Volumetric Printing by reverse tomography: pattern optimization

Felix Wechsler
www.felixwechsler.science

École Polytechnique Fédérale de Lausanne (EPFL)

Laboratory of Applied Photonics Devices (LAPD)

April 3, 2023

Supervisor: Prof. Christophe Moser

3D PRINTING

Volumetric additive manufacturing via tomographic reconstruction

Brett E. Kelly[1,2*], Indrasen Bhattacharya[3*], Hossein Heidari[1*], Maxim Shusteff[2], Christopher M. Spadaccini[4], Hayden K. Taylor[1†]

Object-Space Optimization of Tomographic Reconstructions for Additive Manufacturing

Charles M. Rackson[1], Kyle M. Champley[2], Joseph T. Toombs[3], Erika J. Fong[2], Vishal Bansal[3], Hayden K. Taylor[3], Maxim Shusteff[2], Robert R. McLeod[1].

[1]Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
[3]Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA 94720, USA.
Email addresses of authors: charles.rackson@colorado.edu, champley1@llnl.gov, jtoombs@berkeley.edu, fong26@llnl.gov, vishal-bansal@outlook.com, hkt@berkeley.edu, shusteff1@llnl.gov, robert.mcleod@colorado.edu.
Corresponding author: Charles M. Rackson.

Research Article Vol. 31, No. 4 / 13 Feb 2023 / *Optics Express* 5531

Optics EXPRESS

Versatile volumetric additive manufacturing with 3D ray tracing

DANIEL WEBBER,* YUJIE ZHANG, MICHEL PICARD, JONATHAN BOISVERT, CHANTAL PAQUET, AND ANTONY ORTH

National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada
*daniel.webber@nrc-cnrc.gc.ca

3D PRINTING

Volumetric additive manufacturing via tomographic reconstruction

Brett E. Kelly[1,2]*, Indrasen Bhattacharya[3]*, Hossein Heidari[1]*, Maxim Shusteff[2], Christopher M. Spadaccini[4], Hayden K. Taylor[1]†

Object-Space Optimization of Tomographic Reconstructions for Additive Manufacturing

Charles M. Rackson[1], Kyle M. Champley[2], Joseph T. Toombs[3], Erika J. Fong[2], Vishal Bansal[3], Hayden K. Taylor[3], Maxim Shusteff[2], Robert R. McLeod[1].

[1]Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
[3]Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA 94720, USA.
Email addresses of authors: charles.rackson@colorado.edu, champley1@llnl.gov, jtoombs@berkeley.edu, fong26@llnl.gov, vishal-bansal@outlook.com, hkt@berkeley.edu, shusteff1@llnl.gov, robert.mcleod@colorado.edu.
Corresponding author: Charles M. Rackson.

Research Article Vol. 31, No. 4 / 13 Feb 2023 / *Optics Express* 5531

Optics EXPRESS

Versatile volumetric additive manufacturing with 3D ray tracing

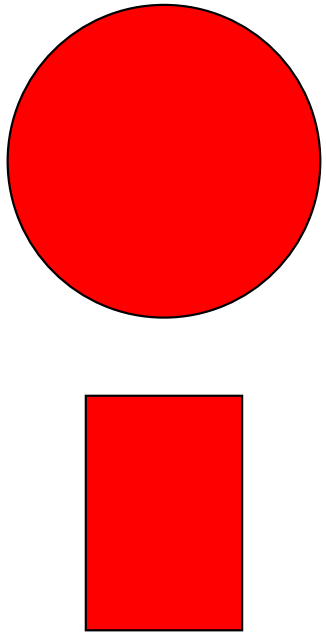
DANIEL WEBBER,* YUJIE ZHANG, MICHEL PICARD, JONATHAN BOISVERT, CHANTAL PAQUET, AND ANTONY ORTH

National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada
**daniel.webber@nrc-cnrc.gc.ca*

Volumetric Additive Manufacturing (VAM)

Revisit Computed Tomography - Angle 0°

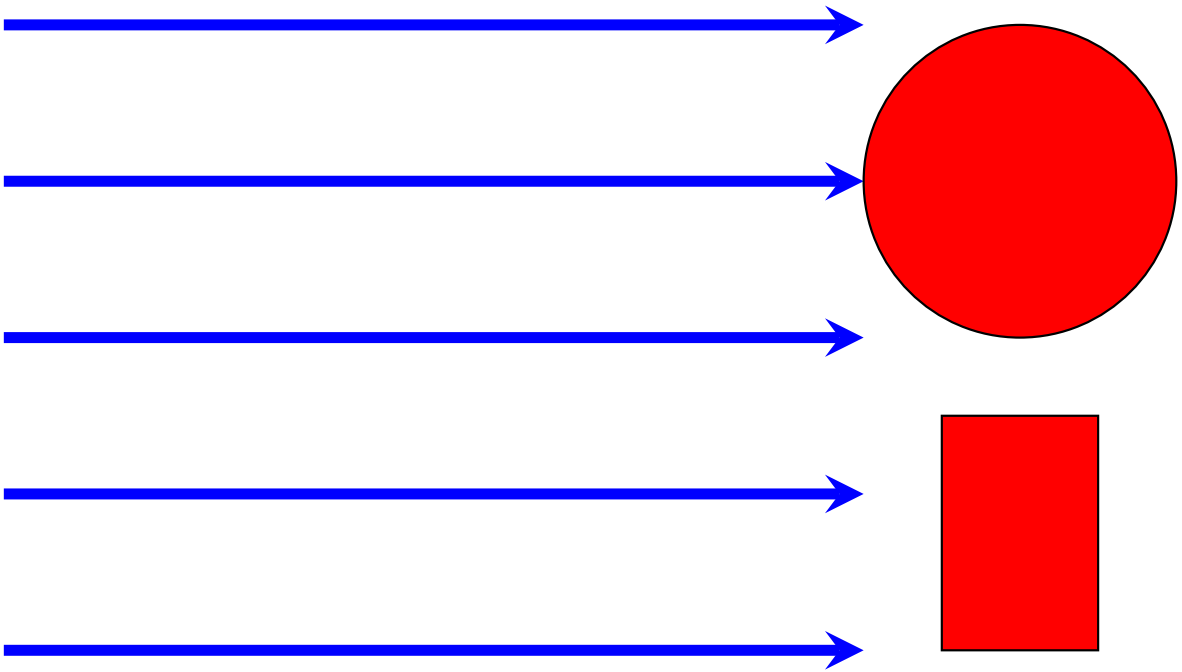
absorbing object



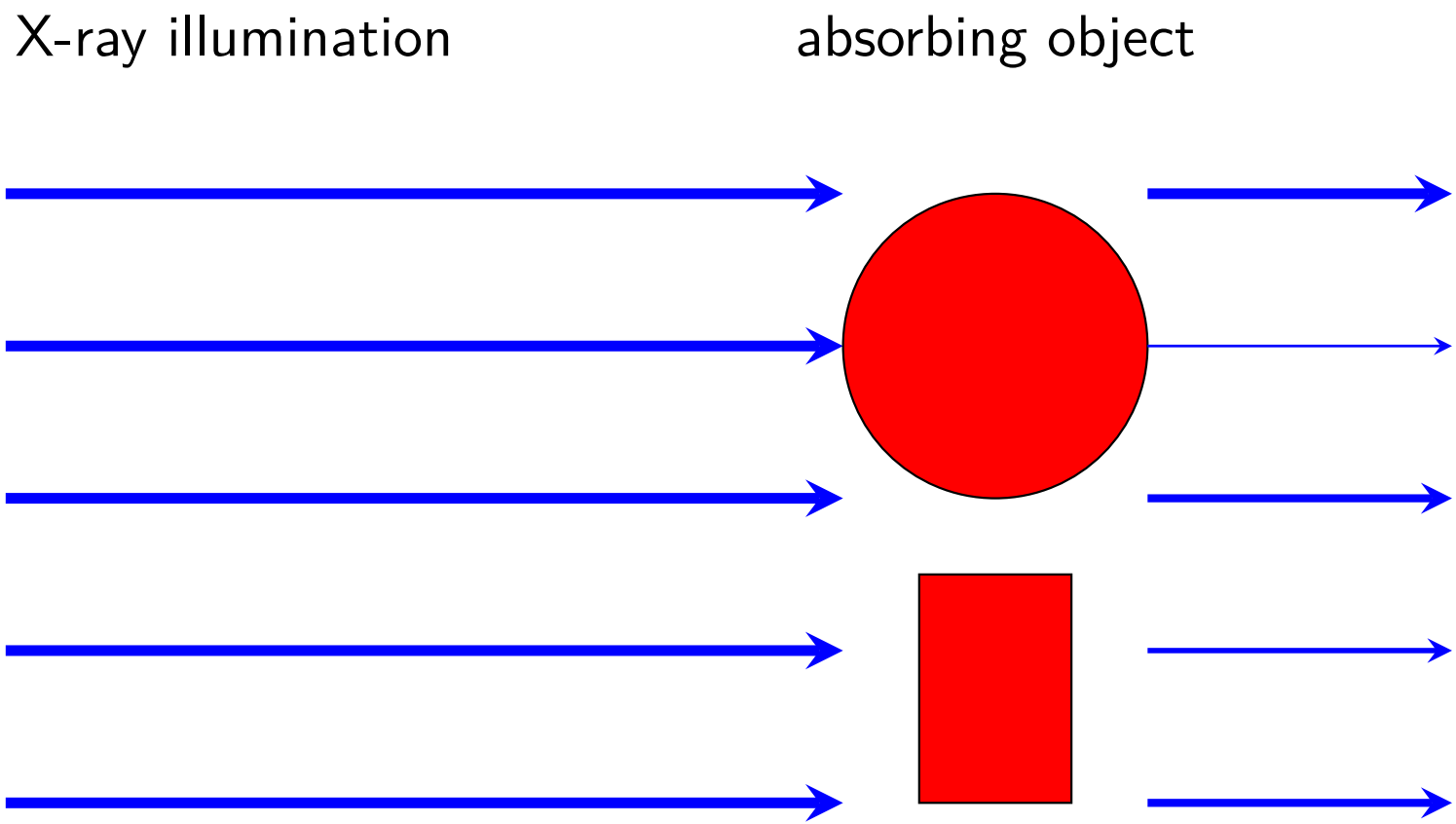
Revisit Computed Tomography - Angle 0°

X-ray illumination

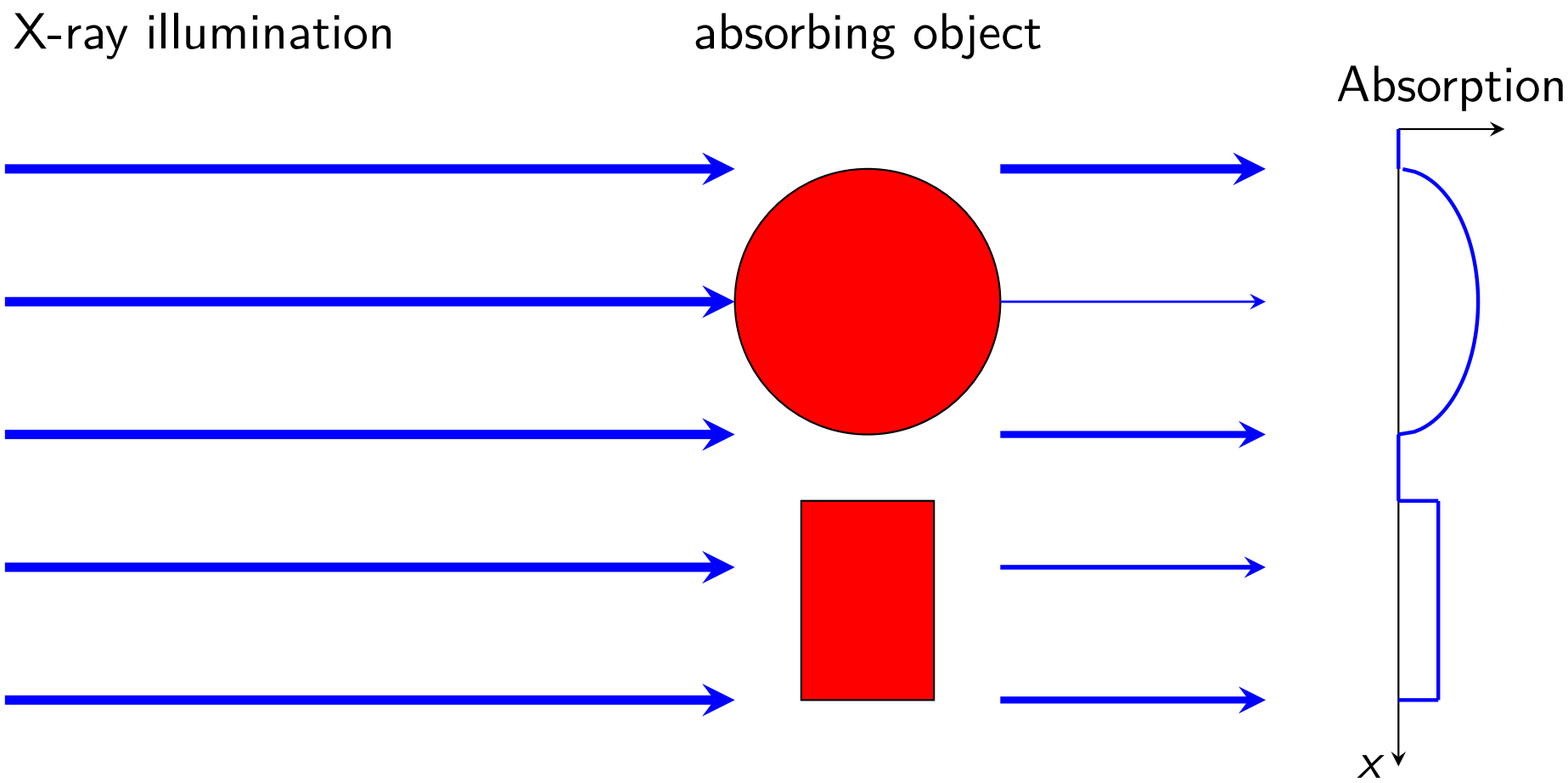
absorbing object



Revisit Computed Tomography - Angle 0°

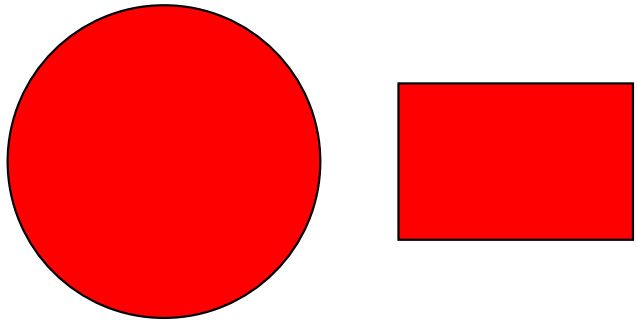


Revisit Computed Tomography - Angle 0°

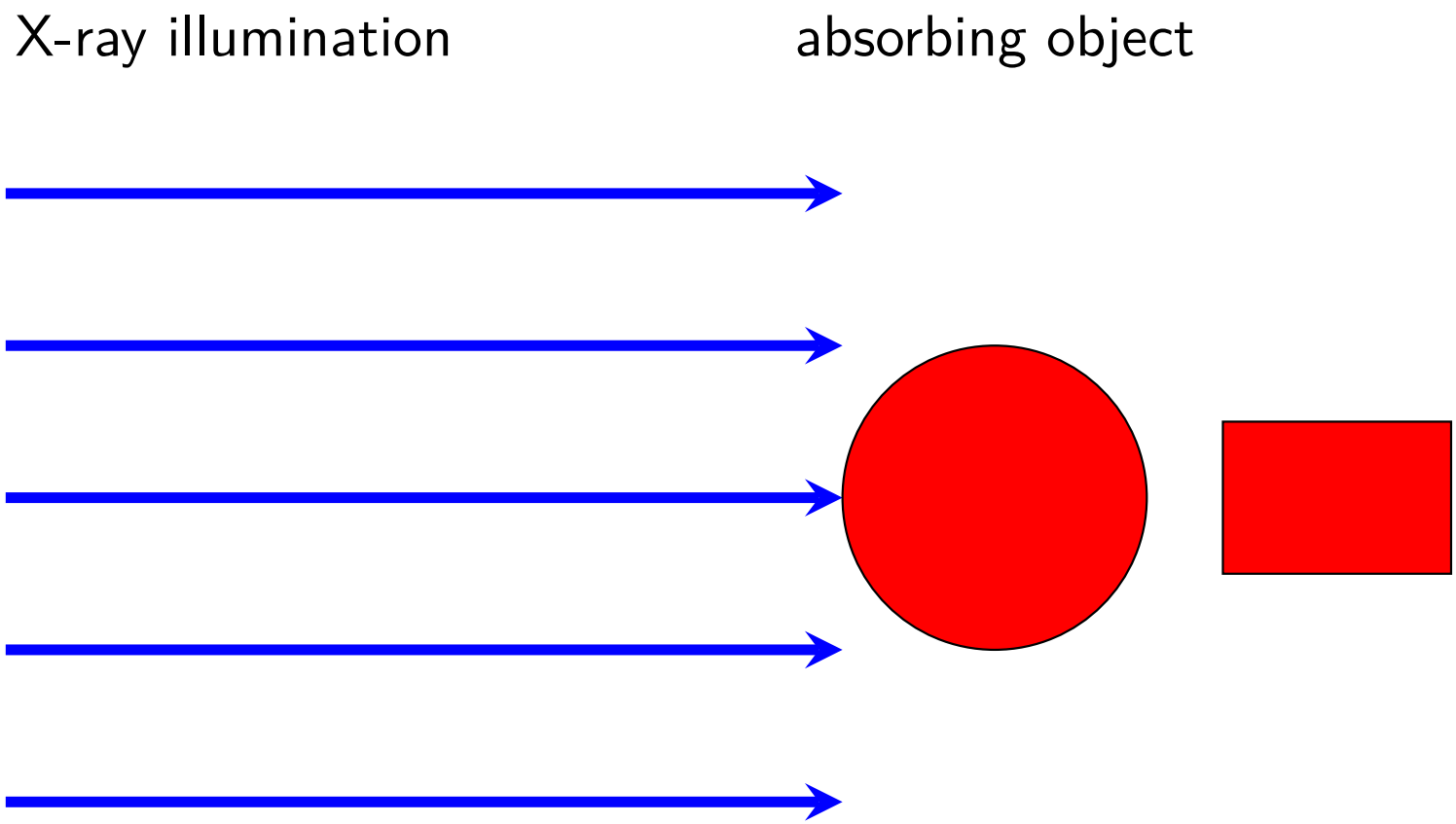


Example CT - Angle 90°

absorbing object

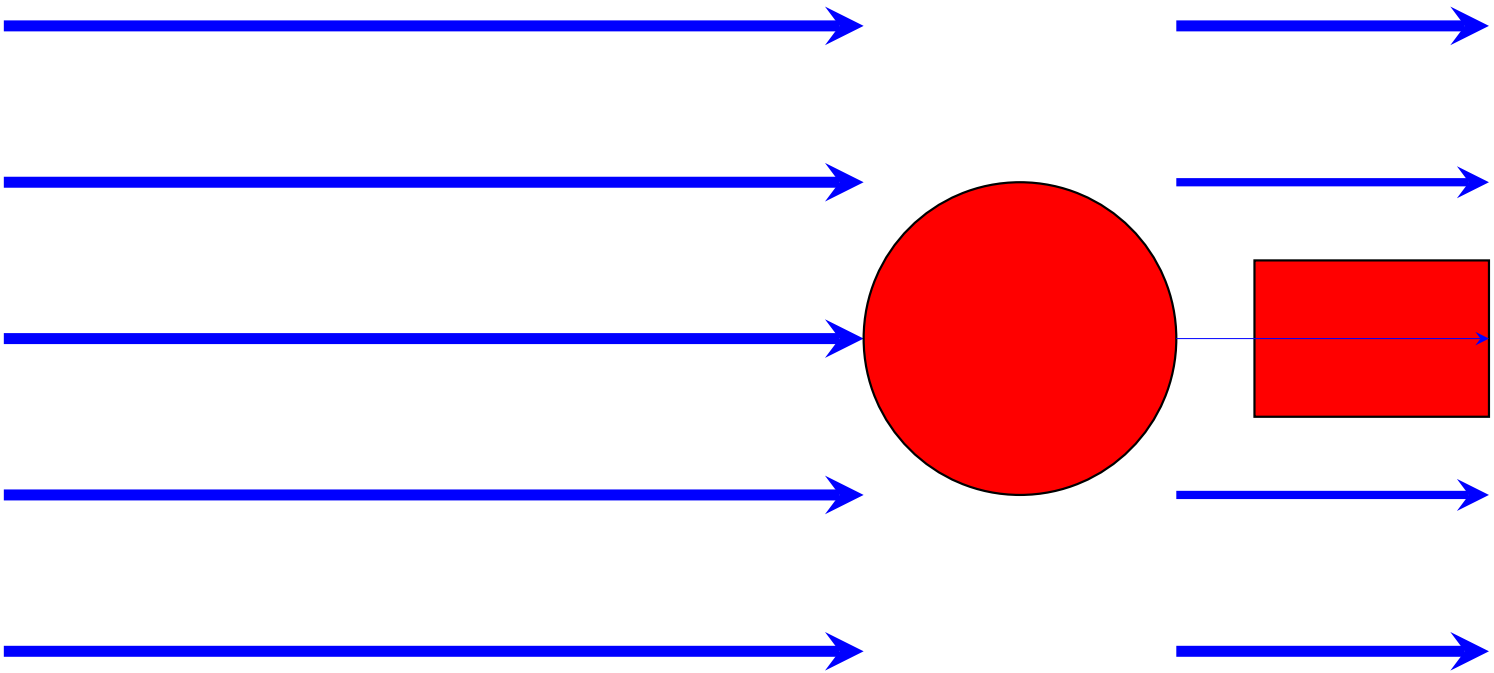


Example CT - Angle 90°

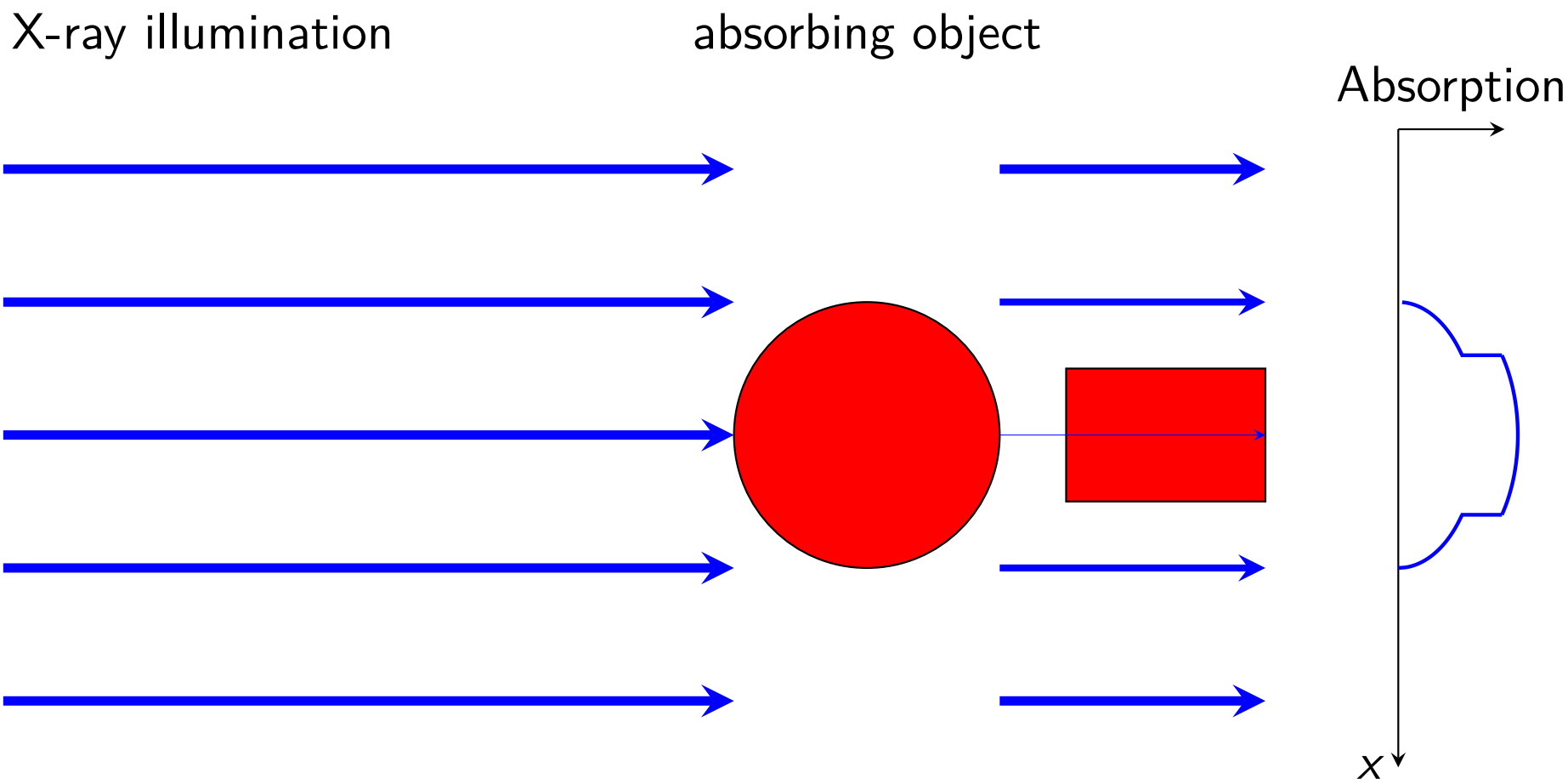


Example CT - Angle 90°

X-ray illumination absorbing object



Example CT - Angle 90°



Revisit Computed Tomography (CT)

The mathematical concept of the CT is the Radon transform $\mathcal{R}$:

$$\mathcal{R}f(\alpha, s) = \int_{-\infty}^{\infty} f((z\sin\alpha + s\cos\alpha), (-z\cos\alpha + s\sin\alpha))\,\mathrm{d}z \quad (1)$$

The sinogram $\mathcal{R}f(\alpha, S)$ stores the integral for each angle and detector position.

- f: the object
- α: rotation angle object
- S: 1D detector coordinate

Live Demonstration

Inverse Radon transform

To reconstruct the object, *smear* each projection of the sinogram back into space:

$$\mathcal{R}^* g(x, y) = \frac{1}{2\pi} \int_0^{2\pi} g(\alpha, \mathbf{n}(\alpha) \cdot (x, y)^T) \, \mathrm{d}\alpha \tag{2}$$

- $g = \mathcal{R} f$
- $\mathbf{n}(\alpha)$ is the normal vector to α

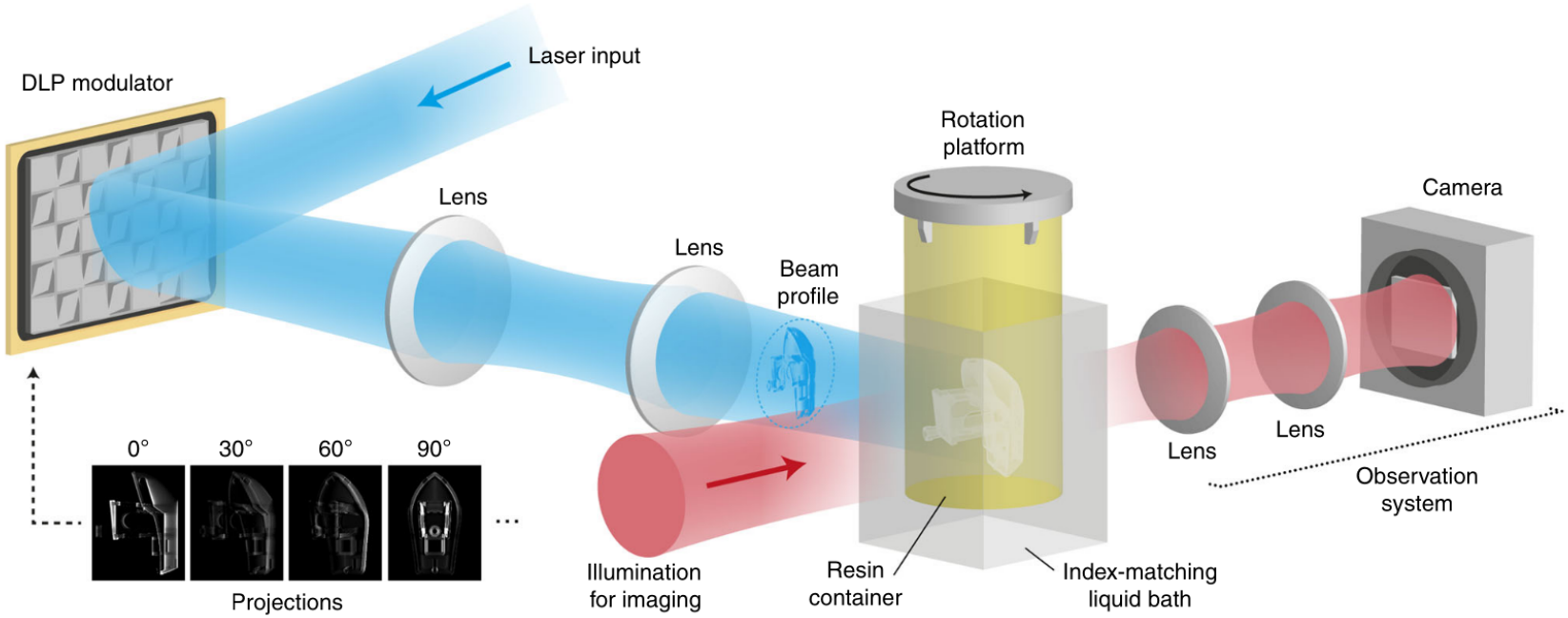
Drawback, it's not an inverse operation!

$$\mathcal{F}\left[\mathcal{R}^* \mathcal{R} f\right](\mathbf{k}) = \frac{\mathcal{F}[f](\mathbf{k})}{\|\mathbf{k}\|} \tag{3}$$

$\Rightarrow$ We need to filter the projection patterns.

Volumetric Additive Manufacturing (VAM)

Volumetric Additive Manufacturing (VAM)

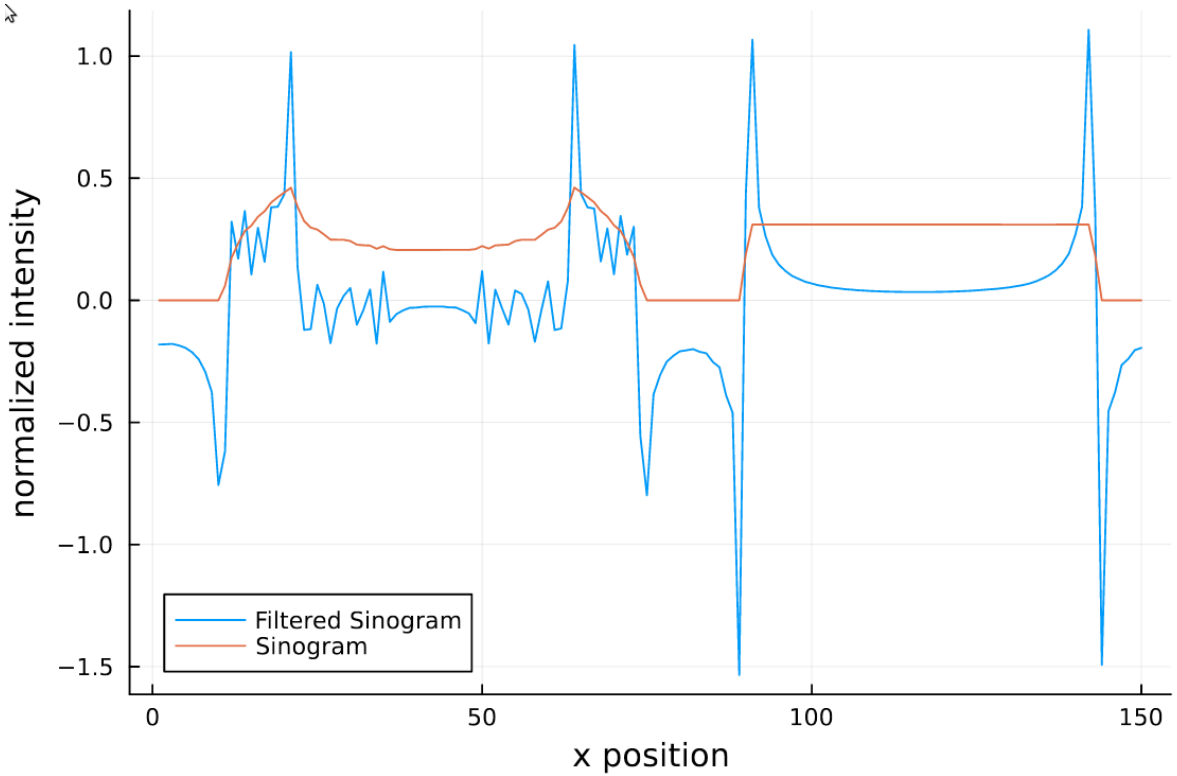


- Coherent Laser $\lambda \approx 405\,\text{nm}$ with $P \approx 6\,\text{W}$
- Photosensitive resin polymerizes after reaching a single photon absorption threshold
- Printing time $\approx 20\,\text{s}$

Figure taken from [LDM20]

Issue with VAM

Filtered sinogram for exact reconstruction contains negative projection intensities



But: We can't project negative intensities (yet).

3D PRINTING

Volumetric additive manufacturing via tomographic reconstruction

Brett E. Kelly[1,2*], Indrasen Bhattacharya[3*], Hossein Heidari[1*], Maxim Shusteff[2], Christopher M. Spadaccini[4], Hayden K. Taylor[1†]

Object-Space Optimization of Tomographic Reconstructions for Additive Manufacturing

Charles M. Rackson[1], Kyle M. Champley[2], Joseph T. Toombs[3], Erika J. Fong[2], Vishal Bansal[3], Hayden K. Taylor[3], Maxim Shusteff[2], Robert R. McLeod[1].

[1]Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
[3]Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA 94720, USA.
Email addresses of authors: charles.rackson@colorado.edu, champley1@llnl.gov, jtoombs@berkeley.edu, fong26@llnl.gov, vishal-bansal@outlook.com, hkt@berkeley.edu, shusteff1@llnl.gov, robert.mcleod@colorado.edu.
Corresponding author: Charles M. Rackson.

Research Article Vol. 31, No. 4 / 13 Feb 2023 / *Optics Express* 5531

Optics EXPRESS

Versatile volumetric additive manufacturing with 3D ray tracing

DANIEL WEBBER,* YUJIE ZHANG, MICHEL PICARD, JONATHAN BOISVERT, CHANTAL PAQUET, AND ANTONY ORTH

National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada
**daniel.webber@nrc-cnrc.gc.ca*

Iradon is not exact

Naively sending non-zero intensities produces smeared image

But:

- Photoresin has a certain absorption threshold

$\Rightarrow$ intensity regions below threshold don't polymerize

Rackson et al. propose iterative scheme to adapt the projections

Object Space optimization

Print object *virtually* with non-negative intensities and adapt the object.

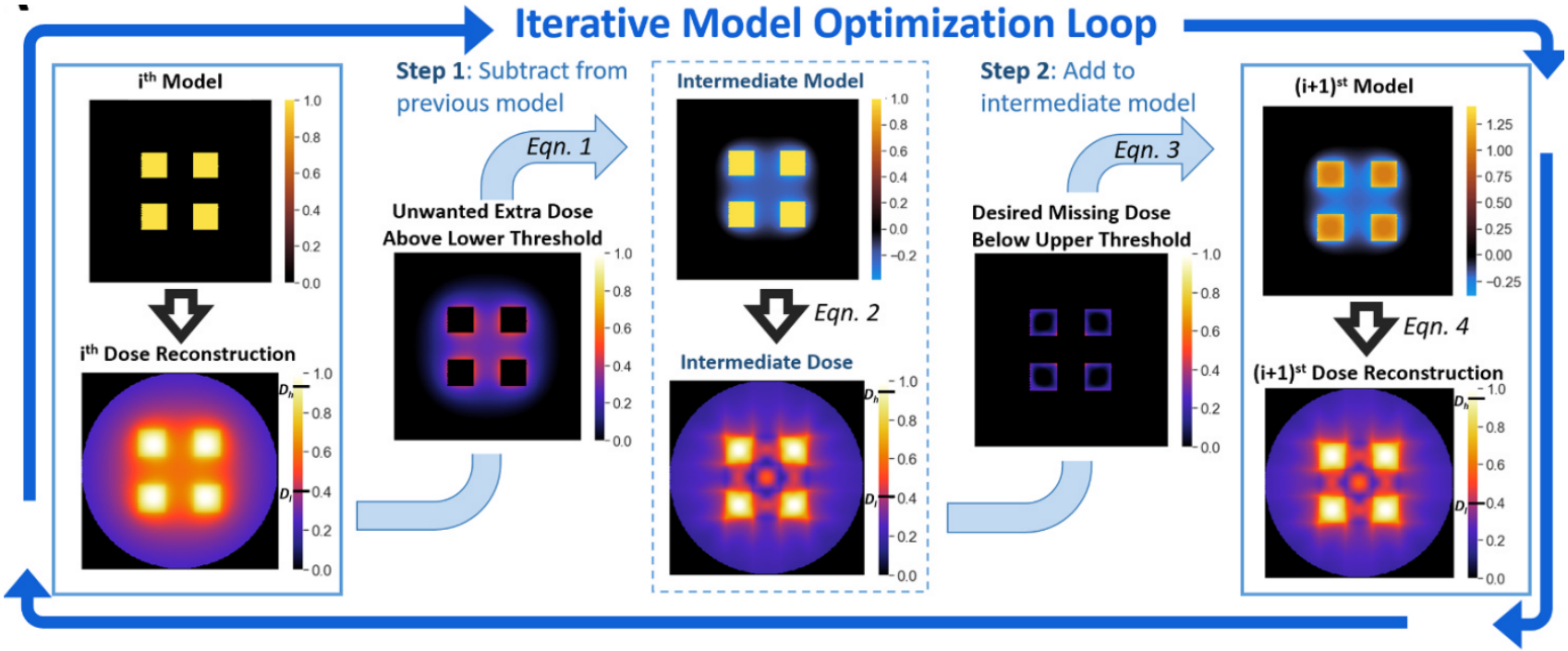
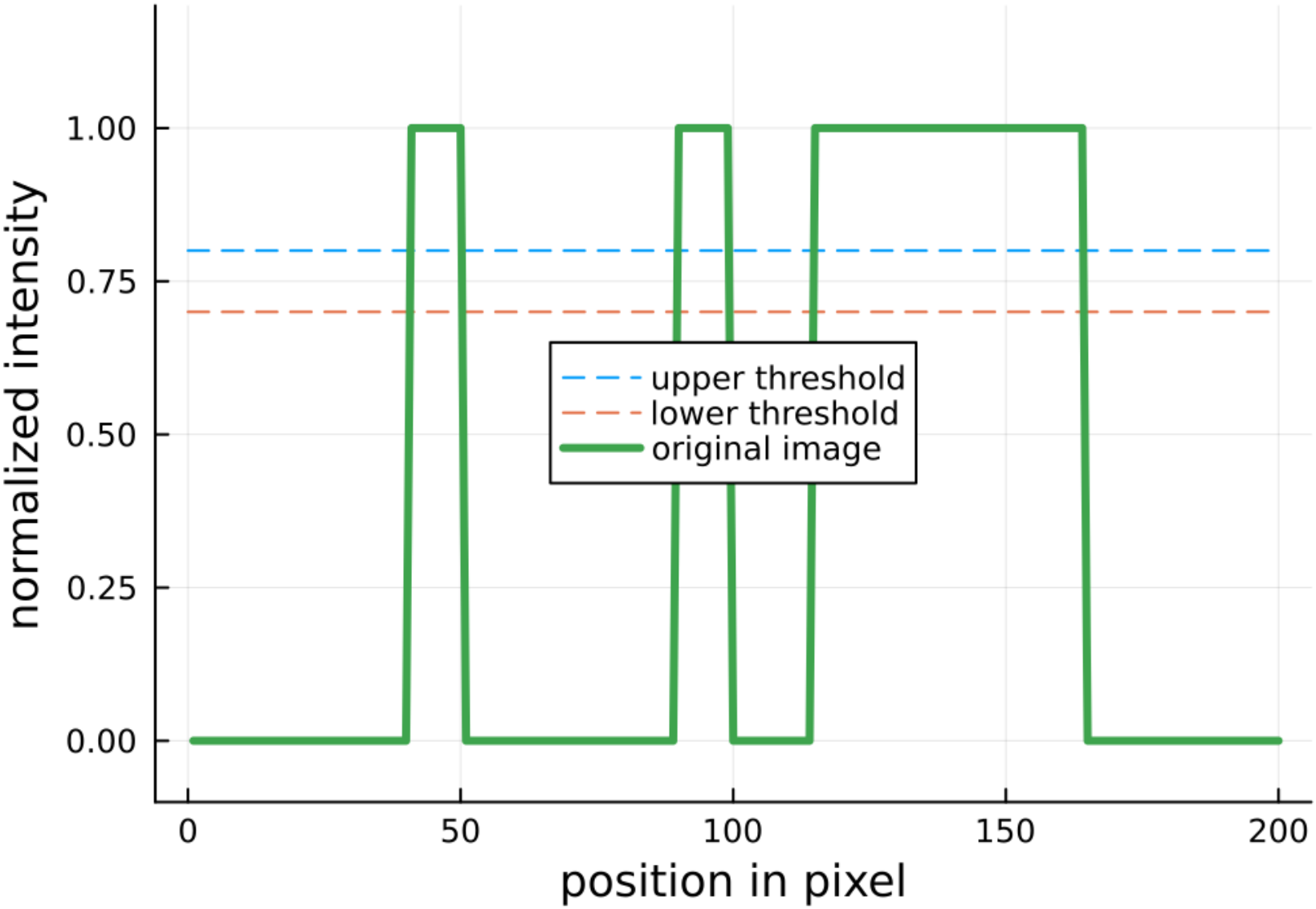
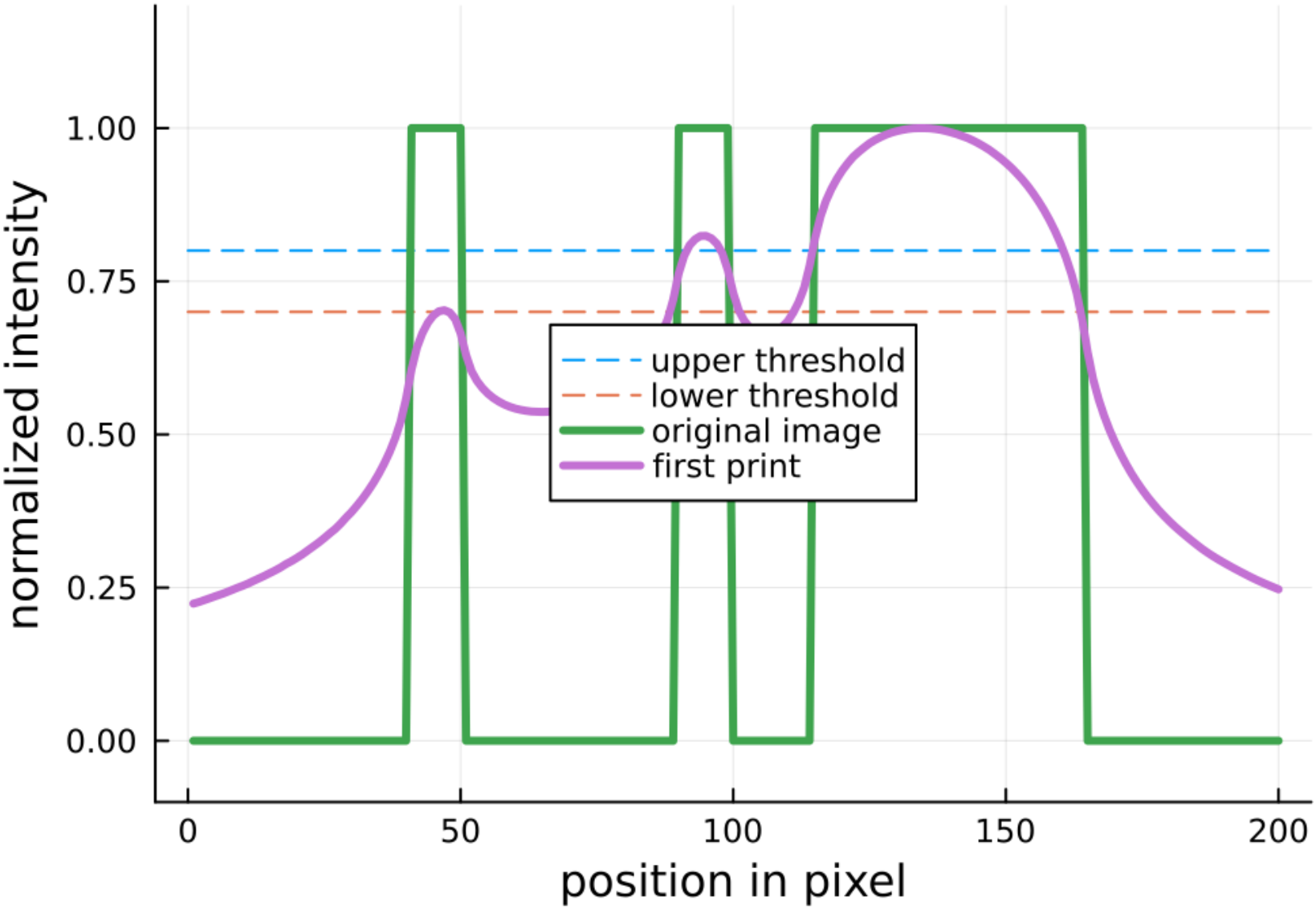


Figure taken from [Rac+21].

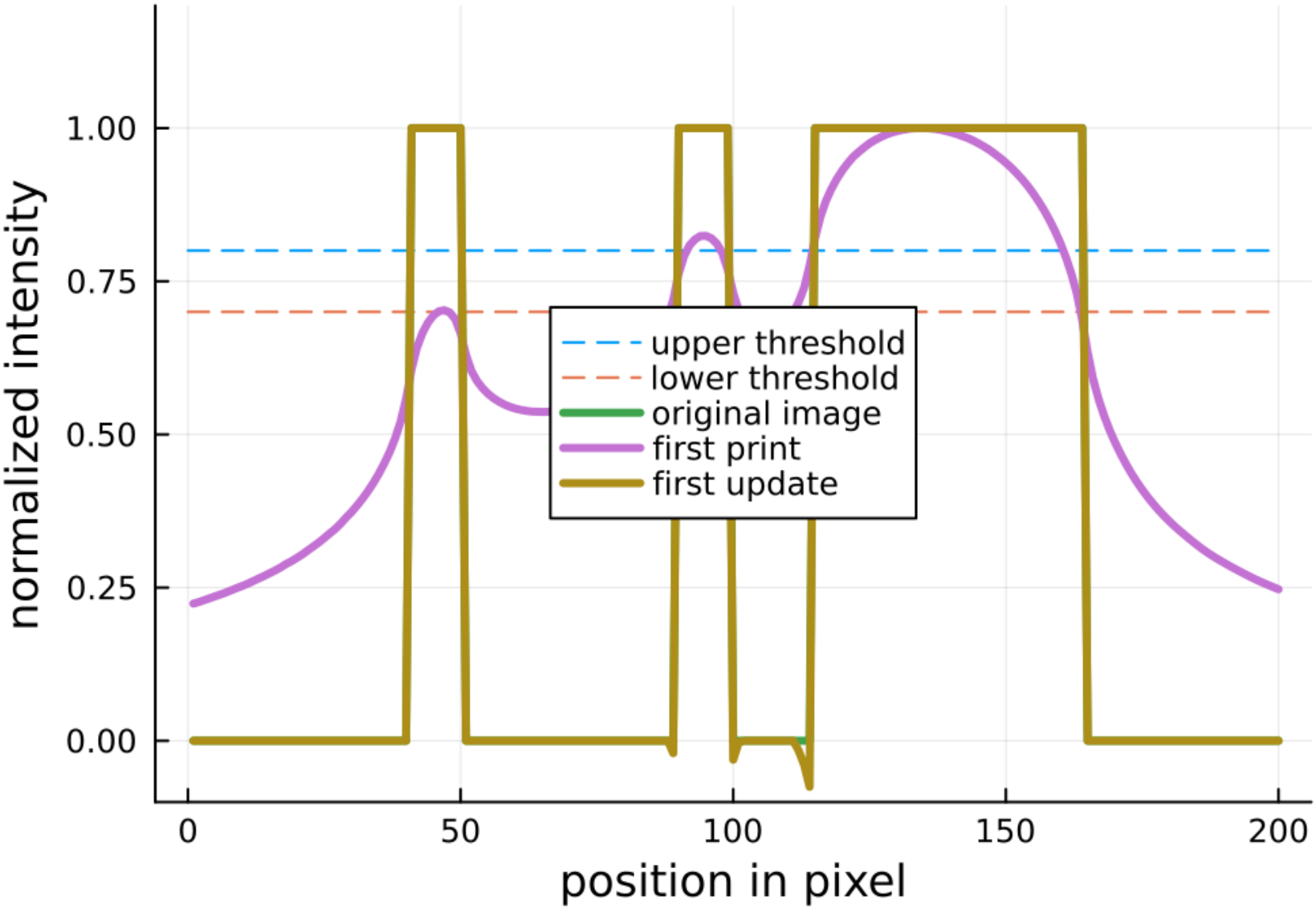
Object space optimization



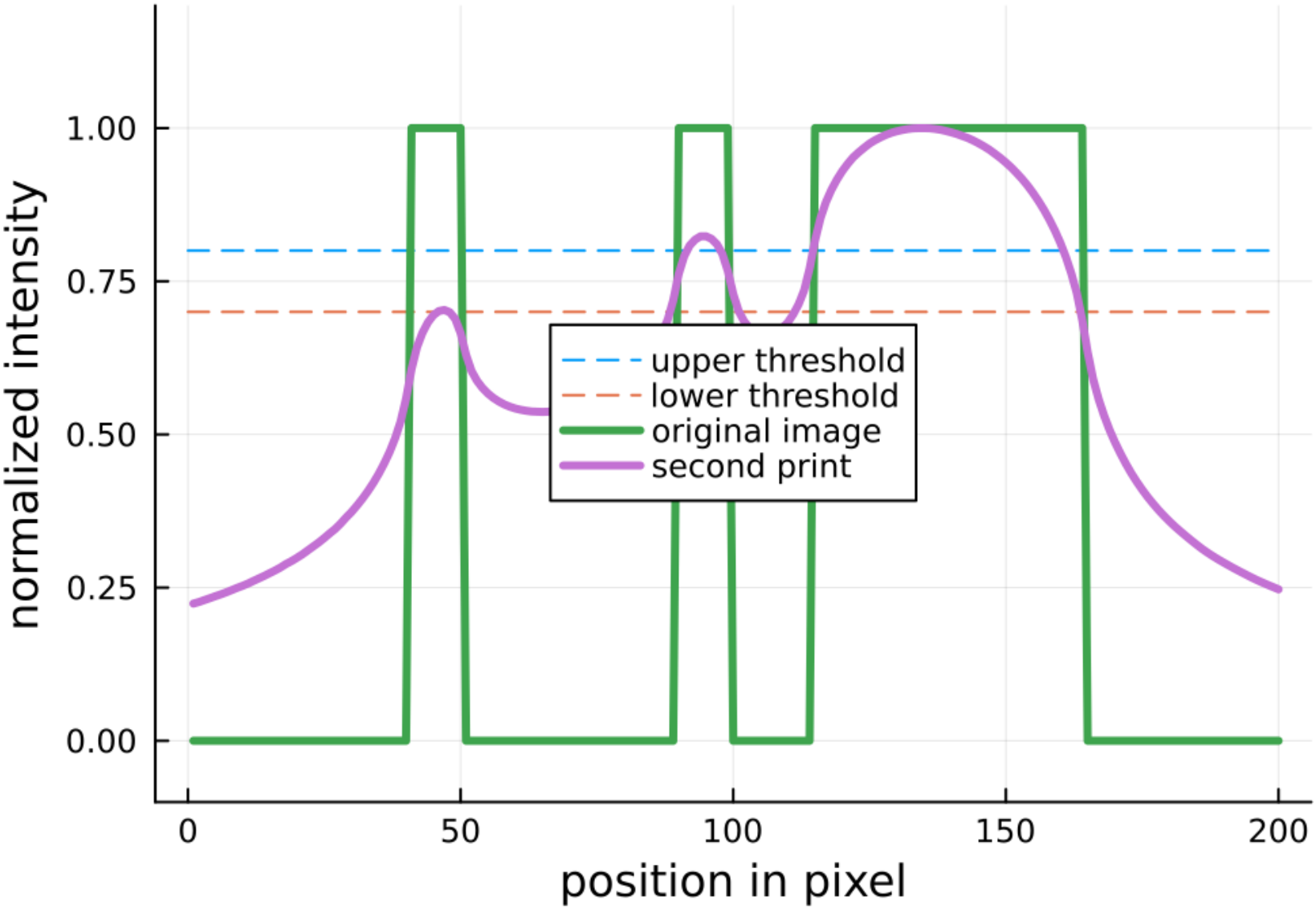
Object space optimization



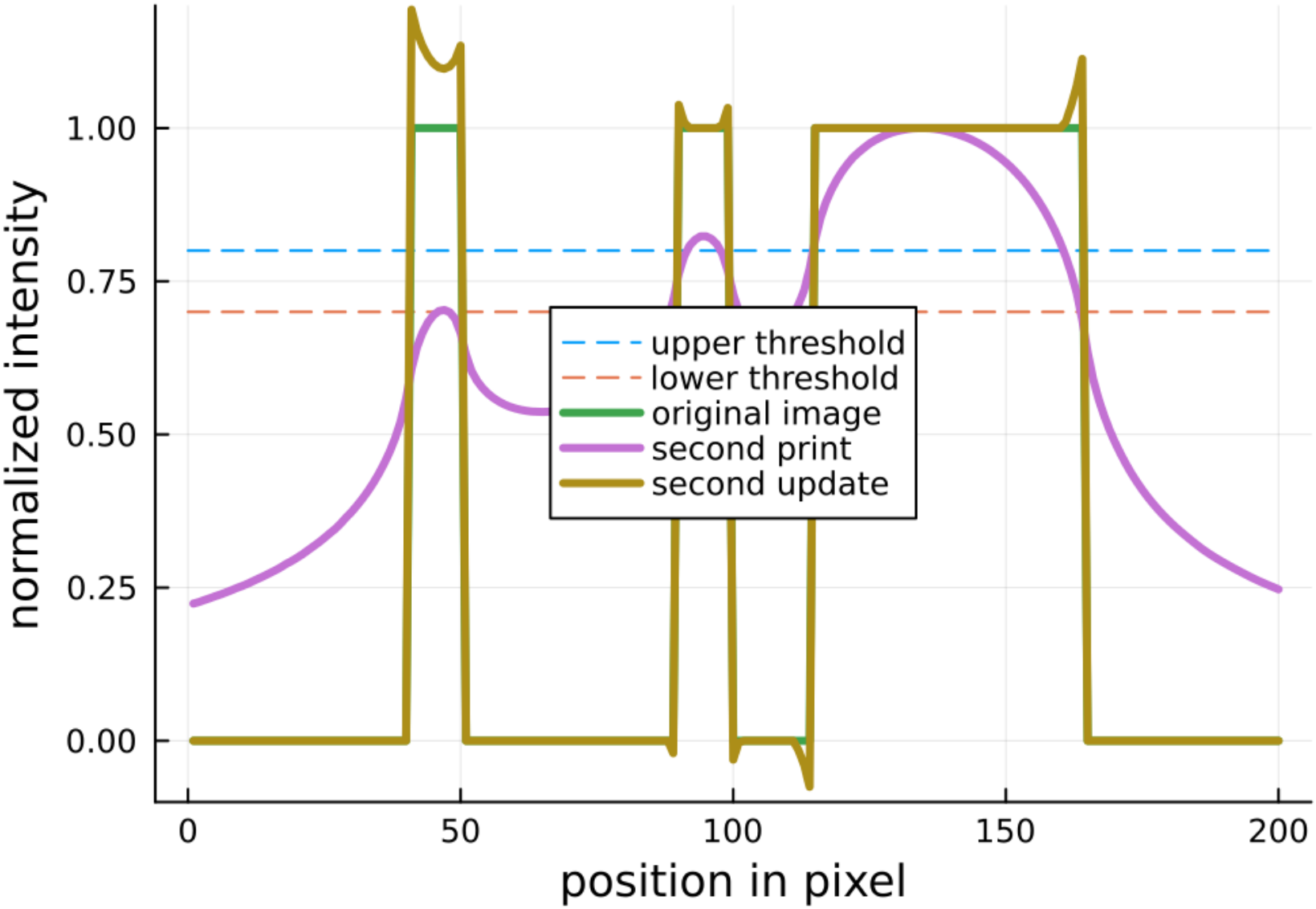
Object space optimization



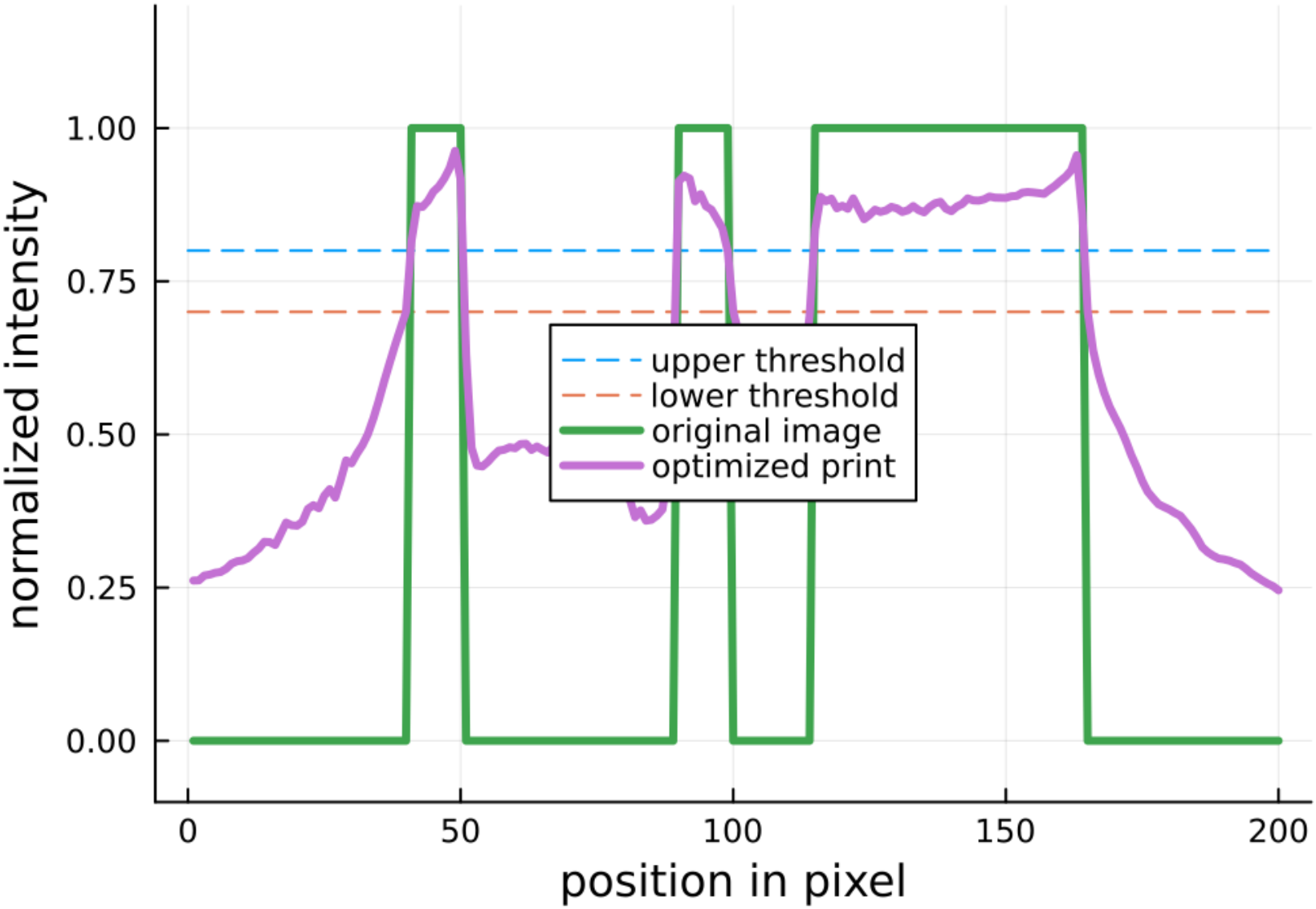
Object space optimization



Object space optimization



Object space optimization



3D PRINTING

Volumetric additive manufacturing via tomographic reconstruction

Brett E. Kelly[1,2*], Indrasen Bhattacharya[3*], Hossein Heidari[1*], Maxim Shusteff[2], Christopher M. Spadaccini[4], Hayden K. Taylor[1†]

Object-Space Optimization of Tomographic Reconstructions for Additive Manufacturing

Charles M. Rackson[1], Kyle M. Champley[2], Joseph T. Toombs[3], Erika J. Fong[2], Vishal Bansal[3], Hayden K. Taylor[3], Maxim Shusteff[2], Robert R. McLeod[1].

[1]Department of Electrical, Computer, and Energy Engineering, University of Colorado, Boulder, CO 80309, USA.
[2]Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.
[3]Department of Mechanical Engineering, University of California, Berkeley, Berkeley, CA 94720, USA.
Email addresses of authors: charles.rackson@colorado.edu, champley1@llnl.gov, jtoombs@berkeley.edu, fong26@llnl.gov, vishal-bansal@outlook.com, hkt@berkeley.edu, shusteff1@llnl.gov, robert.mcleod@colorado.edu.
Corresponding author: Charles M. Rackson.

Research Article Vol. 31, No. 4 / 13 Feb 2023 / *Optics Express* 5531

Optics EXPRESS

Versatile volumetric additive manufacturing with 3D ray tracing

DANIEL WEBBER,* YUJIE ZHANG, MICHEL PICARD, JONATHAN BOISVERT, CHANTAL PAQUET, AND ANTONY ORTH

National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada
*daniel.webber@nrc-cnrc.gc.ca

Replacing Radon Transform

- Simple Radon transform describes collimated rays
- Relax that by enabling full ray tracing

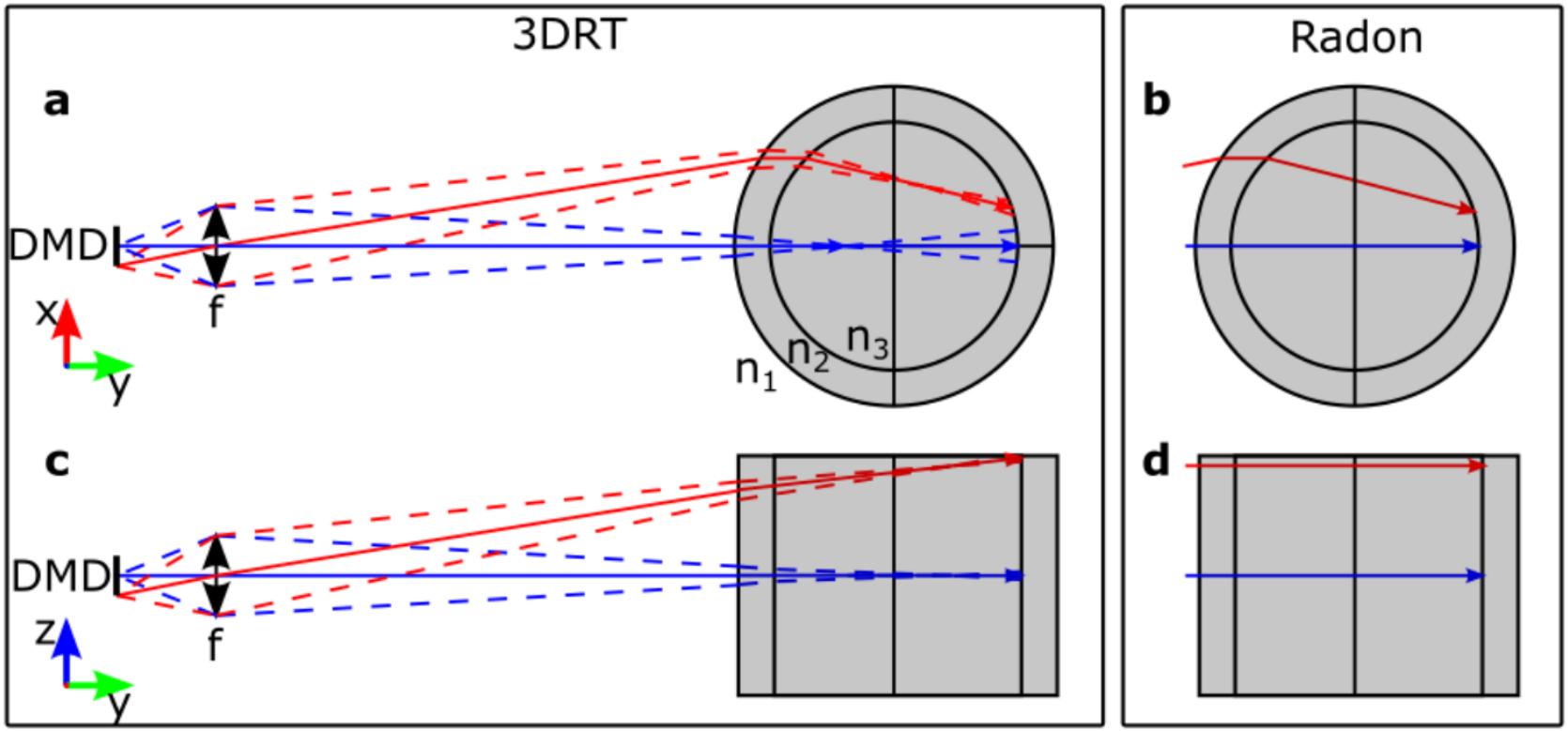
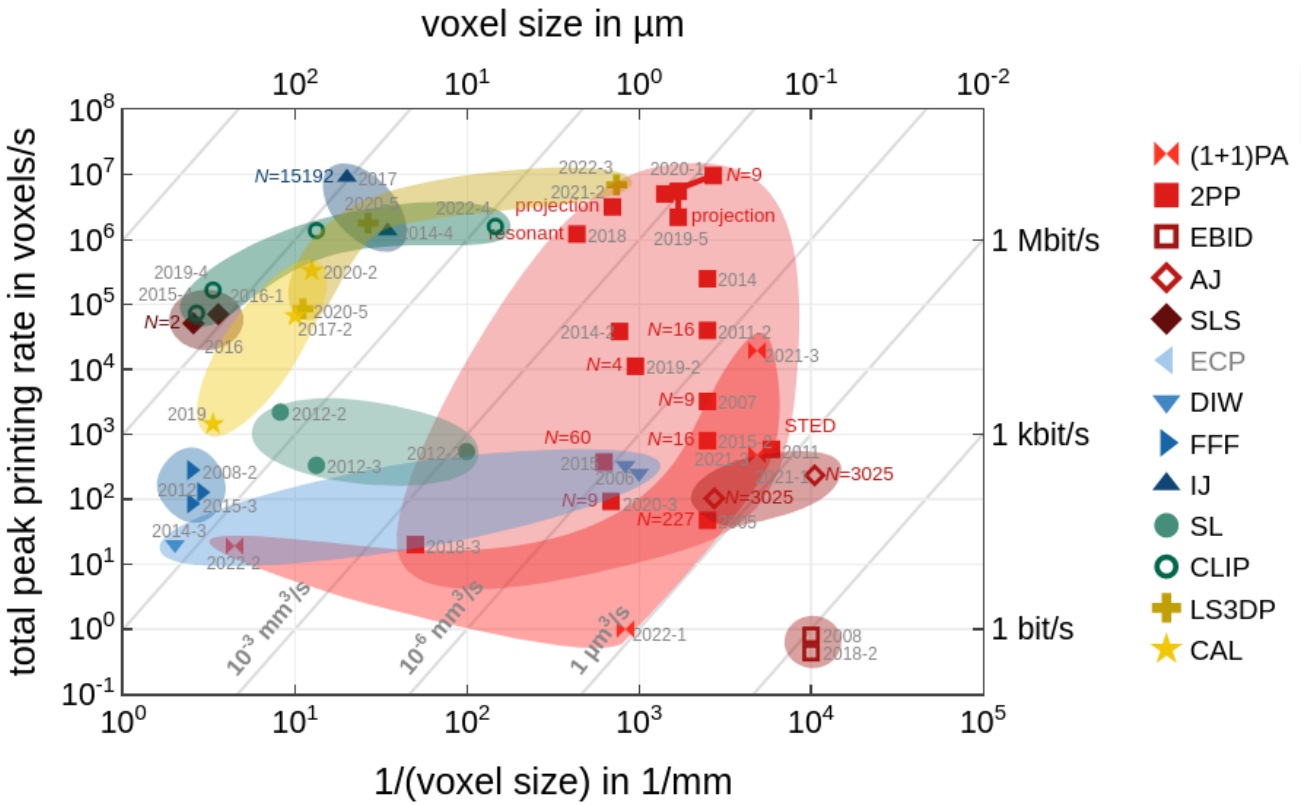


Figure taken from [Web+23]

Summary

Volumetric Printing is fast! However:

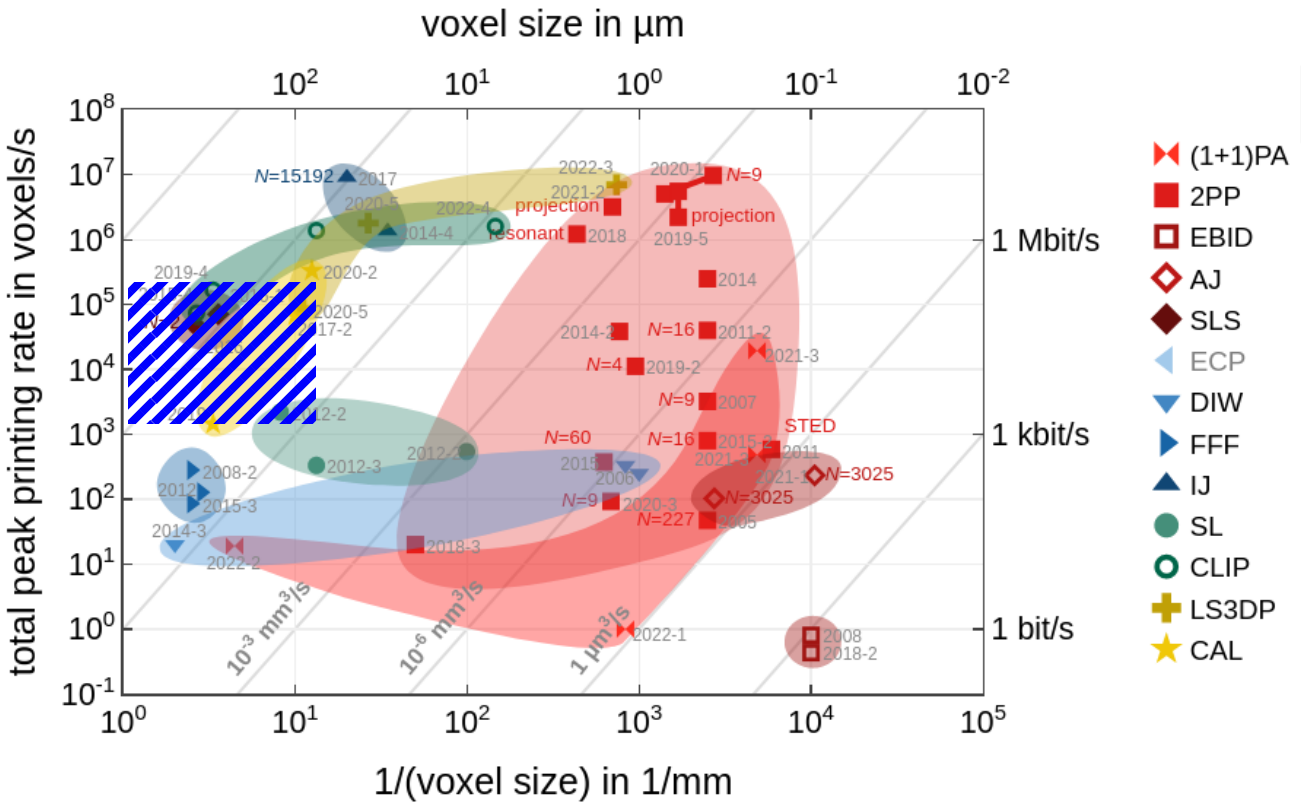
- ✓ non-negative intensity makes reconstruction harder
- ✓ vial geometry makes light propagation harder
- ✗ resolution still limited to $\approx 80\,\mu m$



Summary

Volumetric Printing is fast! However:

- ✓ non-negative intensity makes reconstruction harder
- ✓ vial geometry makes light propagation harder
- ✗ resolution still limited to $\approx 80\,\mu m$



References

Damien Loterie, Paul Delrot, and Christophe Moser. "High-resolution tomographic volumetric additive manufacturing". en. In: *Nature Communications* 11.11 (Feb. 2020). 126 citations (Crossref) [2023-03-03], p. 852. ISSN: 2041-1723. DOI: 10.1038/s41467-020-14630-4.

Charles M. Rackson et al. "Object-space optimization of tomographic reconstructions for additive manufacturing". en. In: *Additive Manufacturing* 48 (Dec. 2021). 7 citations (Crossref) [2023-03-07], p. 102367. ISSN: 2214-8604. DOI: 10.1016/j.addma.2021.102367.

Daniel Webber et al. "Versatile volumetric additive manufacturing with 3D ray tracing". EN. In: *Optics Express* 31.4 (Feb. 2023). 0 citations (Crossref) [2023-02-15], pp. 5531–5546. ISSN: 1094-4087. DOI: 10.1364/OE.481318.