments, was actually for the *ratio* of pulse returns at two separate wavelengths of a CO_2 laser.

Acknowledgment

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