Supplementary: Role of Transients in Two-Bounce Non-Line-of-Sight Imaging

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1. Implementation Details

**Experimental Setup** The object of interest is flanked on each side by parallel white walls. We illuminate the right wall, and measure two-bounce light (shadows) on the left wall, as shown in Fig. 1(c) of the main text. We use a two-axis scanning galvonometer (Thorlabs GVS412) to scan a pulsed laser source (Picoquant LDH-D Series) with 640 nm wavelength across a $10 \times 6$ grid on the right wall. This results in 60 image acquisitions. We obtain the multiplexed measurement by summing these 60 measurements in post-processing. We use a single-pixel SPAD (MPD PDM Series) and another set of galvo mirrors (Thorlabs GVS012) to scan the field of view on the left wall across a $80 \times 55$ detector grid. Scanning a single pixel effectively mimics the output of a SPAD array. The laser source has a pulse repetition rate of 20 MHz, average power of 0.5 mW, and pulsewidth of 90 ps (FWHM). The SPAD has a timing bin width of 8 ps and timing jitter of 50 ps (FWHM). We use a pixel dwell time of 100 ms. The overall instrument response function was measured to be 128 ps (FWHM). A time-correlated single photon counter (TCSPC) (Picoquant Hydracharp 400) was used to synchronously record photon arrival times. The experimental setup is shown in Fig. 1. We don’t include an image of the occluder for simplicity, though in a practical application there would be an occluder blocking the mannequin from the camera. We also make the following assumptions about our scene: (1) all shadows are caused by occluded object and not the occluder itself, (2) the occluded object is completely opaque, and (3) there are no interreflections or higher order bounces (e.g. three-bounce light).

**Estimating Shadow Transients** In order to perform image reconstruction, it is necessary to estimate $i_0$. Doing so requires estimation of the time of flight and radiance throughput of every virtual source and virtual detector pair. The time of flights can be estimated as $(\|l - g\| + \|s - l\| + \|s - h\|)/c$ using known locations of $l$ and $s$ from one-bounce signals, where $g$ and $h$ are the laser and camera positions respectively. Estimating the radiance throughput, however, is non-trivial due to model mismatch and SPAD photon statistics. As mentioned in Eq. (1) of the main text, the radiance is modeled as

$$\alpha_{s,1} = \frac{\alpha}{\|l - s\|^2},$$

where $\alpha$ is a uniform scaling for all $l,s$ pairs. Due to model mismatch we do not directly know $\alpha$. Instead, we treat $\alpha$ as a hyperparameter. We compute $A^\top I_0$ and $A^\top I_l$ separately, where $I_0 = I_0/\alpha$ is known from just ToF information. We then tune $\alpha A^\top I_0 - A^\top I_l$ based on an initial estimate of $\alpha$. 

![Figure 1. Experimental Setup.](image-url)
from the laser power. We find that tuning $\alpha$ is easier in the backprojected space than in transient space $\alpha I_0 - I_I$.

**Backprojection Reconstruction** In practice, computing backprojection $f_{bp} = A^\top I_s$ as a matrix multiplication is impractical due to the large dimensionality of $A$. Instead, we compute $f_{bp}$ one entry at a time (i.e. one voxel at a time). For each voxel $x_i$, we compute the dot product of the $i$th column of $A$ and the shadow transient $I_s (x_i = A_i^\top I_s)$. Computing backprojection one voxel at a time ensures that the matrices can be stored in memory. Recall that the column space of $A$ represents the expected space-time measurement for every voxel in the hidden scene (i.e. the space-time impulse response of individual voxels). This impulse response can be computed by using the known positions of the virtual sources and virtual detectors. If a virtual source lies along the ray connecting the voxel and a virtual detector, then an impulse would appear in the transient measurement of that particular virtual detector. Using the known positions of the virtual source and virtual detector, the specific time of flight of that impulse can be computed. Repeating this process for all virtual detectors yields the space-time impulse response of a particular voxel.