StereoDiff: Stereo-Diffusion Synergy for Video Depth Estimation

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Project page & video results: stereodiff.github.io

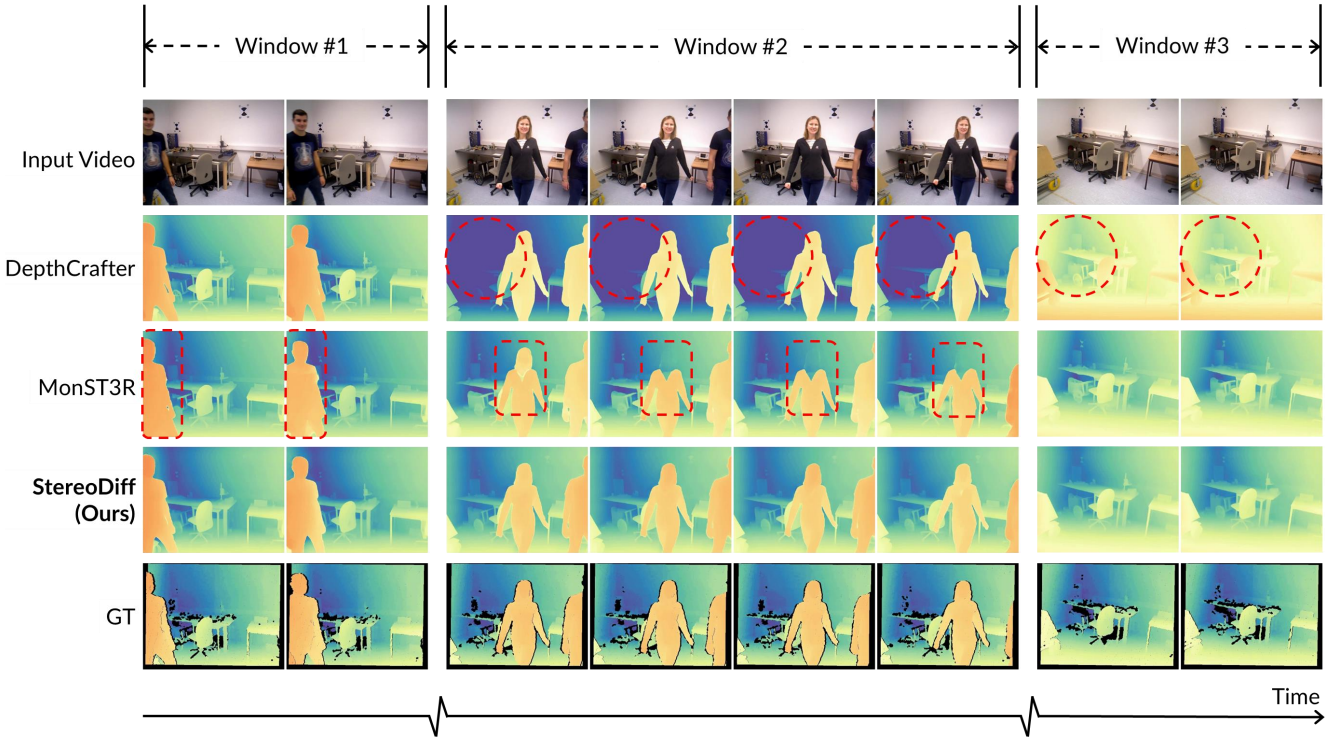


Figure 1. **StereoDiff excels in delivering remarkable global and local consistency for video depth estimation.** In terms of global consistency, StereoDiff achieves highly accurate and stable depth maps on static backgrounds across consecutive windows, leveraging stereo matching to prevent the abrupt depth shifts often seen in DepthCrafter [32], where depth values on static backgrounds can vary significantly between adjacent windows. For local consistency, StereoDiff yields much smoother, flicker-free depth values across consecutive frames, especially in dynamic regions. In contrast, MonST3R [91] suffers from frequent, pronounced flickering and jitters in these areas.

Abstract

*Recent video depth estimation methods achieve great performance by following the paradigm of image depth estimation, i.e., typically fine-tuning pre-trained video diffusion models with massive data. However, we argue that video depth estimation is not a naive extension of image depth estimation. The temporal consistency requirements for dynamic and static regions in videos are fundamentally different. Consistent video depth in static regions, typically backgrounds, can be more effectively achieved via stereo matching across all frames, which provides much stronger global 3D cues. While the consistency for dynamic regions still should be learned from large-scale video depth data to ensure smooth transitions, due to the violation of triangulation. Based on these insights, we introduce **StereoDiff**, a two-stage video depth estimator that synergizes stereo matching for mainly the static areas with video depth diffusion for maintaining consistent depth transitions in dynamic areas. We mathematically demonstrate how stereo matching and video depth diffusion offer complementary strengths through frequency domain analysis, highlighting the effectiveness of their synergy in capturing the advantages of both. Experimental results on zero-shot, real-world, dynamic video depth benchmarks, both indoor and outdoor, demonstrate StereoDiff's SoTA performance, showcasing its superior consistency and accuracy in video depth estimation. Project page: link.*

1. Introduction

Monocular video depth estimation is a foundational task in 3D computer vision. Particularly after the hot trend of leveraging pre-trained Stable Diffusion (SD) [54] for image depth prediction [19, 22, 27, 33, 44], *e.g.*, Marigold [33] and Lotus [27], we have witnessed emerging attentions on video depth estimation in the community [17, 32, 36, 61, 72, 83, 91]. Many of them fine-tune the Stable Video Diffusion (SVD) [4] using large-scale video depth data, *e.g.*, DepthCrafter [32] and DepthAnyVideo [17]. However, most previous methods [17, 32, 61, 75, 82, 83] consider the video depth estimation merely as a video version of image depth estimator, directly modeling a mapping function from the RGB video distribution to the video depth distribution, similar to previous image depth methods that fit a mapping function directly from image distribution to depth.

In this paper, we argue that *video depth estimator is not simply a video version of image depth estimator*. The core attribute of video depth estimation is *consistency*. The consistency for dynamic and static parts of the scene is essentially different and should be handled separately.

① Static regions involve only the camera motion, allowing the 3D structure to be analytically inferred from pairwise correspondences obtained through stereo matching [23, 46, 58, 59, 71, 72, 76, 91] on a sequence of RGB frames, providing strong global 3D cues. The consistency of these areas, primarily about static backgrounds and across all video frames, is termed *global consistency*. Since static elements often occupy a large portion of the scene (*e.g.*, roads, trees, buildings outdoors, or walls, tables, and floors indoors), a strong and robust global consistency is the foundation for achieving consistent and accurate video depth estimation. ② Dynamic parts contain both object motions and camera motion. It is infeasible to achieve analytical 4D reconstruction from RGB sequence alone, as it requires solving unknown object shapes, poses, and motion trajectories simultaneously, which is highly ill-posed. For example, imagine a scene where a person is waving his/her hand from left to right. The predicted depth maps are expected to not only strictly correspond to the RGB inputs in image composition, but also more importantly, maintain consistent, smooth depth changes for the moving hand across consecutive frames, without abrupt fluctuations or flickering. This temporal consistency across short sequences and particularly in dynamic areas, is termed *local consistency*, which should be learned by seeing large amount of video depth data.

Motivated by these analysis, we propose *StereoDiff*, a novel two-stage video depth estimator that synergizes both the stereo matching [36, 72, 91] for accurate global consistency and a video depth diffusion model [17, 32, 61] fine-tuned on large-scale video depth datasets for smooth local consistency. In the first stage of StereoDiff (Sec. 3.2), all video frames are processed in pairs through a stereo matching pipeline and then merged to establish strong global consistency. However, for dynamic objects, depth predictions are limited to pairwise frames (equivalent to a window size of 2), leading to clear inconsistencies (Fig. 1, middle column). Potential camera motion errors can also cause depth jitters across consecutive frames, resulting in suboptimal local consistency. To tackle this issue, in the second stage of StereoDiff (Sec. 3.3), a one-step video depth diffusion process is employed, in order to greatly improve the local consistency of stereo matching-based depth maps while preserving their original strong global consistency, resulting in video depth maps with both high-quality global and local consistency. Leveraging the priors of pre-trained video diffusion models, *e.g.*, SVD, and fine-tuning them with extensive video depth data, video depth diffusion models achieve exceptionally smooth local consistency across neighboring frames. However, it is typically impossible for video diffusion-based video depth estimators to process all video frames simultaneously, which inherently limits their global consistency, as illustrated in the second column of Fig. 1.

We validate StereoDiff on four *zero-shot* video depth benchmarks (Tab. 1): Bonn [47] (real, dynamic, indoor); KITTI [24] (real, dynamic, outdoor); ScanNetV2 [13] (real, static, indoor); and Sintel [8] (synthetic, dynamic, various). The StereoDiff achieves the *best* comprehensive results. We also report the performance on different frequency domains (Tab. 2) and the performance on static and dynamic regions (Tab. 3), to assess on global and local consistency, respectively. StereoDiff effectively retains the strong global consistency established in the first stage while significantly enhancing the local consistency in the second. Additionally, thanks to the one-step denoising policy in the second stage, StereoDiff is ~ 2.1 times faster than DepthCrafter (Please see Sec. 4 in the Supp.). Summarized key contributions are:

- We emphasize that achieving consistent video depth estimation requires distinct treatment for static (background) and dynamic (foreground) regions. Specifically, global consistency is better achieved through stereo matching on static regions, while local consistency for dynamic objects should be learned from large-scale video depth data.
- Based on these insights, we introduce *StereoDiff*, a novel two-stage video depth estimator that synergizes stereo matching for strong global consistency and video depth diffusion for smooth local consistency, delivering reliable video depth estimations. StereoDiff is training-free and does not require test-time optimization.
- Experimental results on dynamic, zero-shot, real-world video depth benchmarks (Tab. 1), both indoor and outdoor, demonstrate StereoDiff's SoTA performance. In addition, analysis across frequency domains (Fig. 3 and Tab. 2) and in dynamic and static regions (Tab. 3) further shows that StereoDiff effectively integrates the strengths of both stereo matching and video depth diffusion models.

2. Related Works

2.1. Image Depth Estimation

Monocular image depth estimation has advanced significantly from early CNN-based approaches [15, 21, 35, 52, 84, 88] to vision transformer-based [14, 53, 85, 89]. To build powerful and generalizable depth estimators, DepthAnything [80, 81] and Metric3D [31, 86] series leveraged extensive training data comprising millions of samples, achieving SoTA performance. Additionally, some methods [1, 5, 48], *e.g.*, DepthPro [5] focus on accurately estimating the metric depth. Recent SD-based depth predictor, *e.g.*, Marigold [33] and GeoWizard [22] incorporated pre-trained diffusion priors for monocular depth estimation, achieved remarkable zero-shot generalizability. More recent studies [27, 44], *e.g.*, Lotus [27], E2E-FT [44], have further shown that single-step diffusion delivers even superior performance.

2.2. Video Depth Estimation

SfM for Video Depth. Traditional Structure-from-Motion (SfM) methods [18, 20, 58, 59, 62, 69, 77, 95] can estimate only static 3D structure and camera positions, as dynamic objects violate triangulation constraints. Neither can those real-time visual SLAM systems [16, 56, 57, 65, 68], *e.g.*, NeuralRecon [65] and DoubleTake [57]. Earlier approaches [23, 46] adapted SfM for motions with strong assumptions, *e.g.*, rigidity. Recently, self-supervised methods [2, 3, 9, 12, 34, 41, 42, 66, 87, 90, 93] have tackled this via jointly estimating of video depth, camera poses, and motion residuals, *e.g.*, GeoNet [87], CasualSAM [93], and Robust-CVD [34, 42]. However, these methods require resource-intensive test-time optimization (or fine-tuning). More recent advancements, *e.g.*, DUSt3R [72], MASt3R [36], and MonST3R [91], deliver more accurate and robust SfM results given monocular videos in an inference-based manner, even with large motions [91]. All video frames are pairwise processed and then merged, which brings global consistency. Nonetheless, due to their pairwise input mechanism, jitters and flickering between consecutive frames still persist, particularly on dynamic objects.

End-to-end Video Depth Estimators. The performance of traditional end-to-end methods [25, 37–39, 67, 70, 73, 75, 82, 83, 90], *e.g.*, DeepV2D [67], NVDS [75], and FutureDepth [83], are inevitable constrained due to limited training data and model capacity. Recently, benefiting from web-scale image datasets [60], diffusion models [11, 26, 28, 45, 50, 51, 54, 55, 63, 64, 92] have achieved exceptional image generation capability, leading to significant progress in video generation [4, 7, 10, 29, 30, 74, 79, 94], *e.g.*, SVD [4] and Sora [7]. More recently, following the advancements of image depth estimation [19, 22, 27, 33, 44], fine-tuning pre-trained video diffusion models using large-scale video depth data has gained traction [17, 32, 61], *e.g.*, DepthAnyVideo [17] and DepthCrafter [32], producing exceptionally smooth video depth predictions. However, input videos are typically divided into windows (of continuous or interpolated frames) and processed sequentially, which can lead to cross-window consistencies due to the absence of global 3D constraints.

Motivated by these methods, StereoDiff synergizes the strengths of both SfM and end-to-end video depth diffusion models, aiming to deliver video depth estimations with both strong global consistency and smooth local consistency.

3. Method

Given a monocular video with a sequence of RGB images $\mathcal{I} = \{I_t\}_{t=0}^{T-1}$, the goal of StereoDiff is to predict consistent depth maps across all video frames. As shown in Fig. 2, StereoDiff is a two-stage video depth estimator designed to achieve both global and local consistency. In the first stage, stereo matching [36, 72, 91] is applied across all frames to establish strong global consistency, *i.e.*, $\mathcal{D}_{\text{s}} = \{D_t^{\text{s}}\}_{t=0}^{T-1} = \Theta_{\text{s}}(\mathcal{I})$. In the second stage, we use a video depth diffusion model [17, 32, 61] to enhance local consistency, particularly for dynamic objects, while preserving the global coherence achieved in the first stage, *i.e.*, $\mathcal{D}_{\text{sd}} = \{D_t^{\text{sd}}\}_{t=0}^{T-1} = \Theta_{\text{d}}(\mathcal{D}_{\text{s}}, \mathcal{I})$. This two-stage approach enables StereoDiff to deliver high-quality video depth that maintain coherence across both static and dynamic regions throughout the video. In Sec. 3.1, we formalize global and local consistency from the perspective of frequency domain analysis. Subsequently, Sec. 3.2 and Sec. 3.3 provide detailed descriptions of each stage.

3.1. Formulation of Consistency

Given a video depth estimation $\hat{\mathcal{D}} = \{\hat{D}_t\}_{t=0}^{T-1}$ and the corresponding GT depth $\mathcal{D}^*$, along with a metric function $f_\epsilon(\cdot)$ to measure the errors between them, we can calculate the sequence of error values:

$$\mathcal{E} = \{\epsilon_t\}_{t=0}^{T-1} = f_\epsilon\left(\mathcal{D}^*, \hat{\mathcal{D}}\right) \tag{1}$$

This error sequence can be represented as a sum of orthogonal waves with different frequencies. In this paper, we use fast Fourier transform (FFT) to compute the Discrete Fourier Transform (DFT) of error sequence $\mathcal{E}$, decomposing it into several frequency components:

$$\mathcal{F}(\epsilon_k) = \sum_{t=0}^{T-1} \epsilon_t \cdot e^{-i2\pi \frac{k}{T} t}, \quad k = 0, 1, \ldots, T-1 \tag{2}$$

where $\mathcal{F}(\epsilon_k)$ represents the frequency component at the k-th frequency domain; T is the total number of frames; and i

[1] For clearer visualization, we filtered out low-confidence 3D points from the full point cloud, like those representing the moving yellow balloon.

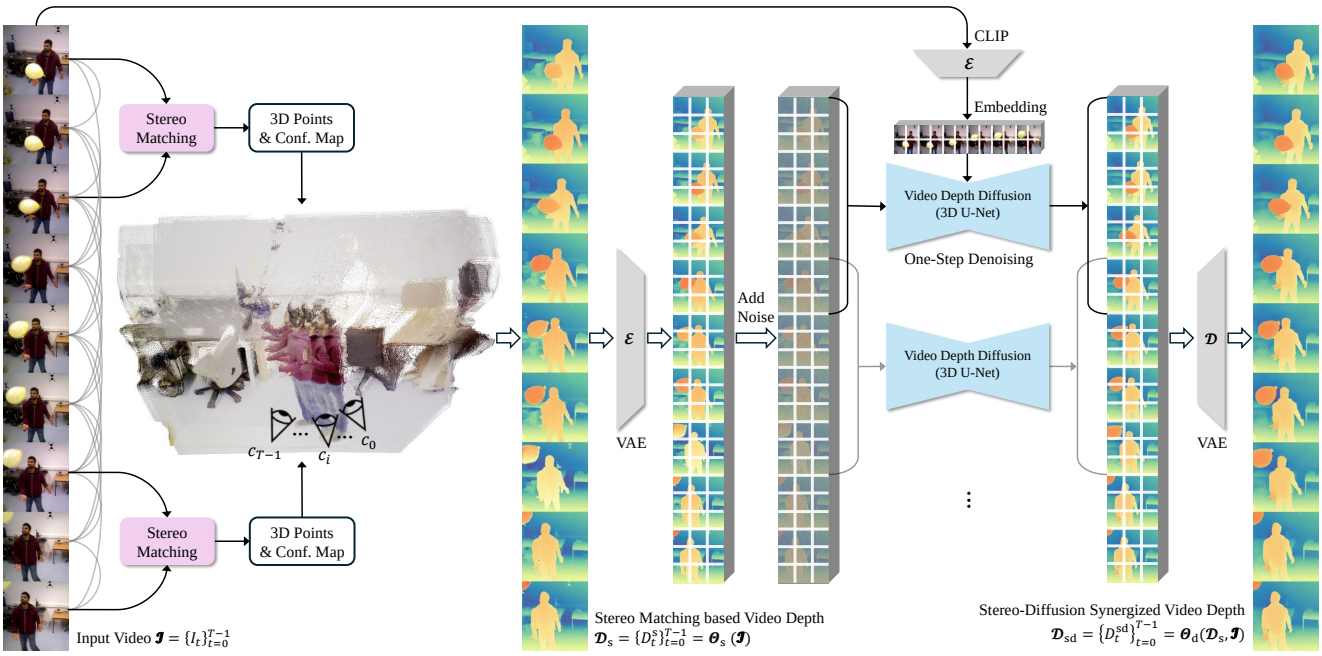


Figure 2. **Pipeline of StereoDiff.** ① All video frames are paired for stereo matching in the first stage, primarily focusing on static backgrounds, in order to achieve a strong global consistency[1]. ② Using the stereo matching-based video depth from the first stage, the second stage of StereoDiff applies a video depth diffusion for significantly improving the local consistency without sacrificing its original global consistency, resulting in video depth estimations with both strong global consistency and smooth local consistency.

is the imaginary unit. The error sequence can further be reconstructed by Inverse DFT:

$$\epsilon_t = \frac{1}{T}\sum_{k=0}^{T-1} \mathcal{F}(\epsilon_k)\cdot e^{i2\pi\frac{k}{T}t}, \quad t = 0, 1, \ldots, T-1 \tag{3}$$

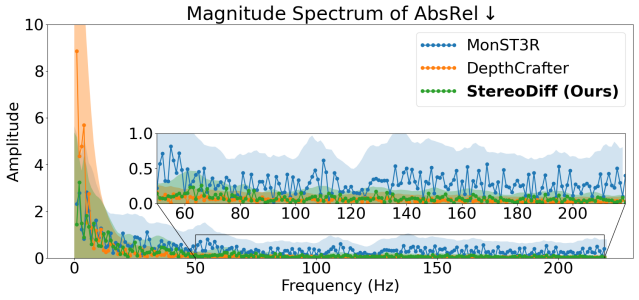
Applying FFT to the error sequence, we can efficiently compute $\mathcal{F}(\epsilon_k)$ for all k frequency domains. This decomposition allows us to analyze the contribution of different frequency bands to the overall error, distinguishing between low-frequency and high-frequency components.

Global consistency refers to the overall stability of depth predictions across the entire video, especially in static backgrounds. For static or minimally dynamic objects, depth changes over time are primarily due to camera motion. Most real-world videos typically have a frame rate much higher than 1 FPS ($\ll$ 1Hz), causing these depth variations to exhibit very low-frequency characteristics, sometimes appearing nearly linear. Global inconsistency often refers to persistent, significant depth deviations that remain stable over long sequences of consecutive frames, which strongly affects the low-frequency components of error sequence $\mathcal{E}$.

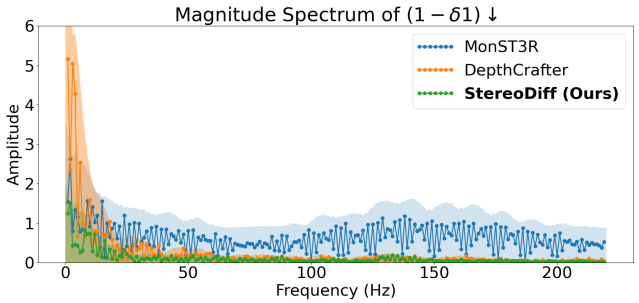
Local consistency focuses on stability between neighboring frames, particularly in dynamic areas with significant motion. Depth variations in these regions are influenced by both camera motion and object motion. Local inconsistencies can arise from: 1) errors in camera motion estimation (common in stereo matching-based methods), causing sudden shifts and depth fluctuations in certain frames; and 2) limited window size, which inevitably prevents consistent and accurate depth tracking of moving objects, resulting in jitters and flickering. Although these local inconsistencies may not be clearly reflected on the overall metrics due to the limited number of affected frames, they can significantly increase the high-frequency amplitudes of the error sequence $\mathcal{E}$.

3.2. Stereo Matching for Global Consistency

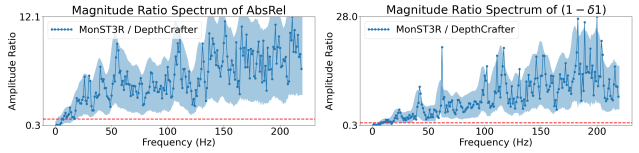
Given the input RGB frames $\mathcal{I}$, the first stage of StereoDiff pairs each frame with the subsequent n frames, forming a total of $nT - (1 + 2 + \cdots + n) = nT - (n+1)n/2$ image pairs. Each pair is then processed through a stereo matching pipeline, resulting in coarse 3D point clouds that ensure the strong global consistency in video depth estimation. Thanks to the advances of SfM [23, 46, 58, 59, 62, 71, 72, 76, 77, 91], we are fortunate to have works like DUSt3R [72], MASt3R [36], and MonST3R [91] that offer highly accurate and robust stereo matching correspondences even without per-scene optimization. In this work, we adopt MonST3R [91] as the stereo matching pipeline, which finetunes DUSt3R [72] with extensive dynamic video data. Compared to DUSt3R, MonST3R more accurately assigns zero confidence to potential low-quality correspondences (*e.g.*, dynamic, blurry) and applies SfM only to static, clear correspondences, significantly enhancing the performance and robustness in dynamic scenes. Typically, an optimization-



(a) Absolute mean relative error (AbsRel) ↓



(b) Inverse accuracy metric $(1-\delta 1)\downarrow$ to align with FFT settings.



(c) Amplitude ratio (MonST3R / DepthCrafter) on AbsRel and $(1-\delta 1)$, with the red dotted line denoting the amplitude ratio $= 1$.

Figure 3. **Magnitude spectrum of the error sequence on Bonn [47] dataset.** The first scene of Bonn, "balloon", containing 438 frames, is used as an example here. Due to symmetry, only the second half of the frequency spectrum is shown. Please see Supp.'s Sec. 2 for the frequency analysis on 3D trajectories.

based post-processing step is applied for improved global alignment after obtaining stereo matching results. However, we exclude this step for three reasons: 1) video depth estimation is a perception task, which is better to be inference-based; 2) the optimization step is both resource-intensive[2] and time-consuming[3]; and 3) Similar to DUSt3R [72] and MASt3R [36], MonST3R [91] inherently maintains global consistency through its closed-form global point cloud initialization, which uses a Minimum Spanning Tree (MST) to find the optimal path in the pairwise stereo matching graph with maximum confidence, followed by rigid point cloud registration [6, 43] to construct the final coarse 3D point clouds. As a result, StereoDiff is not only training-free but also fully inference-based[4].

[2]It requires $>$ 80GB of graphics memory for videos with $\geqslant$ 300 frames at a resolution of 512×384, making it impractical for long videos.

[3]Processing a 200-frame video at 512×384 resolution with a 300-iteration optimization takes over 15 minutes on an NVIDIA A800 GPU.

[4]We omit the Weiszfeld algorithm [49] for focal length estimation, as it requires only 10 iterations and back-propagates gradients into a minimal $T \times 1$ matrix, where T is the number of frames.

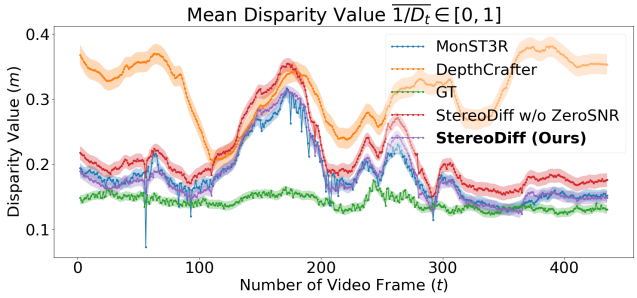


Figure 4. **Comparison of mean disparity[5] value $\overline{1/D_t}$ tested on Bonn [47] dataset** for MonST3R [91], DepthCrafter [32], and StereoDiff. All disparity maps are normalized to $[0, 1]$ on a per-scene basis before comparison. Incorporating ZeroSNR drags the mean value of StereoDiff's disparity maps closer to the GT, resulting in improved performance (Tab. 4).

We denote the depth maps estimated only based on stereo matching as $\mathcal{D}_\text{s} = \{D_t^\text{s}\}_{t=0}^{T-1} = \Theta_\text{s}(\mathcal{I})$ and those only generated by video depth diffusion as $\mathcal{D}_\text{d} = \{D_t^\text{d}\}_{t=0}^{T-1} = \Theta_\text{d}\,(x \sim \mathcal{N}(\mathbf{0}, \mathbf{I}), \mathcal{I})$. As illustrated in Fig. 3, the magnitude spectrum two error sequences measured using AbsRel and $(1-\delta 1)$ (please see Sec. 4.1.3 for specific definitions) are visualized. It is evident that $\mathcal{D}_\text{s}$ exhibits significantly lower low-frequency errors compared to $\mathcal{D}_\text{d}$, indicating strong global consistency. Conversely, $\mathcal{D}_\text{d}$ performs much better in high-frequency domains, which primarily represent the local consistency. These findings demonstrate the promising potential of leveraging the priors from video depth diffusion models to greatly enhance the local consistency of $\mathcal{D}_\text{s}$ while maintaining its original high-quality global consistency.

3.3. Video Depth Diffusion for Local Consistency

Formally, taking $\mathcal{D}_\text{s}$ as input, the video depth diffusion model produces the final video depth prediction, expressed as: $\mathcal{D}_\text{sd} = \{D_t^\text{sd}\}_{t=0}^{T-1} = \Theta_\text{d}(\mathcal{D}_\text{s}, \mathcal{I})$. In this paper, we adopt DepthCrafter [32], a fine-tuned SVD model using $\sim$20K video sequences, to perform a one-step denoising of $\mathcal{D}_\text{s}$. Note that only the pre-trained weight is adopted. Unlike SfM-based video depth estimation, which adheres to the "first principle", video depth diffusion models take a purely "data-driven" approach. These models are fine-tuned from pre-trained video generative models on large-scale video depth data, mapping the RGB video directly to video depth.

As shown in Fig. 3, the depth maps produced by video depth diffusion models $\mathcal{D}_\text{d}$ significantly outperform those based on stereo matching $\mathcal{D}_\text{s}$ in high-frequency domains. Particularly, Fig. 3c depicts the amplitude ratio of the error sequences calculated on $\mathcal{D}_\text{s}$ and $\mathcal{D}_\text{d}$ for clearer demonstration. This suggests that the components in higher frequency

[5]Comparisons are conducted in disparity space rather than true-depth space, because both DepthCrafter and StereoDiff represent their video depth estimations using disparity maps.

domains of $\mathcal{D}_{\text{s}}$, which much more significantly differ from the GT distribution learned by the video depth diffusion models, are more likely treated as noise and effectively denoised. Conversely, the low-frequency characteristics of $\mathcal{D}_{\text{s}}$ align much more closely with the GT video depth distribution, drawing less attention during denoising and thus being better preserved. This results in strong retention of low-frequency features and targeted denoising of high-frequency components, significantly reducing the high-frequency errors in $\mathcal{D}_{\text{s}}$.

Mathematically, substituting $\mathcal{D}_{\text{s}}$ into Eq. 1 yields the corresponding error sequence $\mathcal{E}_{\text{s}} = \{\epsilon_t^{\text{s}}\}_{t=0}^{T-1}$. This temporal signal can then be transformed into the frequency domain $\mathcal{F}(\epsilon_k^{\text{s}}), k \in [0, T-1]$ using FFT (Eq. 2). Similarly, we denote the error sequence of $\mathcal{D}_{\text{sd}}$ as $\mathcal{E}_{\text{sd}} = \{\epsilon_t^{\text{sd}}\}_{t=0}^{T-1}$. $\forall t \in [0, T-1]$, $\epsilon_t^{\text{s}} \geqslant 0$ and $\epsilon_t^{\text{sd}} \geqslant 0$. The average of error sequence yields the final metric: $(1/T)\sum_{t=0}^{T-1} \epsilon_t$. As discussed above and demonstrated in Fig. 3, during the second stage of StereoDiff, the video depth diffusion model acts as a "low-pass filter" on $\mathcal{F}(\epsilon_k^{\text{s}})$. Assuming a threshold K_{thr}, for simplicity, we approximate that after the video depth diffusion process, the magnitudes of all frequency components $> K_{\text{thr}}$ are re-scaled by a factor $\alpha \in (0, 1)$:

$$\mathcal{F}(\epsilon_k^{\text{sd}}) \approx \begin{cases} \mathcal{F}(\epsilon_k^{\text{s}}), & k \leqslant K_{\text{thr}} \\ \alpha \cdot \mathcal{F}(\epsilon_k^{\text{s}}), & k > K_{\text{thr}} \end{cases} \tag{4}$$

Following Parseval's energy theorem, which states that the total energy of the signal in the time domain and frequency domain are equal, we can derive:

$$\begin{aligned} &\sum_{k=0}^{T-1} \left|\mathcal{F}(\epsilon_k^{\text{sd}})\right|^2 \leqslant \sum_{k=0}^{T-1} \left|\mathcal{F}(\epsilon_k^{\text{s}})\right|^2 \\ \Rightarrow \quad &\sum_{t=0}^{T-1} \left|\epsilon_t^{\text{sd}}\right|^2 \leqslant \sum_{t=0}^{T-1} \left|\epsilon_t^{\text{s}}\right|^2 \Rightarrow \frac{1}{T}\sum_{t=0}^{T-1} \epsilon_t^{\text{sd}} \leqslant \frac{1}{T}\sum_{t=0}^{T-1} \epsilon_t^{\text{s}} \end{aligned} \tag{5}$$

This derivation shows that maintaining the low-frequency characteristics of $\mathcal{D}_{\text{s}}$, while reducing the high-frequency components of its error sequence $\mathcal{E}_{\text{s}}$, leads to improved performance. In practice, as illustrated in Fig. 3, StereoDiff's low-frequency error magnitudes $\mathcal{D}_{\text{sd}}$ largely inherit those of $\mathcal{D}_{\text{s}}$, while high-frequency components are significantly reduced by leveraging the video depth diffusion, leading to improved performance (Tab. 1 and 2) and greatly smoothed prediction (Fig. 1), aligning well with our analysis.

ZeroSNR. In diffusion models, the forward process progressively adds Gaussian noise to clean samples according to a pre-defined variance schedule, *i.e.*, $\beta_1, \cdots, \beta_T$:

$$q\left(x_t \mid x_{t-1}\right) = \mathcal{N}\left(x_t; \sqrt{1-\beta_t}x_{t-1}, \beta_t \mathbf{I}\right) \tag{6}$$

Let $\alpha_t = 1 - \beta_t$ and $\bar{a}_t = \prod_{s=1}^{t} \alpha_s$, x_t can be sampled as:

$$q\left(x_t \mid x_0\right) = \mathcal{N}\left(x_t; \sqrt{\bar{a}_t}x_0, \left(1-\bar{\alpha}_t\right)\mathbf{I}\right) \tag{7}$$

Equivalently:

$$x_t = \sqrt{\bar{a}_t}x_0 + \sqrt{1-\bar{a}_t}\epsilon, \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \mathbf{I}) \tag{8}$$

The SNR is defined as: $\text{SNR}(t) = \bar{a}_t/(1-\bar{a}_t)$. Specifically, in DepthCrafter [32] and the standard SVD [4] scheduler[6], the variance sequence is $\beta_0 = 0.00085$ and $\beta_T = 0.012$ with linear scaling, we derive: $x_T \approx 0.0016x_0 + 0.9992\epsilon$. This indicates the input, *i.e.*, x_T, always contains a small amount of signal during training. The leaked signal contains the lowest frequency information, *e.g.*, the mean value. The model learns to denoise with this signal. However, during inference, pure Gaussian noise is used, prompting the model to generate outputs with medium value [40, 44].

As illustrated in Fig. 4, DepthCrafter's video disparity maps have a mean value closer to 0.5 compared to other methods. Although StereoDiff achieves relatively accurate mean disparity values without ZeroSNR due to its first stage (stereo matching), incorporating ZeroSNR further aligns the mean value of StereoDiff's disparity maps closer to GT, resulting in improved performance (Tab. 4).

4. Experiments

4.1. Experimental Settings

4.1.1. Implementation Details

In the first stage, we set $n = 2$ for forming image pairs, symmetrizing them before feeding them into the stereo matching pipeline. The Weiszfeld algorithm [49] is adopted for camera intrinsics, and Procrustes alignment [43] is used for solving camera poses. The maximum resolution is limited to 512. In the second stage, following [32], we set the window size to 110 frames with a 25-frame overlap. The ZeroSNR trick is implemented by setting the `trailing` [40, 44] mode for the timestep spacing in schedulers. Depth maps obtained from the first stage $\mathcal{D}_{\text{s}}$ are resized to the original frame size using `nearest` interpolation before the one-step denoising process, which is performed from denoising timestep $t = 2$ to $t = 1$ with a total number of denoising timesteps $T = 4$.

4.1.2. Evaluation Datasets.

We validate StereoDiff on four *zero-shot* video depth benchmarks: Bonn [47], KITTI [24], ScanNetV2 [13], and Sintel [8]. The complete Bonn dataset comprises 24 dynamic indoor scenes and 2 static indoor scenes. The dynamic motions can be classified into 3 categories: 1) 1 moving object and 1 moving person, 2) only 1 moving person, and 3) 2 moving persons. For the diversity of motions and evaluation efficiency, 6 dynamic scenes (with 332 $\sim$ 580 frames each) are selected: `balloon`, `balloon2`, `person_tracking`, `person_tracking2`, `synchronous`, `synchronous2`. All 13 dynamic outdoor scenes

[6] https://huggingface.co/docs/diffusers/en/api/schedulers/euler

Method	Bonn [47]			KITTI [24]			ScanNetV2 [13]			Sintel [8]			Average
	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	Rank ↓
DepthAnything V2 [81]	0.1250	1.7765	0.8297	0.1758	4.2583	0.6872	0.1445	0.2926	0.7808	0.3983	6.5771	0.5666	6.9
DepthAnything [80]	0.1112	1.5191	0.8860	0.1755	4.3756	0.6875	0.1409	0.2500	0.7978	0.3342	5.5025	0.5833	5.4
DUSt3R [72]	0.1757	2.3618	0.7798	0.3343	7.0966	0.5065	**0.0544**	**0.1184**	0.9782	1.9245	9.8570	0.3964	8.9
MASt3R [36]	0.1748	2.2829	0.7698	0.2250	5.0800	0.6460	0.0957	0.2251	0.9319	0.6130	4.7154	0.5063	7.9
MonST3R [91]	0.0818	1.2412	0.9542	0.1661	4.1881	0.7387	0.0907	0.1631	0.9162	0.5291	4.2812	0.5053	4.1
MonST3R$_{\textbf{OPT}}$ [91]	–	–	–	0.1635	**4.0935**	0.7496	–	–	–	0.5118	**4.2606**	0.5263	3.9
ChronoDepth [61]	0.1248	1.6918	0.8501	0.1749	4.4265	0.7288	0.1955	0.3198	0.6766	0.5421	4.3168	0.5286	7.2
DepthCrafter [32]	0.1104	1.6817	0.8955	0.1617	5.3883	0.7695	0.1879	0.4003	0.6650	**0.2861**	6.1423	**0.6972**	5.7
DepthAnyVideo [17]	0.0942	1.4982	0.9308	0.1487	5.3931	**0.8002**	0.1834	0.4202	0.6771	0.3363	5.5432	0.6378	5.3
StereoDiff$_{\text{DUSt3R}}$	0.1521	2.1402	0.7981	0.2600	6.7388	0.5661	0.0573	0.1393	**0.9789**	1.6521	7.8762	0.3848	8.2
StereoDiff$_{\text{MASt3R}}$	0.1491	2.0866	0.8126	0.1958	5.4359	0.6769	0.0989	0.2600	0.9358	0.4800	7.3534	0.5242	7.7
StereoDiff (Ours)	**0.0799**	**1.2257**	**0.9549**	**0.1469**	4.4183	0.7764	0.0944	0.1985	0.9060	0.3275	5.2812	0.5782	**2.9**

Table 1. **Quantitative comparison of StereoDiff with SoTA methods on zero-shot video depth benchmarks.** The five sections from top to bottom represent: image depth estimators, stereo matching-based estimators, video depth diffusion models, StereoDiff using other stereo matching methods, and StereoDiff. To make sure a comprehensive evaluation, we used four datasets: Bonn [47], KITTI [24], ScanNetV2 [13], and Sintel [8]. We report the mean metrics of StereoDiff across 10 independent runs. MonST3R$_{\textbf{OPT}}$ ($_{\textbf{OPT}}$: with optimization) can not be evaluated on long video depth benchmarks (*i.e.*, Bonn and ScanNetV2) due to computational constraints, please see footnote 2 and 3 for more details. Best results are **bolded** and the second best are underlined.

in KITTI's validation set (with 17 $\sim$ 251 frames each) are used. All 23 dynamic synthetic scenes (each contains 20$\sim$50 frames, most scenes contain 50 frames) of Sintel are used. ScanNetV2 is a static dataset, and randomly selected 4 scenes are used (with 887 $\sim$ 1524 frames each): `scene0078_00`, `scene0192_01`, `scene0348_00`, `scene-0556_01`. During evaluation, the resolution of Bonn, KITTI, ScanNetV2, Sintel are set to 640×480, 1216×352, 640×480, 1280×960, respectively.

Note that for *all* scenes, StereoDiff are evaluated on *full* videos. In comparison, DepthCrafter *cut* the input videos into $\leqslant 110$ frames to avoid cross-window inconsistencies. MonST3R follows DepthCrafter (*e.g.*, Bonn's loading code before evaluation). DepthAnyVideo and DepthAnything series report *single-frame* metrics.

4.1.3. Evaluation Metrics.

Following the affine-invariant evaluation protocols from [17, 19, 27, 32, 33, 44, 61, 91], we firstly align the estimated video depth maps with GT using least-squares fitting, and resize all estimations to match the original size of input video in `nearest` mode. Note that during the least-squares fitting, all frames in a video depth sequence share *identical* scaling and shifting factors, same as DepthCrafter [32] and MonST3R [91]. *Temporal inconsistencies* will lead to worse metrics, *e.g.*, testing MonST3R on Bonn with *per-frame* scale and shift yields an AbsRel of 0.0341, much better than the reported 0.0818. Specifically, given GT $\mathcal{D}^* = \{D_t^*\}_{t=0}^{T-1}$ and fitted predictions $\hat{\mathcal{D}} = \{\hat{D}_t\}_{t=0}^{T-1}$, we report two error metrics: 1) absolute mean relative error (AbsRel) and 2) root-mean-square deviation (RMSE), *i.e.*:

$$\begin{aligned} \text{AbsRel}(\mathcal{D}^*, \hat{\mathcal{D}}) &= \frac{1}{T}\sum_{t=0}^{T-1}\left[\frac{1}{N}\sum_{j=0}^{N-1}\frac{|D_{tj}^* - \hat{D}_{tj}|}{\hat{D}_{tj}}\right] \\ \text{RMSE}(\mathcal{D}^*, \hat{\mathcal{D}}) &= \frac{1}{T}\sum_{t=0}^{T-1}\left[\frac{1}{N}\sqrt{\sum_{j=0}^{N-1}(D_{tj}^* - \hat{D}_{tj})^2}\right] \end{aligned} \tag{9}$$

where $N = H \times W$, indicating the total number of pixels. We also report one accuracy metric: $\delta 1$, denoting the proportion of pixels satisfying $\text{Max}(D_{tj}^*/\hat{D}_{tj}, \hat{D}_{tj}/D_{tj}^*) < 1.25$.

4.2. Quantitative Comparisons

As shown in Tab. 1, StereoDiff achieves the *best* comprehensive results across four zero-shot video depth benchmarks. Furthermore, the results of frequency domain analysis (Tab. 2) demonstrate that StereoDiff effectively maintains the strong low-frequency global consistency achieved via stereo matching, while significantly enhancing the high-frequency local consistency. This enhancement greatly reduces local jitters and flickering across neighboring frames particularly in dynamic areas (Fig. 1), as high-frequency characteristics of $\mathcal{D}_s$ differ much more significantly from the GT distribution learned by the video depth diffusion models, and are more likely treated as noise and effectively denoised. Additionally, Tab. 3 clearly shows that StereoDiff outperforms MonST3R mainly in high-frequency dynamic regions and outperforms DepthCrafter mainly in low-frequency static regions. These results align well with our analysis in Sec. 3.2 and 3.3.

Metrics	Method	Low Freq. ⟵ $\mathcal{F}_0$	$\mathcal{F}_1$	$\mathcal{F}_2$	$\mathcal{F}_3$	$\mathcal{F}_4$	$\mathcal{F}_5$	$\mathcal{F}_6$	$\mathcal{F}_7$	$\mathcal{F}_8$	$\mathcal{F}_9$	⟶ High Freq. $\mathcal{F}_{10}$
AbsRel↓	DepthCrafter	0.1104	0.0152	0.0215	0.0238	0.0286	0.0206	**0.0112**	**0.0062**	**0.0023**	**0.0012**	**0.0009**
	MonST3R	0.0822	**0.0130**	0.0149	0.0142	**0.0149**	**0.0142**	0.0144	0.0116	0.0077	0.0062	0.0067
	StereoDiff (Ours)	**0.0806**	0.0159	**0.0128**	**0.0132**	0.0157	0.0143	0.0135	0.0098	0.0067	0.0043	0.0032
RMSE↓	DepthCrafter	1.6823	0.1783	0.3221	0.2269	0.3125	0.2567	**0.1448**	**0.0884**	**0.0355**	**0.0191**	**0.0144**
	MonST3R	1.2427	**0.0949**	0.1075	**0.1633**	**0.1503**	0.1579	0.1604	0.1356	0.0848	0.0678	0.0726
	StereoDiff (Ours)	**1.2294**	0.1349	**0.1065**	0.1657	0.1659	**0.1565**	0.1469	0.1187	0.0786	0.0517	0.0421
$(1-\delta 1)\downarrow$	DepthCrafter	0.1046	0.0380	0.0655	0.0696	0.0835	0.0619	**0.0331**	**0.0198**	**0.0100**	**0.0046**	**0.0027**
	MonST3R	0.0481	**0.0207**	0.0247	**0.0313**	**0.0408**	**0.0411**	0.0335	0.0258	0.0180	0.0134	0.0150
	StereoDiff (Ours)	**0.0478**	0.0246	**0.0241**	0.0325	0.0428	0.0442	0.0371	0.0261	0.0173	0.0101	0.0069

Table 2. **Quantitative comparisons on Bonn of MonST3R, DepthCrafter, and StereoDiff on different frequency domains.** We use DFT and Inverse DFT to disentangle the components of the metric sequences in various frequency domains. For simplicity, the entire frequency range is divided exponentially into 11 discrete groups: $\mathcal{F}_0, \cdots, \mathcal{F}_{10}$, representing low to high frequencies. We report the results on three well-recognized metrics, AbsRel ↓, RMSE ↓, and $(1-\delta 1)$ ↓. Please see the results on KITTI in the Supp..

Region	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	$\delta 2$ ↑
Dynamic	**-0.0069**	**-0.0844**	**+0.0140**	**+0.0023**
Overall	-0.0020	-0.0150	+0.0013	-0.0042
Static	+0.0009	0	-0.0004	-0.0049

(a) Performance improvement of StereoDiff over MonST3R. For example, $\text{AbsRel} = \text{AbsRel}_{\text{StereoDiff}} - \text{AbsRel}_{\text{MonST3R}}$.

Region	AbsRel ↓	RMSE ↓	$\delta 1$ ↑	$\delta 2$ ↑
Dynamic	-0.0178	-0.2575	+0.0413	**-0.0055**
Overall	-0.0306	-0.4555	+0.0600	-0.0071
Static	**-0.0335**	**-0.4990**	**+0.0641**	-0.0069

(b) Performance improvement of StereoDiff over DepthCrafter.

Table 3. **Quantitative comparisons on dynamic and static regions of Bonn among MonST3R, DepthCrafter and StereoDiff.** We use FlowSAM [78] for masking moving areas. Please see the results on KITTI in the Supp..

Method	AbsRel↓	RMSE↓	$\delta 1$↑	$\delta 2$↑
Naive Solution ***w/*** Latent Sharing ***w/o*** ZeroSNR	0.1245 ±0.0002	1.7807 ±0.0016	0.8503 ±0.0018	0.9719 ±0.0006
w/o Latent Sharing ***w/o*** ZeroSNR	0.0809 ±0.0003	1.2383 ±0.0039	0.9544 ±0.0006	0.9867 ±0.0003
StereoDiff (Ours) ***w/o*** Latent Sharing ***w/*** ZeroSNR	**0.0799** ±0.0001	**1.2257** ±0.0028	**0.9549** ±0.0006	**0.9870** ±0.0004

Table 4. **Ablation studies.** Removing latent sharing strategy and adding the ZeroSNR trick both yield effective performance gains. Here we report the results on Bonn dataset.

5. Ablation Study

As discussed in Sec. 2.2, for video diffusion-based video depth estimators, input videos are typically divided into windows and processed sequentially. In DepthCrafter, this is performed by dividing the video into overlapped windows and sharing the latents of overlapped frames. While this strategy improves continuity, it can still fall short in maintaining consistency between windows, especially on static backgrounds (Fig. 1). As illustrated in Tab. 4, the removal of latent sharing strategy leads to significant performance gains. This is primarily because: 1) the strict spatial correspondence between the diffusion's latent space and the RGB space, making latent sharing ineffective for scenes with moving cameras or objects, which may lead to harmful feature distortions, especially as the timestep $t \to 0$; and 2) in DepthCrafter's original multi-step denoising process, the latent is progressively refined from Gaussian noise, where sharing latents across overlapping frames can not only aids consistency at early timesteps ($t \to T$) but also allows the distortions of latent feature to be gradually refined as $t \to 0$. Additionally, incorporating ZeroSNR aligns the mean value of StereoDiff's disparity maps more closely with the GT (Fig. 4), further enhancing the performance.

Supplementary Material: The quantitative comparisons on temporal consistency and inference speed are detailed in Supp.'s Sec. 3 and Sec. 4. Please also see the Supp.'s Sec. 1, Sec. 2, and Sec. 5 for the qualitative comparisons, frequency analysis on 3D trajectories, and the limitations.

6. Conclusion

In this paper, we emphasize the need for distinct strategies to achieve consistent video depth estimation across static and dynamic regions. Motivated by these insights, we introduce StereoDiff, a novel two-stage video depth estimator that combines stereo matching for strong global consistency provided by the global 3D constraints, and video depth diffusion for significantly enhanced local consistency. Experimental results on two well-acknowledged video depth benchmarks (Tab. 1), including the frequency domain analysis (Fig. 3, Tab. 2), demonstrate StereoDiff's effectiveness in synergizing the strengths of both, achieving SoTA performance in dynamic, zero-shot, real-world video depth estimation.

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