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Supplementary Material for Efficient Environment Map Rendering based on Decomposition

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This document presents additional results generated using various configurations of our method as well as more comparisons to previous methods, including multiple importance sampling [VG95] (MIS, using PBRT3's implementation [PJH16]), fast hierarchical importance sampling (FHIS) [ODJ04], median cut (MC) [Deb05], a variant of median cut based on variance minimization (VM) [VD09], and a method based on tone-mapped mean-shift (TMMS) [FYWY16]. For our method, we also include a version, denoted as Ours (w/o U), which renders the low-frequency component at the original resolution.

Results of decomposition. Fig. 1 illustrates the intermediate results of high-frequency and low-frequency components rendered by our method. Both components closely resemble the reference images visually.

Variants for generating *EnvIndirects*. To demonstrate the effectiveness of our modified illumination cut, as described in Section 3.4 in the main paper, we compared our method with a variant using the original illumination cut [CPWAP08] to generate ***EnvIndirects***. Table 1 presents the average errors across 32 environment maps and four test scenes. Our modified algorithm significantly reduces numerical errors compared to the original version by considering the total energy and the directional extent during cluster generation.

Method for ***EnvIndirects***	RMSE ↓	ꟻLIP ↓
Original Illumination Cut	0.0671	0.1280
Modified Illumination Cut	**0.0438**	**0.0865**

Table 1: **Ablation studies of using various illumination cut algorithms to generate *EnvIndirect*.** The RMSE and ꟻLIP values, averaged across 32 environment maps and 4 test scenes, demonstrate that our modified illumination cut for ***EnvIndirect*** produces significantly lower errors compared to the original method.

Interleaved sampling. Rendering with a global set of representative lights can produce noticeable artifacts near shadow boundaries. We use interleaved sampling to convert these artifacts into minor noise. Fig. 2 compares the rendered images with and without interleaved sampling. For VM, TMMS, and our method, interleaved sampling mitigates image errors and enhances the visual quality of the rendered images.

More comparisons. Table 2 and Table 3 present the RMSE and ꟻLIP [ANSAM21] comparisons of various methods. Each method is evaluated using 4 test scenes rendered with 32 environment maps, as detailed in the main paper. The reported numbers for each environment map are the averages of the RMSE and ꟻLIP values across the 4 test scenes. Additionally, the table includes the ranking of each method among the 7 compared methods in brackets. Our full method, which includes upsampling the low-frequency component, achieves the lowest average errors and demonstrates robust performance across the 32 diverse test cases. Fig. 3 to Fig. 6 provide image comparisons. In these images, our method exhibits significantly less noise and fewer artifacts than previous methods. It is important to note that the RMSE and ꟻLIP values for each case in Table 2 and Table 3 are averaged across the four test scenes and, therefore, differ from the values labeled on the images shown in Fig. 3 to Fig. 6, which are measured per image.

References

[ANSAM21] ANDERSSON P., NILSSON J., SHIRLEY P., AKENINE-MÖLLER T.: Visualizing Errors in Rendered High Dynamic Range Images. In *Eurographics Short Papers* (2021). doi:10.2312/egs.20211015. 1

[CPWAP08] CHESLACK-POSTAVA E., WANG R., AKERLUND O., PELLACINI F.: Fast, realistic lighting and material design using nonlinear cut approximation. In *ACM Trans. Graph. (Proc. SIGGRAPH Asia)* (2008). doi:10.1145/1457515.1409081. 1

[Deb05] DEBEVEC P.: A median cut algorithm for light probe sampling. In *SIGGRAPH Poster* (2005). doi:10.1145/1186954.1187029. 1

[FYWY16] FENG W., YANG Y., WAN L., YU C.: Tone-mapped mean-shift based environment map sampling. *IEEE Trans. on Visualization and Computer Graphics 22*, 9 (2016), 2187–2199. doi:10.1109/TVCG.2015.2500236. 1

[ODJ04] OSTROMOUKHOV V., DONOHUE C., JODOIN P.-M.: Fast hierarchical importance sampling with blue noise properties. *ACM Trans. Graph. (Proc. SIGGRAPH) 23*, 3 (aug 2004), 488–495. doi:10.1145/1015706.1015750. 1

[PJH16] PHARR M., JAKOB W., HUMPHREYS G.: *Physically Based Rendering: From Theory to Implementation*, 3rd ed. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, Nov. 2016. 1

[VD09] VIRIYOTHAI K., DEBEVEC P.: Variance minimization light probe sampling. In *SIGGRAPH Poster* (2009). doi:10.1145/1599301.1599393. 1

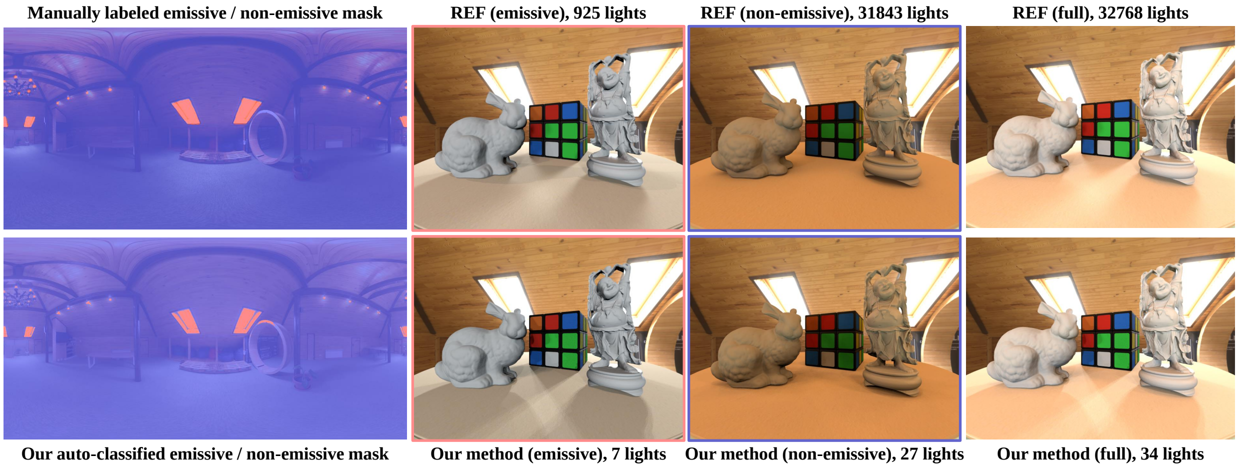


Figure 1: **Our decomposition result.** The top row shows our manually labeled emissive and non-emissive pixels alongside the results rendered by converting these pixels into numerous lights. The bottom row shows our automatic classified mask and the rendered results, which take 4 seconds. Our method accurately approximates both high-frequency and low-frequency components.

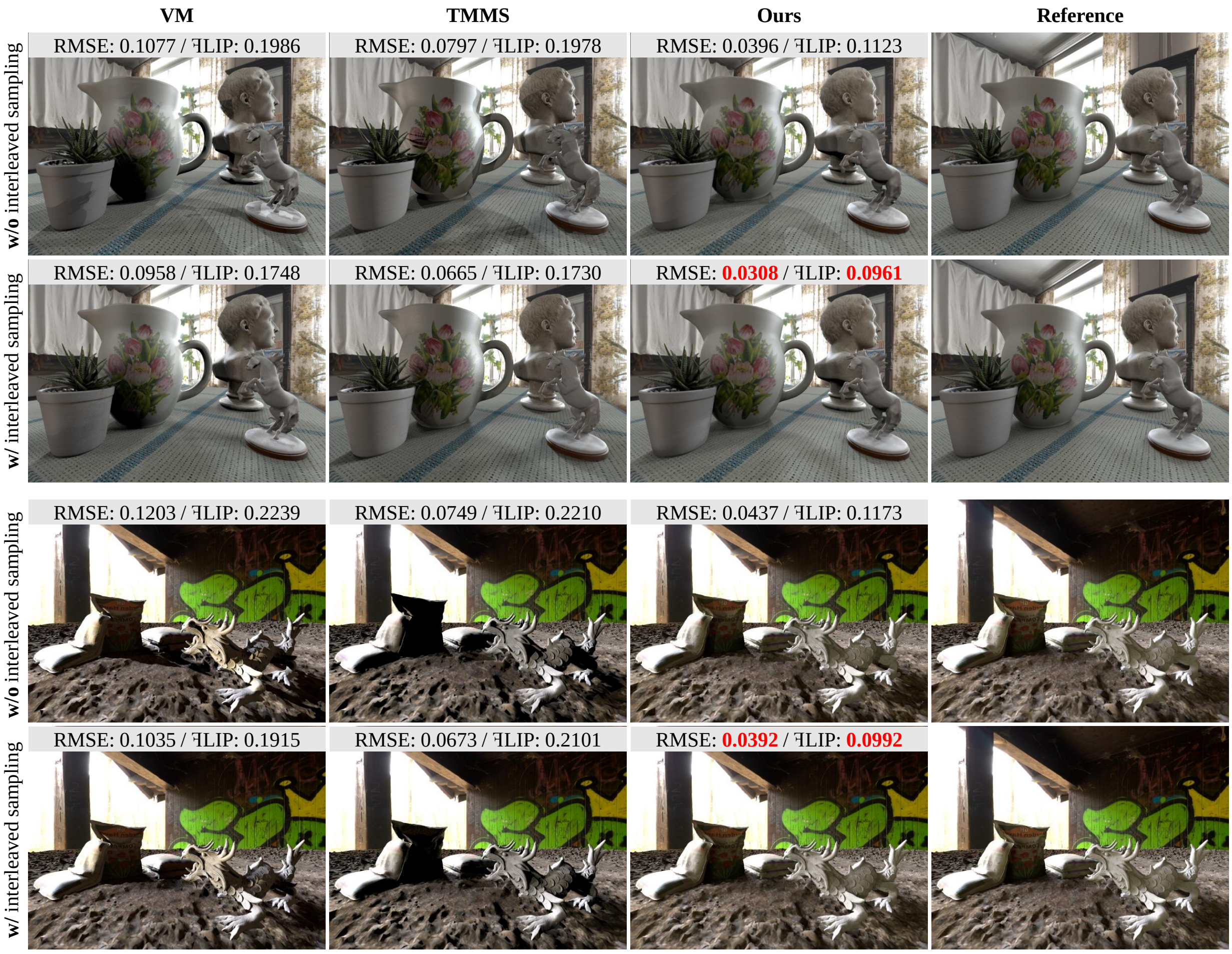


Figure 2: **Comparisons of rendered results with and without interleaved sampling.** The top row shows images rendered without interleaved sampling, while the bottom row shows images rendered with interleaved sampling. Using interleaved sampling significantly reduces shadow boundary artifacts, although it introduces slight image noise.

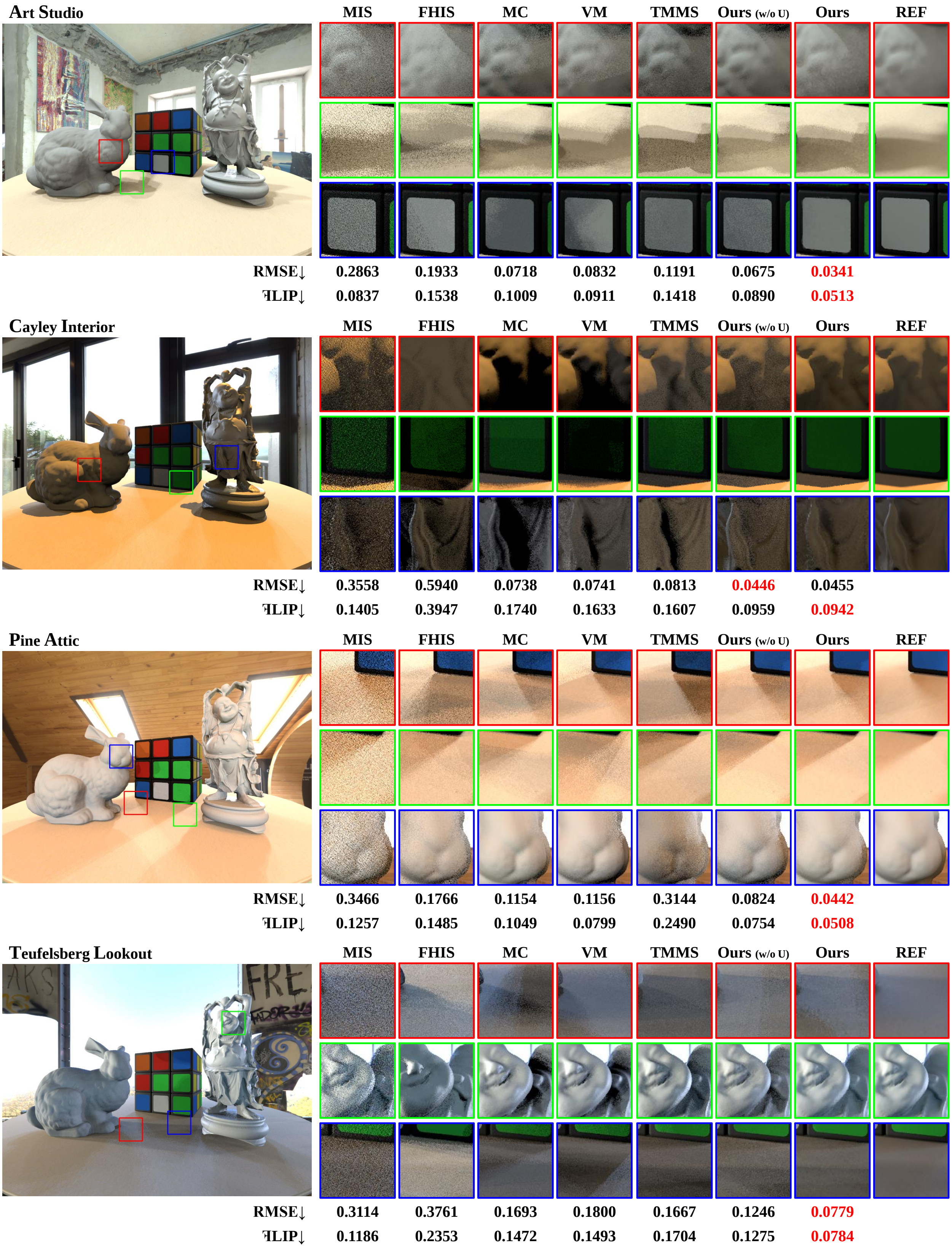
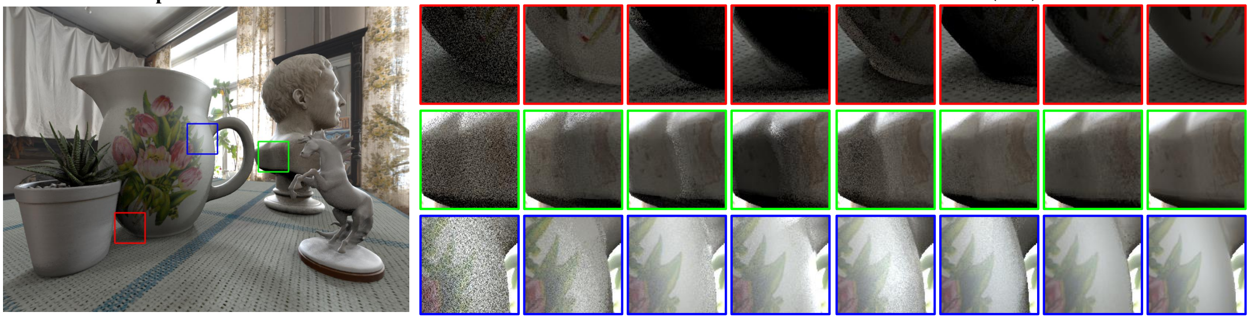


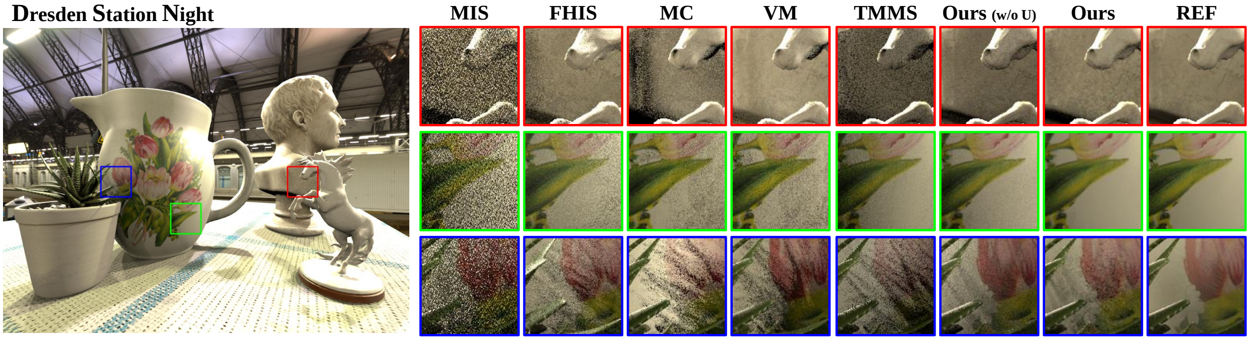
Figure 3: **More comparisons of various environment map sampling methods on the 1^{st} scene.**

Artist Workshop



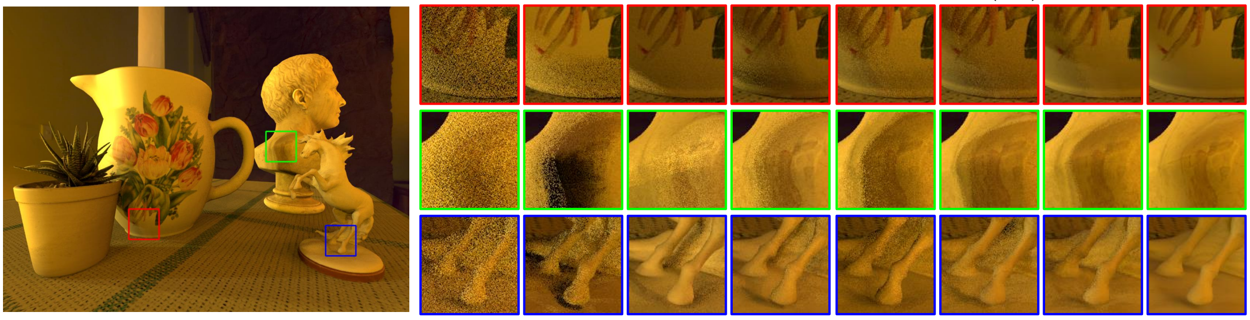
	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours	REF
RMSE↓	0.0975	0.0530	0.0627	0.0958	0.0665	0.0441	0.0308	
ꟻLIP↓	0.0983	0.1324	0.1862	0.1748	0.1730	0.1264	0.0961	

Dresden Station Night



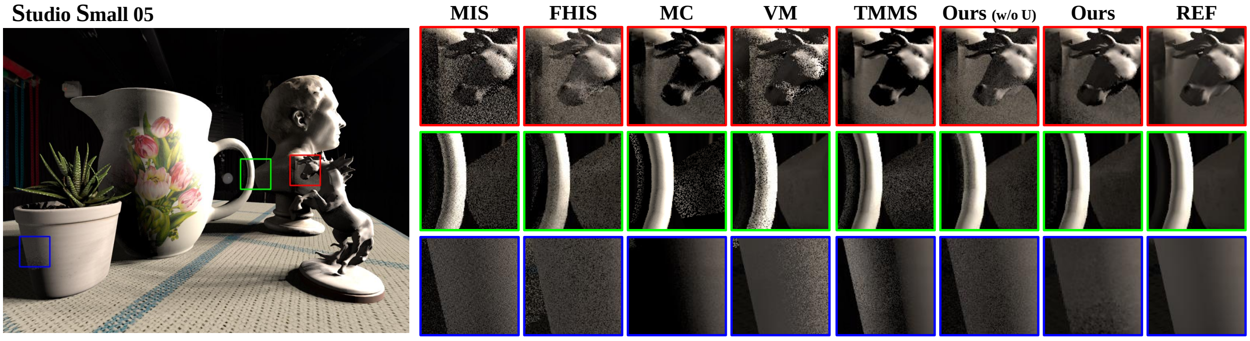
	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours	REF
RMSE↓	0.4631	0.5811	0.1646	0.2310	0.1580	0.1643	0.1113	
ꟻLIP↓	0.1963	0.2144	0.1512	0.1604	0.2063	0.1540	0.0919	

Fire Place



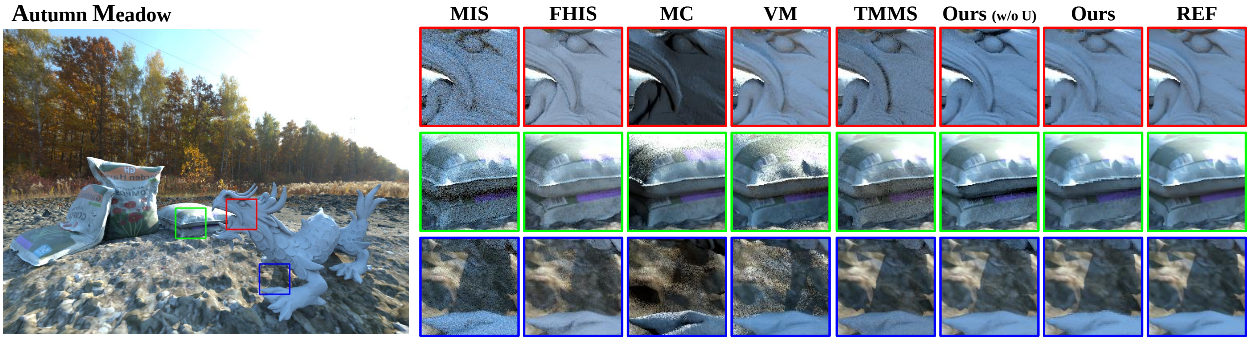
	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours	REF
RMSE↓	0.0794	0.0524	0.0490	0.0228	0.0380	0.0220	0.0165	
ꟻLIP↓	0.1846	0.2352	0.2679	0.1548	0.1818	0.1570	0.1067	

Studio Small 05

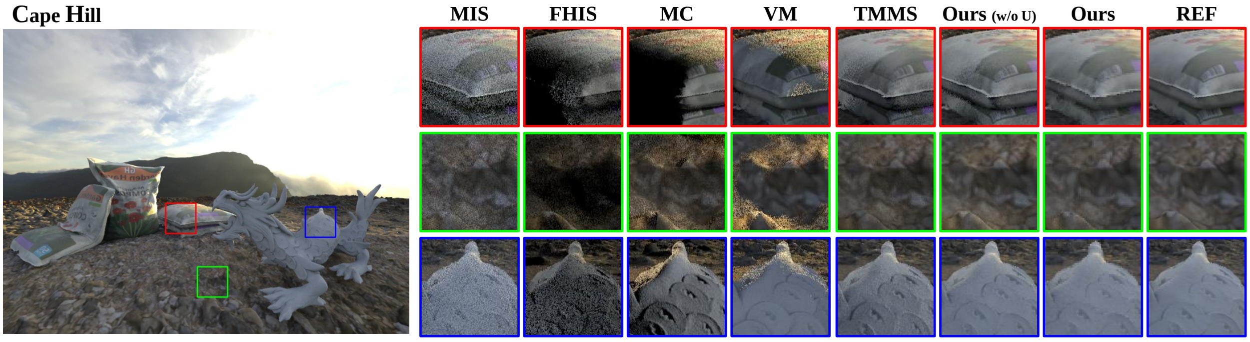


	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours	REF
RMSE↓	0.1430	0.0927	0.0837	0.1834	0.0349	0.0428	0.0294	
ꟻLIP↓	0.1144	0.1789	0.1996	0.1518	0.1589	0.1288	0.1028	

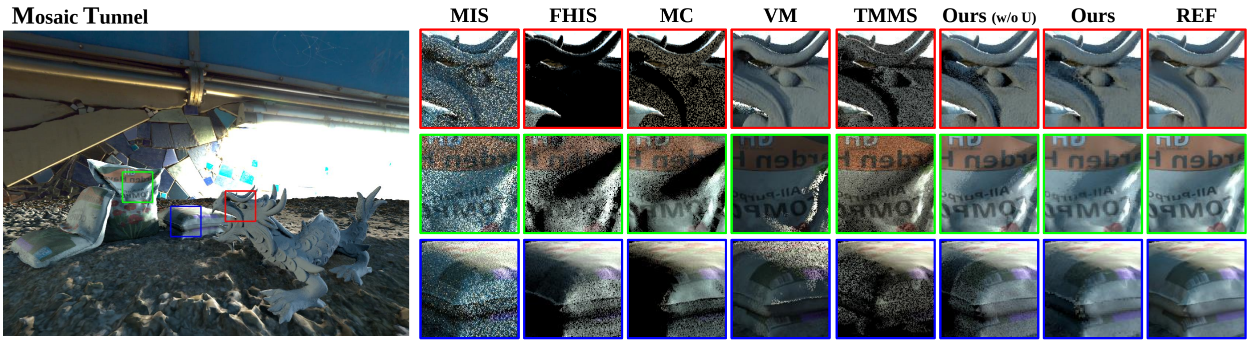
Figure 4: **More comparisons of various environment map sampling methods on the** 2^{nd} **scene.**



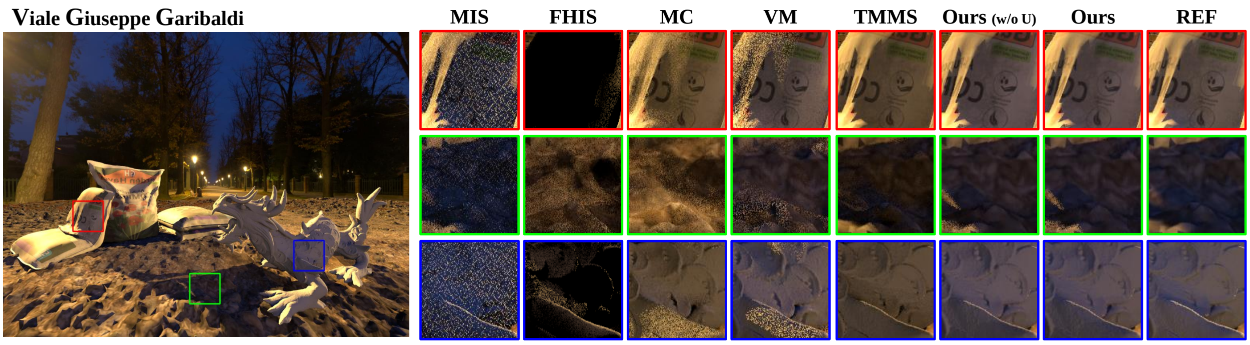
	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours
RMSE↓	0.0463	0.0436	01068	0.0723	0.0412	0.0162	0.0178
ꟻLIP↓	0.0561	0.1370	0.2510	0.1451	0.1533	0.0726	0.0519



	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours
RMSE↓	0.0166	0.0345	0.0352	0.0431	0.0121	0.0078	0.0069
ꟻLIP↓	0.0627	0.3492	0.2767	0.2119	0.1316	0.0917	0.0523



	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours
RMSE↓	0.0441	0.0277	0.0234	0.0411	0.0226	0.0121	0.0094
ꟻLIP↓	0.1773	0.3429	0.3343	0.2877	0.3364	0.1453	0.1214



	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours
RMSE↓	0.0461	0.1421	0.0709	0.0659	0.0354	0.0328	0.0331
ꟻLIP↓	0.1607	0.4043	0.3014	0.2382	0.2424	0.1565	0.1475

Figure 5: **More comparisons of various environment map sampling methods on the 3^{rd} scene.**

Figure 6: **More comparisons of various environment map sampling methods on the 4^{th} scene.**

Environment map	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours (w/ U)
[01] ART STUDIO	0.1781 (7)	0.1427 (6)	0.0598 (3)	0.0637 (4)	0.0891 (5)	0.0547 (2)	**0.0356 (1)**
[02] ARTIST WORKSHOP	0.0728 (7)	0.0409 (3)	0.0465 (4)	0.0646 (5)	0.0722 (6)	0.0328 (2)	**0.0240 (1)**
[03] AUTUMN MEADOW	0.0701 (4)	0.0750 (5)	0.1566 (7)	0.1379 (6)	0.0595 (3)	0.0316 (2)	**0.0270 (1)**
[04] BASEMENT BOXING RING	0.2634 (6)	0.2690 (7)	0.1163 (5)	0.1033 (3)	0.1069 (4)	0.0737 (2)	**0.0551 (1)**
[05] BIRBECK STREET UNDERPASS	0.1874 (7)	0.1094 (6)	0.0687 (4)	0.0636 (3)	0.0705 (5)	0.0520 (2)	**0.0324 (1)**
[06] BLUE PHOTO STUDIO	0.3043 (7)	0.2460 (6)	0.1149 (4)	0.1178 (5)	0.1133 (3)	0.0582 (2)	**0.0580 (1)**
[07] BROWN PHOTOSTUDIO 07	0.1033 (4)	0.2119 (7)	0.0852 (3)	0.1227 (6)	0.1107 (5)	0.0691 (2)	**0.0523 (1)**
[08] CAPE HILL	0.0259 (4)	0.0479 (5)	0.0639 (6)	0.0816 (7)	0.0224 (3)	0.0158 (2)	**0.0141 (1)**
[09] CAVE WALL	0.1431 (7)	0.0378 (5)	0.0339 (4)	0.0396 (6)	0.0315 (3)	0.0313 (2)	**0.0164 (1)**
[10] CAYLEY INTERIOR	0.2099 (6)	0.3328 (7)	0.0623 (4)	0.0648 (5)	0.0589 (3)	0.0359 (2)	**0.0343 (1)**
[11] CAYLEY LOOKOUT	0.1195 (7)	0.0532 (2)	0.0550 (5)	0.0535 (3)	0.0547 (4)	0.0569 (6)	**0.0383 (1)**
[12] CHRISTMAS PHOTO STUDIO 01	0.0908 (6)	0.1430 (7)	0.0601 (3)	0.0891 (5)	0.0655 (4)	0.0522 (2)	**0.0368 (1)**
[13] DERELICT UNDERPASS	0.1507 (7)	0.0861 (3)	0.1129 (5)	0.0870 (4)	0.1132 (6)	0.0724 (2)	**0.0471 (1)**
[14] DRACHENFELS CELLAR	0.0883 (6)	0.0562 (4)	0.0440 (3)	0.1015 (7)	0.0616 (5)	0.0254 (2)	**0.0202 (1)**
[15] DRESDEN STATION NIGHT	0.4167 (6)	0.5772 (7)	0.1641 (4)	0.2436 (5)	0.1450 (2)	0.1464 (3)	**0.0946 (1)**
[16] FACTORY YARD	0.1619 (6)	0.0855 (3)	0.1087 (4)	0.1162 (5)	0.1696 (7)	**0.0697 (1)**	0.0707 (2)
[17] FIRE PLACE	0.0661 (7)	0.0532 (6)	0.0508 (5)	0.0286 (3)	0.0354 (4)	0.0216 (2)	**0.0176 (1)**
[18] GRAFFITI SHELTER	0.2606 (7)	0.1742 (5)	0.1351 (4)	0.2135 (6)	0.1194 (3)	0.0959 (2)	**0.0680 (1)**
[19] HIKERS CAVE	0.0787 (6)	0.0970 (7)	0.0596 (4)	0.0542 (3)	0.0653 (5)	0.0492 (2)	**0.0315 (1)**
[20] INDUSTRIAL PIPE AND VALVE 02	0.1287 (6)	0.1561 (7)	0.0498 (4)	0.0453 (3)	0.0763 (5)	0.0397 (2)	**0.0353 (1)**
[21] KIARA 1 DAWN	0.1676 (6)	0.2033 (7)	0.1256 (3)	0.1416 (5)	0.1406 (4)	0.1018 (2)	**0.0725 (1)**
[22] LAPA	0.2523 (7)	0.1015 (5)	0.0958 (4)	0.1168 (6)	0.0872 (3)	0.0698 (2)	**0.0569 (1)**
[23] LYTHWOOD LOUNGE	0.2957 (7)	0.1547 (5)	0.1440 (4)	0.1390 (3)	0.2208 (6)	0.0973 (2)	**0.0659 (1)**
[24] MOSAIC TUNNEL	0.0775 (6)	0.0499 (5)	0.0383 (3)	0.0861 (7)	0.0383 (3)	0.0259 (2)	**0.0203 (1)**
[25] NEUER ZOLLHOF	0.0707 (5)	0.1519 (7)	0.0665 (4)	0.1127 (6)	0.0422 (3)	**0.0340 (1)**	0.0343 (2)
[26] PINE ATTIC	0.2607 (7)	0.1741 (5)	0.0827 (3)	0.0902 (4)	0.2312 (6)	0.0655 (2)	**0.0453 (1)**
[27] RED WALL	0.1779 (7)	0.1705 (6)	0.0835 (3)	0.0919 (4)	0.1154 (5)	0.0745 (2)	**0.0575 (1)**
[28] STUDIO SMALL 05	0.1235 (6)	0.0808 (5)	0.0608 (4)	0.1522 (7)	0.0290 (2)	0.0354 (3)	**0.0243 (1)**
[29] SUNSET IN THE CHALK QUARRY	0.0805 (7)	0.0723 (6)	0.0716 (5)	0.0702 (4)	0.0675 (3)	0.0570 (2)	**0.0367 (1)**
[30] TEUFELSBERG LOOKOUT	0.3392 (6)	0.5056 (7)	0.1854 (4)	0.1913 (5)	0.1425 (3)	0.1256 (2)	**0.0949 (1)**
[31] VENETIAN CROSSROADS	**0.0231 (1)**	0.1678 (7)	0.1024 (5)	0.1222 (6)	0.0248 (2)	0.0297 (3)	0.0307 (4)
[32] VIALE GIUSEPPE GARIBALDI	0.0655 (4)	0.2019 (7)	0.1147 (6)	0.1065 (5)	0.0559 (3)	0.0517 (2)	**0.0515 (1)**
Average	0.1579 (6.00)	0.1572 (5.63)	0.0881 (4.16)	0.1035 (4.88)	0.0886 (4.00)	0.0579 (2.16)	**0.0438 (1.16)**

Table 2: **RMSE values of various environment map sampling methods on all test environment maps.** Our full method achieves the lowest and most stable RMSE compared to previous methods.

[VG95] VEACH E., GUIBAS L. J.: Optimally combining sampling techniques for monte carlo rendering. In *Proc. SIGGRAPH* (1995), p. 419–428. doi:10.1145/218380.218498. 1

Environment map	MIS	FHIS	MC	VM	TMMS	Ours (w/o U)	Ours (w/ U)
[01] ART STUDIO	0.0881 (2)	0.1742 (7)	0.1127 (5)	0.1017 (4)	0.1521 (6)	0.0987 (3)	**0.0654 (1)**
[02] ARTIST WORKSHOP	0.0804 (2)	0.1163 (4)	0.1516 (6)	0.1418 (5)	0.1975 (7)	0.1084 (3)	**0.0789 (1)**
[03] AUTUMN MEADOW	0.0840 (2)	0.1731 (4)	0.3114 (7)	0.1749 (5)	0.1919 (6)	0.1083 (3)	**0.0721 (1)**
[04] BASEMENT BOXING RING	0.1219 (4)	0.1912 (7)	0.1262 (5)	0.0998 (3)	0.1316 (6)	0.0893 (2)	**0.0739 (1)**
[05] BIRBECK STREET UNDERPASS	0.1304 (5)	0.1663 (7)	0.1103 (4)	0.1009 (3)	0.1388 (6)	0.0905 (2)	**0.0705 (1)**
[06] BLUE PHOTO STUDIO	0.1110 (3)	0.2187 (7)	0.1243 (5)	0.1119 (4)	0.1404 (6)	0.0765 (2)	**0.0731 (1)**
[07] BROWN PHOTOSTUDIO 07	**0.0695 (1)**	0.3537 (7)	0.1447 (5)	0.1404 (4)	0.1588 (6)	0.1134 (3)	0.0792 (2)
[08] CAPE HILL	0.0830 (2)	0.3487 (7)	0.3251 (6)	0.2197 (5)	0.1601 (4)	0.1128 (3)	**0.0691 (1)**
[09] CAVE WALL	0.0558 (5)	0.0797 (7)	0.0537 (2)	0.0547 (3)	0.0559 (6)	0.0547 (3)	**0.0332 (1)**
[10] CAYLEY INTERIOR	0.1577 (3)	0.3951 (7)	0.2056 (6)	0.1783 (5)	0.1713 (4)	0.1069 (2)	**0.0943 (1)**
[11] CAYLEY LOOKOUT	0.0492 (2)	0.0835 (5)	0.0716 (3)	0.0741 (4)	0.0857 (6)	0.0898 (7)	**0.0457 (1)**
[12] CHRISTMAS PHOTO STUDIO 01	0.1104 (2)	0.2146 (6)	0.1899 (4)	0.2020 (5)	0.2824 (7)	0.1483 (3)	**0.1057 (1)**
[13] DERELICT UNDERPASS	0.0722 (2)	0.1125 (5)	0.1216 (6)	0.1009 (4)	0.1342 (7)	0.0861 (3)	**0.0627 (1)**
[14] DRACHENFELS CELLAR	0.1825 (3)	0.2741 (6)	0.2356 (5)	0.2338 (4)	0.3702 (7)	0.1474 (2)	**0.1114 (1)**
[15] DRESDEN STATION NIGHT	0.1668 (5)	0.2038 (7)	0.1360 (3)	0.1423 (4)	0.1754 (6)	0.1249 (2)	**0.0715 (1)**
[16] FACTORY YARD	0.0724 (2)	0.0921 (4)	0.1009 (5)	0.1056 (6)	0.1483 (7)	0.0833 (3)	**0.0615 (1)**
[17] FIRE PLACE	0.1526 (4)	0.2220 (7)	0.2111 (6)	0.1249 (3)	0.1561 (5)	0.1240 (2)	**0.0878 (1)**
[18] GRAFFITI SHELTER	0.1870 (3)	0.2774 (7)	0.2117 (4)	0.2396 (6)	0.2276 (5)	0.1663 (2)	**0.1180 (1)**
[19] HIKERS CAVE	0.1044 (2)	0.2028 (5)	0.2551 (7)	0.1559 (4)	0.2383 (6)	0.1503 (3)	**0.1030 (1)**
[20] INDUSTRIAL PIPE AND VALVE 02	0.1978 (5)	0.4379 (7)	0.1829 (4)	0.1510 (3)	0.3045 (6)	0.1462 (2)	**0.1321 (1)**
[21] KIARA DAWN	0.0687 (2)	0.1916 (7)	0.1349 (6)	0.1224 (4)	0.1322 (5)	0.1066 (3)	**0.0682 (1)**
[22] LAPA	0.1966 (5)	0.2185 (6)	0.2232 (7)	0.1566 (3)	0.1847 (4)	0.1206 (2)	**0.0937 (1)**
[23] LYTHWOOD LOUNGE	0.1213 (2)	0.1319 (4)	0.1567 (6)	0.1458 (5)	0.2557 (7)	0.1304 (3)	**0.0804 (1)**
[24] MOSAIC TUNNEL	0.2054 (3)	0.3948 (7)	0.3512 (6)	0.2896 (4)	0.3330 (5)	0.1774 (2)	**0.1466 (1)**
[25] NEUER ZOLLHOF	0.1206 (2)	0.1956 (6)	0.2182 (7)	0.1927 (5)	0.1680 (4)	0.1336 (3)	**0.0997 (1)**
[26] PINE ATTIC	0.1300 (5)	0.1535 (6)	0.1127 (4)	0.0876 (3)	0.2477 (7)	0.0846 (2)	**0.0621 (1)**
[27] RED WALL	0.0984 (2)	0.1959 (7)	0.1123 (3)	0.1272 (5)	0.1697 (6)	0.1225 (4)	**0.0786 (1)**
[28] STUDIO SMALL 05	0.1272 (2)	0.1769 (6)	0.1884 (7)	0.1468 (4)	0.1679 (5)	0.1316 (3)	**0.1031 (1)**
[29] SUNSET IN THE CHALK QUARRY	**0.0565 (1)**	0.1185 (7)	0.0997 (3)	0.1018 (4)	0.1151 (6)	0.1103 (5)	0.0576 (2)
[30] TEUFELSBERG LOOKOUT	0.1339 (2)	0.2483 (7)	0.1684 (5)	0.1639 (4)	0.1796 (6)	0.1411 (3)	**0.0970 (1)**
[31] VENETIAN CROSSROADS	0.1257 (2)	0.2622 (5)	0.3389 (7)	0.2824 (6)	0.2013 (4)	0.1263 (3)	**0.0923 (1)**
[32] VIALE GIUSEPPE GARIBALDI	0.2177 (3)	0.4681 (7)	0.3347 (6)	0.2762 (4)	0.2873 (5)	0.2015 (2)	**0.1789 (1)**
Average	0.1212 (2.81)	0.2217 (6.19)	0.1819 (5.16)	0.1546 (4.22)	0.1895 (5.72)	0.1191 (2.81)	**0.0865 (1.06)**

Table 3: **ꟻLIP values of various environment map sampling methods on all test environment maps.** Our full method achieves the lowest and most stable ꟻLIP errors compared to previous methods.