# Digital Holography

Wm. Randall Babbitt
Professor of Physics and Director of Spectrum Lab
Montana State University

CLRC 2022 Tutorial
June 26, 2022

Spectrum LAB Montana State University



1

## Outline of Tutorial

- Coherent Lidar
- Digital Holography
  - Holography
  - Interference
  - Image Plane DH
  - Pupil plane DH
    - Optical wave propagation
    - Image Recovery – Post-Focusing
  - DH Requirements
  - Signal to Noise
  - Depth of Field



2

# Digital Holography

The reference wavefront at the film (z = 0) is assumed to be a plane wave)

$$E_{ref}(x,y,t) = E_{ref}\cos(2\pi f\, t - \vec{k}_r \bullet \vec{r} + \phi_{ref}) = real\left(E_{ref}\exp(i2\pi f\, t - i\vec{k}_r \bullet \vec{r}\,)\right)$$

The object wavefront at the film

$$E_{obj}(x,y,t) = A(x,y)\cos(2\pi f\, t + \phi(x,y))$$

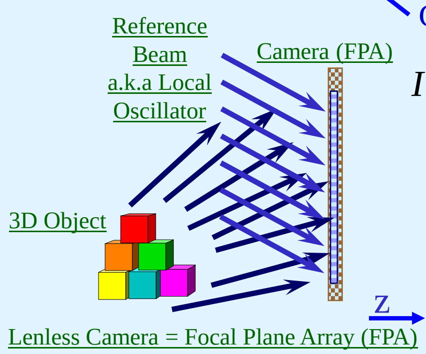
$$= real\left(E_{obj}(x,y)\exp\left(i\left(2\pi f\, t\right)\right)\right)$$

$Note: \vec{k}_{ref} = k_z\hat{z} + \vec{k}_r$ $\quad \left|\vec{k}_{ref}\right| = \frac{2\pi}{\lambda}$

$\vec{r} = x\hat{x} + y\hat{y}$

Assume all light has same polarization

Complex field representation




$$I(x,y) \propto \left\langle \left| E_{obj}(x,y,t) + E_{ref}(x,y,t) \right|^2 \right\rangle_{dt}$$

$$\propto E_{obj}(x,y)\, E^*_{ref}\, e^{i\vec{k}_r \bullet \vec{r}} + \text{c.c.}$$

$$+ I_{obj}(x,y) + I_{ref}(x,y)$$

Complex phase and amplitude information
is stored in a
real-valued spatial interference pattern.

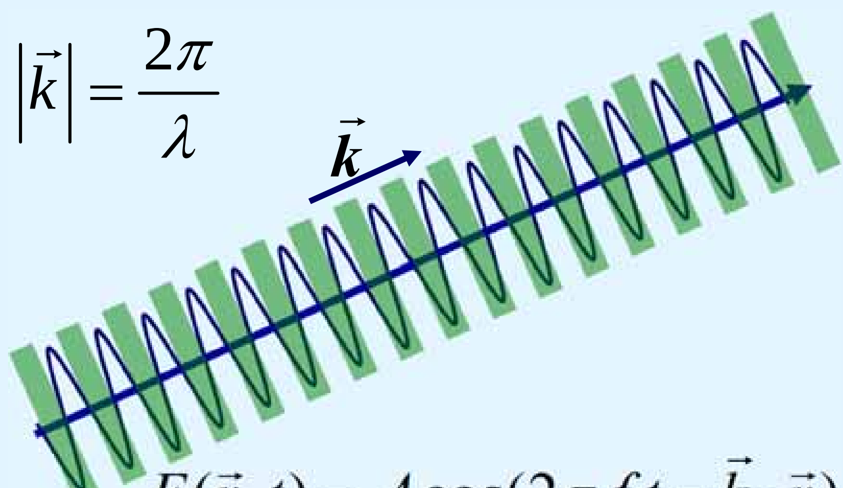
CLRC Tutorial-Babbitt 3

3

# Wavevectors

Plane wave can travel in any direction

$$\left|\vec{k}\right| = \frac{2\pi}{\lambda}$$




$$E(\vec{r},t) = A\cos(2\pi f\, t - \vec{k}\cdot\vec{r})$$

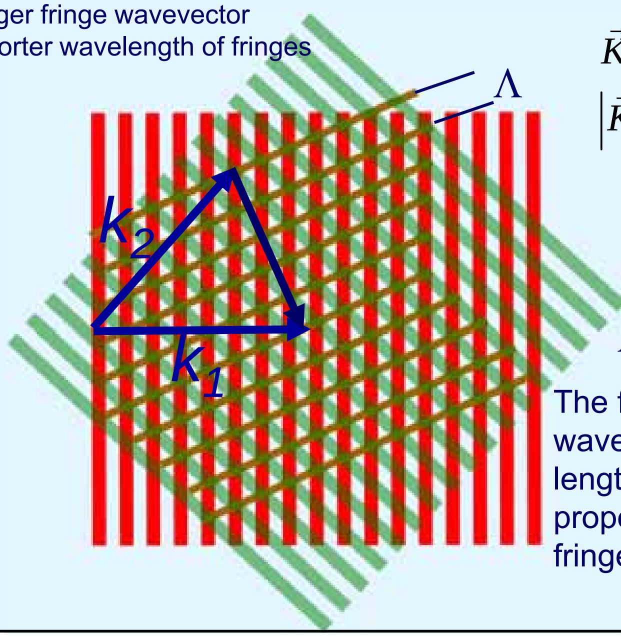
The wave vector $\vec{k}$ has a "length" with units 1/meter
and wave vector's direction points in direction of wave propagation.

CLRC Tutorial-Babbitt 4

4

## Wave Interference and Wavevectors

Greater angle of interference
=> Longer fringe wavevector
=> Shorter wavelength of fringes




$$\left|\vec{k}_1\right| = \left|\vec{k}_2\right| = \frac{2\pi}{\lambda}$$

$$\vec{K} = \vec{k}_1 - \vec{k}_2$$

$$\left|\vec{K}\right| = 2\pi / \Lambda$$

$$\Lambda = 2\pi / |K|$$

The fringe wavevector's length is inversely proportional to the fringe wavelength.

CLRC Tutorial-Babbitt 5

5

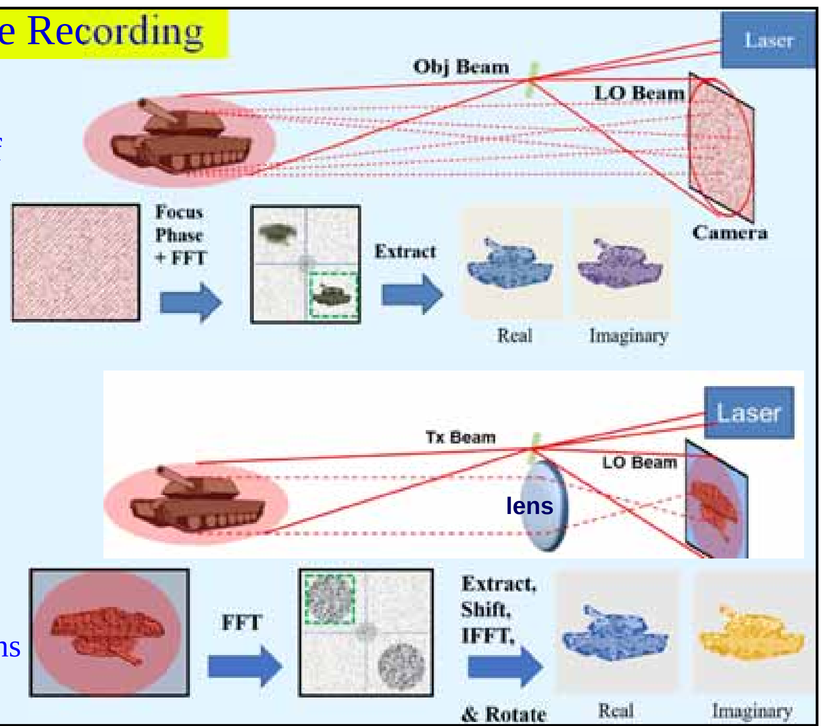
## Pupil Plane vs Image Plane Recording

Pupil plane:

- Object field at camera is FT of field at object
- (+)Wide FOV, no optical elements to cause aberrations
- (-)Small solid angle of light reaches camera
  → low signal strength

Image plane:

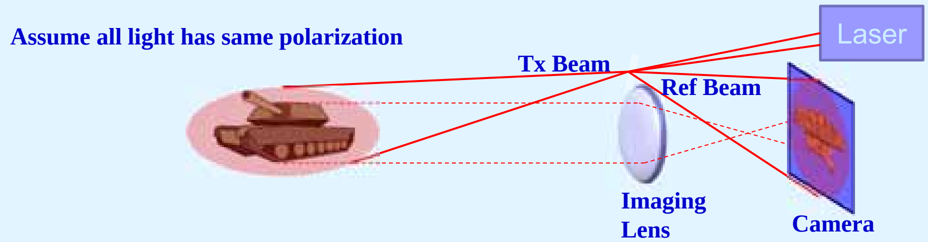
- Object field at camera is scaled copy of field at object
- (+)More light captured
- (-)Aberrations from imaging lens



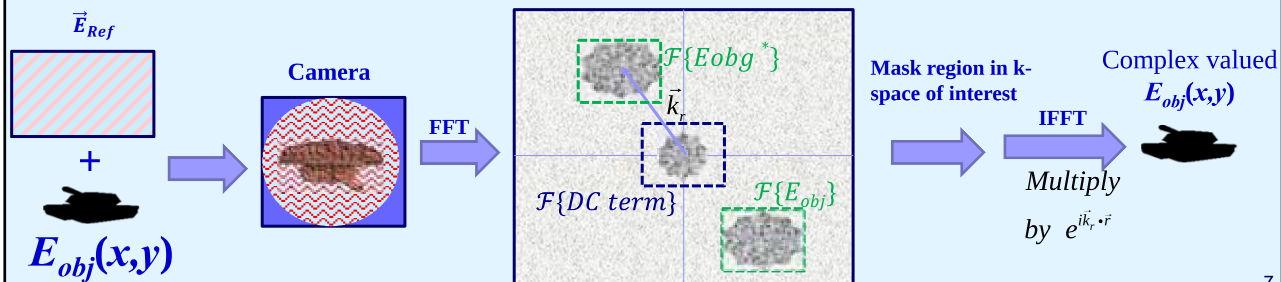

CLRC Tutorial-Babbitt

6

# Digital Hologram Processing: Image Plane Recording




$$I(x,y) \propto E_{obj}(x,y)\, E^*_{ref}\, e^{i\vec{k}_r \cdot \vec{r}} + \text{c.c.} + I_{obj}(x,y) + I_{ref}(x,y)$$

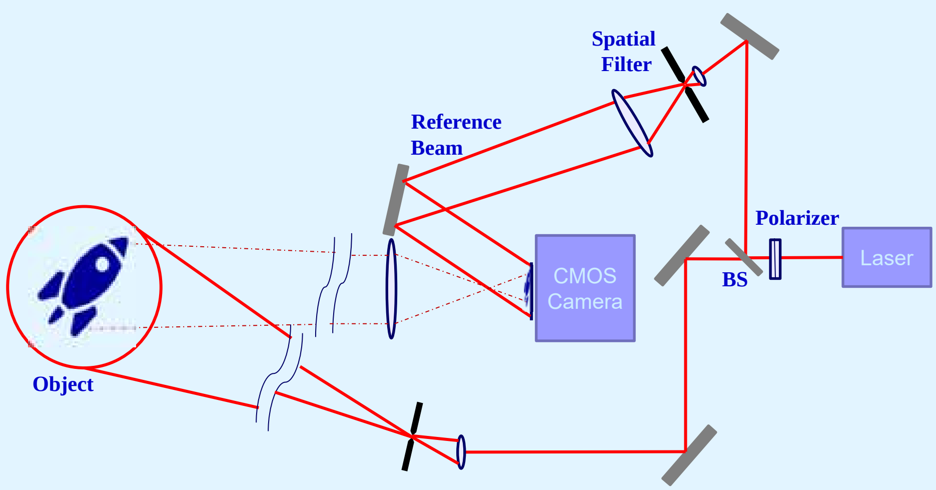



CLRC Tutorial-Babbitt

7

7

# Digital Holographic Set-up: Image Plane Recording

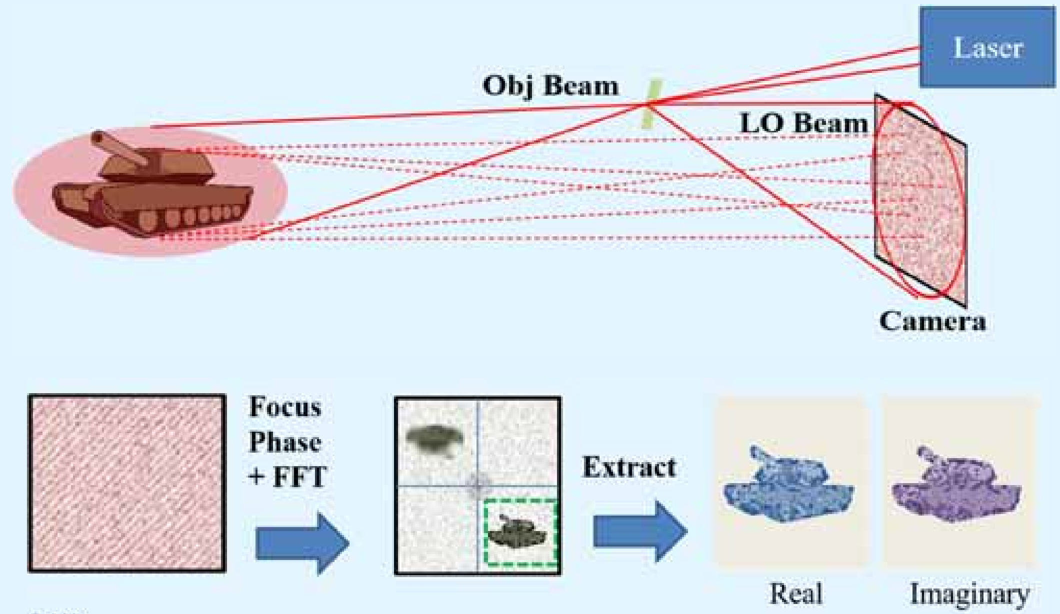



CLRC Tutorial-Babbitt

8

8

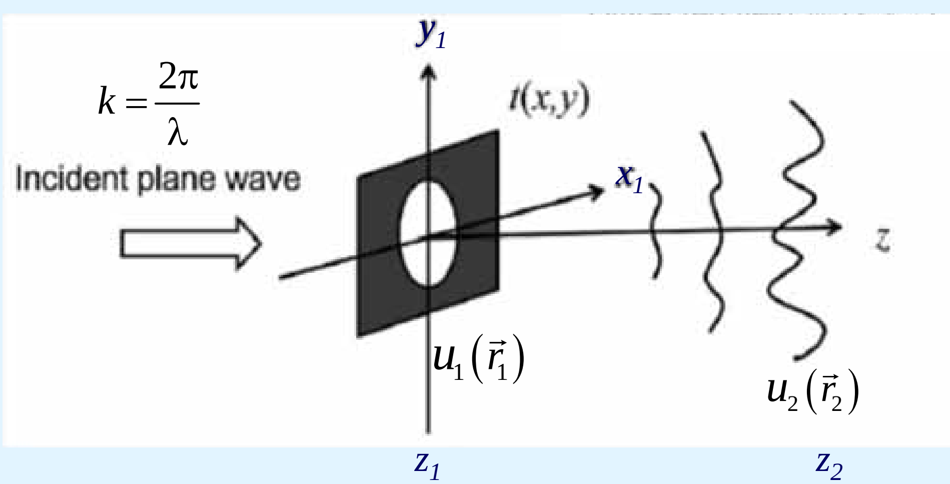
## Lenless Holography: Image Plane Recording




CLRC Tutorial-Babbitt

9

## Optical Field Propagation




$\vec{r}_1 = [x_1, y_1; z_1]$ $\vec{r}_2 = [x_2, y_2; z_2]$

CLRC Tutorial-Babbitt

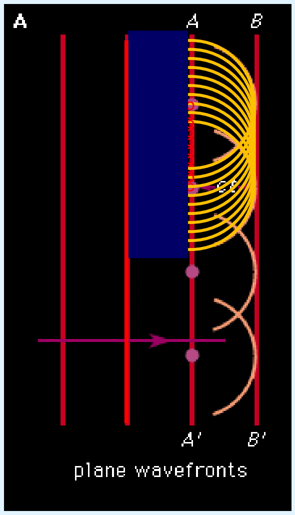
10

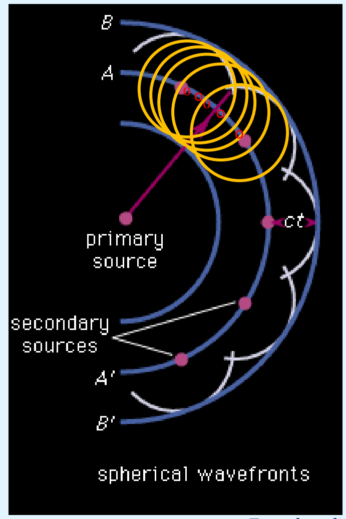
10

# Wave Propagation Based on Huygens' Principle

**Every point on wavefront radiates out a new spherical wave**

Radius of each wavefront is *ct*




Encyclopedia Britannica



# The Huygens-Fresnel Principle

The *Huygens-Fresnel principle describes the* propagation of optical fields.

Given the optical field at any plane, the field at any other plane is a superposition of spherical waves, known as *Huygens wavelets*, emanating from each point in the first plane, with the phase and amplitude of the field at that point.

Huygens wavelets

$$u_2(\vec{r}_2) = \frac{1}{i\lambda}\iint d^2\vec{r}_1 \; u_1(\vec{r}_1)\frac{e^{ikR}}{R}\cos\theta$$

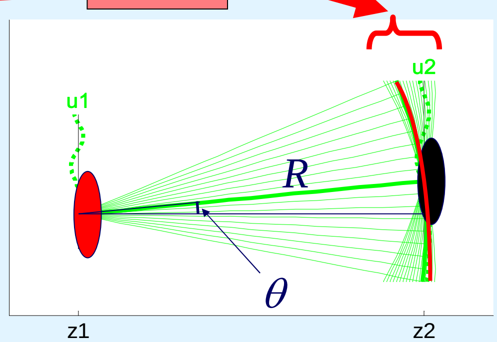
where

$$\vec{r}_1 = [x_1, y_1; z_1], \quad \vec{r}_2 = [x_2, y_2; z_2]$$

$$k = \frac{2\pi}{\lambda}$$

$$R = \sqrt{\left|\vec{r}_2 - \vec{r}_1\right|^2 + \Delta z^2}$$

$$\Delta z = z_2 - z_1$$




Note: $\cos(\theta)$ is an inclination factor, which is a bit complicated to explain, but it will be set to one in next slide as part of Fresnel Approximation.

# The Fresnel Approximations

When the transverse (off-axis) distances in the two planes are small compared to the propagation distance $\Delta z$, small angle approximations yield useful simplifications: Fresnel Diffraction.

$$u_2(\vec{r}_2) = \frac{1}{i\lambda}\iint d\vec{r}_1\, u_1(\vec{r}_1)\frac{e^{ikR}}{R}\cos\theta$$

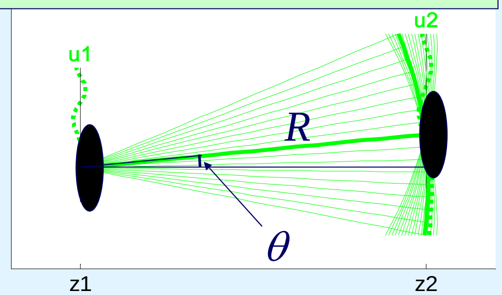
If we assume $|\vec{r}_2 - \vec{r}_1| << |\Delta z|$,

$$R = \sqrt{|\vec{r}_2 - \vec{r}_1|^2 + \Delta z^2} \cong \Delta z + \frac{1}{2\Delta z}|\vec{r}_2 - \vec{r}_1|^2$$

$$\frac{1}{R} \cong \frac{1}{\Delta z}$$

$$e^{ikR} \cong e^{ik\Delta z}\cdot \exp\left(\frac{ik}{2\Delta z}|\vec{r}_2 - \vec{r}_1|^2\right)$$

$$\cos\theta \cong 1$$




The *Fresnel diffraction integral*:

$$u_2(\vec{r}_2) \cong \frac{e^{ik\Delta z}}{i\lambda\Delta z}\iint d^2\vec{r}_1\, u_1(\vec{r}_1)\exp\left(\frac{ik}{2\Delta z}|\vec{r}_2 - \vec{r}_1|^2\right)$$

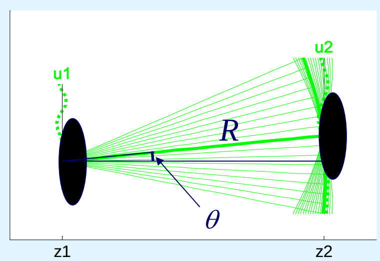
CLRC Tutorial-Babbitt

13

13

# Fourier Optics - Fresnel Propagation

$$u_2(\vec{r}_2) \cong \frac{e^{ik\Delta z}}{i\lambda\Delta z}\iint d^2\vec{r}_1\, u_1(\vec{r}_1)\exp\left(\frac{ik}{2\Delta z}|\vec{r}_2 - \vec{r}_1|^2\right)$$




In terms of x and y coordinates at $z_1$ and $z_2$

$$u_2(x_2, y_2) \cong \frac{e^{ik\Delta z}}{i\lambda\Delta z}\iint dx_1 dy_1\, u_1(x_1, y_1)\exp\left(\frac{ik}{2\Delta z}\left((x_2 - x_1)^2 + (y_2 - y_1)^2\right)\right)$$

Assuming initial field and region of interest for the final field are centered close to axis, and propagation in positive z, the Fresnel condition is:

$$|\vec{r}_2 - \vec{r}_1| << |\Delta z| \quad for\ all\ \vec{r}_2, \vec{r}_1$$

$$\Rightarrow$$

$$|x_1| << \Delta z,\ |y_1| << \Delta z,\ |x_2| << \Delta z,\ |y_2| << \Delta z \quad for\ all\ x_1, y_1, x_2, y_2$$

CLRC Tutorial-Babbitt

14

14

## Fourier Optics - Fresnel Propagation

$$u_2(x_2,y_2) \cong \frac{e^{ik\Delta z}}{i\lambda\Delta z}\iint dx_1 dy_1\; u_1(x_1,y_1)\exp\left(\frac{ik}{2\Delta z}\left((x_2-x_1)^2+(y_2-y_1)^2\right)\right)$$

$$=\frac{ke^{ik\Delta z}}{i2\pi\Delta z}\exp\left(\frac{ik(x_2{}^2+y_2{}^2)}{2\Delta z}\right)\iint dx_1 dy_1\left(u_1(x_1,y_1)\exp\left(\frac{ik(x_1{}^2+y_1{}^2)}{2\Delta z}\right)\right)\exp\left(\frac{ik(x_2x_1+y_2y_1)}{\Delta z}\right)$$

quadratic phase factors

scaled Fourier transform

$$k_x=\frac{kx_2}{\Delta z} \qquad k_y=\frac{ky_2}{\Delta z}$$

$$u_2(x_2,y_2)=\frac{ke^{ik\Delta z}}{i2\pi\Delta z}\exp\left(\frac{ik(x_2^2+y_2^2)}{2\Delta z}\right)\iint dx_1 dy_1\left(u_1(x_1,y_1)\exp\left(\frac{ik(x_1^2+y_1^2)}{2\Delta z}\right)\right)\exp(ik_x x_1+ik_y y_1)$$

The Fresnel diffraction integral decomposes into a sequence of three operations:

1. Multiply initial field by a quadratic phase factor
2. Do a scaled Fourier transform
3. Multiply by a quadratic phase factor.

CLRC Tutorial-Babbitt

15

15

## 2D Fourier Transform (2D FT)

The 2D Fourier Transform of a continuous, non-periodic function $f(x,y)$ is defined as follows:

$$\boldsymbol{F}_{2D}\left(f(x,y)\right)=F(k_x,k_y)=\frac{1}{2\pi}\int\int_{-\infty}^{\infty}f(x,y)e^{-ik_x x}e^{-ik_y y}dxdy$$

Given $F(k_x,k_y)$, we can obtain $f(x,y)$ back using the 2D Inverse Fourier Transform (2D-IFT):

$$\boldsymbol{F}_{2D}^{-1}\left(F(k_x,k_y)\right)=\frac{1}{2\pi}\int\int_{-\infty}^{\infty}F(k_x,k_y)e^{ik_x x}e^{ik_y y}dk_x dk_y = f(x,y)$$

CLRC Tutorial-Babbitt

16

16

## Fourier Optics - Fraunhofer Propagation

$$u_2(x_2,y_2) \cong \frac{ke^{ik\Delta z}}{i2\pi\Delta z}\exp\left(\frac{ik(x_2^2+y_2^2)}{2\Delta z}\right)\iint dx_1dy_1\left(u_1(x_1,y_1)\exp\left(\frac{ik(x_1^2+y_1^2)}{2\Delta z}\right)\right)\exp\left(\frac{ik\left(x_2x_1+y_2y_1\right)}{\Delta z}\right)$$

If the initial object is "small" compared sqrt($\lambda\Delta z$)

$$\frac{k}{2\Delta z}\left(x_1{}^2+y_1{}^2\right) << \pi$$

$$\Rightarrow \quad |r_1| = \sqrt{\left(x_1{}^2+y_1{}^2\right)} << \sqrt{\lambda\Delta z} \;\;, \; for \;\, all \;\; x_1, y_1$$

Then the far field is just the Fourier Transform of the image (with a quadratic phase factor)

$$u_2(x_2,y_2) \cong \frac{ke^{ik\Delta z}}{i2\pi\Delta z}\exp\left(\frac{ik}{2\Delta z}(x_2^2+y_2^2)\right)\iint dx_1dy_1\; u_1(x_1,y_1)\exp\left(\frac{ik}{\Delta z}(x_2x_1+y_2y_1)\right)$$

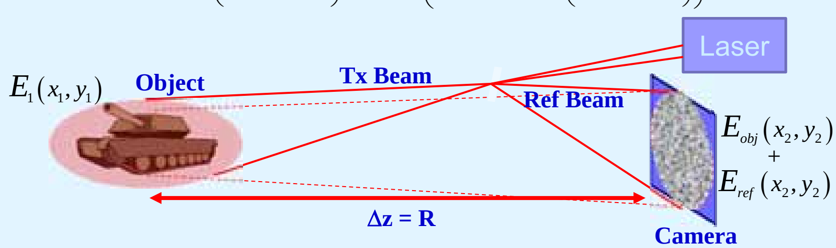
Fraunhofer Diffraction Pattern



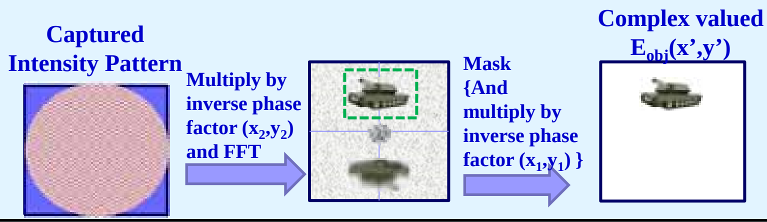
## Digital Holography: Pupil Plane Recording (Lenless)

**Object field after propagation from Object plane to Camera plane without lens**

$$E_{obj}(x_2,y_2) = \frac{ke^{ikR}}{i2\pi R}\exp\left(\frac{ik(x_2^2+y_2^2)}{2R}\right)\iint dx_1dy_1\left(E_1(x_1,y_1)\exp\left(\frac{ik(x_1^2+y_1^2)}{2R}\right)\right)\exp(ik_xx_1+ik_yy_1)$$




$$I(x_2,y_2) \;\propto\; E_{obj}(x_2,y_2)\,E_{ref}^{*}\;e^{i\vec{k}_r\cdot\vec{r}_2} + \text{c.c.} + I_{obj}(x_2,y_2) + I_{ref}(x_2,y_2)$$



# Pupil Plane Processing to get Image Intensity

Object field in camera plane without lens

$$E_{obj}(\vec{r}_2) = \frac{ke^{ikR}}{i2\pi R}\exp\left(\frac{ik|\vec{r}_2|^2}{2R}\right)\iint d\vec{r}_1\left(E_1(\vec{r}_1)\exp\left(\frac{ik|\vec{r}_1|^2}{2R}\right)\right)\exp(i\vec{k}_s\bullet\vec{r}_1)$$

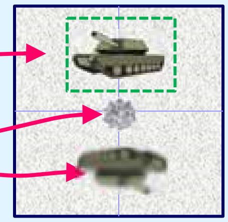
Recorded intensity

$$I(\vec{r}_2) \propto E_{obj}(\vec{r}_2)\,E^*_{ref}\,e^{i\vec{k}_r\bullet\vec{r}_2} + \text{c.c.} + I_{obj}(\vec{r}_2) + I_{ref}(\vec{r}_2)$$

$$\vec{k}_s = \frac{kx_2}{R}\hat{x}_1 + \frac{ky_2}{R}\hat{y}_1$$

Pupil Plane Digital Hologram Processing:

1. Capture $I(r_2)$ with DH system
2. Multiply capture field by complex conjugate of quadratic phase factor(yellow boxes)
3. Do a scaled Inverse Fourier transform to get object field



Computed object field (still with quadratic phase factor) in *primed image* plane

1. $E_1(r_1)$ is object field in object plane
2. $E_1(r_1')$ is object field in primed image plane

$$u_1'(\vec{r}_1') \propto \boldsymbol{F}^{-1}_{scaled}\left\{\exp\left(\frac{-ik|\vec{r}_2|^2}{2R}\right)I(\vec{r}_2)\right\} \propto E_1(\vec{r}_1' - \vec{r}_{shift})\exp\left(\frac{ik|\vec{r}_1' - \vec{r}_{shift}|^2}{2R}\right) + \cdots$$

$$|u'_{1,masked}(\vec{r}_1')|^2 \propto I_1(\vec{r}_1' - \vec{r}_{shift})$$

Shifted by scaled $\boldsymbol{k_r}$

Unshifted or shifted by scaled $\boldsymbol{k_r}$

CLRC Tutorial-Babbitt

20

20

# Pupil Plane Processing to get Image Amplitude

Object field in camera plane

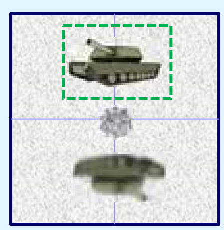
$$E_{obj}(\vec{r}_2) = \frac{ke^{ikR}}{i2\pi R}\exp\left(\frac{ik|\vec{r}_2|^2}{2R}\right)\iint d\vec{r}_1\left(E_1(\vec{r}_1)\exp\left(\frac{ik|\vec{r}_1|^2}{2R}\right)\right)\exp(i\vec{k}_s\bullet\vec{r}_1)$$

Recorded intensity

$$I(\vec{r}_2) \propto E_{obj}(\vec{r}_2)\,E^*_{ref}\,e^{i\vec{k}_R\bullet\vec{r}_2} + \text{c.c.} + I_{obj}(\vec{r}_2) + I_{ref}(\vec{r}_2)$$

Pupil Plane Digital Hologram Processing:

1. Capture $I(r_2)$ with DH system
2. Multiply capture field by c.c. of quadratic phase factor(yellow boxes)
3. Do a scaled Inverse Fourier transform
4. Mask if desired (stop here if you just want object intensity, $|u_1|^2$ )
5. Multiply by c.c. of quadratic phase factor (red boxes) to get complex $u_1$



Computed complex reimaged object field

$$u_1'(\vec{r}_1') \propto \exp\left(\frac{-ik|\vec{r}_1'|^2}{2R}\right)\boldsymbol{F}^{-1}_{scaled}\left\{\exp\left(\frac{-ik|\vec{r}_2'|^2}{2R}\right)I(\vec{r}_2)\right\} \propto E_1(\vec{r}_1' - \vec{r}_{shift}) + \cdots$$

Note the quadratic phase factors are functions of *R*, which allows
- post-capture focusing of the object(s)
- processing multiple objects by bringing each into focus separately.

CLRC Tutorial-Babbitt

21

21

## DH – Pupil Plane Recording – Diffraction Limits

If the initial object is "small" compared sqrt($\lambda\Delta z$)

$$|\vec{r}_1| = \sqrt{\left(x_1^{\,2} + y_1^{\,2}\right)} << \sqrt{\lambda \Delta z} \;\;,\; for\ all\ \ x_1, y_1\ \ for\ which\ object\ is\ non-zero$$

Then you don't need to worry about quadratic phase factor with $x_1$ and $y_1$ and only worry about quadratic phase factor with $x_2$ and $y_2$ if complex field is desired(Fraunhofer regime)

$$u_2(x_2, y_2) \cong \frac{k e^{ik\Delta z}}{i 2\pi \Delta z} \exp\left(\frac{ik(x_2^2 + y_2^2)}{2\Delta z}\right) \iint dx_1 dy_1 \,\left(u_1(x_1, y_1)\right) \exp\left(\frac{ik\left(x_2 x_1 + y_2 y_1\right)}{\Delta z}\right)$$

If the captured image is "small" compared sqrt($\lambda\Delta z$)

$$|\vec{r}_2| = \sqrt{\left(x_2^{\,2} + y_2^{\,2}\right)} << \sqrt{\lambda \Delta z} \;\;,\; for\ all\ \ x_2, y_2\ \ for\ which\ u_2(x_2, y_2)\ is\ non-zero$$

Still need to worry about quadratic phase terms(NOT Fraunhofer regime)

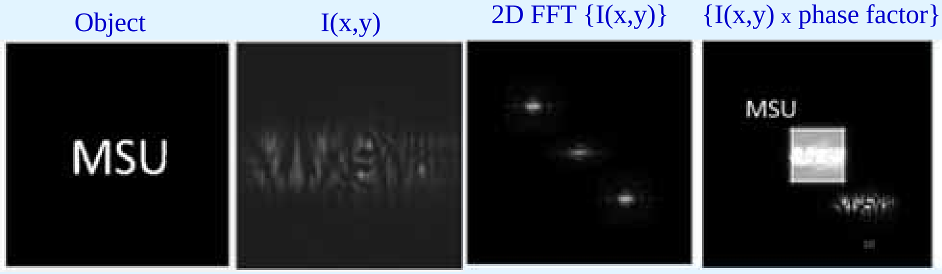
$$u_2(x_2, y_2) \cong \frac{k e^{ik\Delta z}}{i 2\pi \Delta z} \iint dx_1 dy_1 \,\left(u_1(x_1, y_1) \exp\left(\frac{ik(x_1^2 + y_1^2)}{2\Delta z}\right)\right) \exp\left(\frac{ik\left(x_2 x_1 + y_2 y_1\right)}{\Delta z}\right)$$



## Pupil Plane Digital Holography: Simulation Example

$$u_1'(\vec{r}_1') \propto \exp\left(\frac{-ik\left|\vec{r}_1'\right|^2}{2R}\right) \boldsymbol{F}^{-1}_{scaled} \left\{ \exp\left(\frac{-ik\left|\vec{r}_2'\right|^2}{2R}\right) I(\vec{r}_2) \right\} \propto E_1\left(\vec{r}_1' - \vec{r}_{shift}\right) + \cdots$$

Object | Object + Ref captured on camera I(x,y) | 2D FFT {I(x,y)} | 2D FFT of {I(x,y) x phase factor}



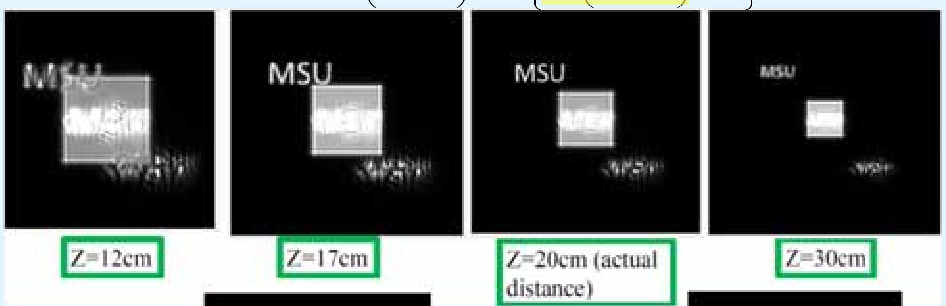

Equation above is for general field, used if you want to recover the complex field. In this example, we just wanted object intensity, so outside quadratic phase term is ignored


Images courtesy of Matt Goodman, MSU Spectrum Lab

# Pupil Plane Digital Holography: Refocussing

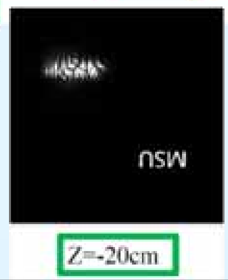
Varying the phase factor (focal distance Z (=R))

$$u_1'(\vec{r}_1') \propto \exp\left(\frac{-ik|\vec{r}_1'|^2}{2R}\right) \boldsymbol{F}_{scaled}^{-1}\left\{\exp\left(\frac{-ik|\vec{r}_2'|^2}{2R}\right) I(\vec{r}_2)\right\} \propto E_1(\vec{r}_1' - \vec{r}_{shift}) + \cdots$$




Apply mask(s) to separate desired image from other features.


Apply a "negative lens" and conjugate comes into focus






Images courtesy of Matt Goodman, MSU Spectrum Lab



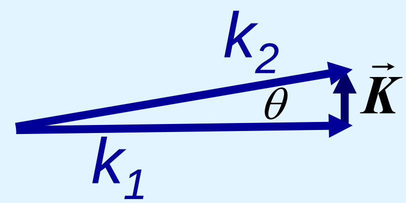
# DH - Requirements

- Stable laser:
  - Single Frequency
  - Coherence length greater than object-reference difference
  - Wavelength that matches system requirements
- Spatial stability
  - Path difference constant to better than $\lambda/4$ during exposure
    - The faster the exposure, the better.
- Post-processing
  - Preferred: Real-time camera capture and post-processing
    - -Fast data link with camera followed by fast CPU, FPGA, or GPU
- Local Oscillator/Reference Beam
  - High spatial coherence
  - Preferred: plane wave
    - Spherical wave: just multiply in post-processing by it's quadratic wavefront
  - Angled w.r.t. Object beam (unless implementing phase shifted DH)
- Camera
  - Operation at system wavelength
  - Preferred: Fast frame rate
  - Number of pixels: Trade-off between resolution and frame rate
  - Pixel size: Smaller size => higher LO angles, but less object resolution (w/ fixed # of pixels).

## Reference-Object Angle and Camera Pixel Spacing

For small angle of separation, $\theta$, of the object and reference waves

$$\vec{K} = \vec{k}_2 - \vec{k}_1 \sim k\theta = 2\pi\theta / \lambda$$




And the fringe wavelength, Λ , is roughly

$$\Lambda = 2\pi / \left|\vec{K}\right| \approx \lambda / \theta$$

To capture the fringes on the camera, it is good to have the spacing of the pixel of the camera, *s*, to be smaller than ½ Λ, Nyquist limit

$$s \leq \Lambda / 2 \approx \lambda / (2\theta)$$

Given a fixed pixel size on the camera and fixed operating wavelength, the maximum angle between object and reference is

$$\theta_{max} \approx \lambda / (2s)$$

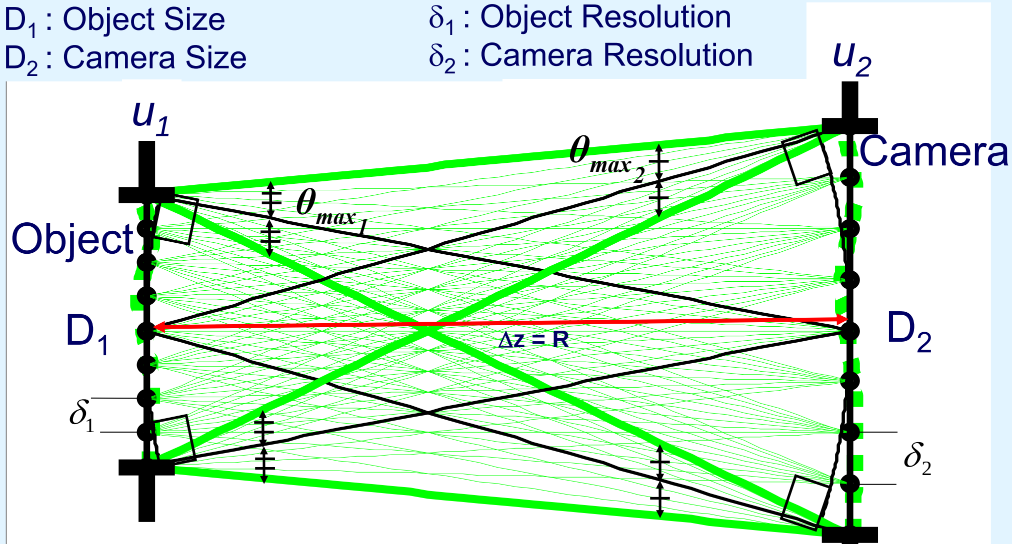
CLRC Tutorial-Babbitt 26

26

## Nyquist Criteria for Sampling Object Field

$D_1$ : Object Size
$D_2$ : Camera Size

$\delta_1$ : Object Resolution
$\delta_2$ : Camera Resolution




Resolution requirements in addition to accounting for angled reference beam.

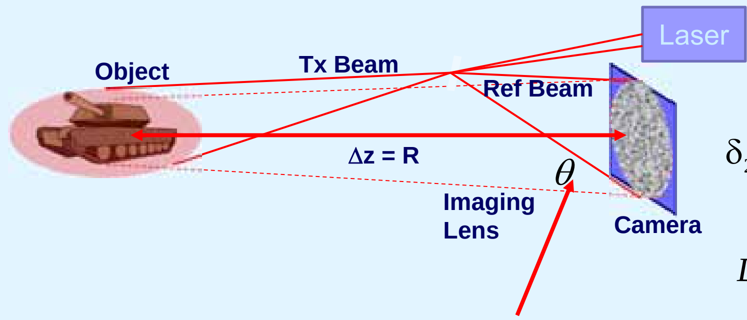
$$\delta_1 \approx \frac{\lambda}{2\theta_{max1}} \cong \frac{\lambda R}{2D_2}$$ ⇐ For large R ⇒ $$\delta_2 \approx \frac{\lambda}{2\theta_{max2}} \cong \frac{\lambda R}{2D_1}$$

CL 27

27

## DH: Pupil Plane Recording - Requirements

$D_1$ : Object Size  $\delta_1$ : Object Resolution
$D_2$ : Camera Size  $\delta_2$ : Camera Resolution




$$\delta_2 \le \frac{\lambda R}{2D_1}$$

$$D_2 \approx \frac{\lambda R}{2\delta_1}$$

$$\theta_{\max} \approx \Lambda / 2 \approx \lambda / (2\delta_2)$$

For image plane recording: Camera resolution and size should "match" object's image resolution and size, not accounting for angled reference beam.

CLRC Tutorial-Babbitt 28

28

## DH Signal-to-Noise

- After masking and inverse Fourier transforming, we obtain estimate of complex field for reconstructed image

$$E_{Reconstruct} \approx E_{LO}{}^{*}U \propto \sqrt{\bar{m}_{LO}\bar{m}_S}$$

$$SNR = \frac{\sqrt{\bar{m}_{LO}}\sqrt{\bar{m}_S}}{\sqrt{\bar{m}_{LO}} + \sqrt{\bar{m}_S} + \sigma_N}$$

- If $\bar{m}_{LO} \gg \bar{m}_s$

$$SNR = \frac{\sqrt{\bar{m}_{LO}}\sqrt{\bar{m}_S}}{\sqrt{\bar{m}_{LO}} + \sigma_N}$$

Typically set LO power to produce $\bar{m}_{LO} <\approx well\ depth$

- If the number of photoelectrons generated from LO field is much greater than camera readout noise, $\sqrt{\bar{m}_{LO}} > \sigma_N$

$$SNR \approx \sqrt{\bar{m}_S}$$

  - The system SNR is then limited by the shot noise of the signal

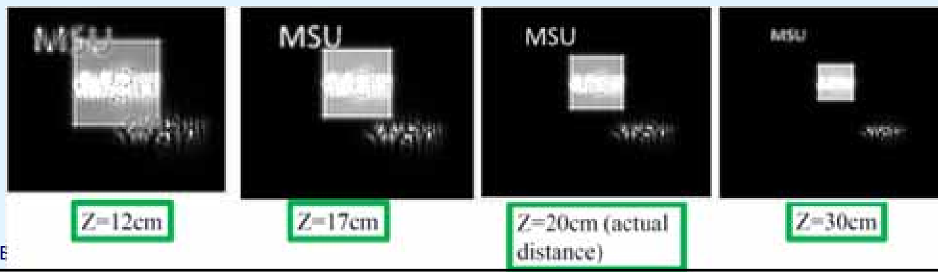
CLRC Tutorial-Babbitt

30

## Depth of Field (DOF)

- For conventional imaging and CW DH, the Depth of Field (DOF) is axial distance around "focused" object plane over which the image is in "focus".
- Diffraction Limited: $DOF_{DL} = 2\lambda \left(\frac{R}{D}\right)^2,$
- Feature Limited: $DOF_{NDL} = 2\delta\ \frac{R}{D}.$

$R$: Object Range
$D$: Entrance pupil diameter
$\delta$: Feature size

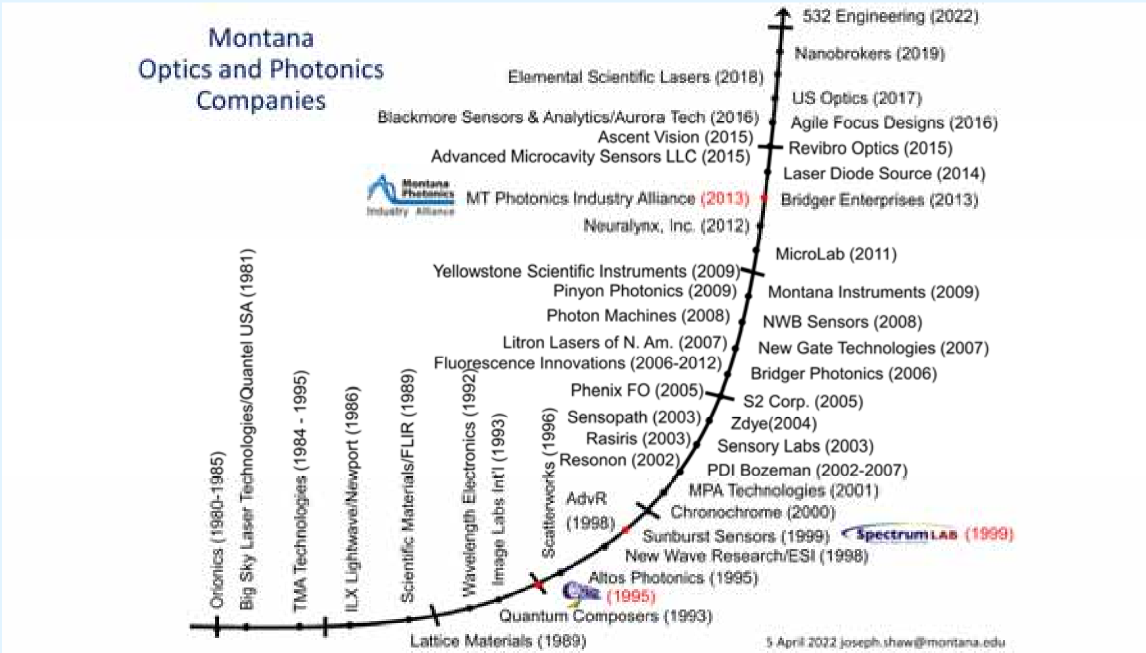





## Montana Photonics Industry Alliance (MPIA)


- MSU helped found the MPIA
- MSU faculty and staff serve on the MPIA Board of Directors
- MSU and MPIA collaborate continuously to grow and sustain relationships in Montana and world-wide

# Montana Optics and Photonics Companies




CLRC 33

33

# Spectrum Lab Overview

**History**

- **Montana State University Research Center since 1999**
- **Research Expenditures/Assets**
  - **>$1M per year in research expenditures**
  - **>>$2M of accumulated equipment for optics and photonics research**
- **Research Spin-offs**
  - **Four successful (25-75 employees, >>$1M annual revenue) direct and indirect "research spin off" companies**
    - **S2 Corporation, Bridger Photonics, Blackmore Sensors/Aurora, Montana Instruments**

**Spectrum Lab's Mission**

- **Develop and help commercialize Montana grown photonic technologies.**
- **Transfer developed technologies to Montana companies.**
- **Provide enhanced educational and employment opportunities for Montana undergraduate and graduate students.**

**Expertise**

- **Applied Research and Development: Spatial-Spectral Holography, Microwave photonics, Precision Lidar, Coherent Imaging, Laser Development**
- **Interdisciplinary Research: Students/Collaborators in Optics and Photonics, Physics, Material Science, Electrical and Computer Engineering, and Mechanical Engineering**
- **IP generation and protection => Fostering research spin-offs**
- **Educating students for careers in optics and photonics industry.**
- **Controlled unclassified (CUI) research facility. Personnel at secret and higher.**

CLRC Tutorial-Babbitt 34

34

# Recent Spectrum Lab Projects

Spectrum LAB Montana State University

- **Coherent Lidar and Imaging**
  - **Stable, Linearized Optical Chirps**
  - **Range-Resolved Digital Holographic Imaging (See Thursday talk by Matt Goodman)**
  - **Polarimetric Digital Holography**
  - **Imaging through Turbulence and Fog (See Thursday talk by Corey Pearson)**
  - **Temporal Heterodyne Range-Resolved Digital Holography (See Monday Poster by Cole Hammond)**

- **Quantum Networks**
  - **Quantum information transfer in free space and through multi-core fibers**
  - **Materials for quantum memories and sources**

- **Spatial-Spectral Holographic Microwave Signal Processors**
  - **Microwave Photonics**
    - » **Extremely broadband, high resolution spectrum monitoring and geolocation**
      - **0-110 GHZ, 40 GHz IBW, sub-MHz resolution, >1 KHz frame rates, >60 dB SFDR**
    - » **Broadband, high SFDR analog photonics links**
  - **Real-Time High Bandwidth Correlator**
    - » **Broadband "noise" radar and geolocation**
    - » **Massively parallel cyclostationary signal processing**