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Interpretation of OTF Scatter Loss Scans

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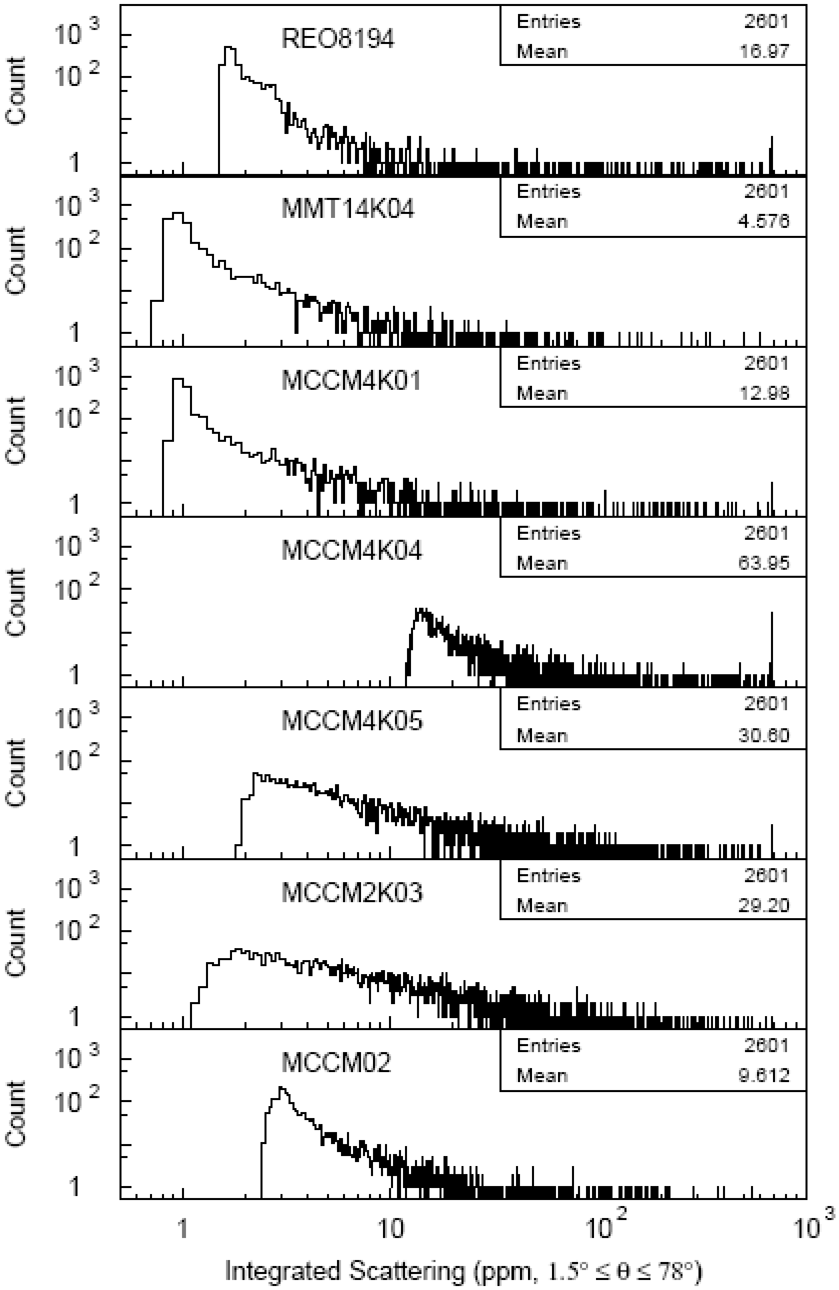
INTRODUCTION

By now (end 2007) a great amount of data has been collected in the Caltech OTF on beam scatter from HR coated optical surfaces. The quality of the apparatus has improved to the point where scans of small surface patches (~1 cm^2) give reliably calibrated (relative to a reference scattering surface), reproducible and high sensitivity (fractional ppm loss from the probe beam) 2D maps of HR surface "loss". False color map representations of these scans, as well as quantitative histograms of their content have been widely distributed and discussed (figure 1, for example).



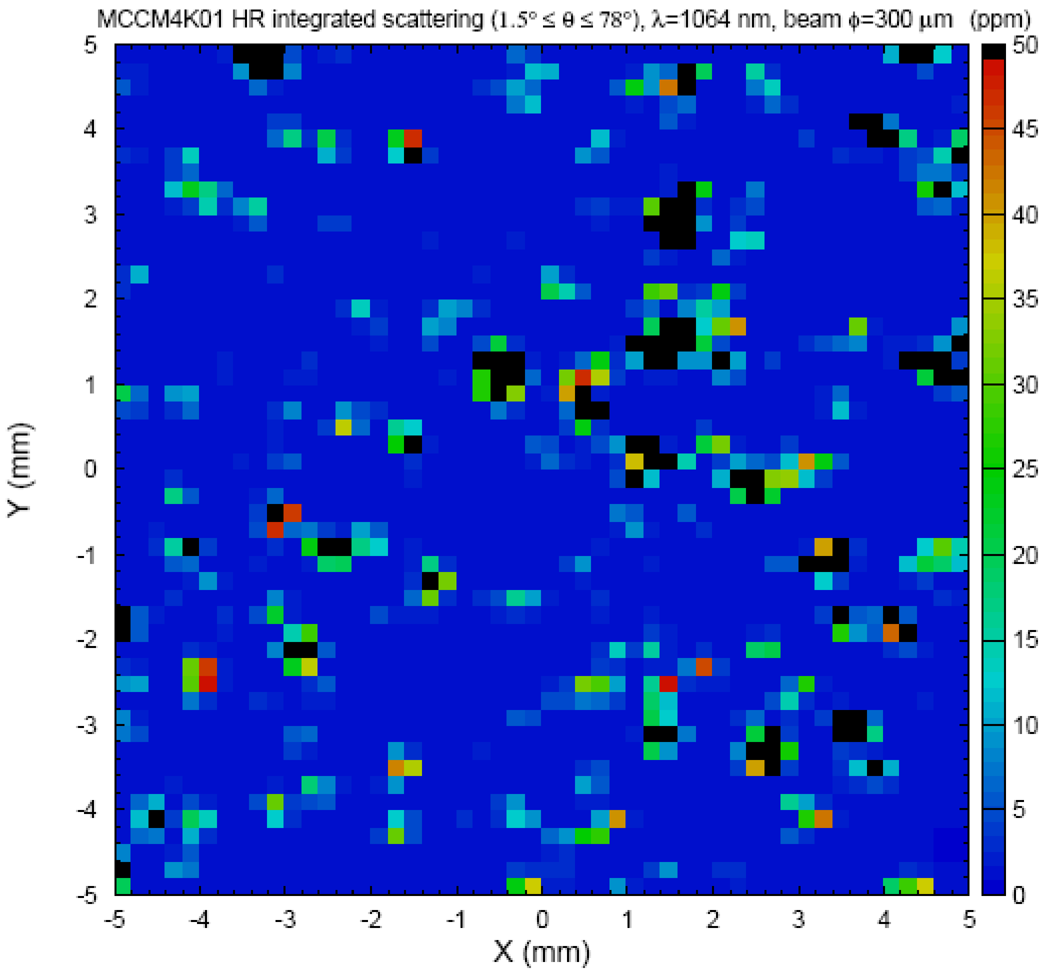
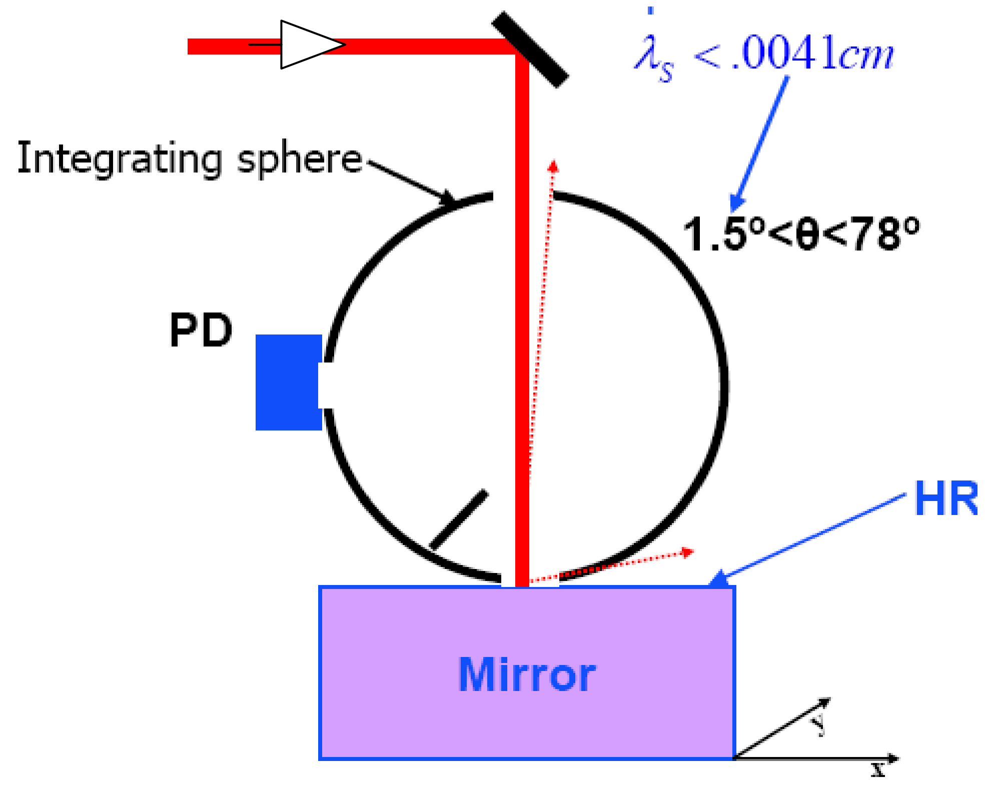


Figure 1. Recent (with improved RTS optical configuration, post 9/2007) OTF scatter loss scan results on small, sample HR mirrors. Calibration (ppm) is "naïve" method described in text. False color map of one scan is displayed.

However there has been no comprehensive interpretation of what these data imply for full scale (~6.0cm Gaussian radius beams on ~17cm radius HR surfaces) Advanced LIGO arm cavity losses. In this note these scan measurements, their calibration and their interpretation in terms of Advanced LIGO loss is discussed in detail. We also comment on some other related methods of determining loss, for comparison.

Description of the Scan measurements.

The apparatus (named "RTS") used to generate the scans of Figure 1 is schematisized in Figure 2.   The Mirror is scanned in 0.2mm c-c **xy** step pattern (for the data format of Figure 1) covering ~1cm^2 of the HR surface. The probe beam (1064 nm, matching the HR stack design center wavelength) is focused to approximately match this surface step pixel size (~0.1 mm Gaussian radius). An efficient IS (Labsphere "Modular Integrating Sphere" 4P-GPS-033-SL which, in this configuration, actually has substantial cavity gain) is used to capture a wide angular range of back scattered light. The design of the IS is such, and we assume, that back scattered light over the entire range of IS acceptance angles is uniformly sampled by the PD, so that the PD signal is accurately proportional to the backscatter loss to the angular range 1.5 – 78°.

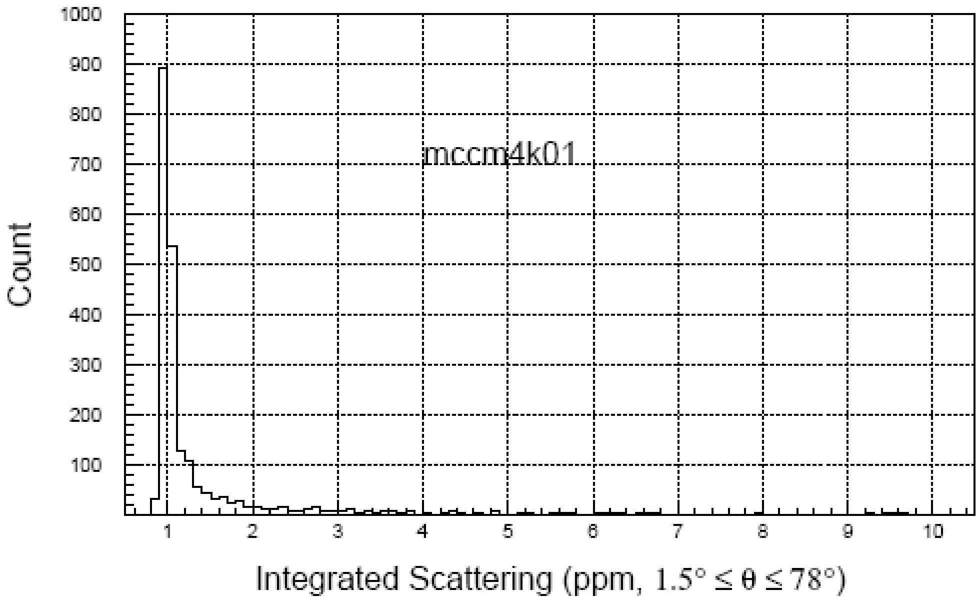


TIS: collimated beam, Dia.~.25 mm, modest spatial resolution, more collected scattering light.

Typically presented data (e.g. Figure 1) is “calibrated” as ppm of probe beam loss. It is crucial for interpretation to appreciate precisely what this means. The “calibration” procedure consists of substituting a sheet of SPECTRALON diffusing material at the same position as the scanned HR mirror surfaces. This material has the property of scattering back ~0.99 of 1064nm incident light in a completely diffuse (Lambertian) distribution. Since typically scanned mirrors backscatter no more than ~100 ppm of incident light, a probe beam attenuator must be introduced so that the calibration signal is not saturating. The “calibration” then consists merely of dividing the PD value (for any given scan pixel reading) for a mirror under test by the PD value measured with SPECTRALON substituted times this necessary probe beam attenuation factor. Therefore this “calibration” only accurately yields total beam loss if the BRDF angular dependence of the tested mirror were to be also Lambertian (BRDF ~ Cos[Θ]). Evidently such a calibration introduces a strong bias for the type of very smooth HR surfaces we are interested in where the BRDF is fractal like ($\sim\Theta^{-2}$).

Detailed interpretation

For example we study the MCCM4K01 scan and replot the histogram of figure 1:



This accentuates the fact that the pixilated surface actually consists of two location types. First there are a predominant number of minimally scattering locations with nearly the same sampled scatter loss. In this scan ~76% of the scanned area has IS sampled scatter within 1.1 +/-0.2 ppm, with the distribution FWHM being more like 0.15 ppm. This then leaves a sporadic tail consisting of 24% of the pixels scanned. This tail, however, accounts for 94% of the apparent mean scattered light.

We propose the following model of this type surface. The sporadic tail of the distribution is assumed to be due to “point” scatterers who’s BRDF, in the mean, is isotropic. Of course the exact nature of these scattering centers/defects is undetermined. Indeed there are probably several different types (surface dust, coating defects, substrate surface defects, etc.) and a wide range of sizes. The important point, and what is assumed, is that, in the mean, the scatter from these defect locations is isotropic and thus fairly sampled by the IS. That is, the naïve instrumental “calibrated” pixel reading is an accurate measure of net beam scatter loss. For the example scan (mccm4k01) this indicates that the true mean surface loss (e.g. what an impinging beam far wider than the scanned area would suffer) due to such “point” scatterers is ~12 ppm.

These “point” defects are then randomly superimposed on a perturbative (i.e. phase disturbance of the impinging wavefront << π) “micro-roughness” background[1]. For extraordinarily clean surfaces (mccm4k01 being an example) most pixels are “point” defect free and scatter according to this micro-roughness perturbation. For the probe beam size, D_{probe} still $>>\lambda_0$, and the large IS collection solid angle ($>> [\lambda_0/D_{probe}]^2$) of these experiments it may be shown that the statistical fluctuation in pure micro-roughness scattered light is negligible [1]. That is, the expected scan distribution from a similar surface but without the "point" defects would be ~ single bin representing the mean micro-roughness scatter loss. This is our interpretation of the sharp threshold spike in the actual distribution. However the naïve instrumental calibration cannot be directly applied to it. This is quantitatively illustrated in Figure 3 which plots wide beam scatter loss integrated from $\lambda_{surface} \sim \lambda_0$ (corresponding to $\Theta \sim 90^0$) through any arbitrary $\lambda_{surface}$ (corresponding to $\sin\Theta = \lambda_0 / \lambda_{surface}$) for surfaces

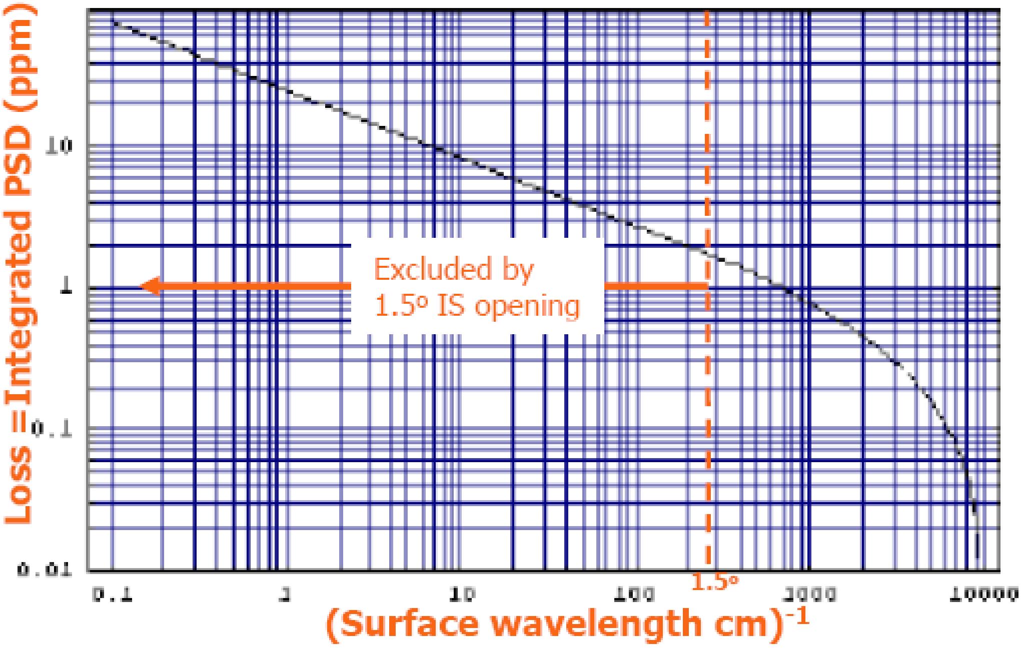


Figure 3. Estimated scatter loss for coherent beam (width > $\lambda_{surface}$) impinging on mirror with surface PSD= derivative of this curve, using best fit to CSIRO polish data PSD [3]. Angles $\sin\Theta > \lambda_0 / \lambda_{surface}$ are included in Loss($\lambda_{surface}$).

with micro-roughness known to be of approximately the same spectrum as the scanned mirrors in Figure 1. For a wide, LIGO sized, beam most of the light scattered (and lost) will be to angles < 1.5^0. From Figure 3 we estimate (the long $\lambda_{surface}$ cutoff is a delicate choice depending on beam radius, finite mirror diameter, and beam shape) that only ~5% of the scatter loss is collected by an IS opening > 1.5^0[5]. This means that the micro-roughness peak in the example (mccm4k01) must be interpreted as a mean loss >~20x higher, or ~22 ppm for Advanced LIGO application. Combined with the additional "point" scatter component, mirrors of this quality would have net scatter loss of ~34 ppm in Advance LIGO arm cavity service.

Although it is a considerable extrapolation to claim that at least ~95% of the scattered light in our OTF RTS scans is missed by the IS detection, it is clear that *some* substantial fraction is. Ideally such scans would employ a probe beam diameter "matched" to the IS opening angle. By "match" is meant that $D_{probe} < \lambda_0$

/SinΘ. For the current experiments of figure 2, $1/D_{probe}$ ~ 50/cm still allows more than half the probe beam scatter to the escape the IS opening cutoff (247/cm).

One set of experiments has been performed where D_{probe} is naturally "matched" to the loss measured. The situation has to do with table top (~ 50 cm long) contamination cavities whose net dissipation (loss) is determined while they are locked, in-vacua [2]. In this case D_{probe} ~ 500 μm, close to that of the probe used for the scans of figure 1. In these experiments *minimum* loss per cavity mirror of 4-5 ppm was found. It must be emphasized that the systematics pertaining to this contamination cavity loss are much different. No sampling scan of the mirror surface is performed, so that no meaningful *average* loss (for the D_{probe} involved) can be determined. One has to presume that this *minimum* contamination cavity loss corresponds to the scan probe pixel patches of the *peak* in figure 2, in which case the agreement is quite good.

General conclusions

The lowest loss surfaces (figure 1) also appear to have a well defined background level which may be associated with intrinsic micro-roughness scatter. For these cases our re-interpretation of the data changes the balance of mean scatter loss for large area [~LIGO] beams from "point" defect dominated to micro-roughness dominated. For overall lossier surfaces (e.g. MCCM4K04, MCCM4K05, and MCCM2K03 in figure 1), a true background level or threshold is not so perceptible. In such cases the density of high scattering pixels is such that no background level is topographically obvious (as in the false color scan of figure 1). That is, there may be a "point" defect scatter contribution to every scan pixel, with the true micro-roughness background unresolved. The sharpness of the histogrammed scatter threshold, say in MCCM4K05 and MCCM2k03 is the best indication that this level represents the true intrinsic micro-roughness. Interpreting in this way and still using the extrapolation to Advanced LIGO loss of figure 3, the wide beam loss of MCCM4K05 and MCCM2K03 would be ~78 and ~57ppm, respectively. On the other hand this same threshold level identification of micro-roughness would give an interpreted loss of ~350 ppm for MCCM4K04.

Previously, several actual LIGO I HR TM mirrors have been RTS scanned (although the setup was not as refined; the measurements as reproducible; and calibration as accurate) [2]. The data (calibrated histograms) from those scans were quite similar (pronounced threshold "background" peaks with long "point" tails) with mean, naïve IS calibrated loss in the range ~8-30 ppm. Re-interpreted according to the analysis of the last section, these would represent LIGO arm cavity mirror losses of ~36- 200 ppm which are consistent with per mirror scatter loss determined by various in situ measurements of LIGO arm cavity scatter/loss[5].

REFERENCES:

1. *Isotropy and the Relation of One and Two dimensional Surface roughness,* LIGO-T070310-00-D

2. L. Zhang LIGO G-080162-00-D, and LIGO-G070423-00.

3. C. Walsh, A. Leistner, and B. Oreb, Appl. Opt. **38**, 4790 (1999).

4. The integrated PSD plotted in Figure 3 does not take into account a factor “D” ~ 1.2 correction described in LIGO-070082-03-E. However only *fractional* losses are used in the argument discussed here.

5. LIGO-T070051-00-D