LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Initial LIGO COC Loss investigation Summary

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INTRODUCTION

Starting in ~2001 The Hanford H1 interferometer was locking stably enough to begin inferring the losses of its component HR surfaces from overall performance. In situ observations used here include ones dating back to this epoch. Other data (COC pathfinder and fabrication certification data, e.g. compiled in LIGO-T980065) dating even earlier are also used in comparison. Finally a "new" (dating from ~ 2004, and resurrected from the long dormant facility described in LIGO-P990029-00) program of OTF ("Optical Test Facility" located in the sub-basement of the Caltech W. Bridge building) measurements on LIGO I associated optics (spare TMs, a couple of TMs removed from interferometers, and various similarly polished and coated samples) have been ongoing. Goals have been 1. to characterize specific anomalously behaving optics, and 2. to elucidate the specific mechanism(s) for the losses inferred from the in situ observations.

The basic conclusions from the initial in situ H1 studies (epoch '01-'03), that the HR surfaces have far higher scatter loss than anticipated consistent with observed H1 recycling gain, has been re-analyzed several times but not substantially changed. These observations have been reviewed in presentations: NSF review of 11/03; Optics Summit talks (L. Zhang, and LIGO-G060586-00); commissioning meeting slide presentations of 12/23/02 and 6/23/03; and all original data contained in LHO ilog entries.

Two broad categories of "loss" will be distinguished: scatter (which dominates the net arm cavity loss) and absorption (which, through its heating affects, dominates beam propagation/coupling changes). Historically these arouse as distinct problems in interferometer commissioning and operation. They were studied in different epochs with different methods. In the OTF, different experiments were brought to bear. Particular distinct emphasis was placed on investigation of the HR absorption of 4ITM07 (H1 X arm ITM removed in June 2005. During the same access its similarly contaminated Y arm sister and nearby BS were cleaned and remained in situ). The results of these absorption studies have been widely discussed and previously summarized, see LIGO-G060040.

1. Absorption in HR surfaces

Clean, high quality HR coatings of the type employed in LIGO I (all applied by REO) were previously known to absorb less than 1 ppm at 1064nm (a key reason for choosing this wavelength for LIGO). This has routinely been confirmed by direct measurement of 1" diameter "sample" HR coated mirrors assembled as cavities in vacuum in the OTF (described in LIGO-P990020-00, and T980003-00). Individual examples of < 0.5 ppm coating absorption have been observed. This work has a long history at LIGO (A. Abromovici, et al, Appl. Opt. **34**, 183, 1995). Site interferometer absorption of anywhere near this low level constitutes a small fraction of total cavity loss, so that in situ absorption can only be inferred from its thermal modification of the interferometer gross optical properties (see LIGO-T050074-01, and T050178-00).

The existing RTS optic scanning platform in the OTF (which operates in ambient air, described in LIGO-P990020) was adapted for crossed beam absorption measurement (whereby the thermal lens produced by optic material absorption of a chopped, high power 1064nm pump beam is probed, at its focus, by an intersecting HeNe monitor beam) of full TM size optical material in early 2004. The basic technique had been well established (e.g. A.C. Boccara, et al J. de Phys. IV, C7-631 or E. Welsch and D. Ristau Appl. Opt. **34**, 7239) The optic can be incrementally positioned by the platform, so that a pixelated, 2D map of absorption may be obtained (LIGO-G060040). Initially this capability was developed for coarse resolution studies of Sapphire bulk absorption (successful results of which were incorporated in the decision process leading to abandoning Sapphire as a TM material for AdLIGO, see LIGO-G030035-01-D). With the identification of anomalous HR coating absorption in the H1 ITMs (LIGO-T050074-01), this setup was modified (higher pump power with tighter focus) to study coating absorption.

One H1 ITM (4kITM07) was removed in June 2005 and subjected to extensive analysis in the OTF (and by other means). A standard RTS absorption scan consisted of a 1cm^2 surface patch dissected into 100^2 uniform grid of measurements. Pump focus to ~0.15 mm diameter was achieved, well matching the pixel size. Since the ITM surface is >300 cm^2 it was convenient to compare patches of untouched [contaminated] surface with ones which had been thoroughly cleaned. Untouched patches exhibited mean (over all 10^4 pixels) absorption of 13.3 ppm, in excellent agreement with the in situ heating inferred absorption. Cleaned patches had mean absorption of 1.2 ppm with a well defined distribution peak at ~0.7 ppm, consistent with typical other [uncontaminated] HR samples and TMs. This return to normal with cleaning is entirely consistent with the <2ppm absorption determined for the sister ITM which was cleaned and remained in H1. Calibration of the absorption was carefully established via identical scans of small HR mirrors whose absolute absorption could be determined via the OTF vacuum cavity procedure (LIGO-T980003).

The distribution of pixel absorption values for an untouched scan was revealing. The histogram showed two components. First, was a well defined low absorption peak (~1ppm, not much higher than the dominant peak for cleaned patches) comprising ~1/2 the pixels (< 2ppm). Second was a long featureless tail extending to ~500 ppm. Thus the contamination appeared not to be film like. In this vein scans were performed where, simultaneous to absorption, large angle (~45^o) pump beam scatter was measured. For pixels with high (tail component) absorption, the scatter level was highly (~0.5 properly normalized) correlated. Indeed the mean scatter value for untouched scans was ~10 times higher than for cleaned patch scans.

This last observation requires some comment. As we describe below (summary of TM HR scatter understanding) cleaned LIGO I TM HR surfaces appear to have a mean patch scan scatter loss of ~20-50 ppm (when the scatter is detected at a single large angle). This loss value is calibrated by comparison with a scan on small mirrors whose absolute *total* scatter loss can be determined via OTF vacuum cavity ring down. By this procedure, 4ITM07 was found to have a quite typical (~36 ppm) mean scatter loss on clean patches. But this implies that untouched patches have mean loss >300 ppm. Such high loss, if operative in the actual H1 arms, would limit the interferometer recycling gain to <15 (Fig. 1). To the best of my knowledge it was not observed (previous to the contaminated ITMs removal/cleaning) that the H1 recycling gain had sharply fallen off (from a nominal value 40-50). This puzzle can be explained two ways. First, the calibration of loss from scatter may be questionable (and indeed it has some weakness, see below). Second, these 4ITM07 absorption/scatter correlation scans were performed ~8 months after the TM was removed from H1 vacuum. The TM was subject to continual experimentation, mostly face up in an ordinary lab, not stored in some dust free environment. The “untouched” patches were literally not even dusted, so mean scattering from them could be completely dominated by accumulated dust. (before concluding, then, that OTF determined absorption itself might just be due to subsequent dust, note that initial absorption scans were performed much sooner (~weeks), and there is much evidence that “ordinary” lab accumulated dust does not significantly absorb).

Aside from the RTS scan approach, tests were performed to directly identify what this contaminating “stuff” was which could be easily cleaned off. Patches were swabbed off and the residue [chemically] analyzed. The result was that the surface seemed to be remarkably clean: residues were at the limit of the chemical procedure’s resolution. “Sticky” stampings were made and SEM scanned. Identifiable particulate density determined from this was very small (much smaller than would be inferred from the RTS scans if all high absorption were particulate). Unfortunately this technique has a limiting “particle” size it can “see” (distinguish from background). What was realized is that there is a distinct class of dust (~smoke) consistent with all the observations. Its particles are extremely small (< micron). Density is low (< 1 per RTS pixel). Absorption is high (~10%-100%). Thus it is elusive, yet not implausible. On the other hand each of the tests had loopholes: chemical analysis only identifies soluble species; the “stuff” may not “stick” to “sticky” stamp, etc.

2. Scatter [loss] in HR surfaces (*in situ*)

Most of the observations concerning scattering as it translates into TM HR loss predate discovery of the anomalous TM absorptive contamination described above. Therefore “loss” has usually been understood to sensibly mean *scatter* loss. Especially in the LIGO I regime where the scatter loss (per HR) appears to be > 60ppm, even the above anomalous absorption is not dominant. So, in this section we equate net loss with *scatte*r loss. The LIGO configuration and optics quality are in a regime (~ negligible ETM and AS port “transmission loss”, and minor AR “pick off loss”: or these regarded and included as net scatter loss) then, where G_R (interferometer recycling gain) depends, to a very good approximation, only on this scatter loss value. Two such values may be distinguished. First, the mean *arm cavity* scatter loss dominates G_R and the discussion here focuses on this. Second, a total *recycling cavity* specific loss (which includes AR reflections, AS port leakage, ITM bulk absorption) which will be regarded as a fixed lumped configuration parameter. This view of G_R dependence on mean scatter loss is displayed in figure 1 (LIGO I reflectivity parameters).

At the time (c 1995) of the LIGO I detailed design modeling, mean arm loss of up to ~200 ppm was considered possible, just allowing the SRD G_R >30. The actual COC, when fabricated, were measured to be far smoother than this worst anticipation, so that far lower mean loss and higher G_R were expected.

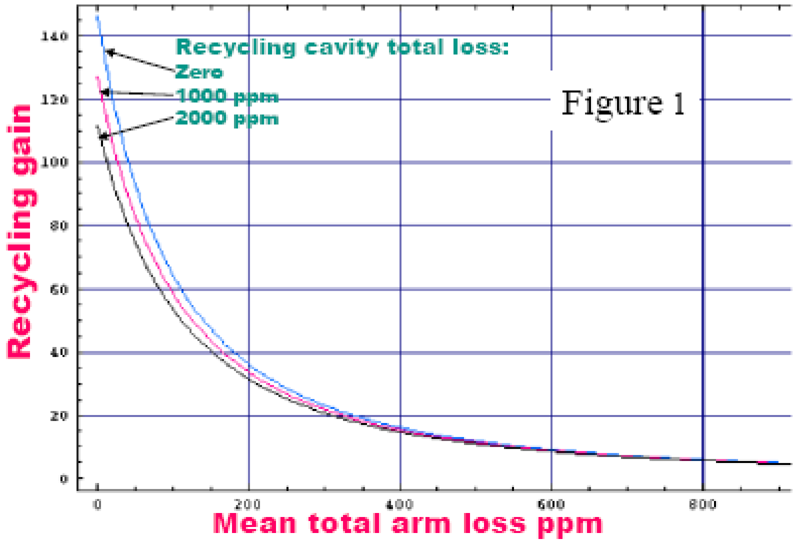


Figure 1

2.1 Visibility measurements

The earliest accurate, in situ, loss measurements were of single arm “visibilities” ($\boldsymbol{V}$, which we define here to be one minus the ratio of reflected to incident beam intensity from a well aligned locked arm cavity). Measurements were made on all four LHO arms from 2001 through late 2002. The technique is very robust, and is self calibrating in the sense that, nearly simultaneously and with the same setup, the known ITM reflectivity is measured (by misaligning the ETM). I consider this method of determining the mean loss to be the most certain.

In this epoch all four LHO arm visibilities were found to be the same within ~15%. Here, and in the sequel, we limit discussion to the H1 interferometer. The mean H1 $\boldsymbol{V}$=.0228. Total arm RT loss is then taken to be = $\boldsymbol{V}/G_A$ (where $\boldsymbol{V}$ is corrected, ~10%, for SB power content, and $G_A = 4/T_{ITM}$). This gives a mean H1 arm loss of 180 ppm (or 83 ppm intrinsic scatter per HR surface, allowing for ~14 ppm total cavity end transmission and absorption). Figure 1 indicates that this visibility loss should result in G_R= 37 (reasonably consistent, if not high compared to full H1 locking gains of this epoch).

Recently similar visibility measurements have been performed on the 40m interferometer arms. Remarkably close, ~175 ppm/arm total loss values have been determined. The 40m mirrors are of the same coating pedigree and are of smoother polish quality (“super-polish”) than the H1 mirrors (Also, see below, the smaller 40m beam diameter would be expected to significantly limit the surface scales contributing to scatter compared with LIGO cavity beams).

2.2 Recycling gain

Independent measurement of [H1] G_R may be used to determine mean loss (now averaged over 4 TM HRs, and allowing for RC loss). Since ~2003 full, interferometer lock has been routine and stable enough to determine intrinsic (loss dominated) G_R by directly measuring steady state arm stored beam power. Technically this is accomplished by measuring the ratio of arm stored light intensity with and without recycling (full lock vs single arm locked and RM misaligned). Unfortunately this is a rather delicate measurement since the ratio is ~2000 (the inferred G_R being the product of this and the RM transmission), and two distinct locks are utilized. The inferred G_R has varied from ~30 (during initial commissioning, pre-2003, which was probably degraded by poor interferometer alignment and stability) to 64 (late 2006). It appears reasonable to believe that GR ~45-50 is the correct physical value in the current (~ S5) epoch. Then Fig. 1 indicates that mean arm loss is ~130ppm (about 30% lower than that inferred from $\boldsymbol{V}$).

2.3 FFT simulations: excess loss.

It is important to distinguish components of the total mean loss determined in the last sections, since different components can be controlled by distinct aspects of the HR mirror fabrication. The "FFT" simulation (B. Bochner, thesis, MIT, 1998) allows many loss components (ETM and AS transmission, modal "scatter" due to mirror aberrations) to be exactly modeled. It then allows for a, lumped, "excess" loss for each optic surface. This excess loss may then be adjusted such that the net simulated G_R agrees with observation. Of course the simulation is "normalized" such that it agrees with Fig. 1 in the limit where *all* the loss introduced into the arms is this lumped excess (e.g. no modal aberrations).

The most recent full FFT simulation of H1, targeting G_R=47.5, requires such an *excess* loss per arm cavity HR of 45.5 ppm. Aside from a negligible possible absorptive loss/HR of <2 ppm, the only know *excess* loss from such mirrors would be the so called "micro-roughness" loss, i.e. scatter from surface irregularities of scale < the pixel size (2.7mm) of the aberration "maps" included in the FFT simulation. According to the "grating" formula for coherent light scatter, λ/(surface scale) = Sin(scatter angle), all such excess scatter is promptly lost from the extreme large aspect ratio LIGO arm cavities. For such loss the convenient relation

$$fractional\ loss = (4\pi\sigma_{surface} / \lambda)^2 \tag{1}$$

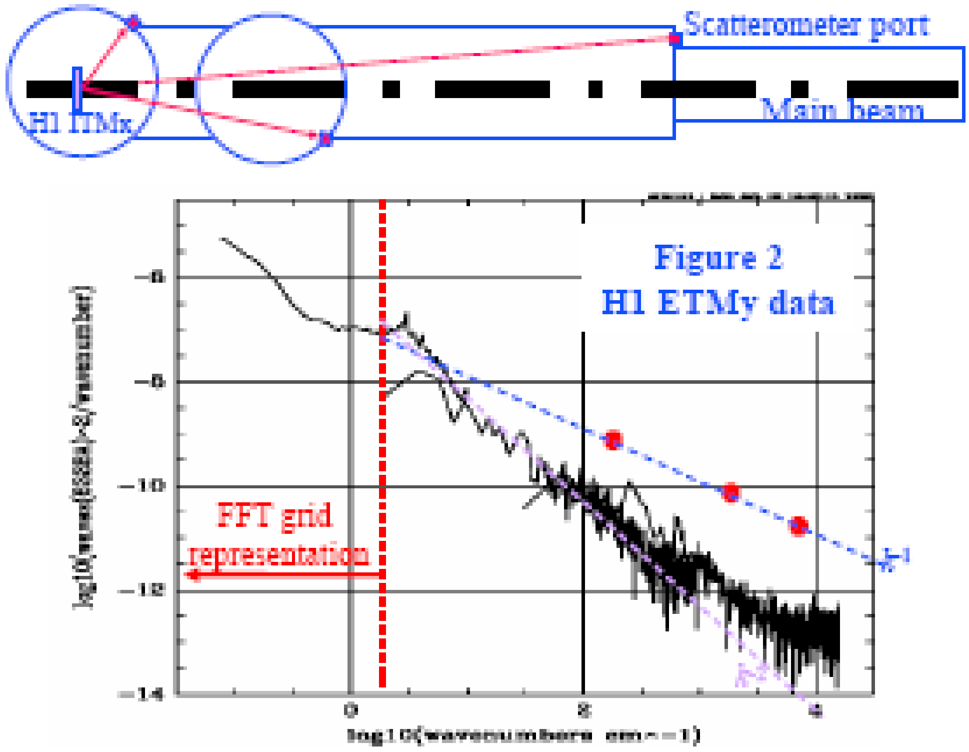
applies. The convenience is that the surface rms roughness, $\sigma_{surface}$ is easily directly measured by micro-profilometry of the surface (either the bare polished substrate or of the effective mirror phase front). The polished substrates used in H1 were so measured to have a mean roughness of ~0.16 nm (rms), implying loss = 4 ppm. Of course the instrument measuring this does not happen to have an aperture ~ 2x FFT pixel size. Therefore a rather delicate extrapolation is typically necessary to correct this micro-roughness loss to "excess" loss. Here the extrapolation amounts to 4ppm $\rightarrow$ 10 ppm (this is equivalent to integrating the k^{-2} curve in Fig. 2 back to the "FFT grid" line). For LIGO I design consideration this difference was a virtually insignificant detail.

Here then we have the central mystery: there appears to be a net *unexplained* [scatter] loss per mirror of 45.5-10=36ppm, based on the direct measured G_R= 47.5. If instead the ***V*** inferred G_R=37 is taken, then the unexplained loss/mirror = 52 ppm.

2.4 Scatterometer loss.

We conclude that each HR arm surface scatters ~40 ppm to large angles. At full lock, with one Watt input to the interferometer, this amounts to >1/4 Watt radiating from a ~ few cm size spot. So it should be easily detected on small photo-detectors. To do so a portable "scatterometer" PD/telescope assembly was set up on view ports as in figure 2 (LHO H1 ITMy case). These signals had two remarkable properties: 1. they were approximately the same for any accessible view of an optic; and 2. the signal, when normalized to cavity beam intensity was approximately the same for every optic (viewed from identical points).

To interpret the first property note that the view port geometry was such that each view point was approximately the same transverse distance from the beam line. For small view angles, and assuming the scatter is azimuthally constant, according to the micro-roughness loss formula (1) this implies a PSD spectrum of surface roughness rms^2 falling as (surface feature scale)^1. Figure 2 illustrates the detected scatter (June 2003) for an optic where 3 view points were accessible. The PSD representation of these points



clearly show such a (surface feature scale)^1 dependence. These are superimposed on a plot of PSD representation of fabrication metrology data of the surface shape of the same substrate. The traced (surface feature scale)^2 line is included to display the notion that highest quality “super-polished” surfaces may have so steeply (or steeper) a falling spectrum.

The second property strongly indicates that this view port detected scatter is “universal”. Similar observations at LLO (same scatterometer) were not inconsistent with the LHO set. However all HR surfaces are hardly identical. Such scatterometer measurements were conducted from 2/2002 thru 2/2006. Only the original H2 ITMx showed much different scatter (lower, but this ITM was otherwise anomalous and was replaced with one fitting the universality). Generally there appears to be no correlation of the scatterometer level with TM history. Further, the TMs are not intrinsically all the same: the H2 (and LLO) ETMs were polished by a different process, resulting in a significantly (~factor 6) lower micro-roughness PSD than plotted for the ITM in Fig. 2 in the region of the scatterometer points.

These overall properties, plus the fact that the HR mirrors do have one commonality, their coating process, suggests that the actual mirror scatter loss is entirely dominated by scattering added by the coating. Note that this does not rule out a “coating” of dust (except that such dust would have to be “universal” in the sense described). Weight is added to this suggestion by study of the locked cavity beam spot *image* on the HR surface. Since the earliest days of single arm locking (c. 2000) it has been observed that these images appear to consist of densely packed points (see image in LIGO-G060586). A featureless, diffuse glow would be expected from pure micro-roughness scatter. The points (as far as could be anecdotally determined) appear fixed (intensity, position) over time (years).

This “globular cluster” pattern also appears universal over all HR surfaces. Since the “stars” in the cluster pattern are easily distinguished with modest cameras it should be possible determine from detailed image analysis an upper limit to any diffuse, background component. Subtracting this from the total [image intensity] would then yield the fraction of the scatter due to the points. A dominant point scattering component would be just the sort which could give a $(\text{surface feature scale})^1$ tail to the PSD spectrum (the 3 view points of Fig. 2). Such an image analysis was crudely done (for one H1 HR in 10/2003). Peak to valley image brightness in sharp images was compared to mean brightness of the same image defocused. The conclusion was that any diffuse background was less than ~30% of the total. However I regard this as a very shaky determination, entirely limited by the [poor] available imaging hardware and software available. Repeating this experiment with readily available, far superior technology would be the easiest route to real progress on TM scatter/loss mystery.

A large fraction (at least) of these point scatters are minute ($< \lambda/2$). This is concluded by observation of the globular cluster image on diagonal COC (the BS and FMs in H2). On these mirrors most of the “stars” twinkle. If there is sufficient seismic excitation the on/off extinction of the twinkle is ~100%. This phenomenon is evidently due to the “scanning” of the cavity standing wave crests across the [moving] HR surface. The high extinction ratio indicates that the scattering point size cannot be much larger than, say, $\lambda/4$.

Unlike most of the above *relative* observations (viewport to viewport, often within the same continuous lock), it is a delicate matter to deduce a net “excess” loss (i.e.

comparable to those discussed in **2.3**) from the scatterometer data. The largest uncertainty in determining *individual* view point losses (i.e. the individual scatterometer points in Fig. 2) is in the normalization to incident power. The incident (arm cavity) power is proportional to the product of interferometer incident beam power and G_R. Both have been quite uncertain, even controversial (e.g. the discussion of G_R over epoch in **2.2**). Then, given this normalization (say of the 3 points in Fig. 2), what should be the extrapolated integrated scatter (area under curve inferred from the 3 points in Fig. 2)? For example, take the k^{-1} fit to these 3 points and integrate from the "FFT grid" limit to λ^{-1} (the exact limits do not strongly affect the result since the integral is logarithmic). This results in an excess loss = 53 ppm/surface (comparable to the 36-52 ppm described in **2.3**).

3. Scatter [loss] in HR surfaces (OTF).

Extensive OTF investigation of the [large angle: ~ the lowest *k* scatterometer point in Fig. 2 and higher] scatter from LIGO I HR surfaces (6 in all have been measured) has been conducted over the last three years. The outstanding feature of the experiment (RTS scans similar to described in **1.**) is that it is basically the same as the *in situ* scatterometer measurements. Important differences are, 1. the RTS experiment is in air; 2. the incident beam is chopped (and detection is via synchronous lockin); 3. the incident beam is much smaller (ϕ 0.1-1.0 mm); 4. the normalization (to determine loss) is entirely different. The first two of these are not considered to be problematic. For comparison to *in situ* observations (our motivation !) two supplemental uncertainties arise. First, these OTF measurements are on different HR surfaces than the *in situ* (with two exceptions: 4ITM07 and 2ITM04 which were removed from LHO because they had anomalous problems with their optical surfaces). Second, is that the storage history of these mirrors are quite different. This is particularly problematic since "dust" has not been ruled out as the dominant scatter culprit. All the OTF scatter measurements described here were on freshly well cleaned HR surfaces (with the exception of the contaminated patches described in section **1.**)

3.1 Calibration of OTF/RTS scatter scans.

The results of typical scans of $1cm^2$ patches of several HR surfaces are displayed in figure 3. Each plot is a histogram of the signal for each pixel of the scan of light scattered into an "integrating sphere" collecting 1.5^o – 78^o (corresponding to log[*k*]>2.5 in Fig.2) with respect to normal incidence. Unlike for the scatterometer (section **2.4**), "loss" scale is not determined by absolute knowledge of the incident beam power and detection sensitivity. Here loss is calibrated with respect to the scatter signal from a diffuse reference surface which scatters all incident light isotropic. Presumably such a calibration is reasonable only for an ~isotropicaly scattering "point" component on the surface.

On the other hand typical total loss measured for ϕ 1" test mirrors (such as the "REO8124" in Fig. 3) has indicated a scatter component (~4-5 ppm) consistent with the k^{-2} micro-roughness line in Fig. 2. However only select beam spot locations on these mirrors yield such low ring down loss. These presumably are those in the lowest bin of the histogram. Since the cavity ring down loss includes scatter to far smaller angles (~ cavity Rayleigh angle, or log[k] ~1.0 of Fig. 2) than the 1.5° minimum of the RTS collection, it is not surprising that this bin is far underrepresented in the mean RTS loss.

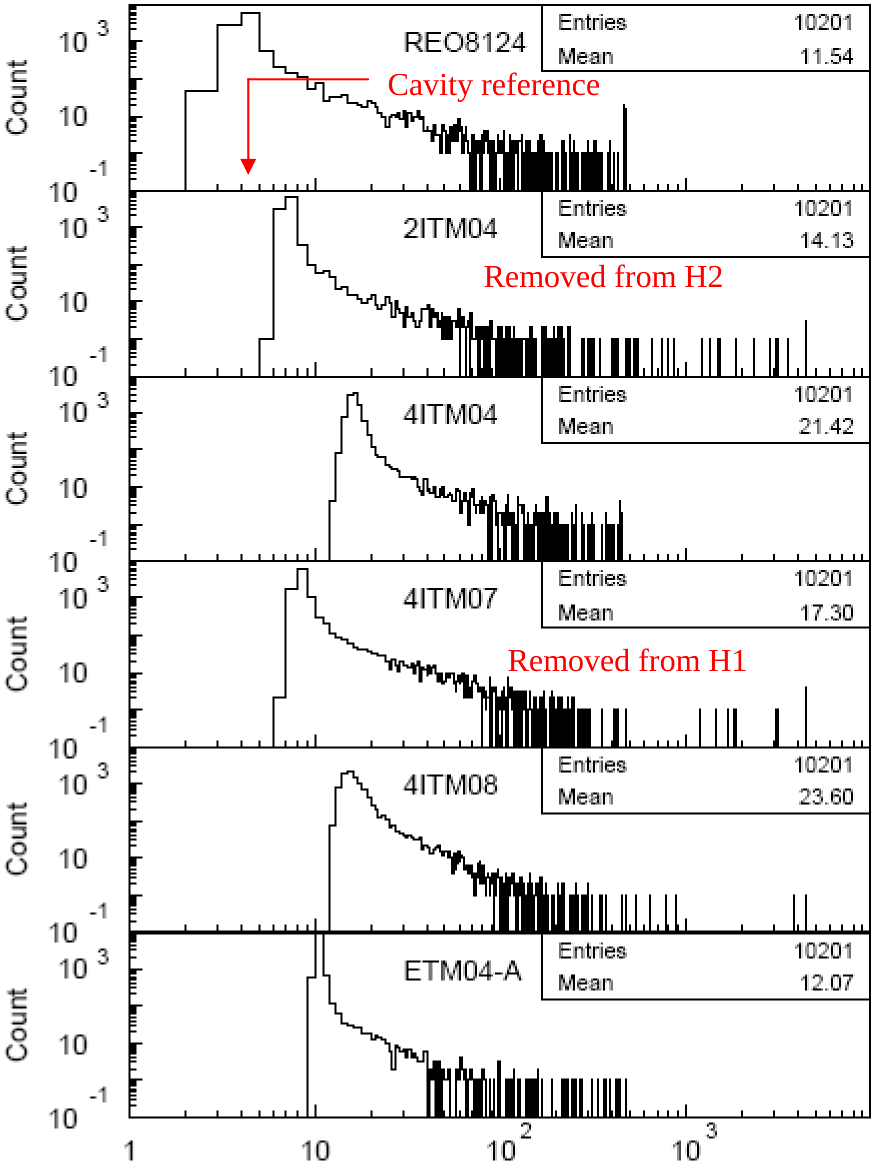


Figure 3 Integrated Scattering (ppm, 1.5° ≤ θ ≤ 78°)

3.2 Interpretation of OTF/RTS scatter scans.

Of primary practical interest is any *unexplained* excess scatter loss comparable to that discussed in section **2.3**. In accord with the previous analysis (expressed graphically in Fig. 2) we take as *explained* ~2 ppm of the mean loss in each of the Fig. 3 histograms. After this correction assume that the remainder of each TM histogram is in accord with the phenomenological k^{-1} dependence of *in situ* HR mirrors. This assumption requires a correction to the naïve isotropic ($k^{o} - k^{1}$ dependence) histogram calibration by a factor ~ℓn[(FFT limit)/(collection sphere limit)] =2.4. Interpreted in this manner, the HR surface scans displayed in Fig. 3

imply unexplained loss from 24.2 to 51.8 ppm, not inconsistent with the *average* unexplained loss/HR, 36 and 52 ppm, independently deduced in **2.3**. Note that the vacuum cavity reference mirror (REO8124) would also be predicted to have large “unexplained” loss in the LIGO regime despite its demonstrated very low loss in an OTF vacuum cavity. Its Fig. 3 histogram emphasizes that a preponderance of high scatter points (pixels) strongly skews the mean from the minimum.

Additional scatter scan studies support this interpretation. For instance, scans with single large angle (45^o) detection were performed. In this case the ratio of mean (or peak) histogram values for TM HR surfaces to ϕ 1” test HR surfaces was 2-3 times higher. On the other hand, mean (over the scan pixels) detected scatter does not change over a factor 25 variation in pump surface spot area (ϕ 0.1 – 0.5 mm). This would be expected for much smaller scattering point scale, and since the minimum k value sampled (246/cm corresponding to 1.5^o) is larger than the minimum beam diameter allowed scatter angle (100/cm).