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Light Transmission Fluctuations from Extended Air Showers Produced by Cosmic-Rays and Gamma-Rays

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Abstract

Cosmic-ray and gamma-ray experiments that use the atmosphere as a calorimeter, such as the High Resolution Fly's Eye (HiRes) and the Telescope Array (TA), require understanding the transmission of the light from the air shower of particles produced by the cosmic-ray or gamma-ray striking the atmosphere. To better understand the scattering and transmission of light to the detectors, HiRes measures light from different calibrated sources. We compare scattered light from laser shots a few kilometers away from the two HiRes detectors with direct light from stable portable light sources placed a few meters in front of the phototubes. We use two HiRes detectors to study and isolate contributions to fluctuations of the measured light. These contributions include fluctuations in the source intensity, the night sky background, scattering and transmission of the laser beam, the phototubes and electronics, and photostatistics.

1 Introduction:

To understand the atmosphere's effects on Extended Air Showers (EAS) from cosmic-rays, the High Resolution Fly's Eye (HiRes) observatory at Dugway, Utah simulates observing EAS by observing the scattered light from laser shots. Sets of laser shots of different energies (adjusted by using filters in front of the laser) made in January, April, and November 1998 are being studied. These laser beams were observed by several mirrors that are part of the ring of mirrors at the original Fly's Eye site, referred to here as BigH (or BH; the HiRes 1 site) and by mirror 4 at the new HiRes 2 site (HR2m4). Since BigH mirror 4 looks in away from the laser and is not used in this study, the subscript "4" can refer to the mirror 4 at site 2, while the numbers 7 and 16 refer to mirrors which are at the BigH site.

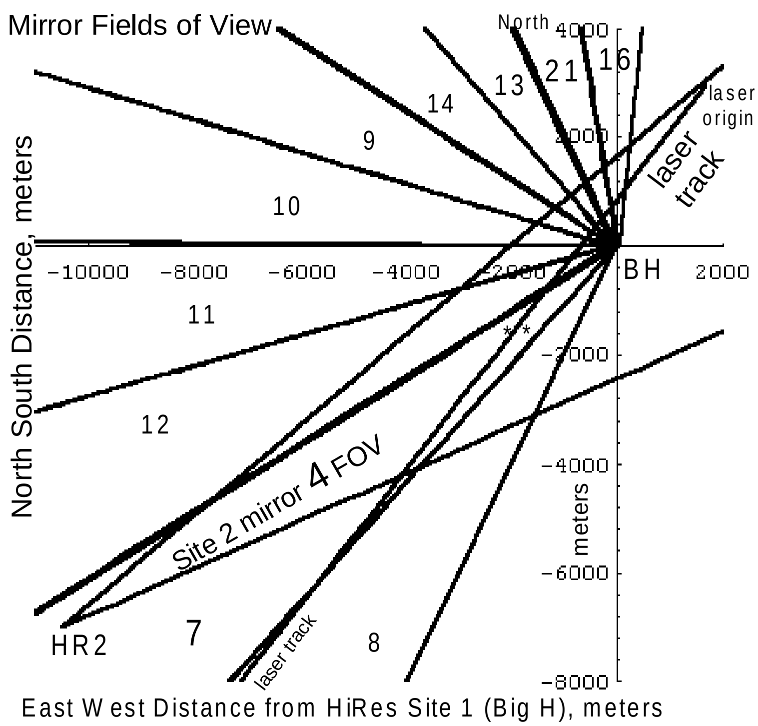

Figure 1: Map of Field of Views (FOV) of detector mirrors and laser beam with BigH (site 1) at the origin. Laser track enters HR2 mirror 4's lower FOV between the two asterisks (*/*).

The fluctuation σ of the detected photoelectrons received is the fluctuation of the received photons broadened by the photomultiplier tube (PMT) and associated electronics. This broadening factor c is generally close to 1.2, though here we look for c from the data.

2 Laser fluctuation f_ℓ and noise broadening term c:

From adding the relative noise terms σ/S in quadrature we should get the total noise:

$$\sigma^2/S^2 = f_\ell^2 + c^2/S\,(\ldots + \text{sky noise} + \text{atmospheric fluctuations} + \ldots)\ , \tag{1}$$

where c is an ad hoc constant for other factors that widen the spread from pure photon statistics. c = 1 for pure photon statistics, though phototubes generally broaden c to values closer to 1.2.

2.1 Laser jitter from site 2 mirror 4: The laser jitter f_ℓ should remain constant for different intensities of the laser light S and spread σ. Approximating the sky noise to be near zero, the brighter laser shots should give a fairly constant value of f_ℓ., but as the intensity goes to zero the non-zero sky noise would manifest itself in f_ℓ starting to rise as the signal S decreases, in the following equation:

$$f_\ell^2 = \sigma_4{}^2/S_4{}^2 - c^2/S_4\ , \tag{2}$$

where the subscripts "4" have been added for the following calculations using measurements from HiRes site 2 mirror 4 (HR2m4): S_4 is the number of photoelectrons seen by HR2m4, and δS_4 is the width of the distribution of S_4 using a Gaussian fit sigma. Table 1 shows the fit according to 7 energy levels, with energy level E0 being the laser with no filter and levels E1 (brightest) to E6 (dimmest) corresponding to filters 1 though 6.

These data give the most consistent f_ℓ with c=1, with $f_{\ell(\mathrm{I})} \approx 0.03$ for the brighter measurements, and the at the dimmer measurements it is expected that the night sky fluctuation will increase the residual fluctuation.

Table 1
Finding Broadening Factor c from HR2 mirror 4 data

Energy	$1/S_4$	S_4	δS_4	$\delta S_4/S_4$	$f_{\ell(\mathrm{i})}$, c=1	$f_{\ell(\mathrm{i})}$, c=2	$f_{\ell(\mathrm{i})}$, $c=\sqrt{2}$
0	2.77E-05	36092	870.0	0.0241	**0.0235**	0.0217	0.0229
1	7.18E-05	13919	442.1	0.0318	**0.0306**	0.0269	0.0294
2	1.18E-04	8492	274.8	0.0323	**0.0305**	0.0240	0.0285
3	1.69E-04	5919	196.4	0.0332	**0.0305**	0.0206	0.0276
4	3.33E-04	3002	126.7	0.0422	**0.0381**	0.0212	0.0334
5	9.62E-04	1040	82.5	0.0793	**0.0730**	0.0495	0.0661
6	1.27E-03	790	72.2	0.0915	**0.0843**	0.0575	0.076

2.1 Is fluctuation from site 1 mirror 7 consistent with this f_ℓ?: For the BigH mirror 7 data shown in Table 2, we find that these f_ℓ and c=1 used on the mean number of photoelectrons per shot using

$$\sigma_{\text{prediction}} = \sqrt{\sigma_{\text{pe}}^2 + \sigma_\ell^2} = \sqrt{\frac{c^2}{S_7} + f_\ell}\ , \tag{3}$$

give fairly good rough peak width predictions for all but the of the BHm7 peak width measurements (except the no filter measurement E0), where the sigmas **σ** from Gaussian fit to the distribution of ***S*** are found using

$$\sigma_{\text{measured}} = \frac{c \cdot \partial S_7}{S_7}\ . \tag{4}$$

The lower than predicted measured peak width for the brightest measurement E0 is because the data is noisy as is shown below. The divergence at the dimmer measurements (E5 and E6) is expected due to the night sky background.

Table 2
Predicted σ_{pred} for BHm7 for c=1 and f_ℓ = 0.031

E	S_7	$\sigma_{\text{prediction}}$	σ_{measured}	$\dfrac{\sigma_{\text{measured}}}{\sigma_{\text{prediction}}}$
0	113064	0.031142	0.012105	0.388699
1	32432	0.031493	0.040283	1.279099
2	24318	0.031656	0.029039	0.917308
3	15534	0.032021	0.028965	0.904562
4	7949	0.032967	0.032374	0.982026
5	2683	0.03652	0.044715	1.224399
6	2087	0.03795	0.051322	1.352352

3 The Quality of the Measured Fluctuations and Ratios:

If the night sky background and the atmospheric fluctuations dominate the fluctuations of the source laser, one could use $R_i^2 = \sigma_i^2/S_i^2 - c^2/S_i$ for the residual fluctuations R_i^2 (replacing f_ℓ^2 + noise in (1)) for determining the atmospheric fluctuations along the part of the beam detected by mirror *i*. However, we find the difficulty posed by the excellent clear desert sky at Dugway is that the fluctuation f_ℓ produced by the laser are much larger than the atmospheric fluctuation.

We attempt to remove the effect of f_ℓ by dividing the photoelectron amplitude S_i and spread σ_i from mirrors 7 and 4 which measure the beam far from the laser by S_{16} and σ_{16} from mirror 16 which is observes the beam much closer to the laser. Mirror 16 is roughly 1 km from the beam of the laser, and the laser beam segment seen by mirror 16 is roughly 3 km from the laser. The segment seen by mirror 7 has traveled through roughly 5 km of atmosphere upon entering mirror 7's field of view (FOV) and roughly 9 km where it is no longer detected; roughly all but the first half km of this same 4 km long segment is seen by mirror 4.

The same shot by shot laser jitter seen in mirrors 7 and 4 (i) is seen in mirror 16 (j), and so a shot by shot division of the number of photoelectrons S_i/S_{16} and its shot by shot spread $\sigma_{i/16}$ (note slash) should satisfy the following equation:

$$\frac{\sigma_{i/j}^2}{(Si/Sj)^2} = \frac{\sigma_i^2}{S_i^2} + \frac{\sigma_j^2}{S_j^2} - 2\frac{\sigma_{i-j}^2}{S_i S_j} \quad , \text{ or } \quad \sigma_{i-jpred}^2 = \frac{S_i S_j}{2}\left[\frac{\sigma_i^2}{S_i^2} + \frac{\sigma_j^2}{S_j^2} - \frac{\sigma_{i/j}^2}{(Si/Sj)^2}\right] \qquad (5)$$

(error propagation theory from Bevington & Robinson). The last term on the right which uses the covariance $\sigma_{i\text{-}16}$ (note dash) must be included because of the correlation between the distant measurements from mirrors (i = 7 and 4) and the close mirror (j=16). The covariance also allows the determination of the amount of correlation $r_{i,j} = \sigma_{i\text{-}j}^2/\sigma_i\sigma_j$ between the segments measured by mirrors i and j (Bevington & Robinson, taking σ=s). With one exception (likely indicating the presence of noise in this one measurement), the correlation between the near and far measurements are greatest (nearest 1) for the brightest laser shots and the correlation decreases as the brightness decreases. This is evidence for the night sky background being in the terms in Eq. 5, and evaluation of this contribution is planned to be presented.

Table 3 (continues on next page)

Test of Covariance predicted by (5) vs. measured, and Linear Correlation Coefficients

Mirror 7

E	BHm7		BHm16		BHm7/BHm16		Covariance ^2	$\sigma_{7\text{-}16\,meas}^2 / \sigma_{7\text{-}16\,pred}^2$	Linear Correlation Coefficients
	Mean	Sigma	Mean	Sigma	Mean	Sigma	$\sigma_{7\text{-}16}^2$ meas		$r_{7\text{-}16}$
0	403654	5166	604900	5332	0.668	0.0033	4259	**0.268**	0.185
1	158260	4666	314765	6527	0.504	0.0064	4840	**0.940**	0.850
2	86866	2484	195353	5022	0.444	0.0058	5264	**0.989**	0.910
3	55475	1607	132174	3418	0.420	0.0068	3113	**0.934**	0.777
4	28387	919	69161	1930	0.411	0.0103	2105	**0.984**	0.807
5	9583	429	24744	904	0.388	0.0173	1070	**0.988**	0.646
6	7453	383	19710	731	0.378	0.0202	432	**1.082**	0.482

Table 3 (continued from previous page)
Test of Covariance predicted by (5) vs. measured, and Linear Correlation Coefficients

Mirror 4

E	HR2m4		BHm16		BHm7 / BHm16		Covariance^2	$\sigma_{4\text{-}16}{}^2{}_{meas}$ / $\sigma_{4\text{-}16}{}^2{}_{pred}$	Linear Correlation Coefficients
	Mean	Sigma	Mean	Sigma	Mean	Sigma	$\sigma_{4\text{-}16}{}^2{}_m$		$r_{4\text{-}16}$
0	129829	2739	604900	5332	0.215	0.0035	3738	**0.999**	0.830
1	49706	1579	314765	6527	0.158	0.0036	3474	**1.100**	0.826
2	30364	973	195353	5022	0.156	0.0033	2724	**1.007**	0.720
3	21135	702	132174	3418	0.160	0.0043	1797	**0.936**	0.661
4	10718	453	69161	1930	0.155	0.0062	1204	**0.986**	0.605
5	3713	295	24744	904	0.150	0.0122	628	**1.049**	0.452
6	2821	258	19710	731	0.143	0.0129	261	**1.183**	0.255

Since the covariance is obtained separately from the other terms in the equation, comparing how close to equal Eq. 5 solved for the covariance squared $\sigma_{i\text{-}16}{}^2$ (predicted, or "pred" $\sigma_{i\text{-}16}{}^2{}_{pred}$) and the measured covariance squared $\sigma_{i\text{-}16}{}^2{}_{meas}$ are provides an effective test of the quality of the data. As seen in Table 3, the brightest measurement by mirror 7 does not satisfy this equation. A visual inspection of the histogram of this measurement indeed shows this measurement to be flawed as there is an "echo" of the main signal with a lower S_7 than most of the signal. Also, the dimmest measurements indeed have greater inequality than most of the rest of the measurements which all have agreement within 10%. The level of agreement of the covariance calculated in (5) with the directly measured covariance provides a quantitative criterion of the quality of the measurements.

Further Work:

Further work on the full sequence of mirrors that see the laser beam from mirror 16 to mirror 7 from the first night are planned, as are analysis of laser measurements made on other nights. This will allow a more careful look for the small atmospheric fluctuation signal.

Conclusions:

The excellent clear desert sky at Dugway keeps the atmospheric fluctuation much smaller than the fluctuation f_ℓ produced by the laser. This makes it difficult to determine the atmospheric fluctuations of clear atmosphere, a known difficulty among many atmospheric scientists who are best able to see atmospheric effects only during "bad" weather. For the purpose of high energy particle produced extended air shower detection, this shows that on nights of clear weather the atmospheric fluctuation is in fact small, as has been assumed.

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