Relativistic Effects for Time-Resolved Light Transport

Adrian Jarabo\textsuperscript{1} \hspace{1cm} Belen Masia\textsuperscript{1,2,3} \hspace{1cm} Andreas Velten\textsuperscript{4}
Christopher Barsi\textsuperscript{2} \hspace{1cm} Ramesh Raskar\textsuperscript{2} \hspace{1cm} Diego Gutierrez\textsuperscript{1}

\textsuperscript{1}Universidad de Zaragoza \hspace{1cm} \textsuperscript{2}MIT Media Lab \hspace{1cm} \textsuperscript{3}I3A \hspace{1cm} \textsuperscript{4}Morgridge Institute for Research
Motivation
Motivation – Time-resolved Imaging

[Velten et al. SIGGRAPH 2012; 2013]
Motivation – Time-resolved Imaging

Can we visualize the data from different viewpoints?

Time-Resolved Data

+ Obtained Geometry
Motivation – Time-resolved Imaging

Can we visualize the data from different viewpoints?
Can we visualize the data from different viewpoints?
Motivation – Time-resolved Imaging

Can we visualize the data from different viewpoints?
Motivation – Time-resolved Imaging

In the scene, the camera is moving at relativistic speeds.

The need to model relativistic effects naturally arises when visualizing time-resolved data.
Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering...

[Hsiung et al. 1990; Chang et al. 1996; Weiskopf et al. 1999; 2000] [Weiskopf et al. 2006]
Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering...

OpenRelativity [Kortemeyer et al. 2013]
A Slower Speed of Light
Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering...

Limitations of previous methods:

(1) do not deal with non-constant irradiance
Time-Resolved Imaging & Relativistic Rendering

Us (Time-resolved) vs Previous Work
Time-Resolved Imaging & Relativistic Rendering

Real Captured Data [Velten et al. SIGGRAPH 2013]

Synthetic Data [Jarabo et al. SIGGRAPH ASIA 2014]
Limitations of previous methods:

(1) do not deal with non-constant irradiance
Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering...

Limitations of previous methods:

(1) do not deal with non-constant irradiance
(2) do not consider camera transformations
Time-Resolved Imaging & Relativistic Rendering

We are not the first to do relativistic rendering...

Limitations of previous methods:

(1) do not deal with non-constant irradiance
(2) do not consider camera transformations
(3) do not handle relativistic rotation
Rendering Relativistic Effects

\[ L_\lambda(\theta, \phi, \lambda, t) \quad \leftrightarrow \quad L'_\lambda(\theta', \phi', \lambda', t') \]

Radiance in world frame

Radiance in camera frame

\[ v = \beta \cdot c \]
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

Previous Work

Geometry deformation
Relativistic Effects – Light Aberration

Static

\[ \beta = 0 \quad \beta = 0.3 \quad \beta = 0.6 \quad \beta = 0.9 \quad \beta = 0.99 \]

Camera approaching the scene

Camera moving away from the scene
Render Relativistic Effects

Five main phenomena:

- Light aberration → Geometry deformation
- Doppler effect → Color shift
- Searchlight effect
- Time dilation
- Camera deformation

Previous Work
Relativistic Effects – Doppler Effect

*Static*

\[ \beta = 0 \quad \beta = 0.15 \quad \beta = 0.25 \quad \beta = 0.35 \quad \beta = 0.50 \quad \beta = 0.55 \]

Camera approaching the scene

UV
Rendering Relativistic Effects

Five main phenomena:

- Light aberration → Geometry deformation
- Doppler effect → Color shift
- Searchlight effect → Change in brightness
- Time dilation
- Camera deformation

Previous Work
Relativistic Effects – Searchlight Effect

Static

$\beta = 0$  $\beta = 0.2$  $\beta = 0.3$  $\beta = 0.4$  $\beta = 0.5$

Camera approaching the scene
Rendering Relativistic Effects

Five main phenomena:

- Light aberration → Geometry deformation
- Doppler effect → Color shift
- Searchlight effect → Change in brightness
- Time dilation
- Camera deformation
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation
Relativistic Effects – Time Dilation
Relativistic Effects – Time Dilation

\[ t_1 = t_0 + \frac{d}{c} \]
Relativistic Effects – Time Dilation

Lorentz contraction

\[ l' = \frac{l}{\gamma} \]
\[ \Delta t' = \gamma \Delta t \]
\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

\[ t_1 = t_0 + \frac{d}{c} \]
Relativistic Effects – Time Dilation

Lorentz contraction

\[ l' = \frac{l}{\gamma} \]
\[ \Delta t' = \gamma \Delta t \]
\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

\[ t'_1 = \gamma t_0 + \frac{d}{(\gamma c)} \]
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

Increase Frame Rate
Non-Constant Rad. Integration
Rendering Relativistic Effects
Rendering Relativistic Effects
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation

Previous Work
Relativistic Effects – Camera deformation

Old camera model:
Relativistic Effects – Camera deformation

Old camera model:

- Incoming Light
- 0D Camera
Relativistic Effects – Camera deformation

Pinhole camera model:
Relativistic Effects – Camera deformation

\[ v = \beta c \]

Lorentz contraction

\[ d = \frac{d'}{\gamma} \]

- **Sensor**
- **Pinhole Aperture**
- **FOV** \( \alpha/2 \)
- **Incoming Light**
Relativistic Effects – Camera deformation

\[ v = \beta c \]

Lorentz contraction

\[ d = \frac{d'}{\gamma} \]
Relativistic Effects – Camera deformation

\[ \alpha' = 2 \arctan \left( \frac{\tan(\alpha/2)}{\gamma} \right) \]
Relativistic Effects – Camera deformation

Without

With

\[ \beta = 0.35 \]
Relativistic Effects – Camera deformation

Without

With

$\beta = 0.50$
Rendering Relativistic Effects

Five main phenomena:

- Light aberration
- Doppler effect
- Searchlight effect
- Time dilation
- Camera deformation
Relativistic Effects – All together...
Relativistic Effects – All together...
Rendering Relativistic Effects

More than just linear non-accelerated motion...

Relativistic Acceleration

Relativistic Rotation
Relativistic Acceleration
Relativistic Acceleration

\[ \beta_{\text{sensor}} = 0.7 \]
Relativistic Acceleration

\[ \beta_{\text{sensor}} = 0.7 \]
Relativistic Acceleration

\[ e_1 \rightarrow e_2 \]

\[ \text{time} \]

\[ \text{space} \]

\[ \beta_{\text{sensor}} = 0.7 \]
Relativistic Effects – Camera deformation

\[ \alpha' = 2 \arctan \left( \frac{\tan(\alpha/2)}{\gamma} \right) \]
Relativistic **Acceleration**

Constant Speed  Acceleration

\[ \beta = 0.6 \]
Relativistic Acceleration

Constant Speed

Acceleration

$\beta = 0.9$
Relativistic Acceleration

Constant Speed

Acceleration
Rendering Relativistic Effects

More than just linear non-accelerated motion...

Relativistic Acceleration

Relativistic Rotation
Relativistic Rotation

No commonly accepted theory for relativistic rotation
Relativistic Rotation

\[ \beta = 0.2 \quad \beta = 0.4 \quad \beta = 0.8 \quad \beta = 0.99 \]
Relativistic Rotation

\[ \theta \approx 0^\circ \]

\[ d\beta_0 \]

\[ dx_0 \]

\[ dx_2 \]

\[ \beta_2 \]

Sensor
Relativistic Effects – Rotation
Conclusion & Future Work

Relativistic rendering framework of time-resolved data:
• **non-constant** time-resolved radiance
• **acceleration** and **rotation** for visualization
• **pinhole camera** model with **camera deformation**

**Future Work:**
• General relativity -> Gravitational Forces
• More sophisticated camera models
• Lift Lambertian surface assumption
Relativistic Effects for Time-Resolved Light Transport

THANKS!

Adrian Jarabo\textsuperscript{1} \quad Belen Masia\textsuperscript{1,2,3} \quad Andreas Velten\textsuperscript{4}
Christopher Barsi\textsuperscript{2} \quad Ramesh Raskar\textsuperscript{2} \quad Diego Gutierrez\textsuperscript{1}

\textsuperscript{1}Universidad de Zaragoza \quad \textsuperscript{2}MIT Media Lab \quad \textsuperscript{3}I3A \quad \textsuperscript{4}Morgridge Institute for Research
Implementation Details

Standalone app., **real-time**, OpenGL

x-y-t data => 3D texture in GPU in world time

Light aberration => geometry needs to be **re-tessellated**

Doppler effect => wavelength-to-RGB 1D texture

Searchlight effect => pre-integrate (in time) irradiance values & **anisotropic mipmapping** to later access them
Time Unwarping

Captured (camera time)

Corrected for depth

Corrected for depth and scattering
# Femto-photography Setup System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Resolution</td>
<td>2 ps (0.6 mm)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>672 by up to 1000 pixels</td>
</tr>
<tr>
<td>Time gating contrast</td>
<td>100% (sensor)</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Photon counting, ~10% quantum efficiency</td>
</tr>
<tr>
<td>Illumination Power</td>
<td>500 mW</td>
</tr>
<tr>
<td>Capture Time</td>
<td>About 1 hour for presented videos (limited by camera SNR and amount of available photons)</td>
</tr>
</tbody>
</table>
Femto-Photography Setup

Laser

BS

Synchronization

Streak Tube

Scene

D

L

Zoom Lens
Image Intensifier
Femto-Photography Setup

- Laser
- Streak Tube
- Synchronization
- Zoom Lens
- Streak Camera View

Diagram showing the setup with labeled components: Laser, BS, Streak Tube, Synchronization, Zoom Lens, and Scene.
Camera Picture – *a 1D Movie*
Going from 1D to 2D