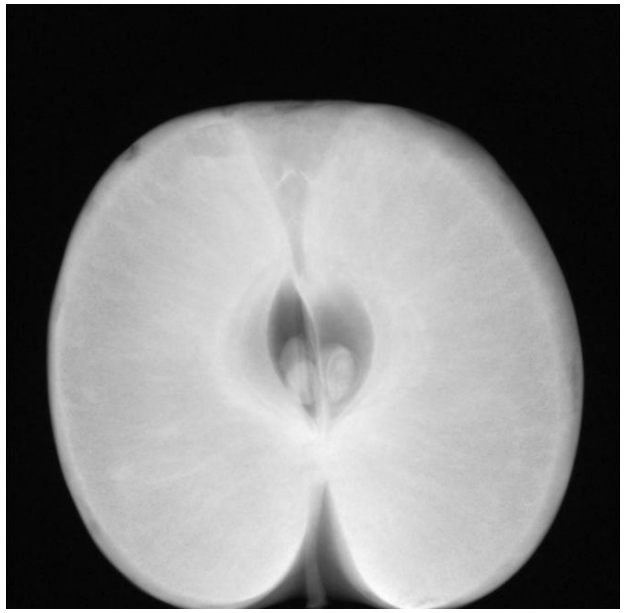
VIRTUAL STUDIES IN GRATING-BASED PHASE-CONTRAST IMAGING

Janne Vignero

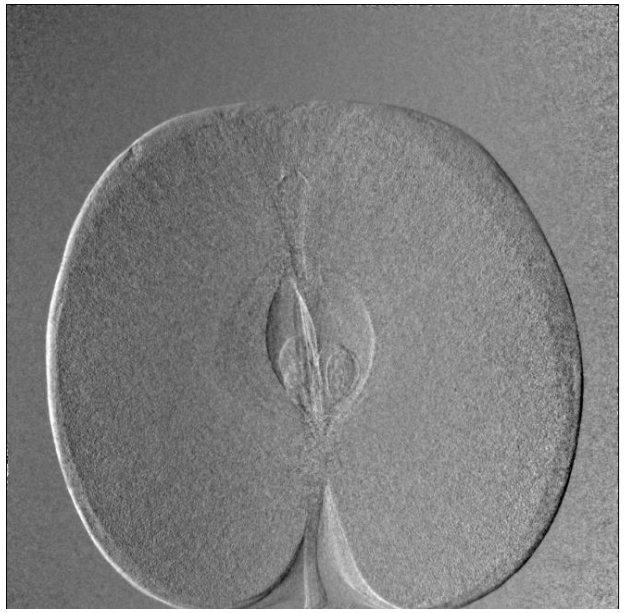
INTRODUCTION

Talbot-Lau Interferometry (TLI)

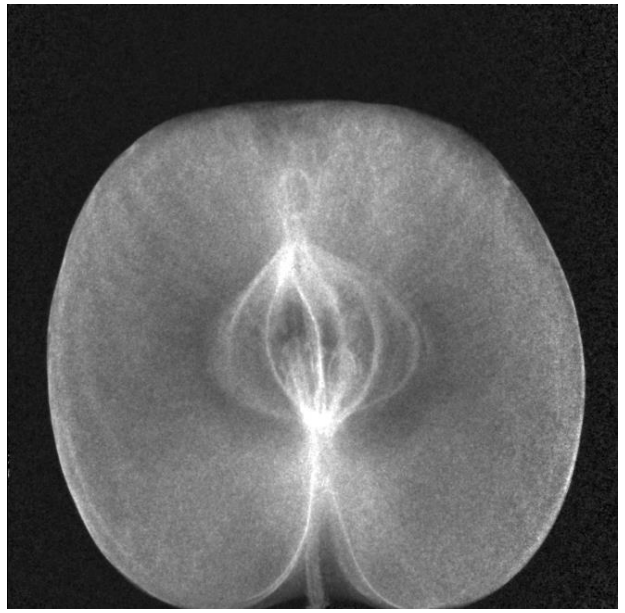
Transmission Image



Differential phase Image



Dark Field Image



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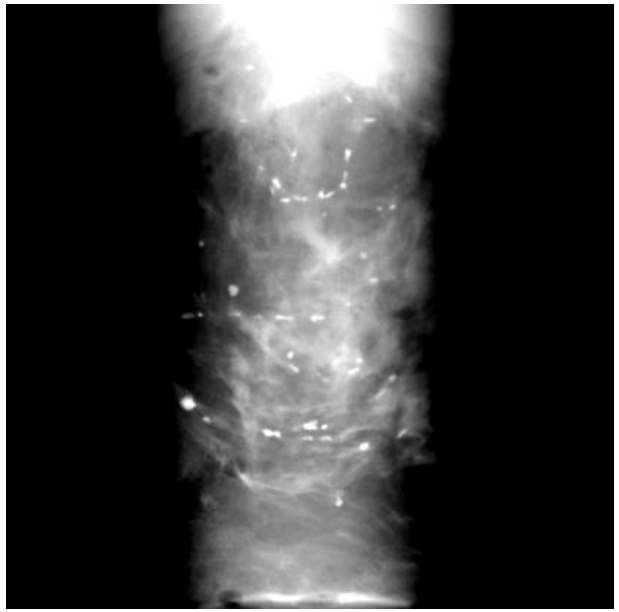

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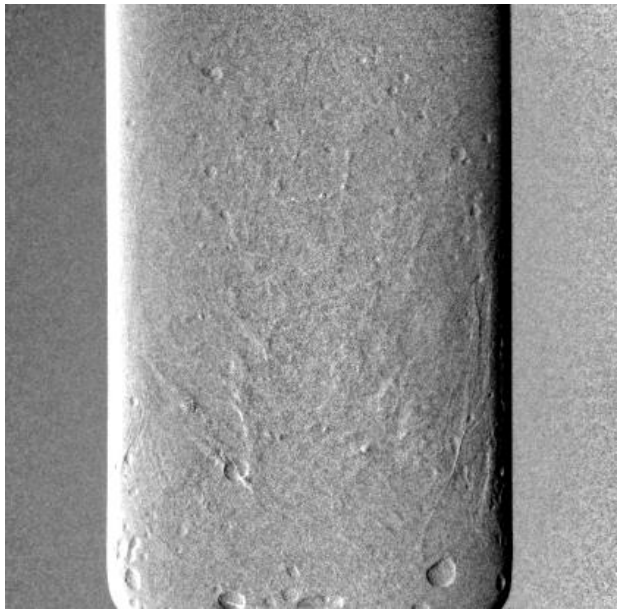
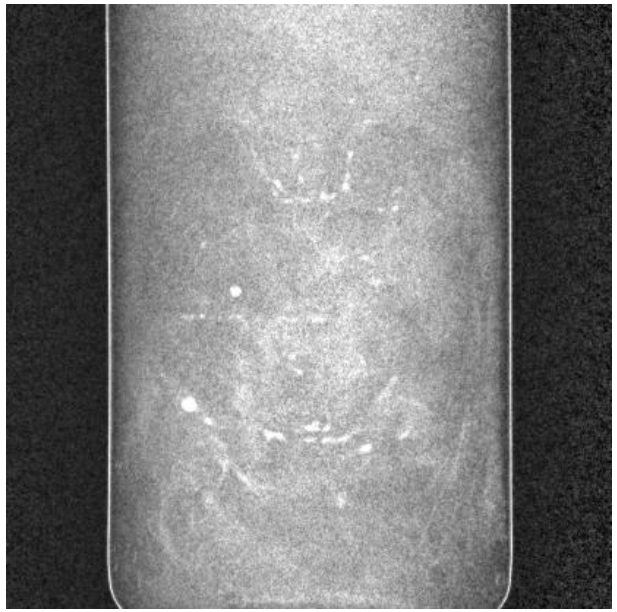


Soft tissue contrast

Dark Field Image



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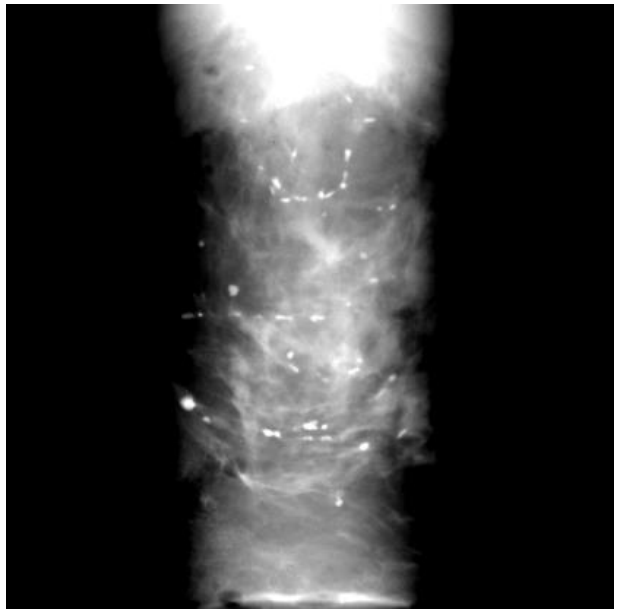

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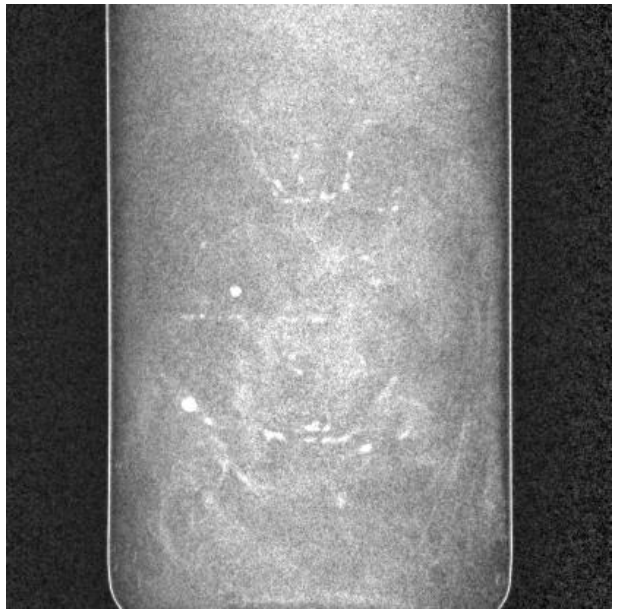

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Comparison via contrast-to-noise ratios

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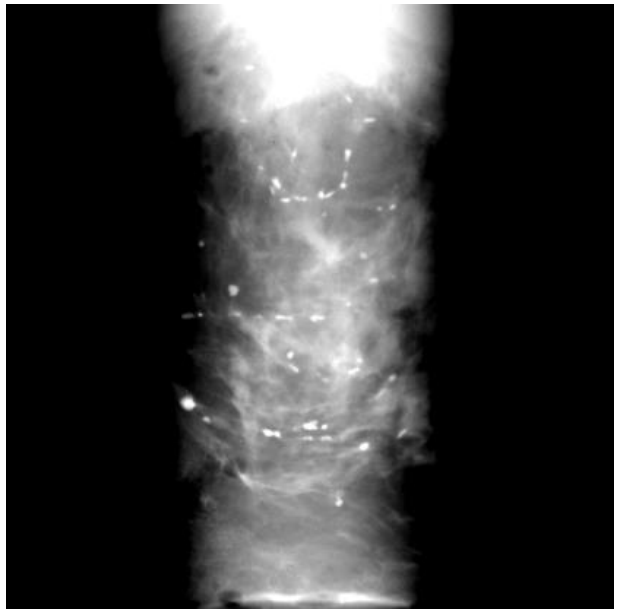

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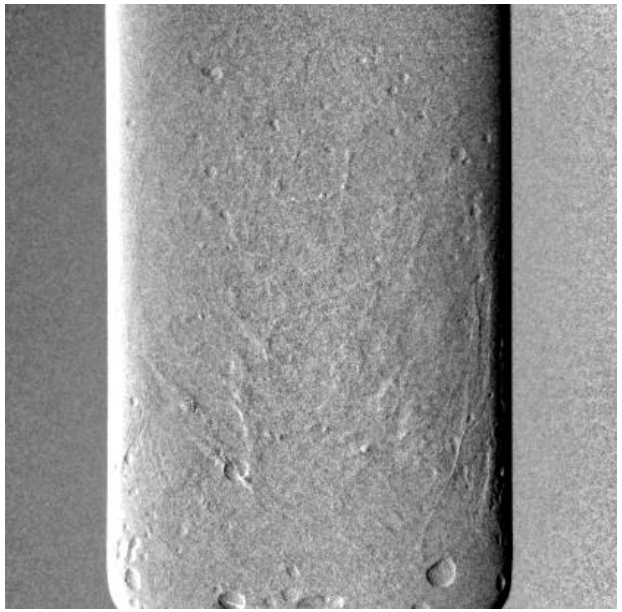

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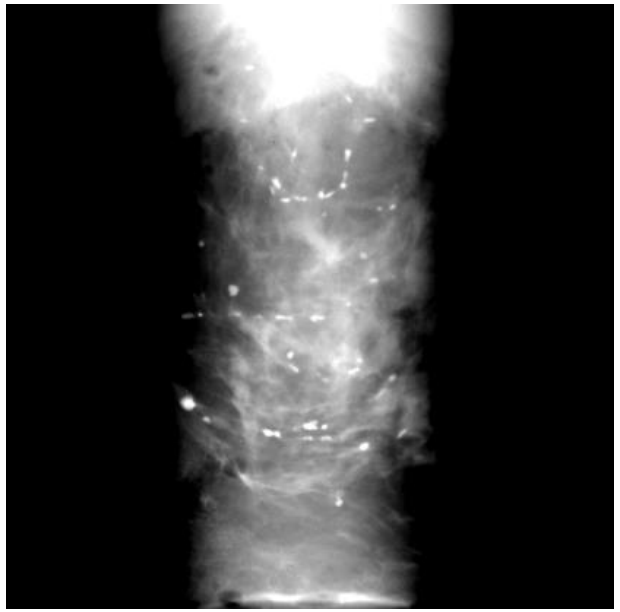

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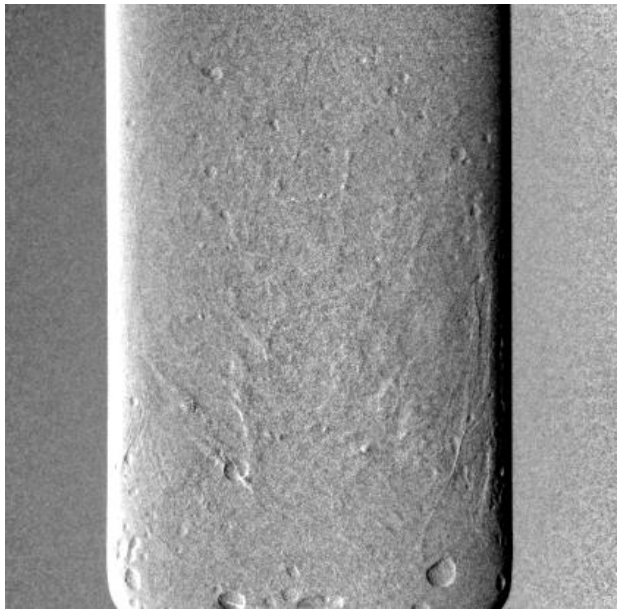

Soft tissue contrast

How to quantitatively compare Tr and dP imaging?

OUTLINE

- Talbot-Lau interferometry
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  - generate ‘realistic’ imagines that match those of a TLI scanner
- A detectability study
  - a task-based study
  - human reader studies (4-AFC)
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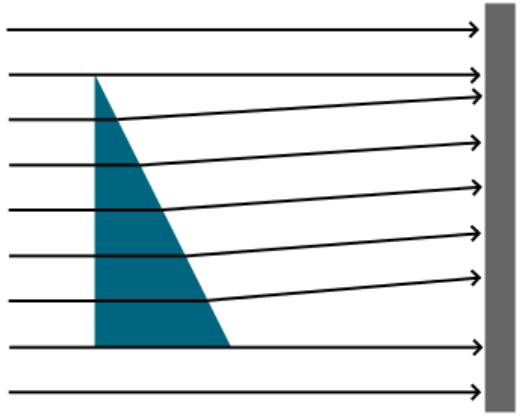
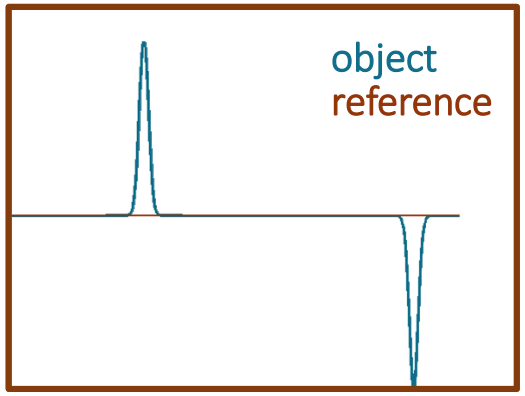
Illumination by a **homogeneous** x-ray field



Creates intensity disturbances at the edges



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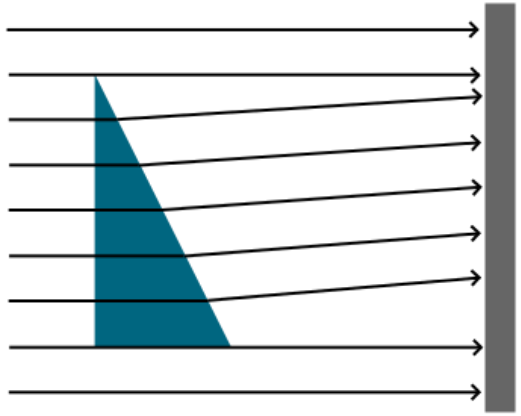

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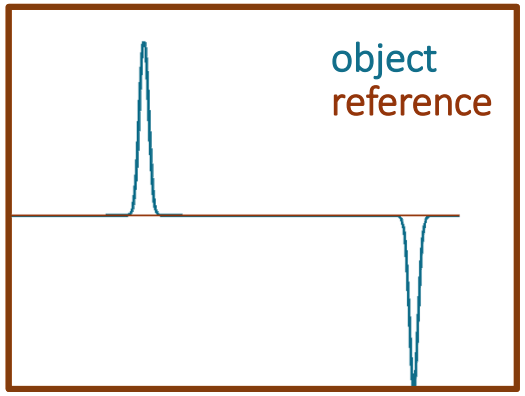
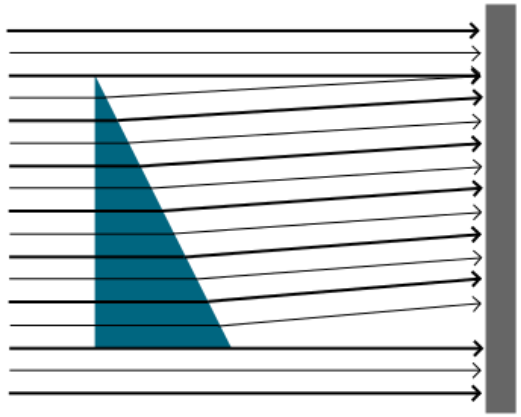
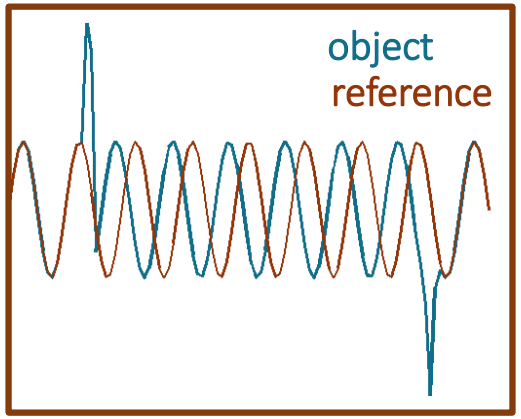


Illumination by a **periodic** x-ray field



Allows to measure the intensity shifts in addition to the edges



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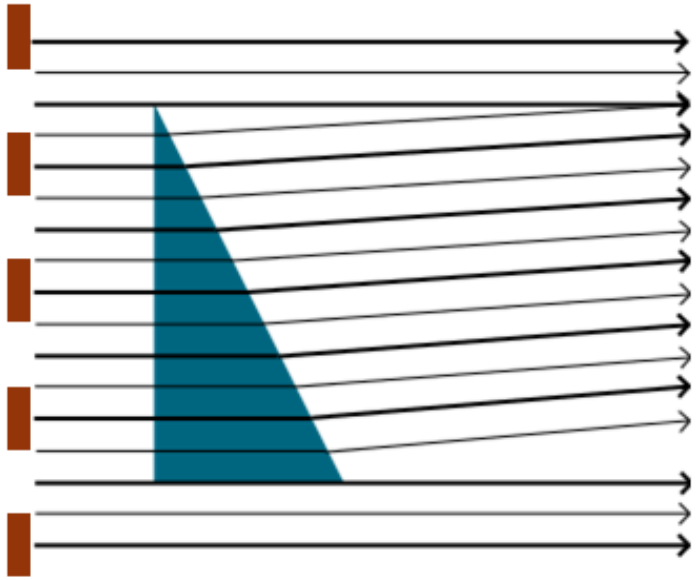
Periodic x-ray field is **created** by a grating; ‘the Talbot effect’



4 µm

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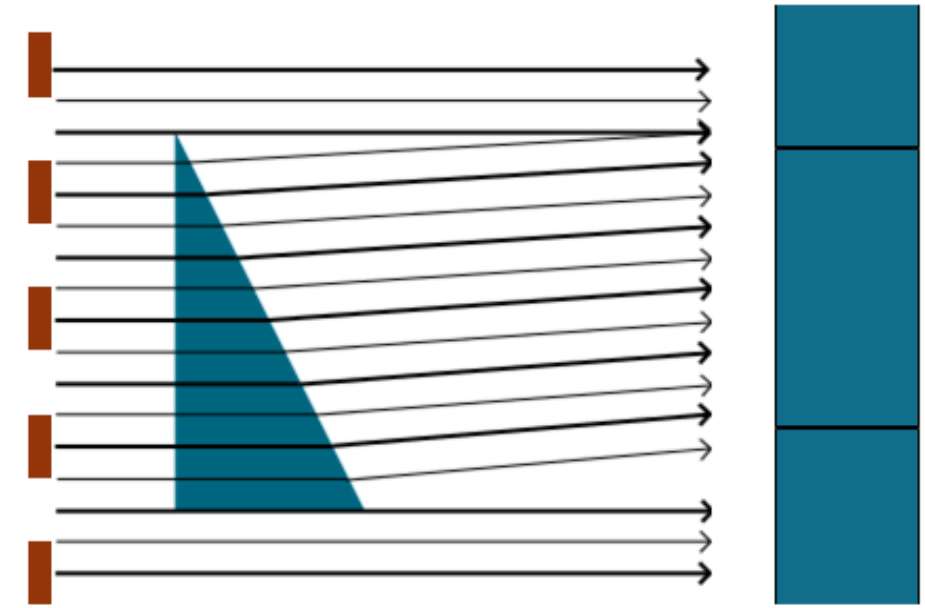

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100 μm

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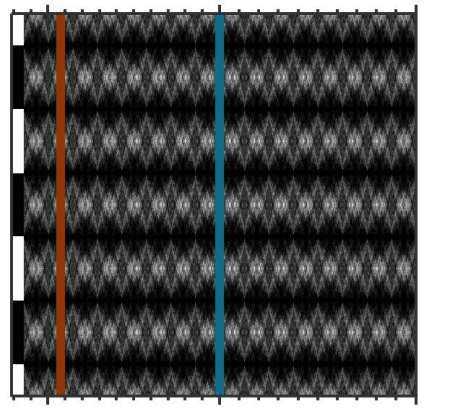

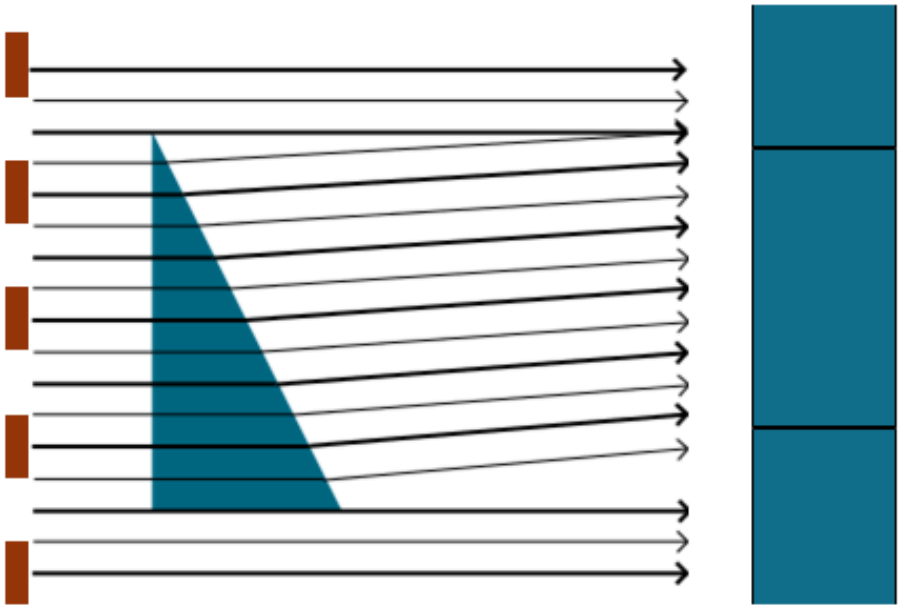

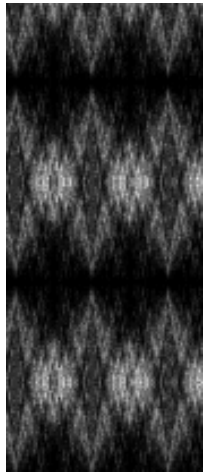

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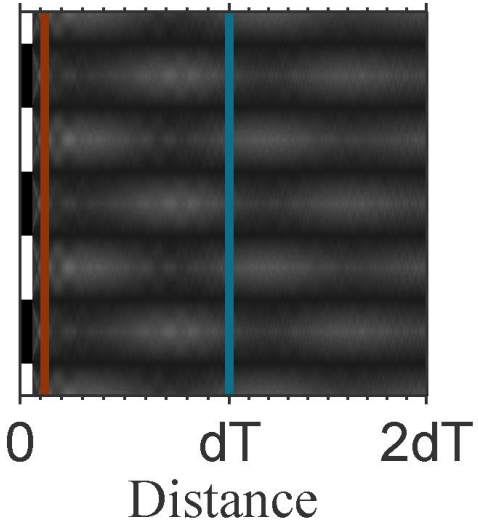

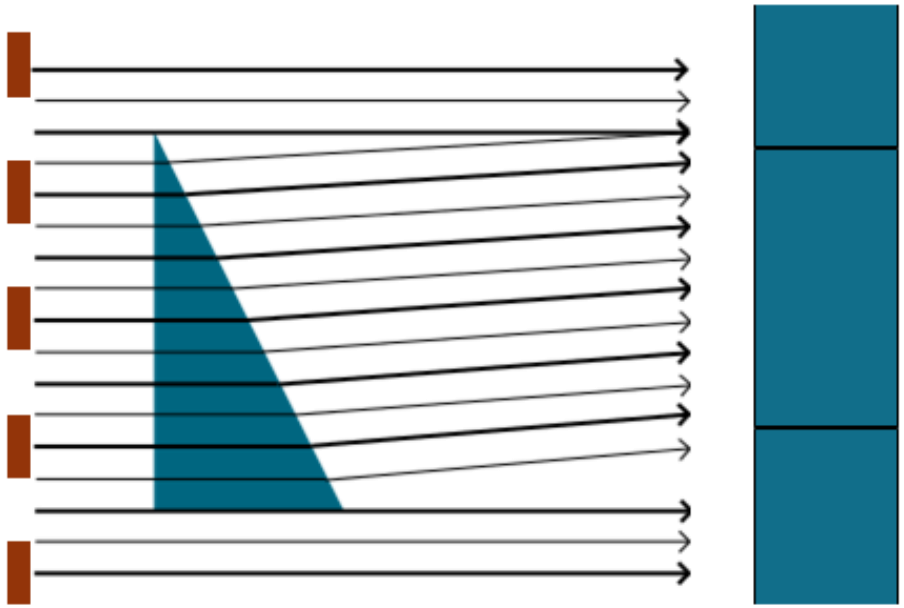

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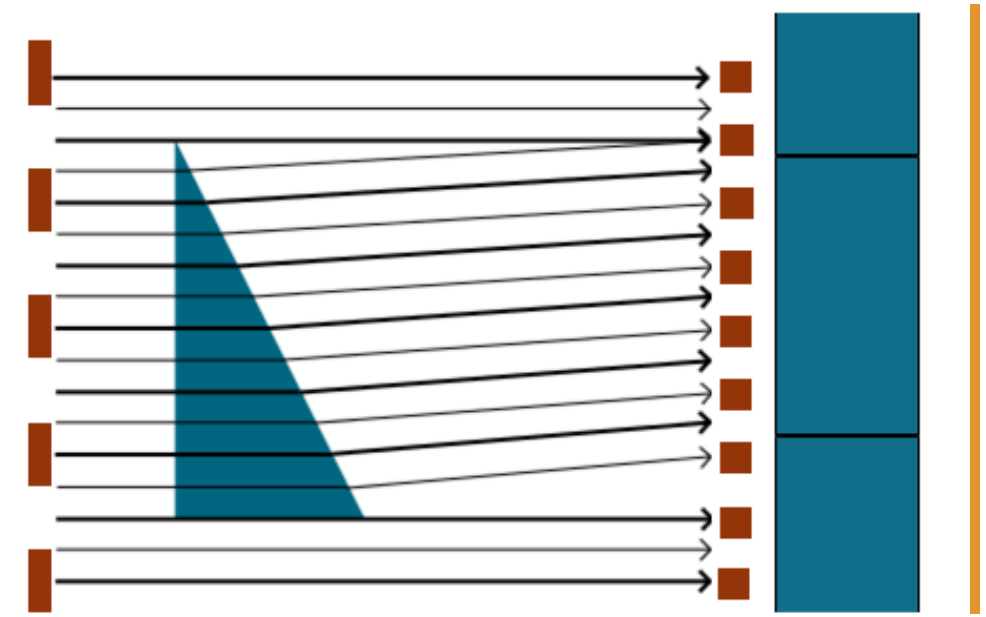

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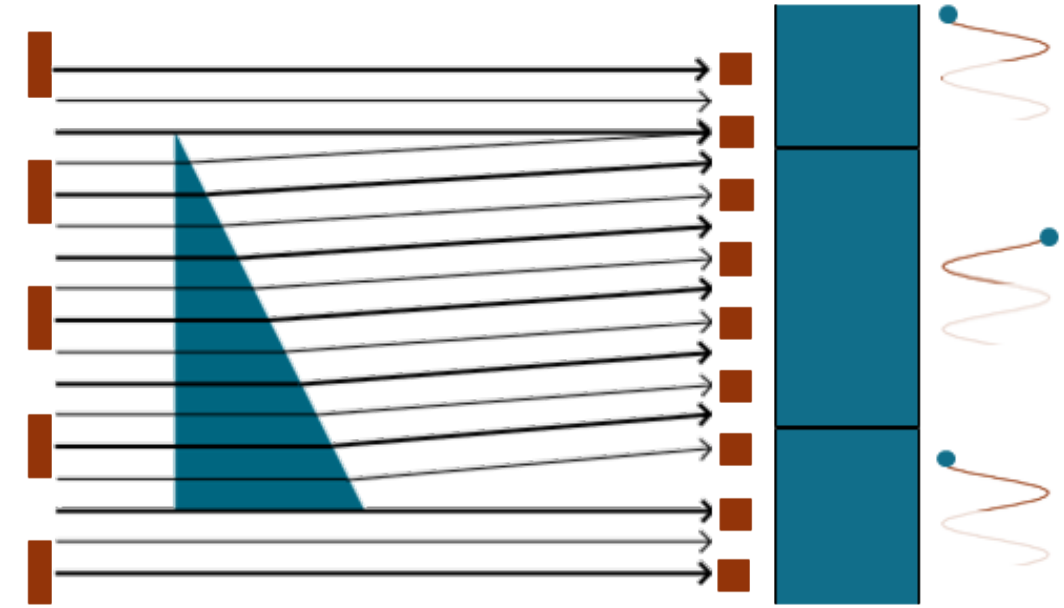

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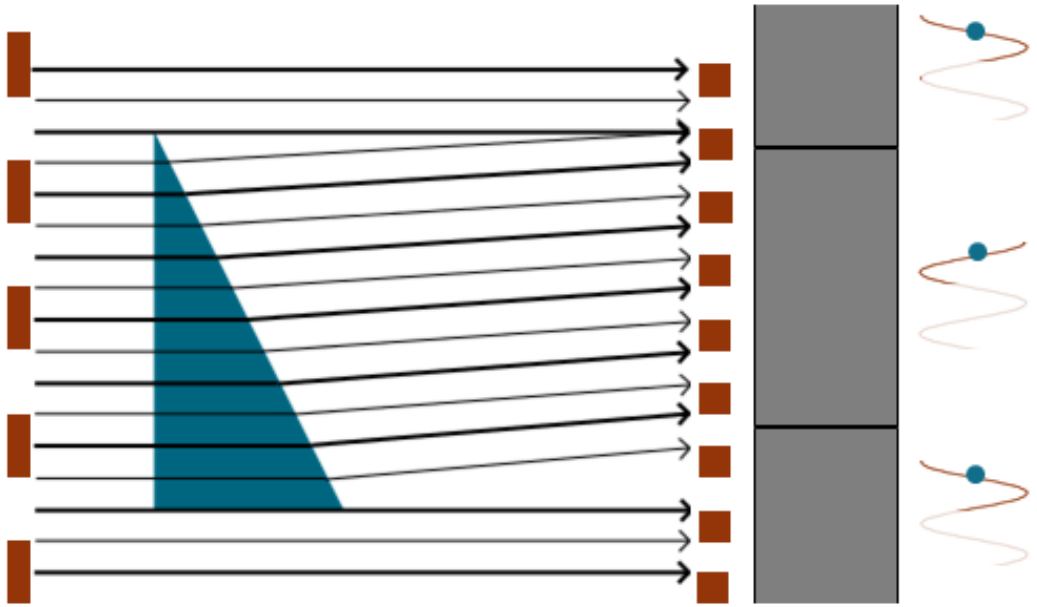

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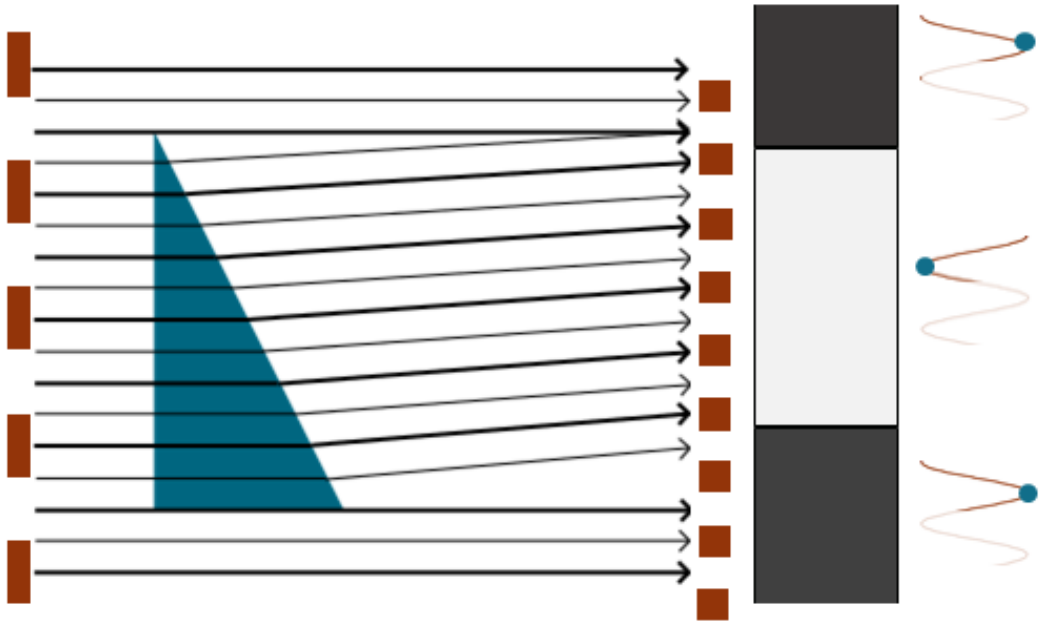

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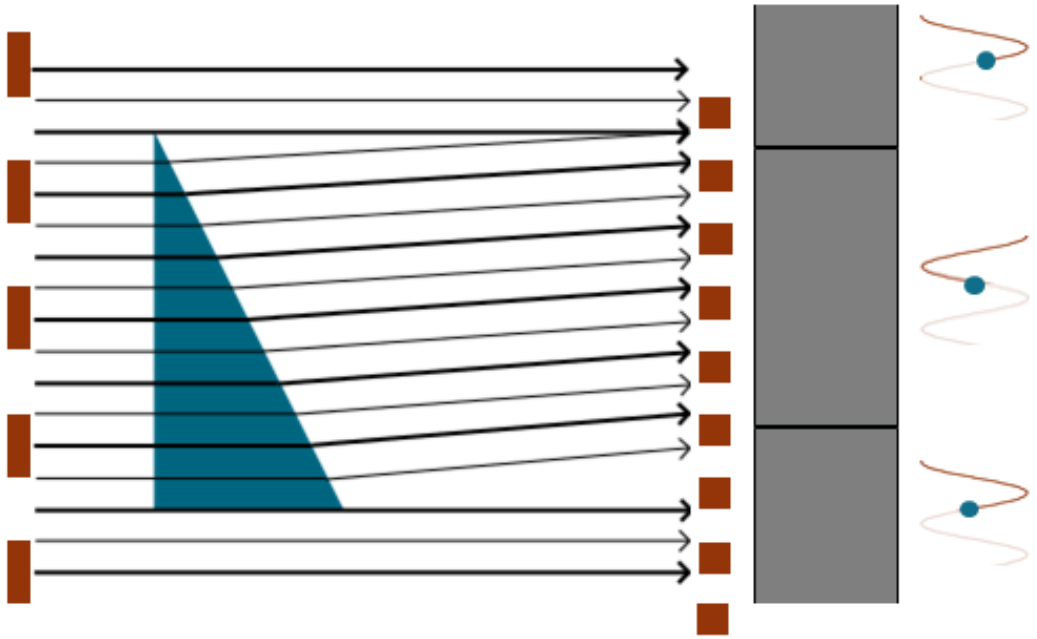

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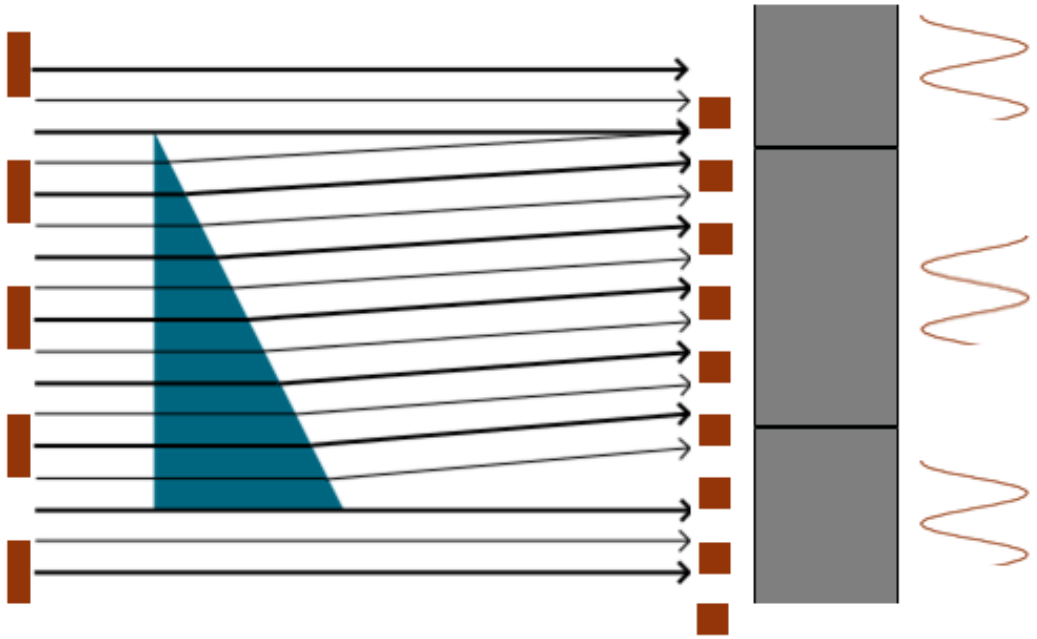

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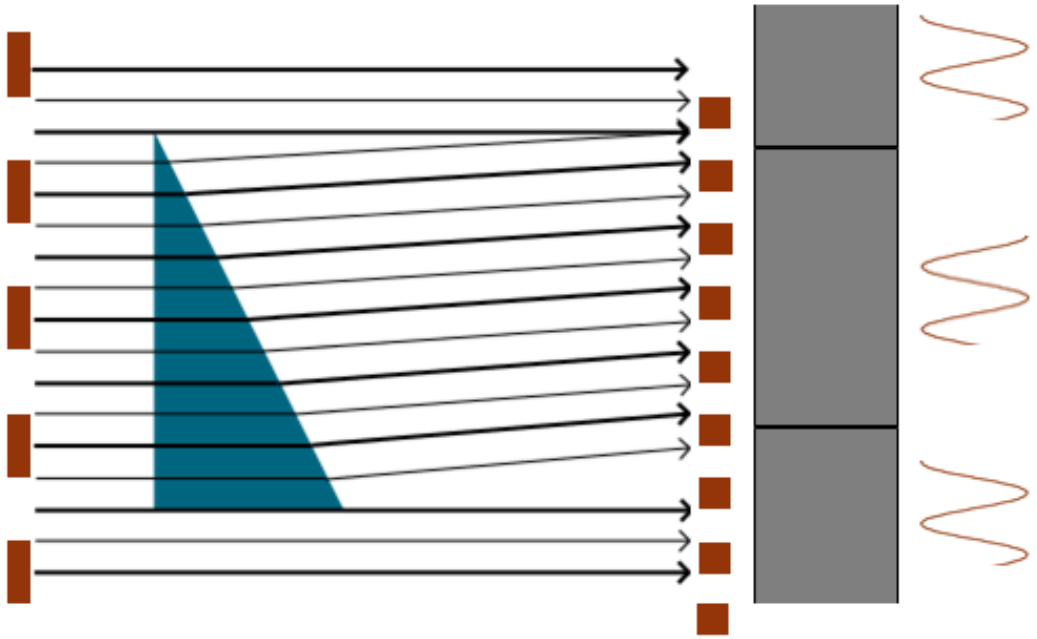

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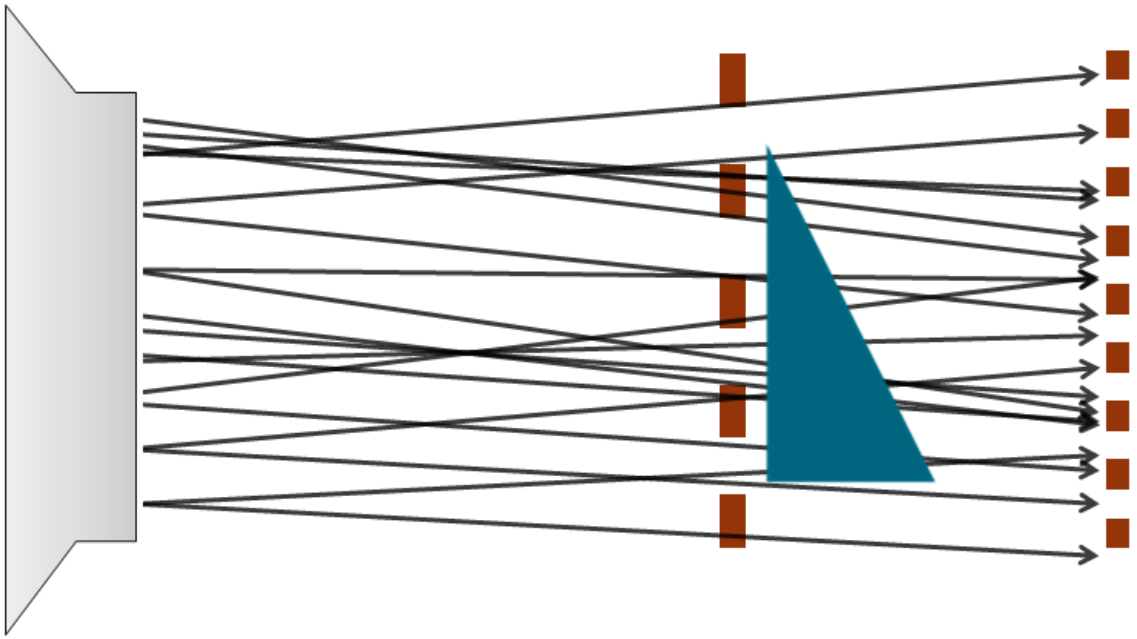

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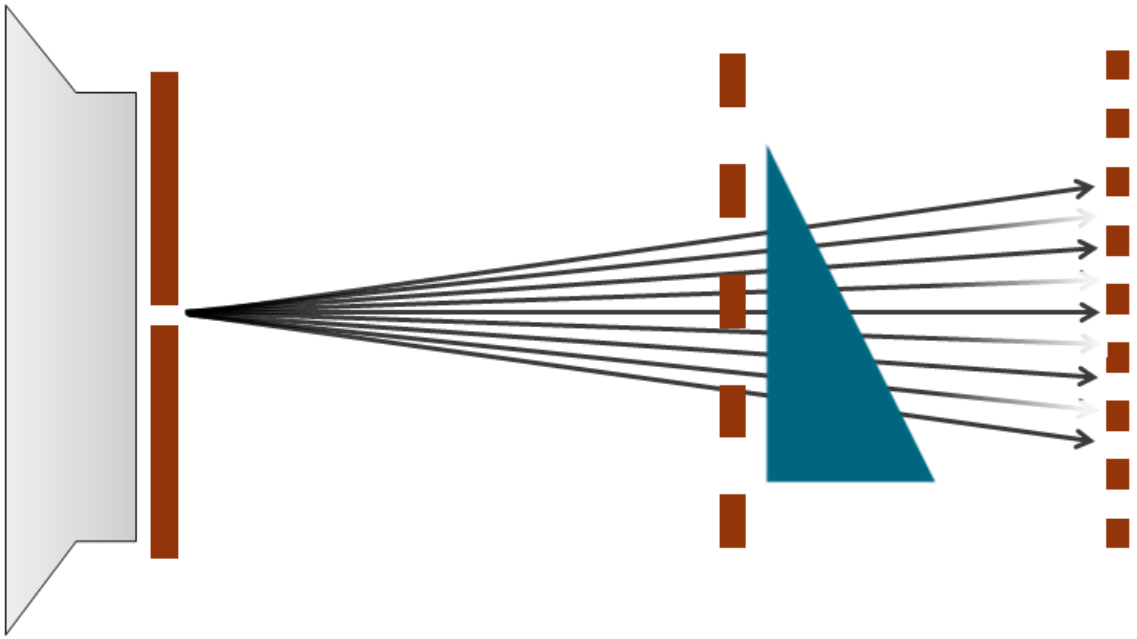

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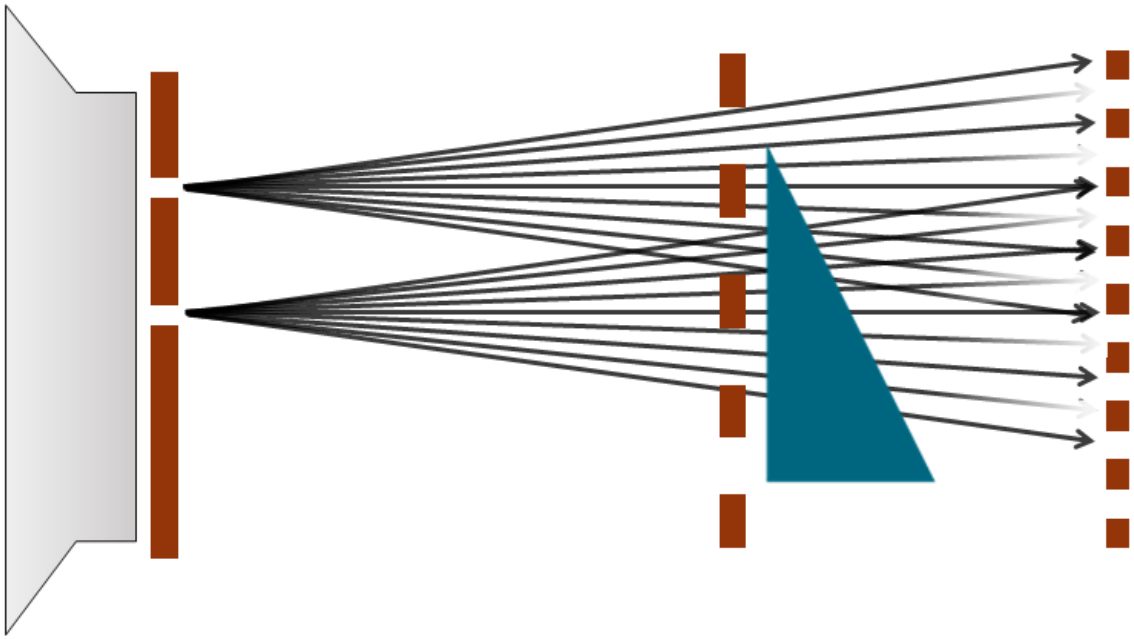

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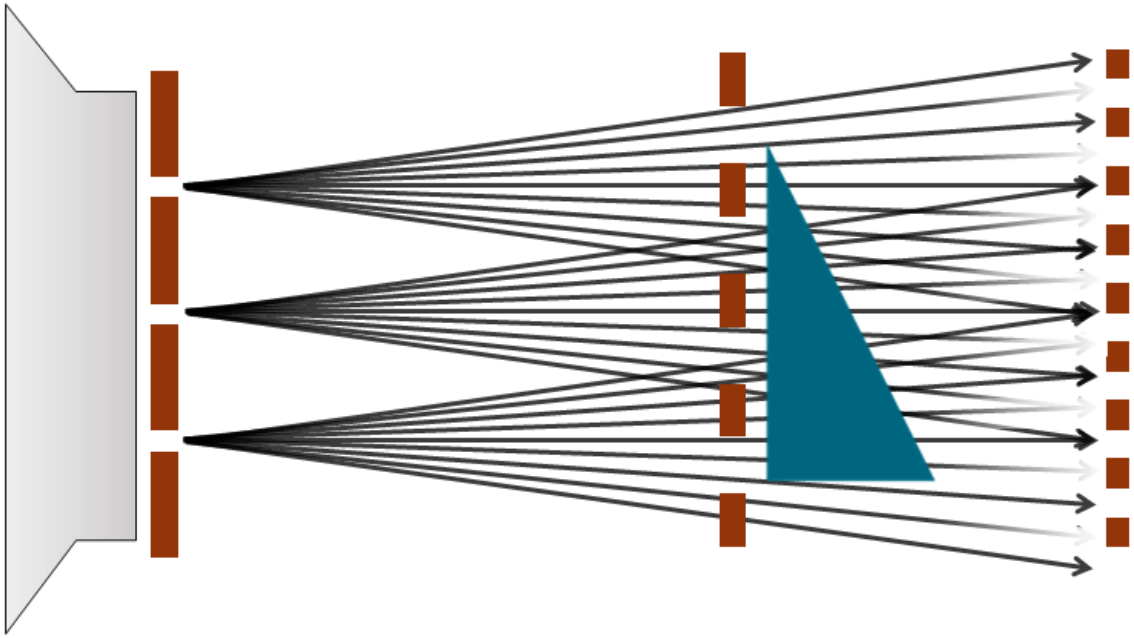

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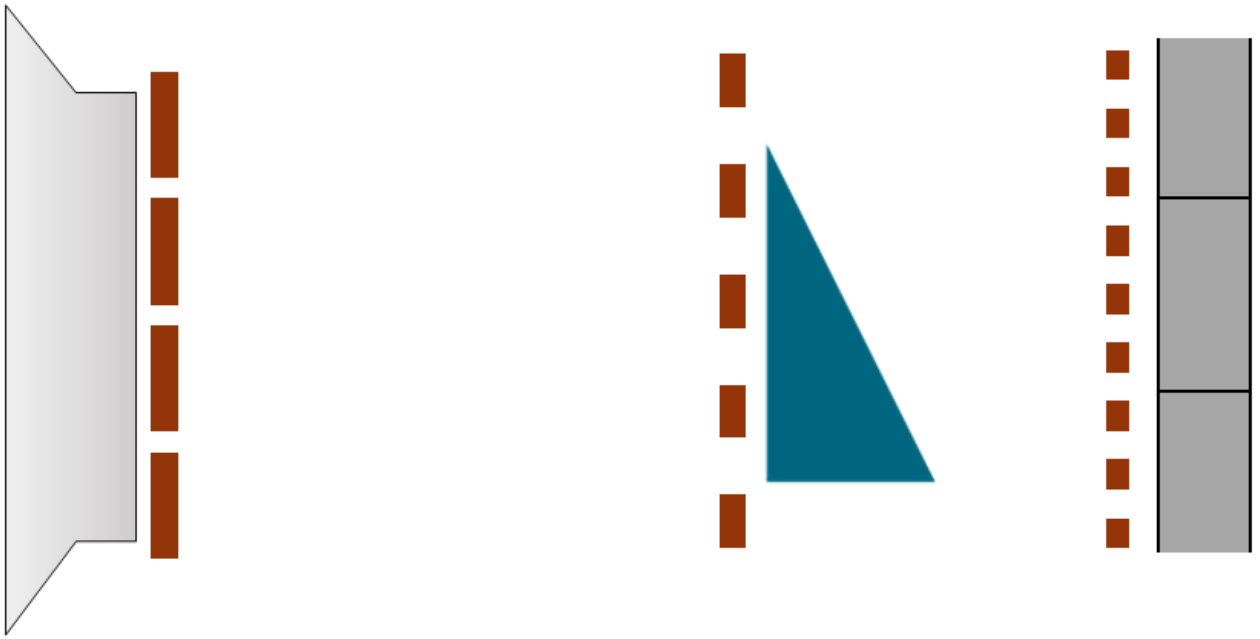

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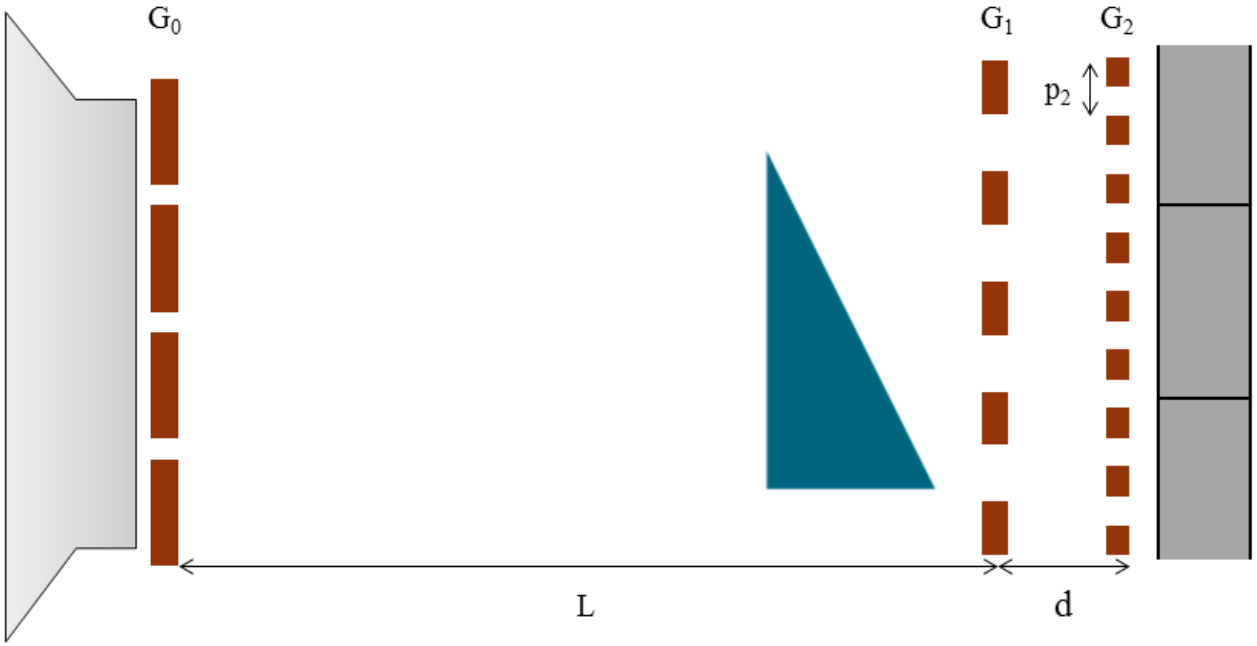

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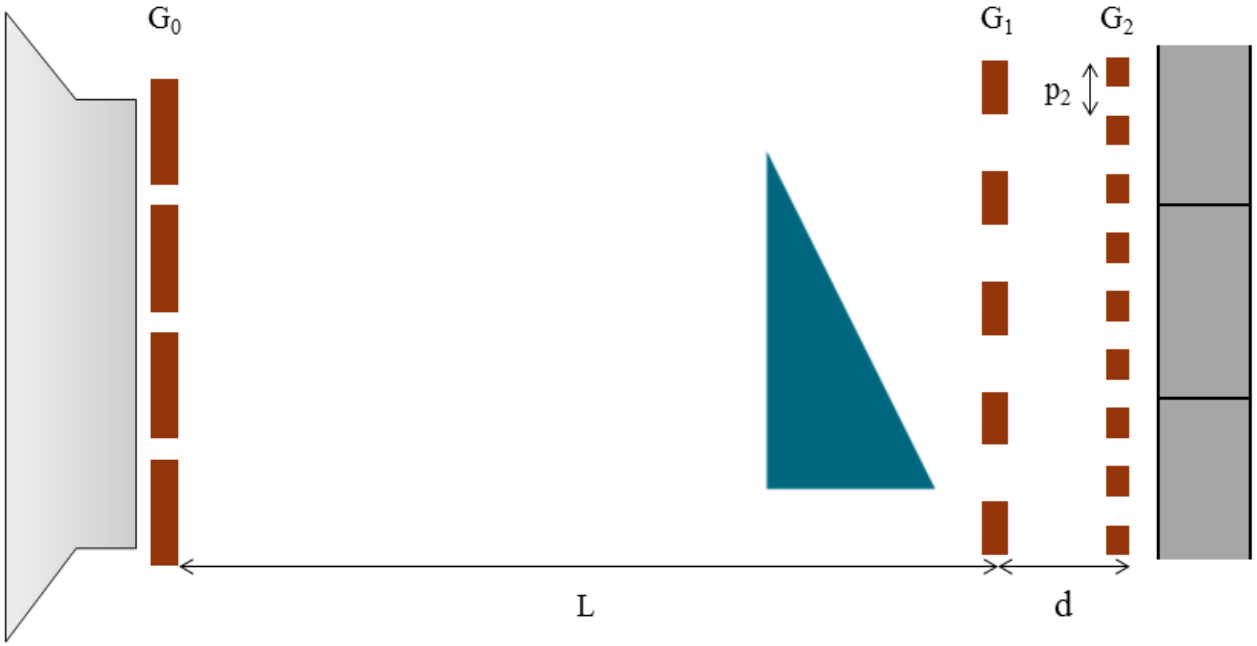

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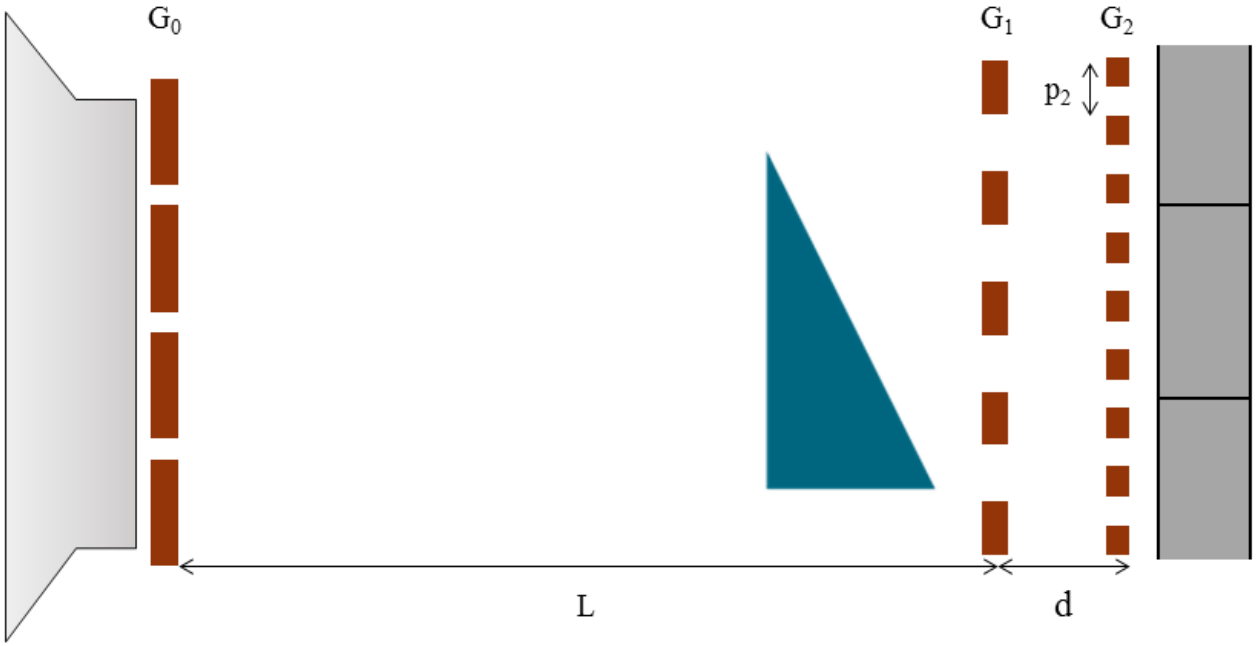

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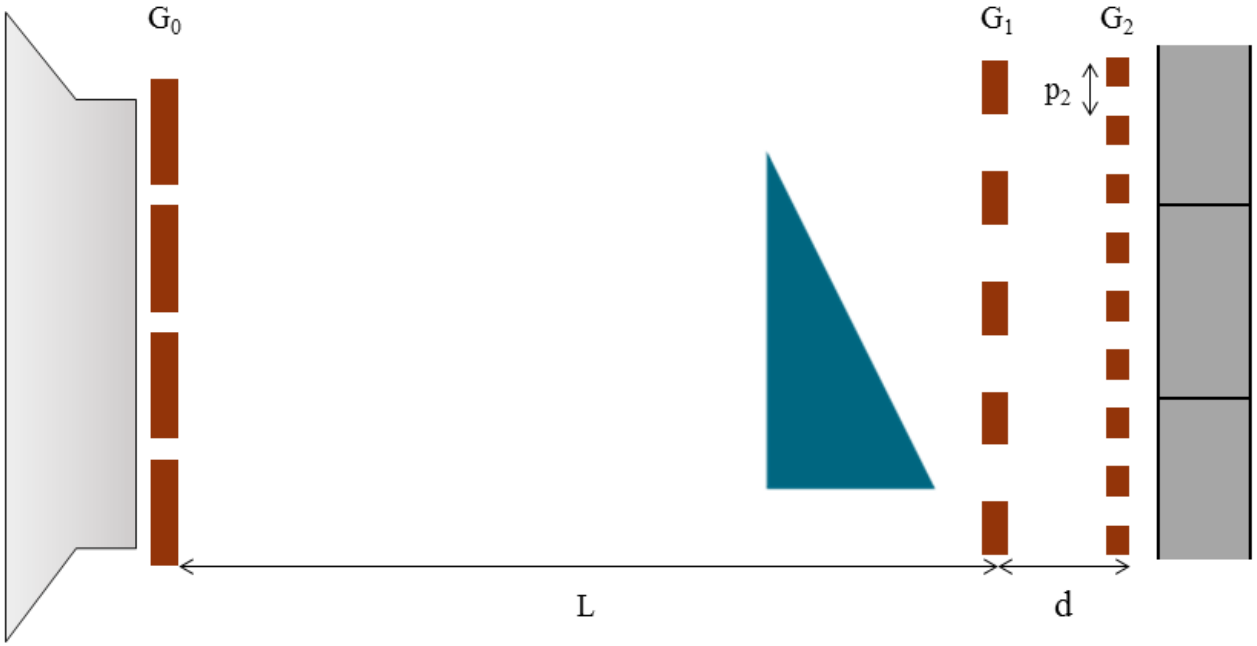

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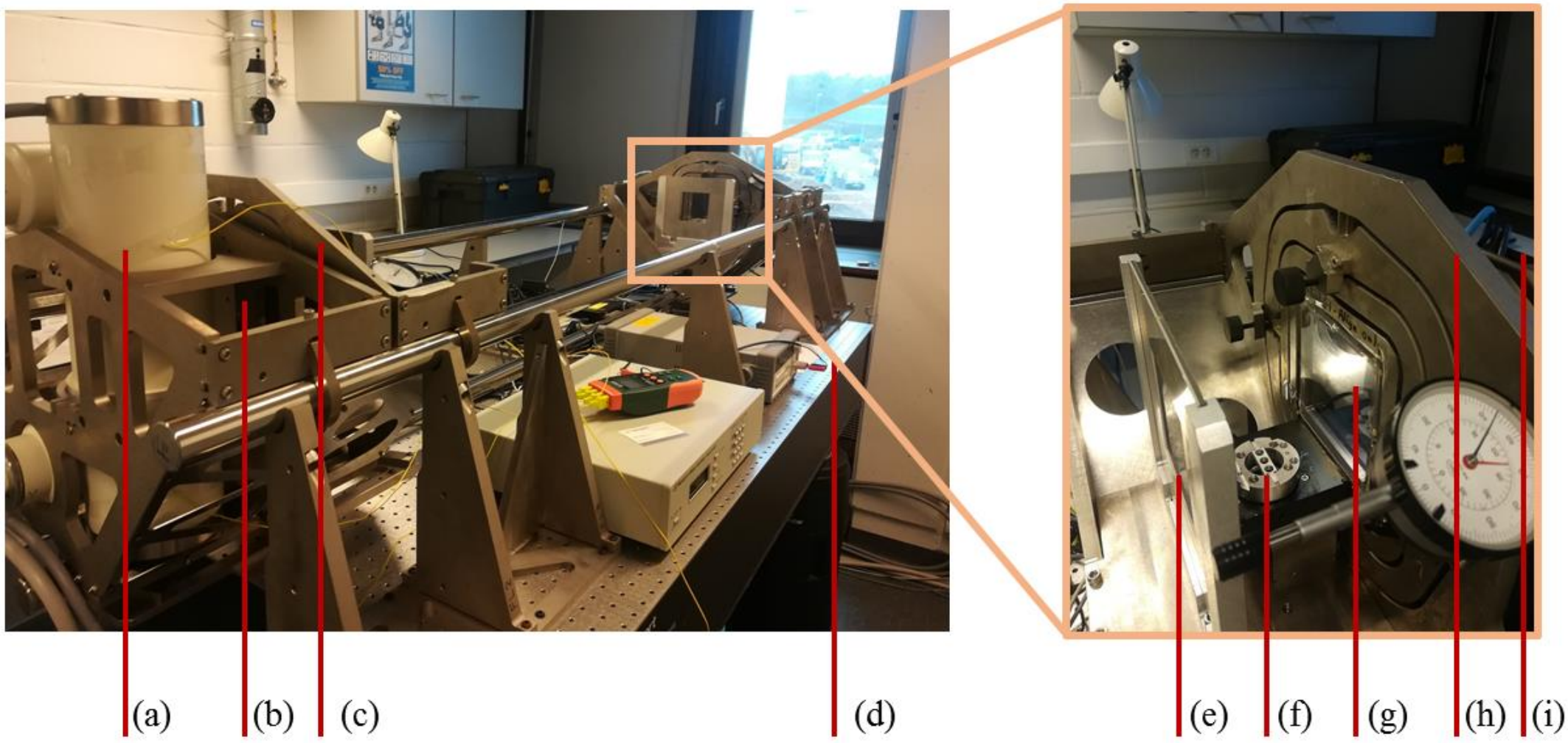
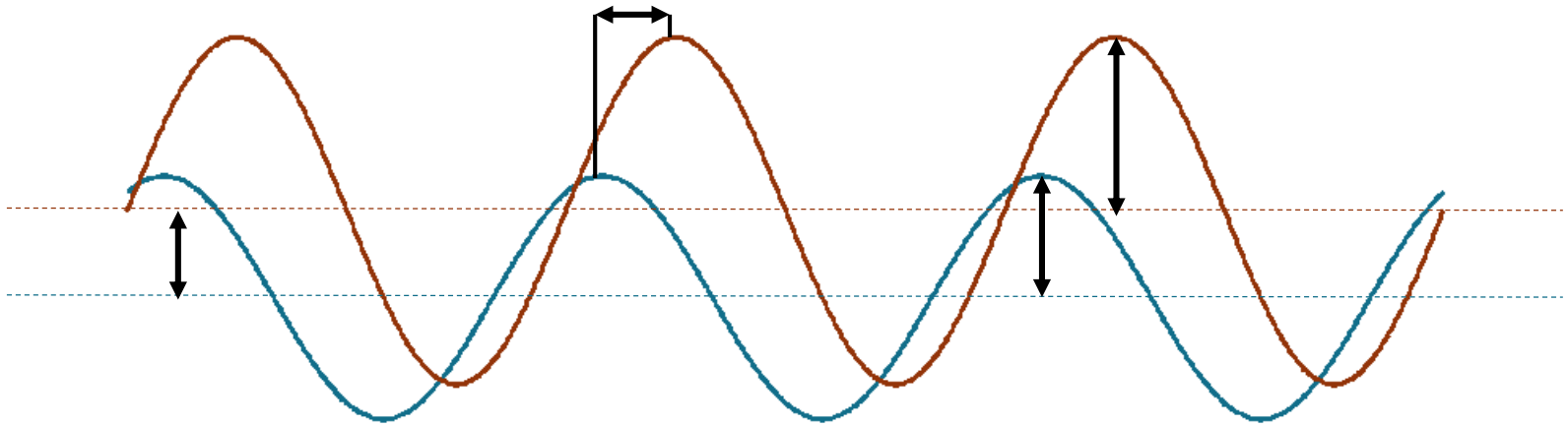


TALBOT-LAU INTERFEROMETRY (TLI)

For each pixel we measure an average intensity pattern with and without object



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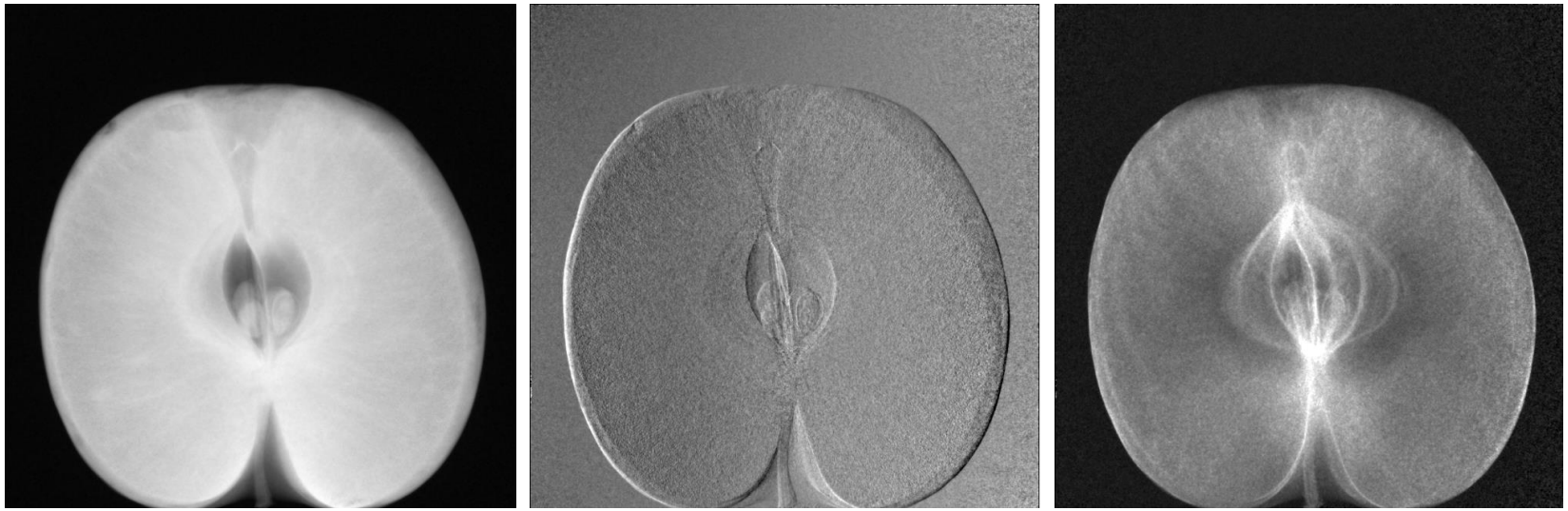
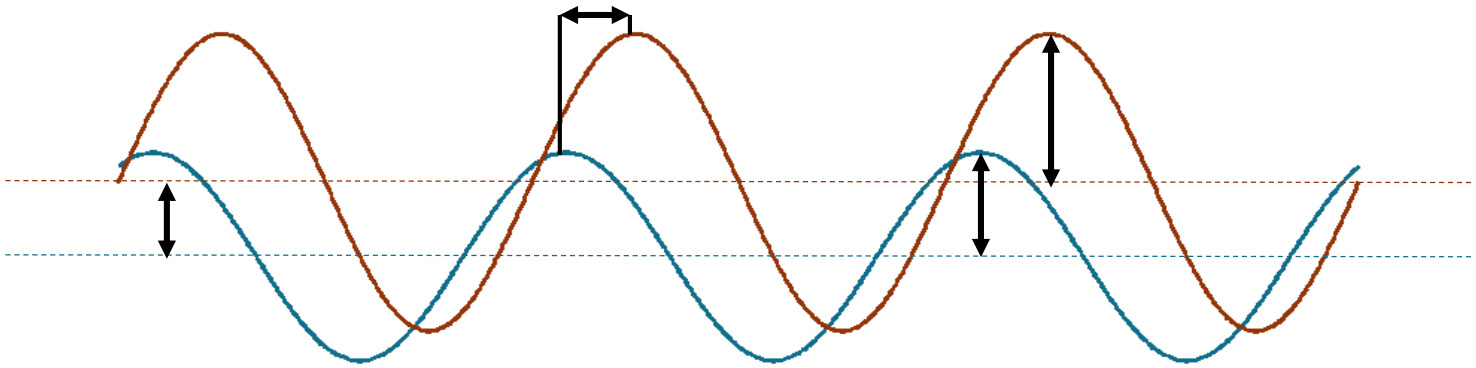
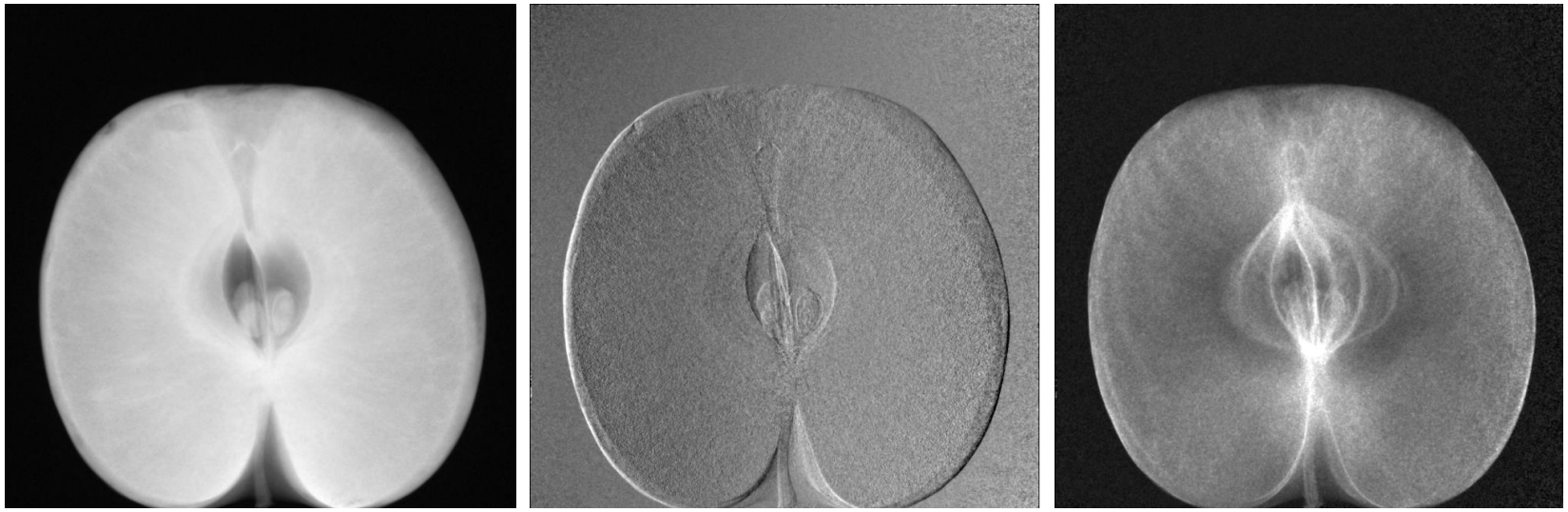
For each pixel we measure 3 parameters ➡ 3 images can be constructed

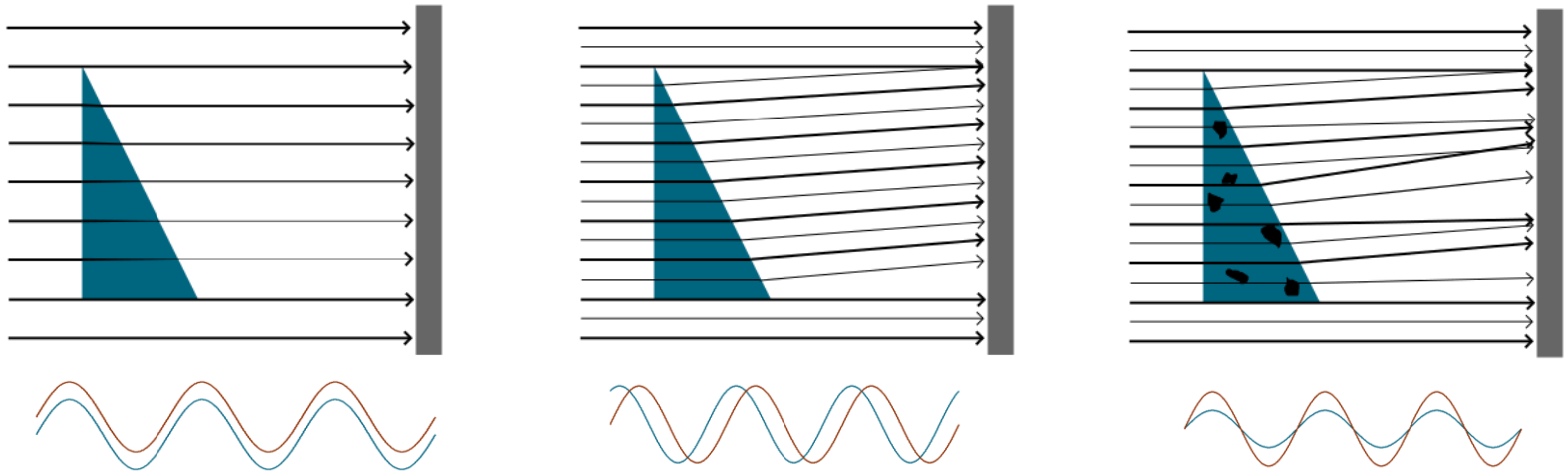




TALBOT-LAU INTERFEROMETRY (TLI)

Transmission Image | Differential phase Image | Dark Field Image





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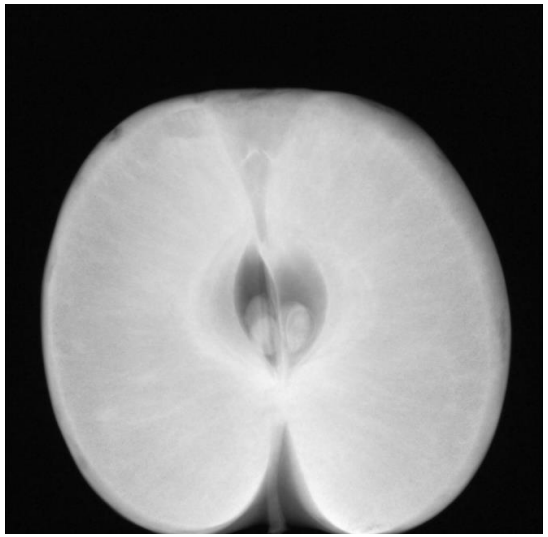
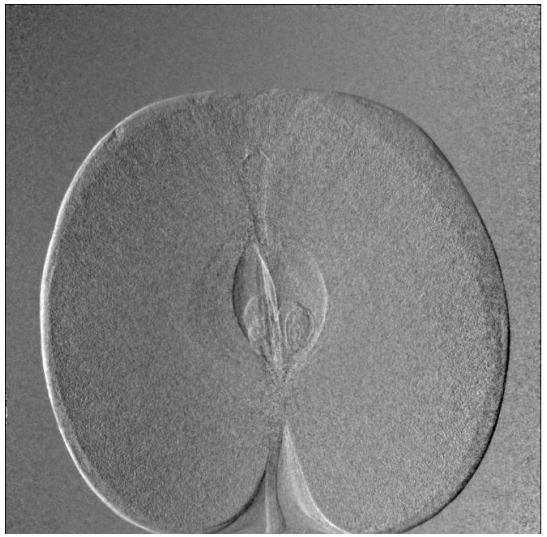
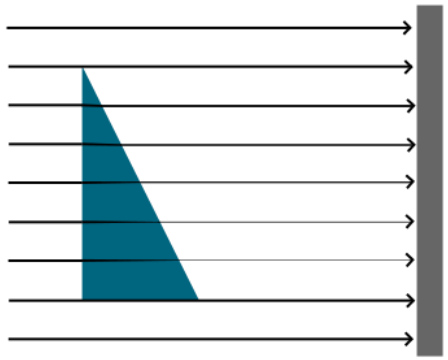
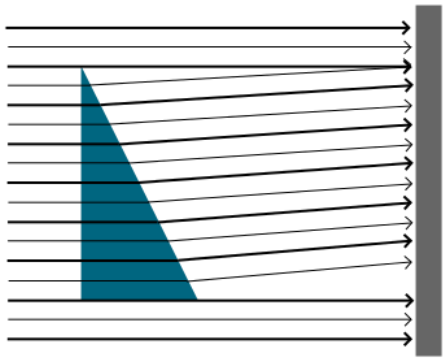


Differential phase Image







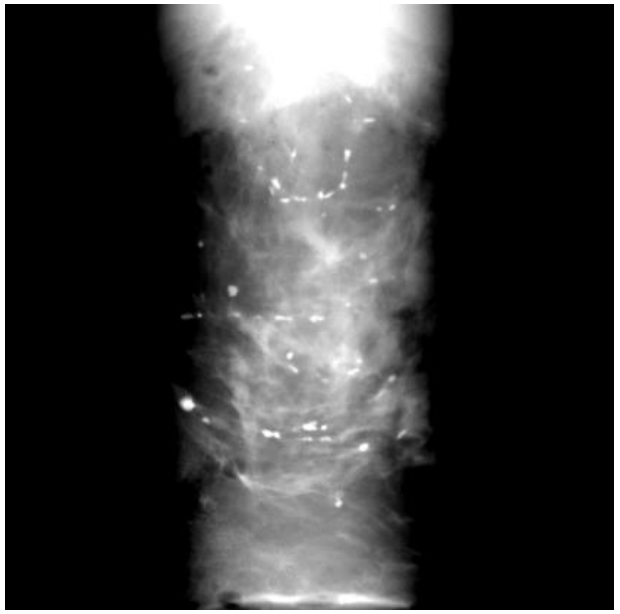
$$S_{\mathrm{Tr}} = \exp(-\mu t) = \exp(-2k\beta t)$$

$$S_{dP} = \frac{2\pi d}{p_2} \tan\left(\frac{\partial \delta t}{\partial x}\right)$$

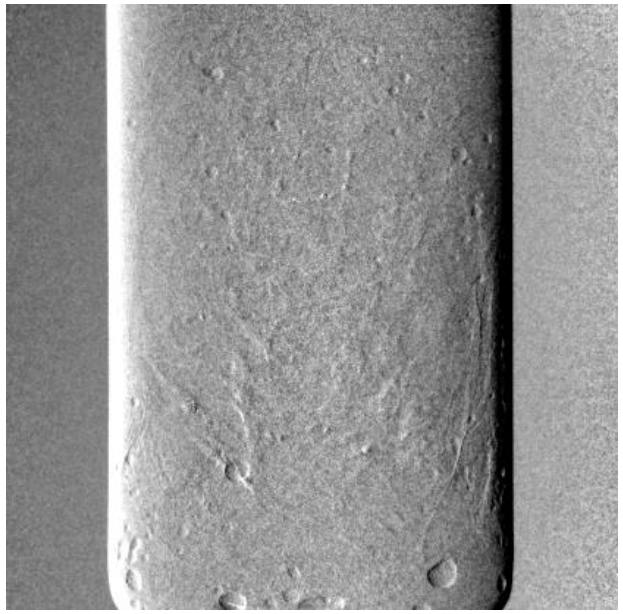
RESEARCH QUESTION

How to quantitatively compare Tr and dP imaging?

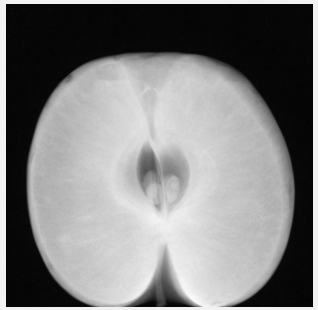
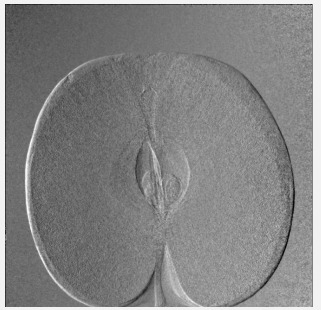
Transmission Image



Differential phase Image



TRANSMISSION VERSUS DIFFERENTIAL PHASE IMAGING

	 Transmission (Tr)	 Differential phase (dP)
Signal	$S_{\mathrm{Tr}} = \exp(-\mu t)$ $= \exp(-2k\beta t)$	$S_{dP} = \frac{2\pi d}{p_2} \tan\left(\frac{\partial \delta t}{\partial x}\right)$
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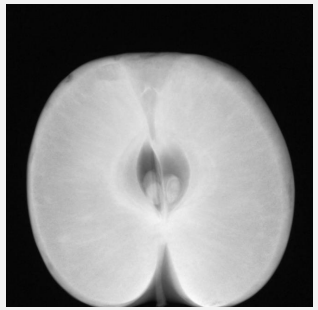
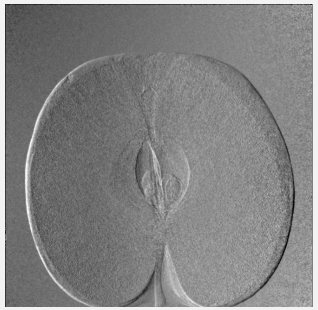
	 Transmission (Tr)	 Differential phase (dP)
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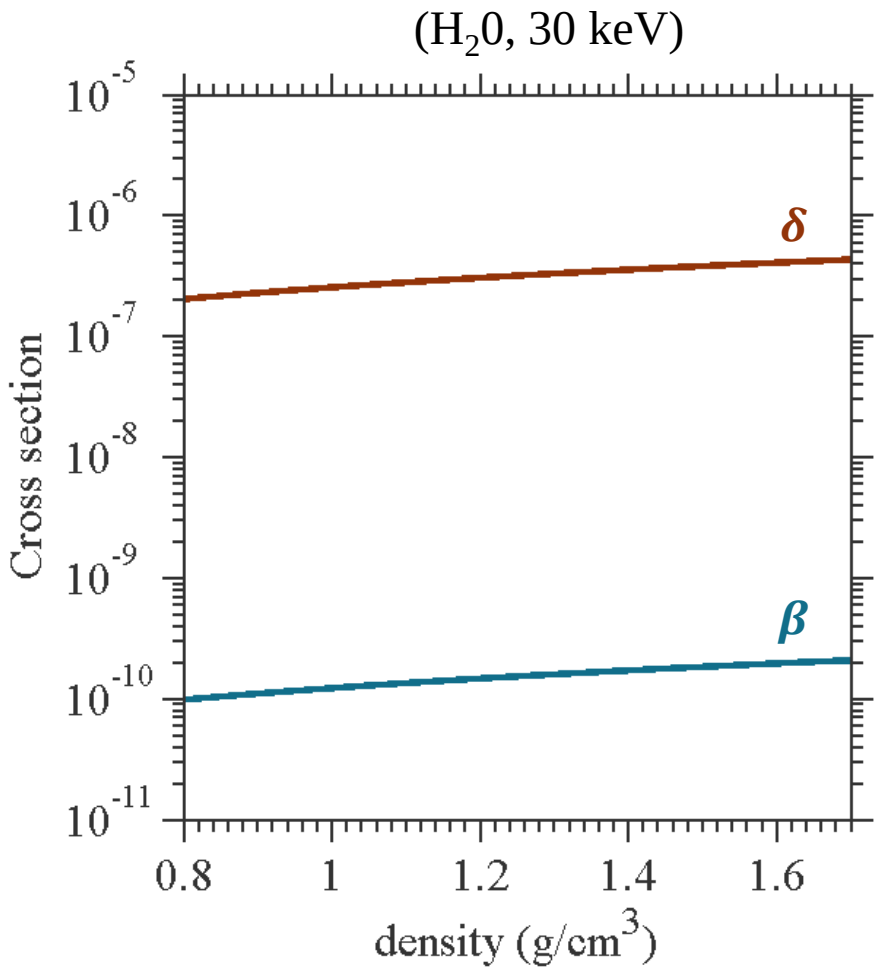
1. Beta versus delta

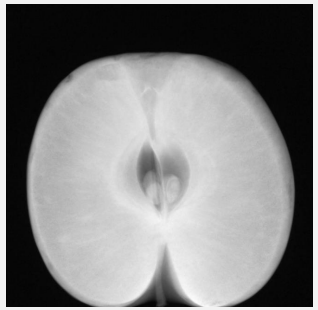
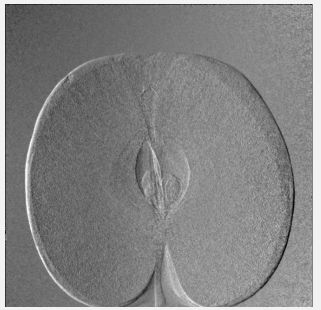
1. BETA VERSUS DELTA



For soft tissues $\delta \approx 1000 \cdot \beta$

$\neq$ 1000 times better performance of dP in comparison to Tr

TRANSMISSION VERSUS DIFFERENTIAL PHASE IMAGING

	 Transmission (Tr)	 Differential phase (dP)
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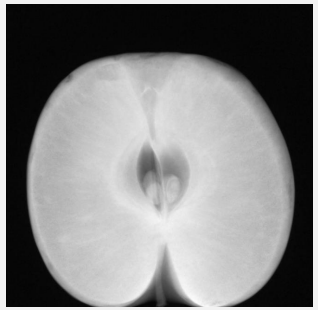
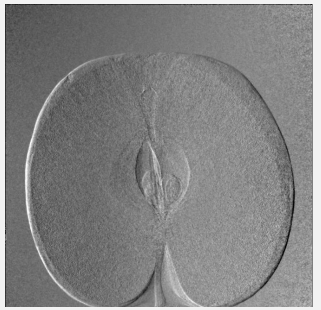
	 Transmission (Tr)	 Differential phase (dP)
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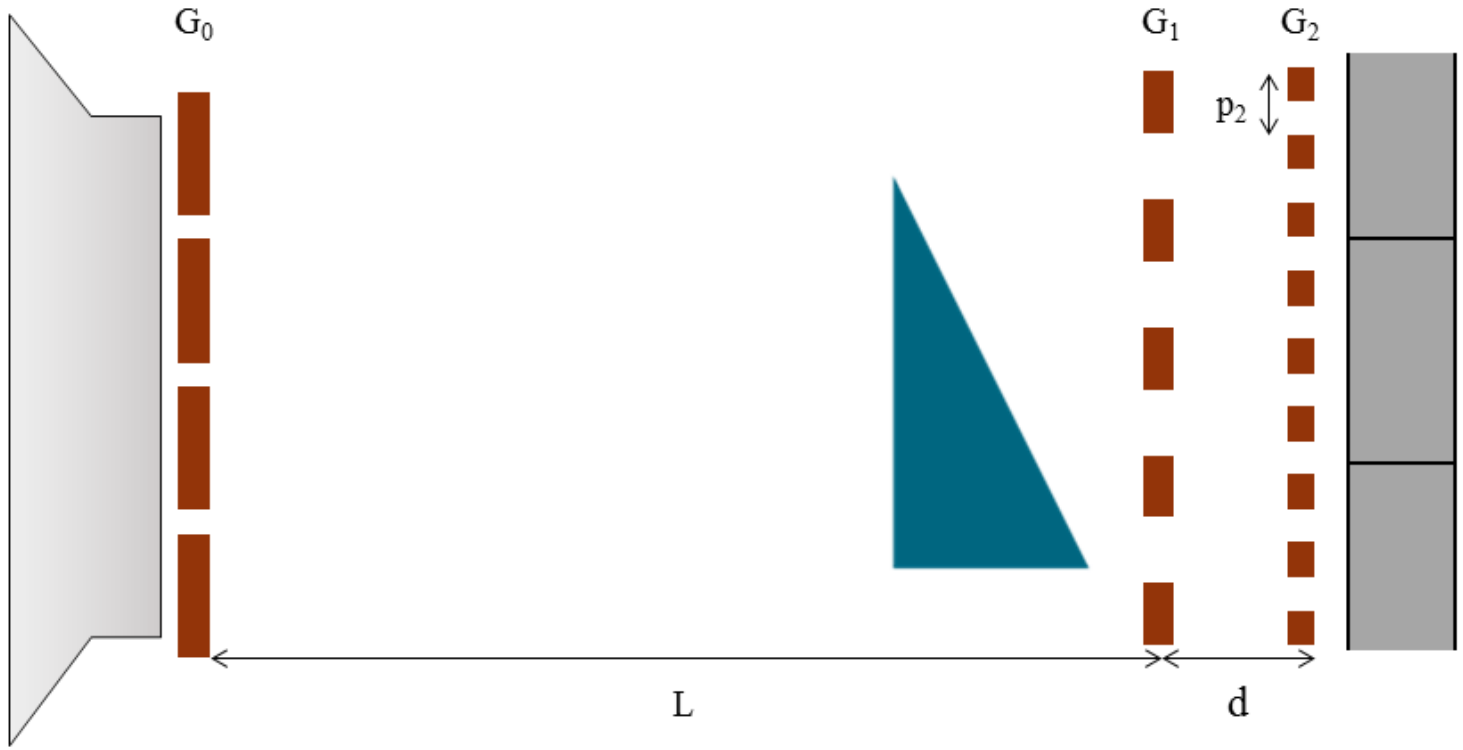
1. Beta versus delta
2. '$\boldsymbol{d, p_2}$' the sensitivity

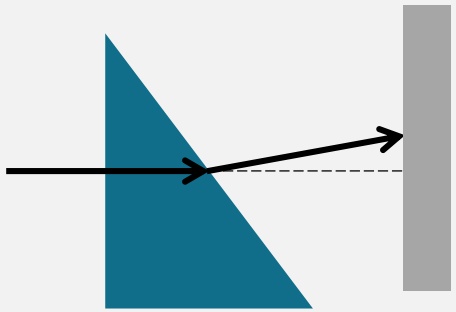
$$S_{Tr} = \exp(-\mu t) = \exp(-2k\beta t)$$

$$S_{dP} = \frac{2\pi d}{p_2} \tan\left(\frac{\partial \delta t}{\partial x}\right)$$



3. THE SYSTEM SENSITIVITY

The G1-to-G2 distance ‘d’



The system sensitivity

$$\frac{2\pi d}{p_2}$$

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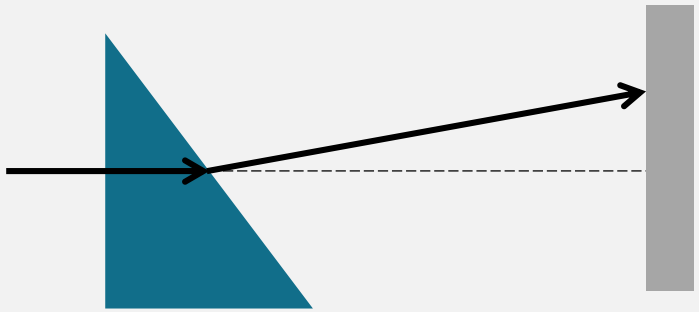

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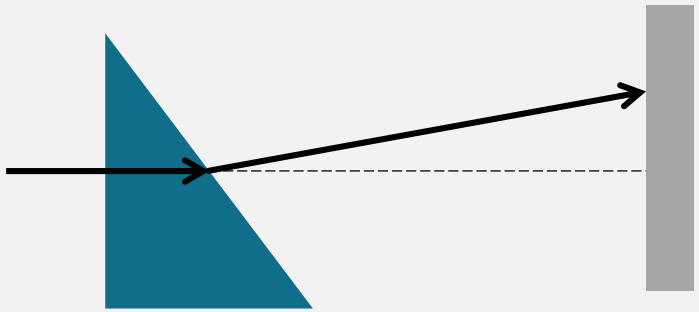
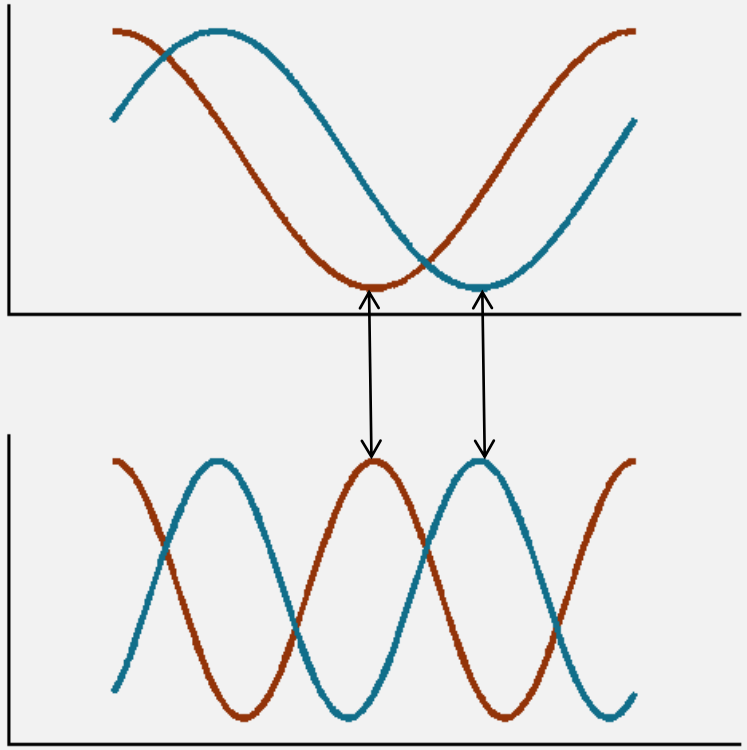


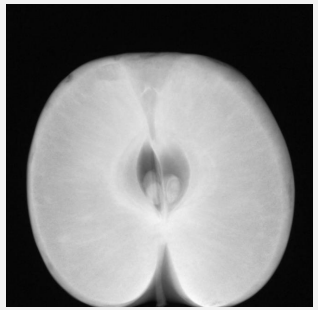
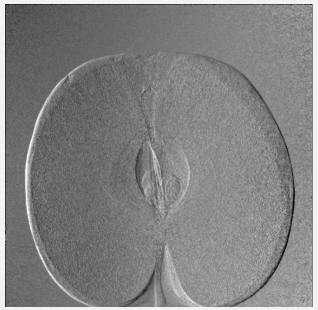
The system sensitivity

$$\frac{2\pi d}{p_2}$$

The period of the interference pattern ‘p_2’



TRANSMISSION VERSUS DIFFERENTIAL PHASE IMAGING

	 Transmission (Tr)	 Differential phase (dP)
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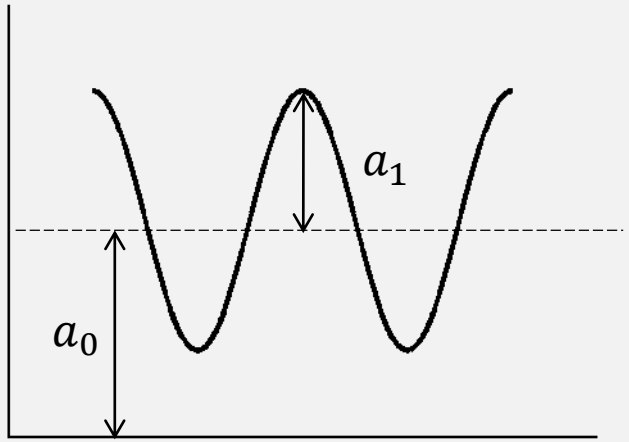
1. Beta versus delta
2. 'd, p_2' the system sensitivity
3. **'v', the system visibility**

3. THE SYSTEM VISIBILITY

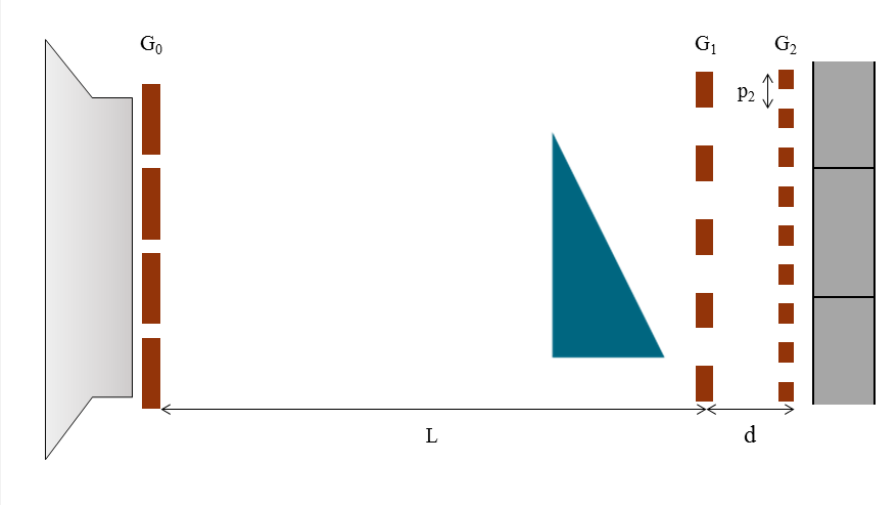
The visibility

$$v = a_1/a_0$$



Decreased by

- Polychromatic source
- Finite width G0 slits
- Finite height G2 grating
- Beam divergence



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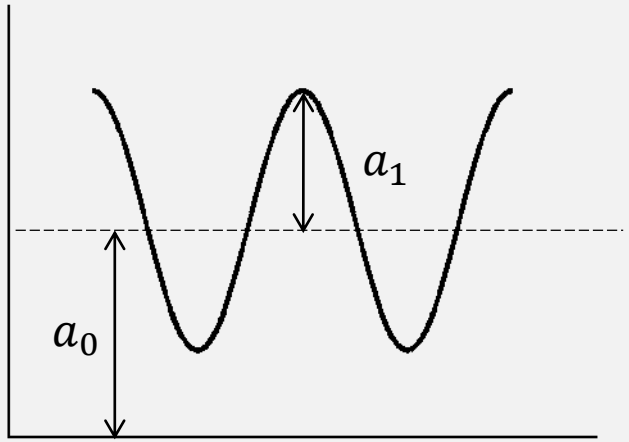
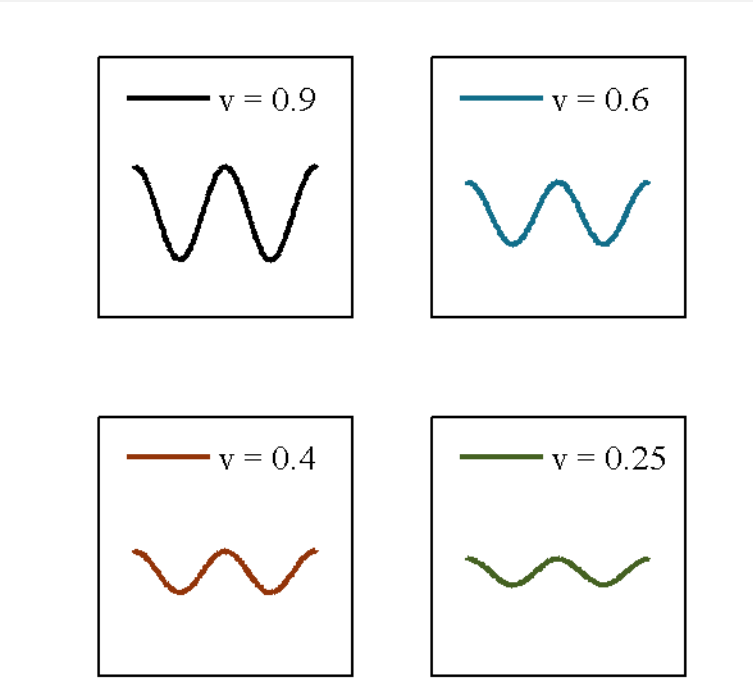


Determines noise in dP image



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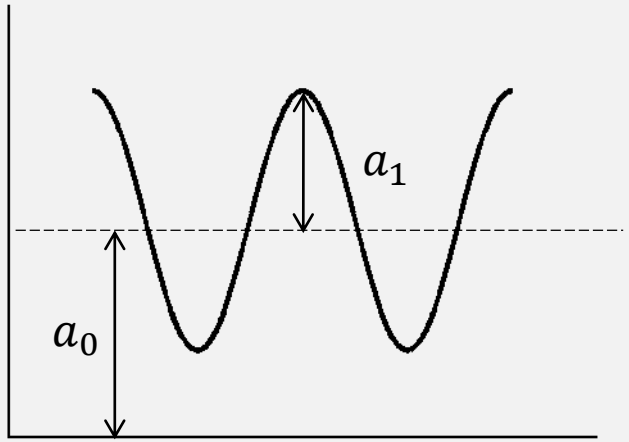

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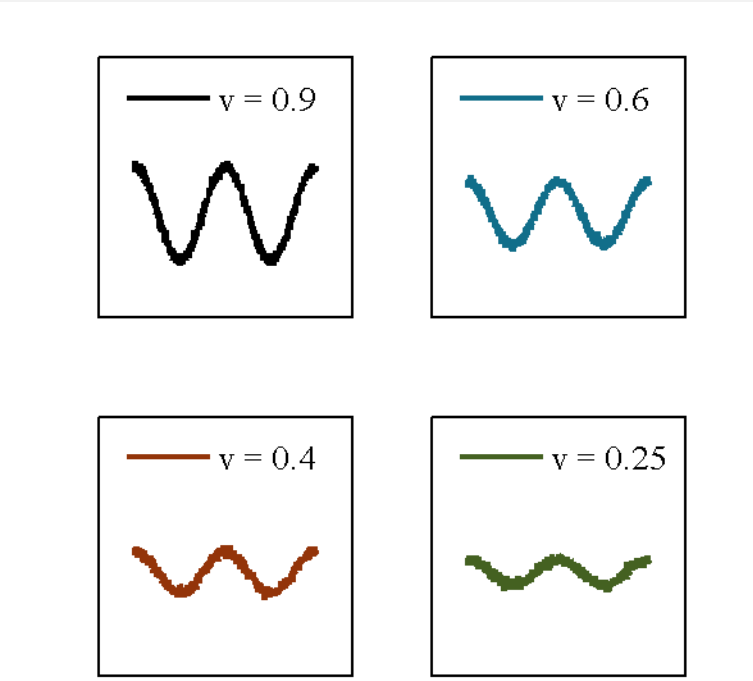

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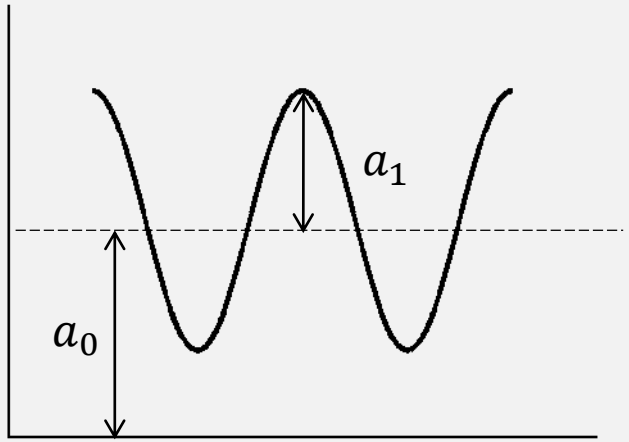

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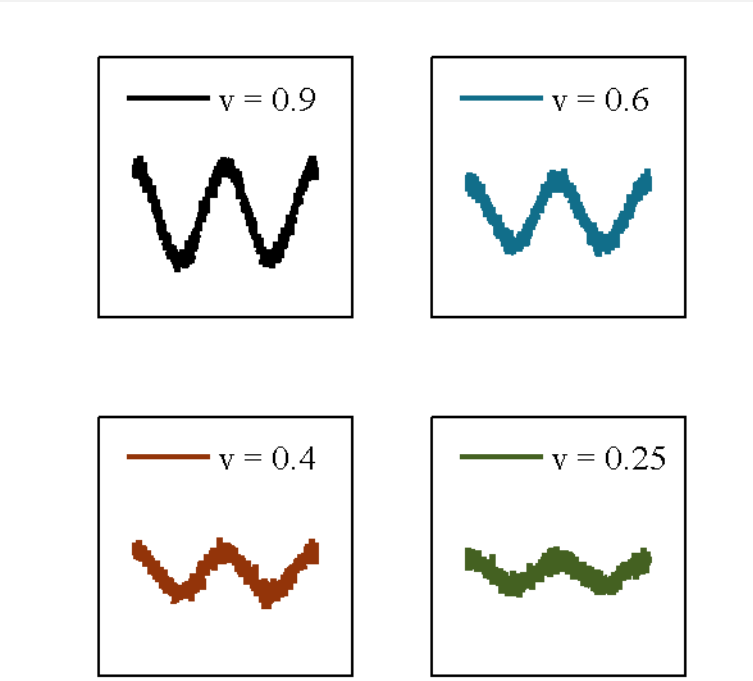

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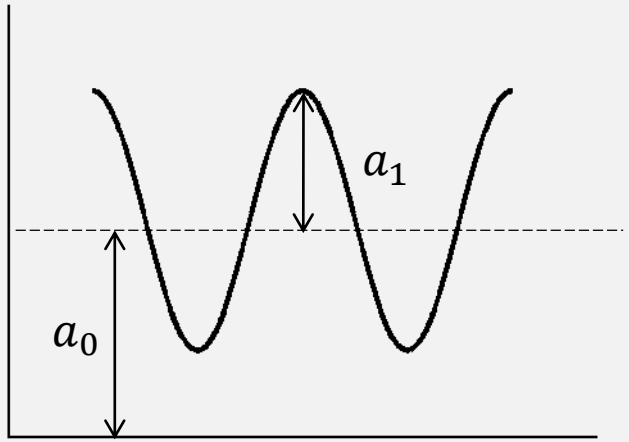

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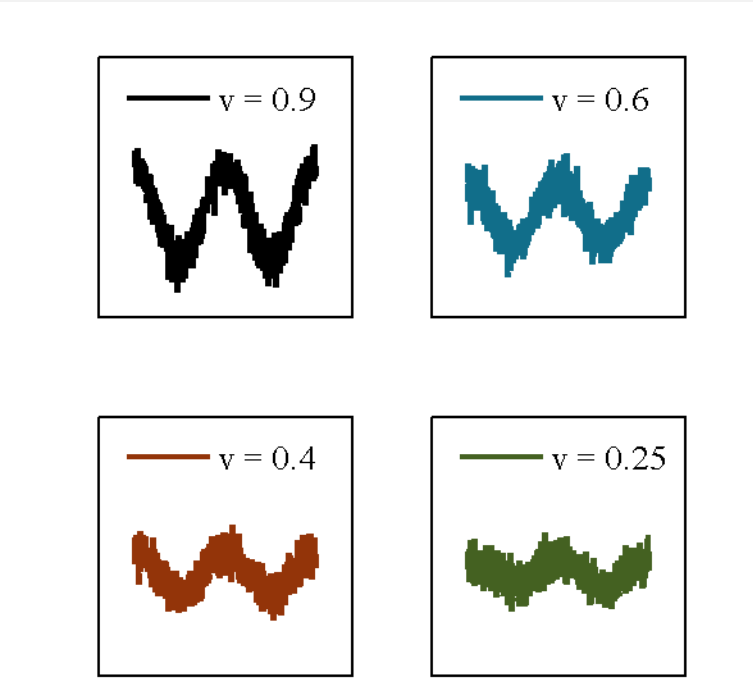


TRANSMISSION VERSUS DIFFERENTIAL PHASE IMAGING

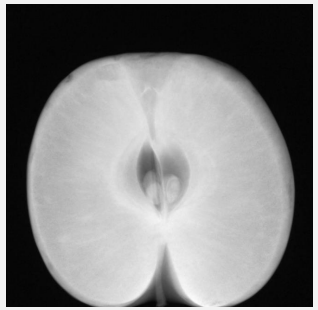
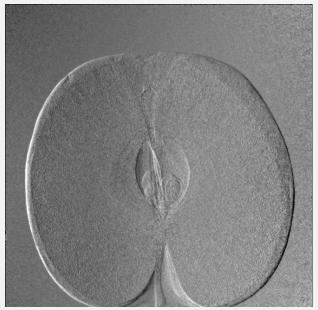
Benchmarking the CH-TLI setup

System	CH-TLI	Birnbacher *et al.* [2016]	Michel *et al.* [2013]
d [cm]	4.35	85.7	15.9
p_2 [μm]	2	5.4	2.4
Sensitivity [10^5]	1.37	9.97	4.16
Visibility	22%	38.7%	20.7%
$(S_s \cdot v)_{rel}$	1.00	12.8	2.90
α_{min}	$1.64 \cdot 10^{-7}$	$1.7 \cdot 10^{-8}$ rad	-

2. 'd, p_2' the system sensitivity

3. 'v', the system visibility

TRANSMISSION VERSUS DIFFERENTIAL PHASE IMAGING

	 Transmission (Tr)	 Differential phase (dP)
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1. Beta versus delta
2. 'd, p_2' the system sensitivity
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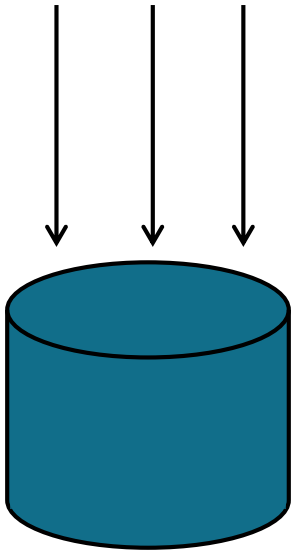
4. Projection vs differential

2. PROJECTION VERSUS DIFFERENTIAL IMAGING



Transmission

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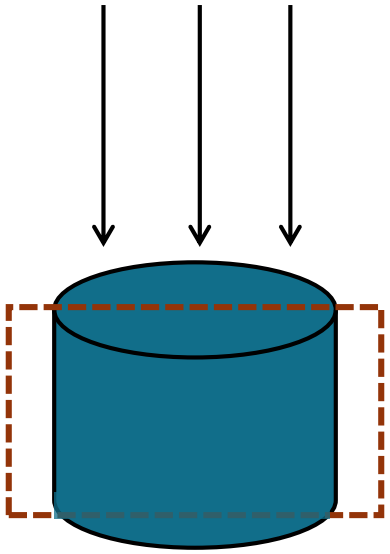

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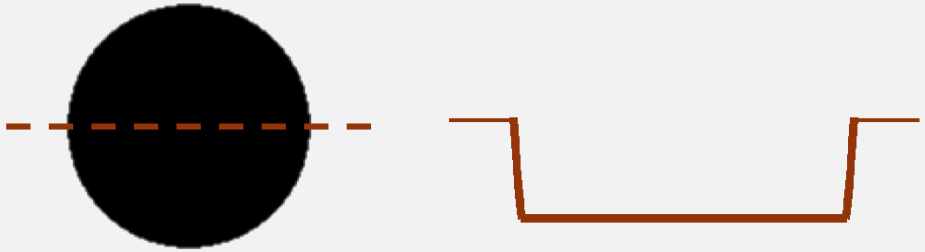

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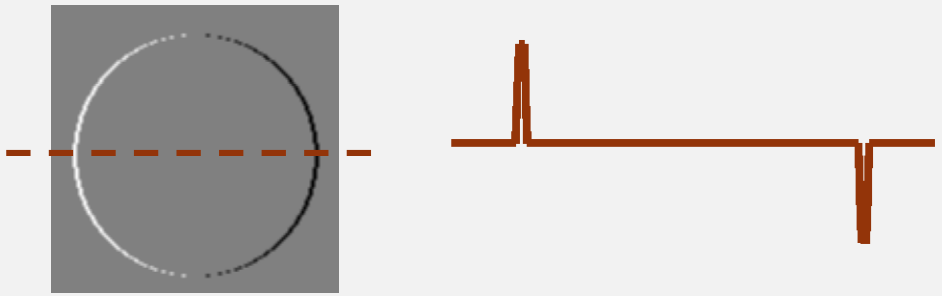

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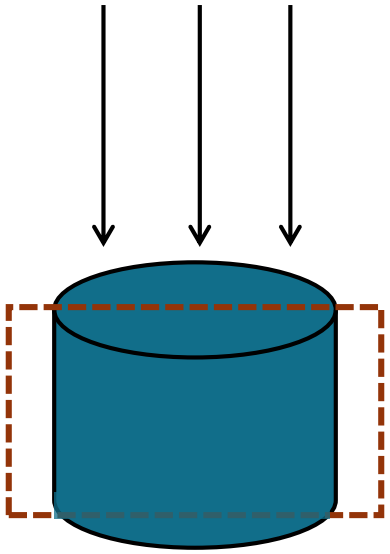

Contrast-to-noise metrics are not applicable

So, even theoretically, how to compare Tr and dP?

Transmission

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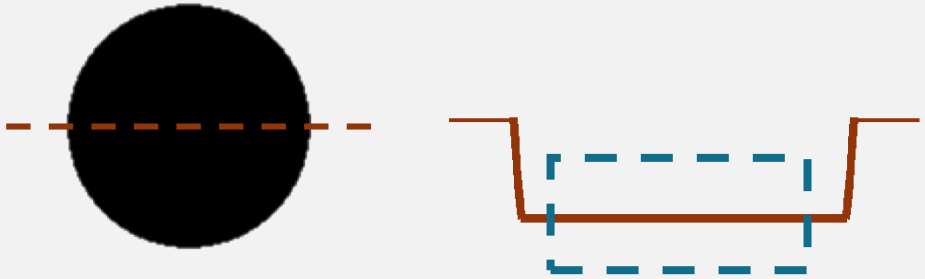

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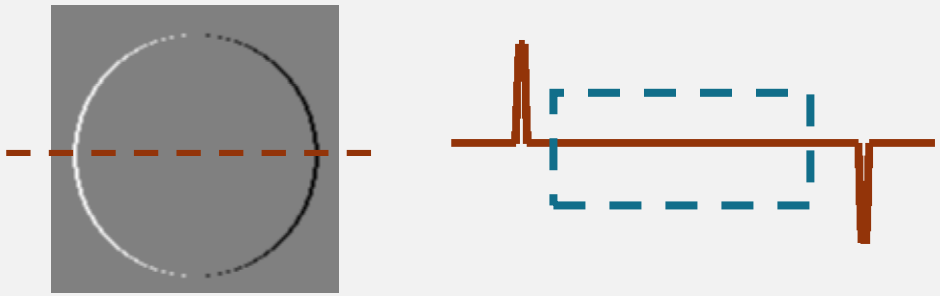

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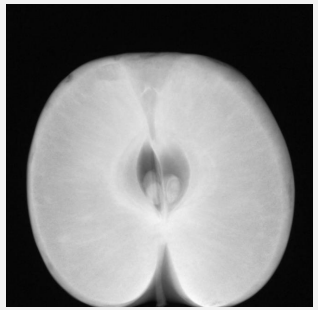
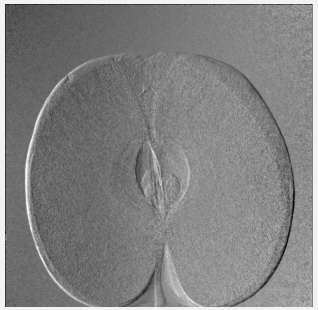
	 Transmission (Tr)	 Differential phase (dP)
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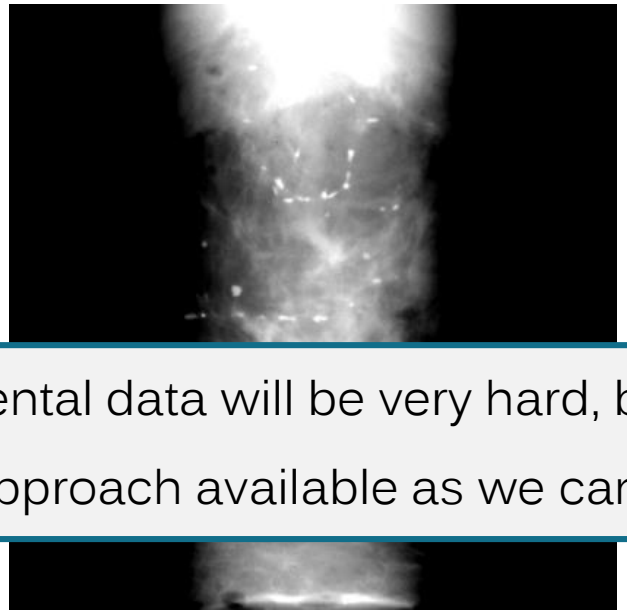
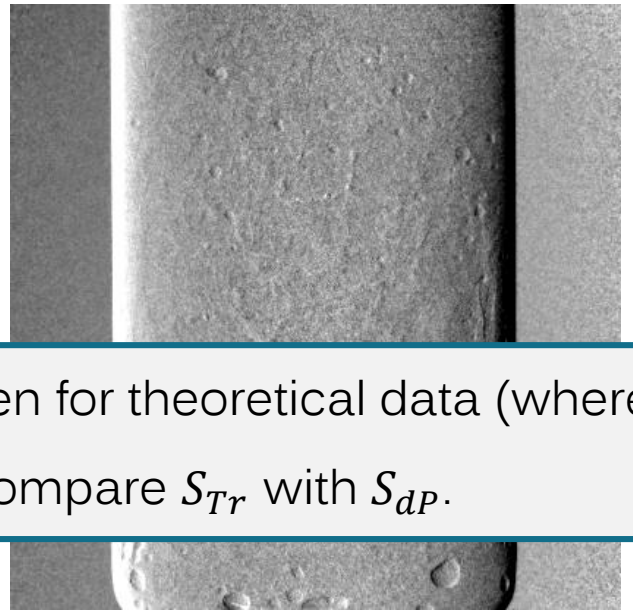


Differential phase Image



Comparing experimental data will be very hard, but even for theoretical data (where the ground truth is known) there is no approach available as we cannot compare S_{Tr} with S_{dP}.

RESEARCH QUESTION

How to quantitatively compare Tr and dP imaging?

Performance metric:

Relative dose required for a lesion to be detectable in Tr and dP

Use virtual studies to benchmark the dP performance against the Tr performance

→ Requires a simulation platform to produce rapidly 'realistic' dP and Tr images

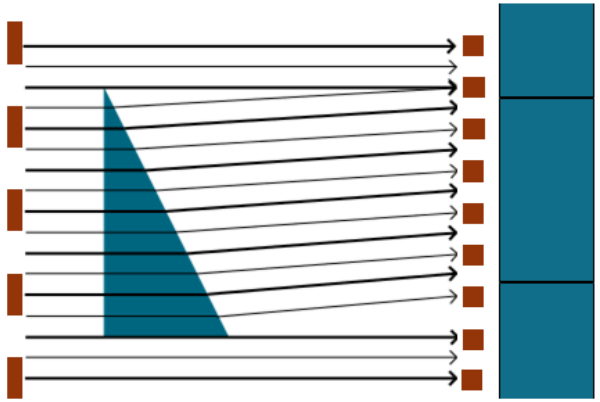
OUTLINE

- Talbot-Lau interferometry
- **A hybrid simulation framework**
  - generate ‘realistic’ imagines that match those of a TLI scanner
- A detectability study
  - a task-based study
  - human reader studies (4-AFC)
- Application: mammography

HYBRID IMAGE MODELLING

Numerical wave propagation

Computationally expensive, not practical for virtual studies where you need a lot of data and large fields of view.



4 μm

Hybrid image modelling

Combining analytical equations with experimentally measured metrics

HYBRID IMAGE MODELLING

Expected signal

$$S_{Tr} = \exp(-\mu t) = \exp(-2k\beta t)$$

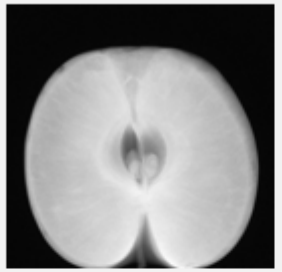
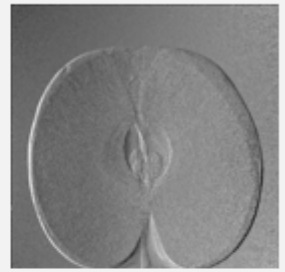
$$S_{dP} = \frac{2\pi d}{p_2}\tan\left(\frac{\partial \delta t}{\partial x}\right)$$

Expected noise level

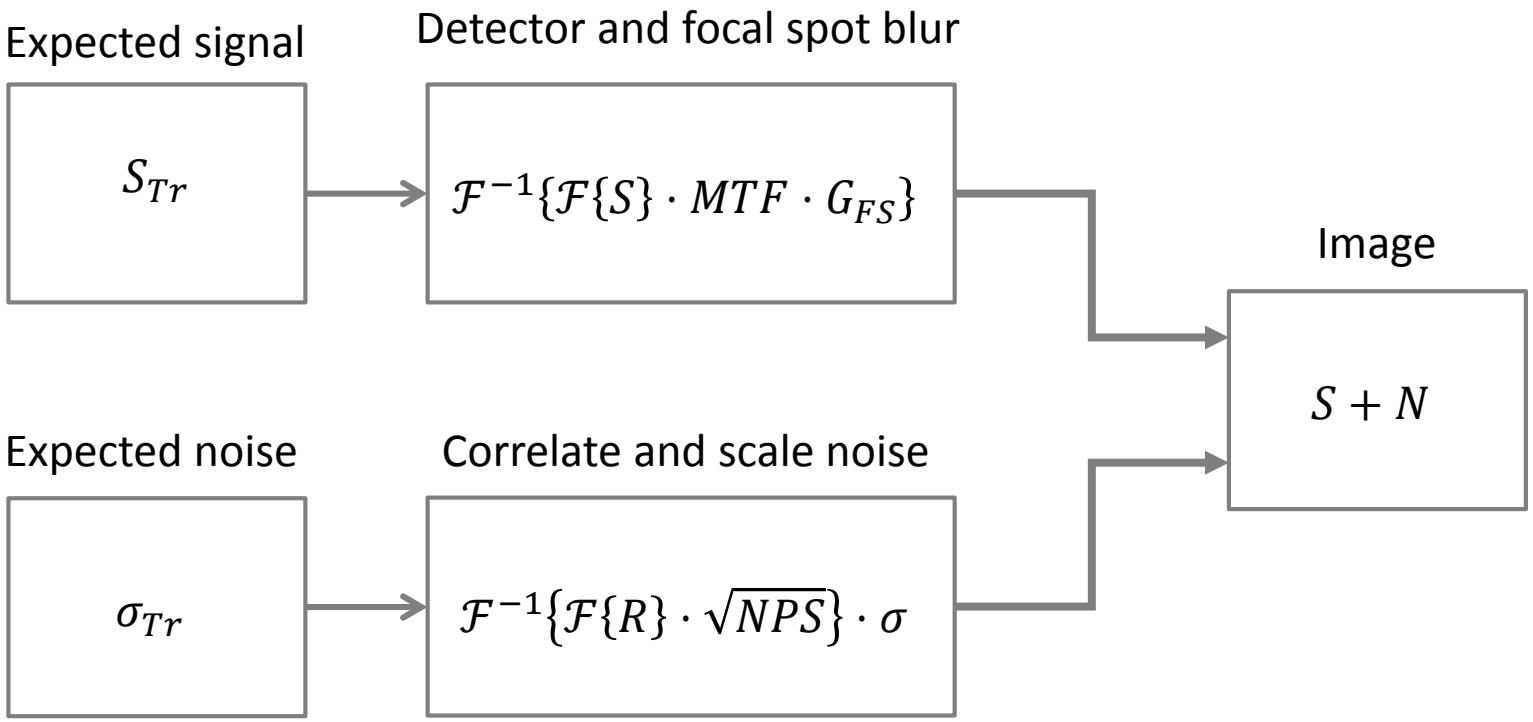
$$\sigma_{Tr} = \frac{S_{Tr}}{\sqrt{PV}}\sqrt{1+\frac{1}{S_{Tr}}}$$

$$\sigma_{dP} = \frac{1}{\sqrt{PV}}\sqrt{\frac{2}{v^2}\left(1+\frac{1}{S_{Tr}}\right)\left(1+\frac{1}{S_{Tr}D^2}\right)}$$

Chabior et al. [2012]

	 Transmission (Tr)	 Differential phase (dP)
Signal	$S_{Tr} = \exp(-\mu t) = \exp(-2k\beta t)$	$S_{dP} = \frac{2\pi d}{p_2}\tan\left(\frac{\partial \delta t}{\partial x}\right)$
Noise	$\sigma_{Tr} \propto \frac{1}{\sqrt{PV}}$	$\sigma_{dP} \propto \frac{1}{\sqrt{PV}} \cdot \frac{1}{v}$

HYBRID IMAGE MODELLING



HYBRID IMAGE MODELLING

Expected signal

S_{Tr}

Detector and focal spot blur

$\mathcal{F}^{-1}\{\mathcal{F}\{S\} \cdot MTF \cdot G_{FS}\}$

Expected noise

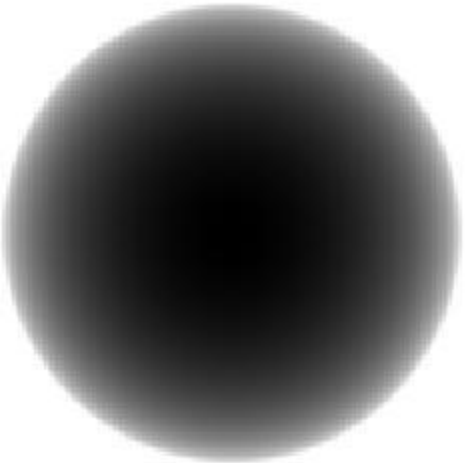
σ_{Tr}

Correlate and scale noise

$\mathcal{F}^{-1}\{\mathcal{F}\{R\} \cdot \sqrt{NPS}\} \cdot \sigma$

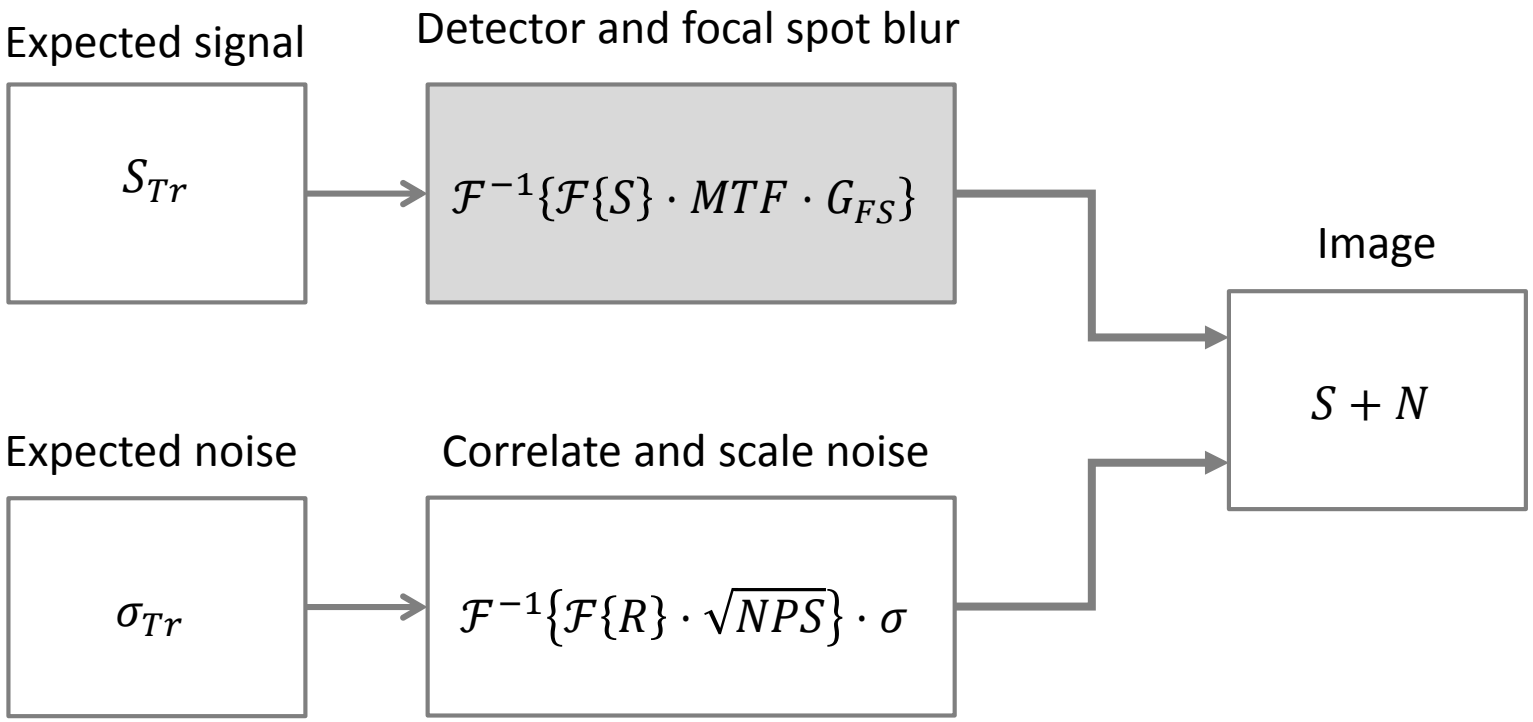
Image

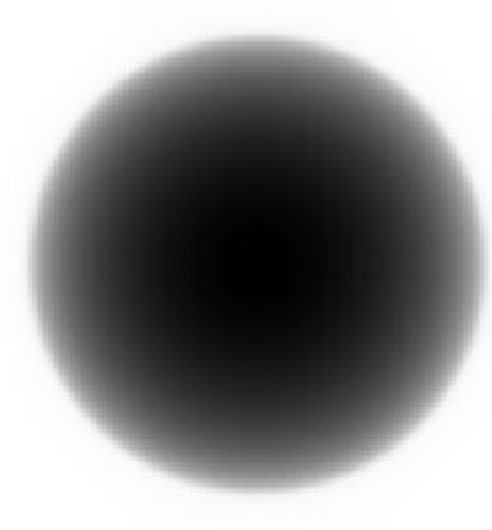
$S + N$



$$S_{Tr} = \exp(-\mu t) = \exp(-2k\beta t)$$

HYBRID IMAGE MODELLING





MTF : measured
G_{FS}: analytical

HYBRID IMAGE MODELLING

Expected signal

S_{Tr}

Detector and focal spot blur

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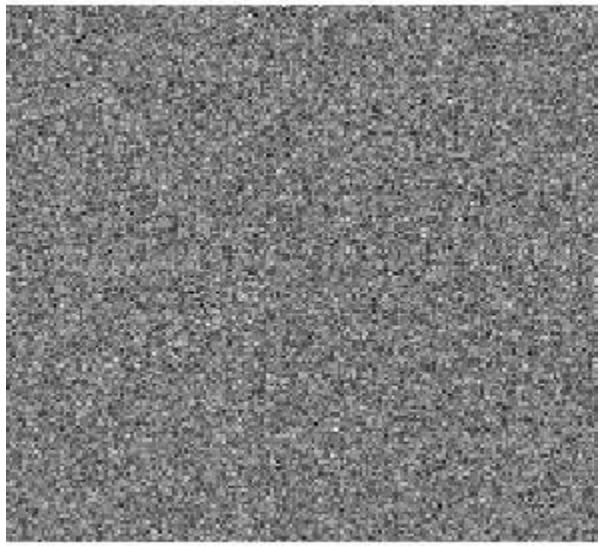
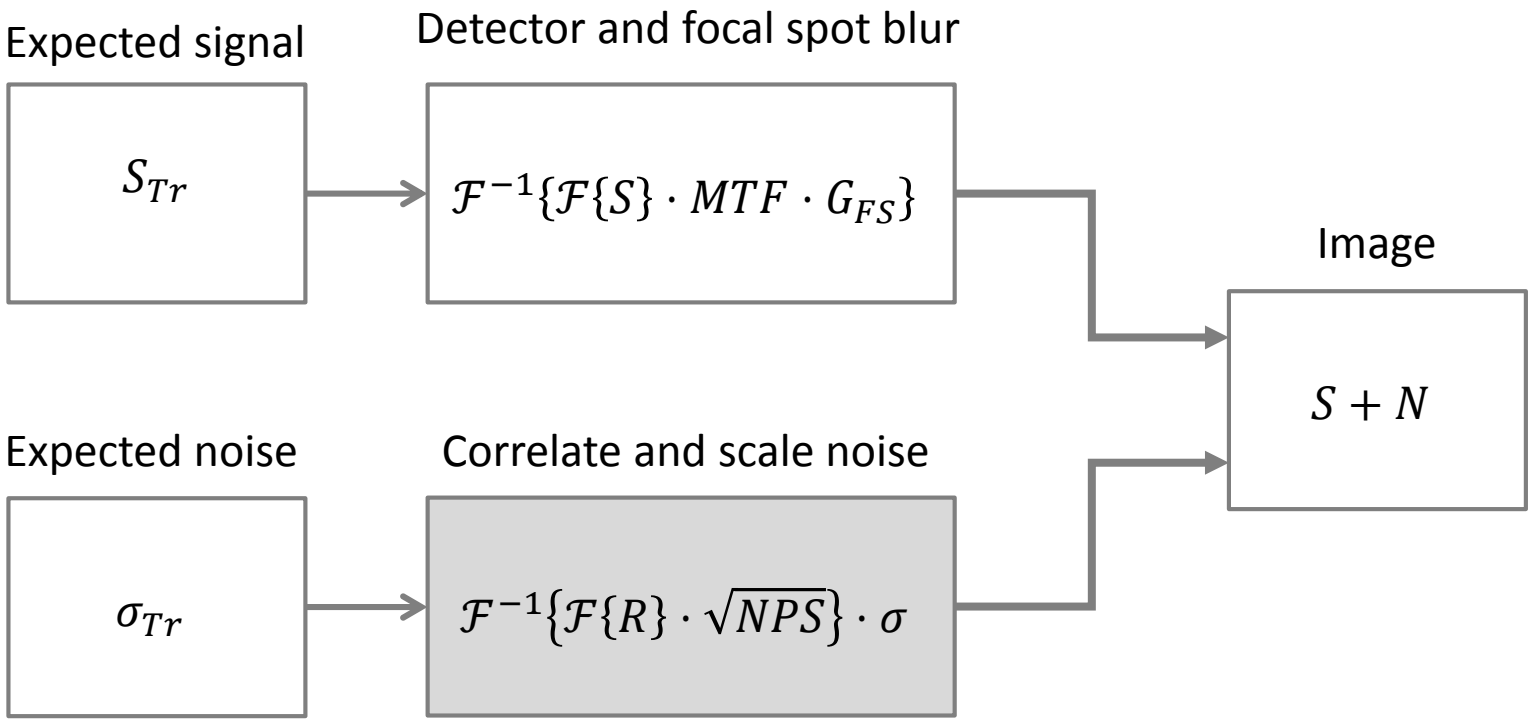
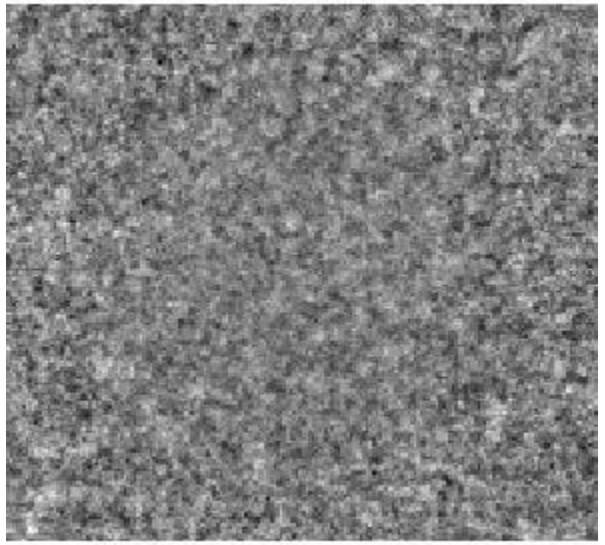


R = random generated values with a zero mean and a unit variance

HYBRID IMAGE MODELLING

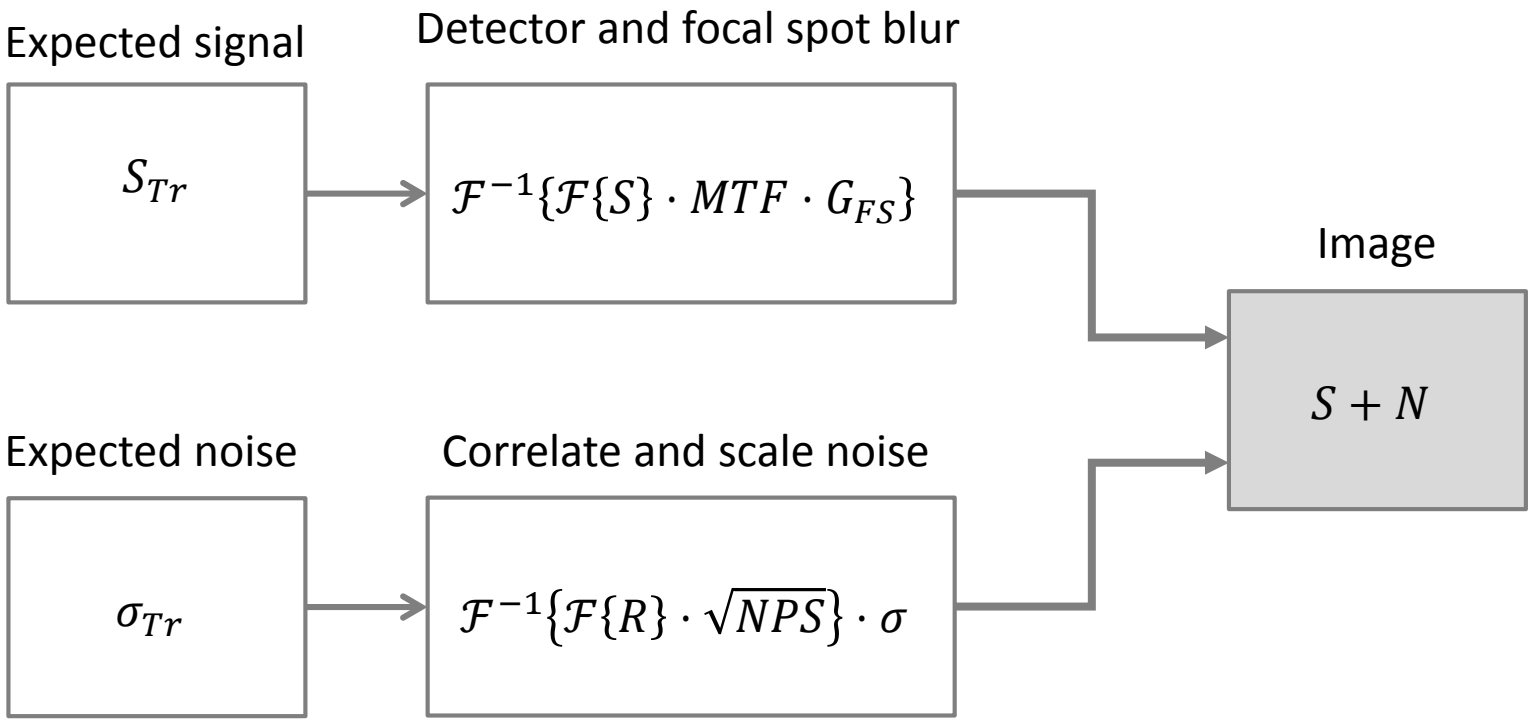


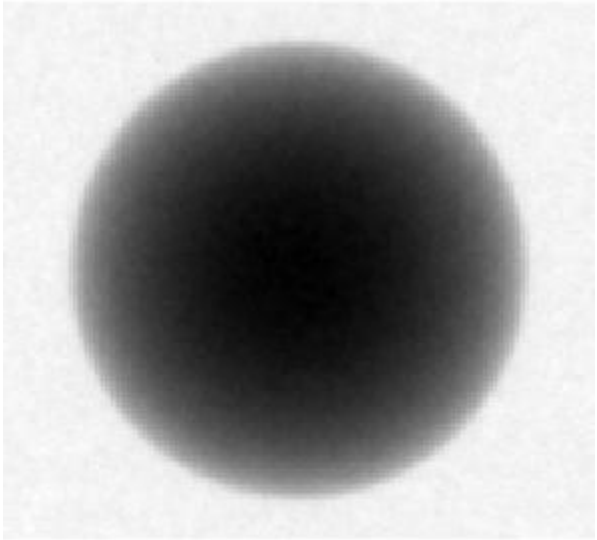


$$\sigma_{Tr} = \frac{S_{Tr}}{\sqrt{PV}} \sqrt{1 + \frac{1}{S_{Tr}}}$$

NPS : measured
PV: measured

HYBRID IMAGE MODELLING





HYBRID IMAGE MODELLING

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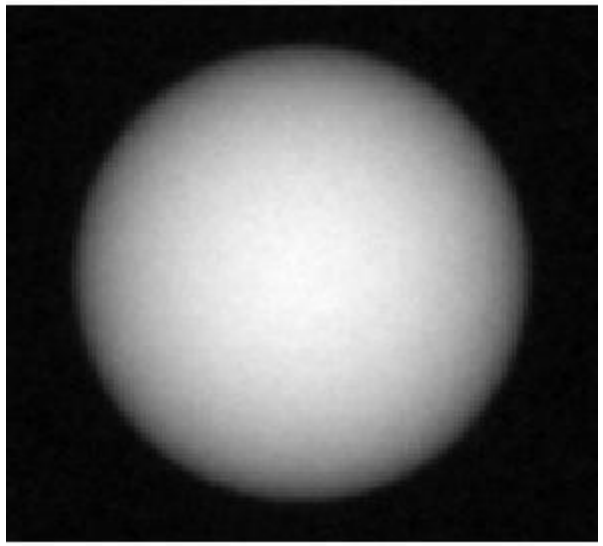
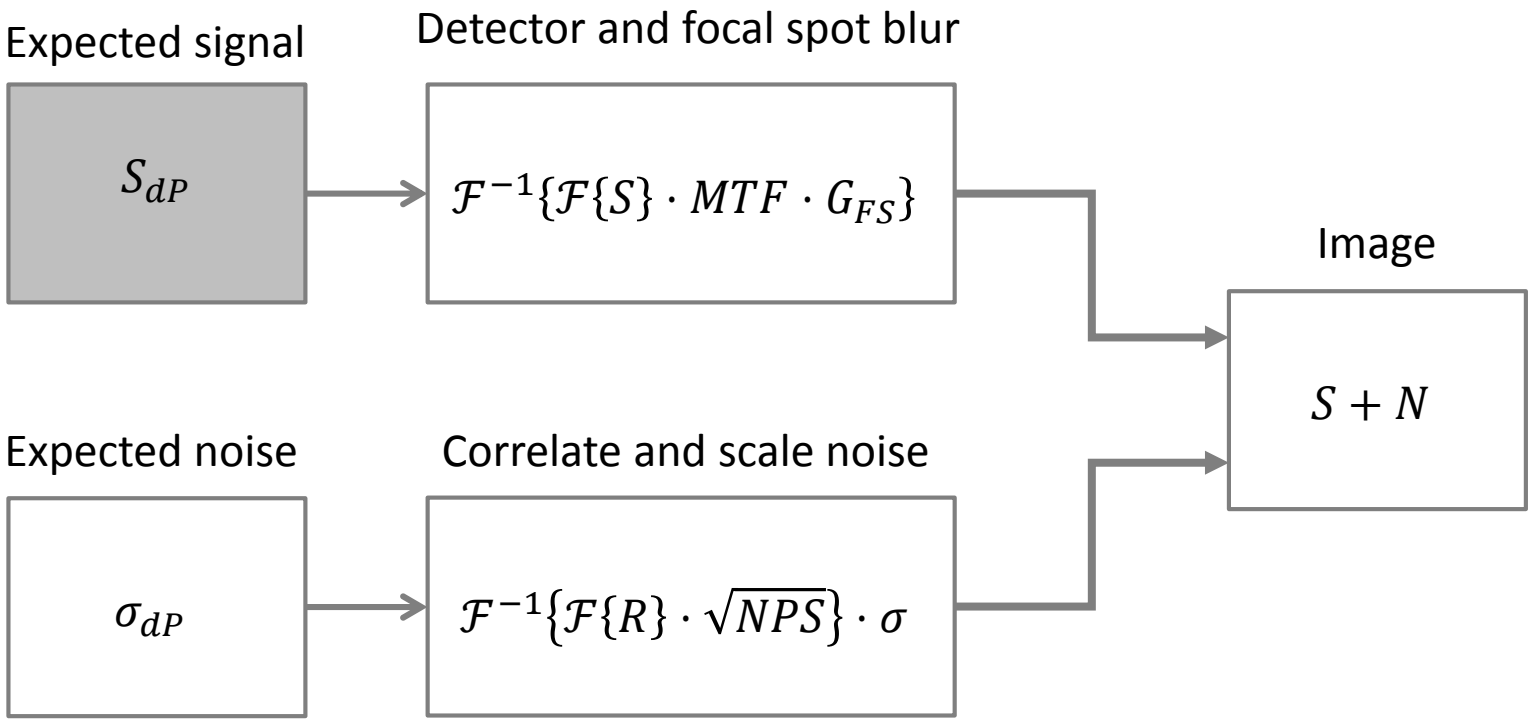
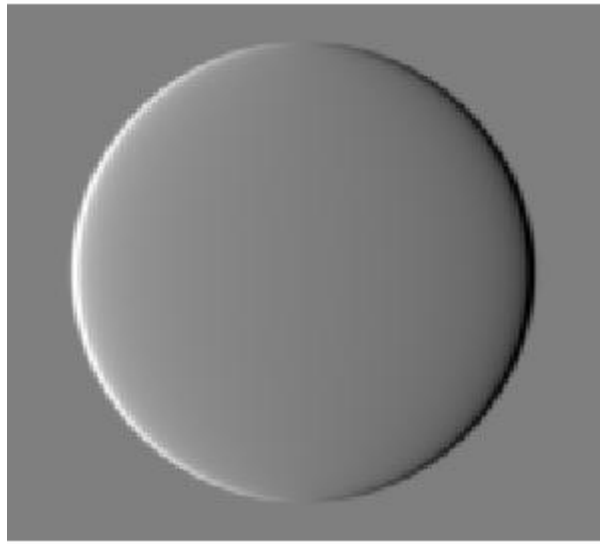


$-\log()$

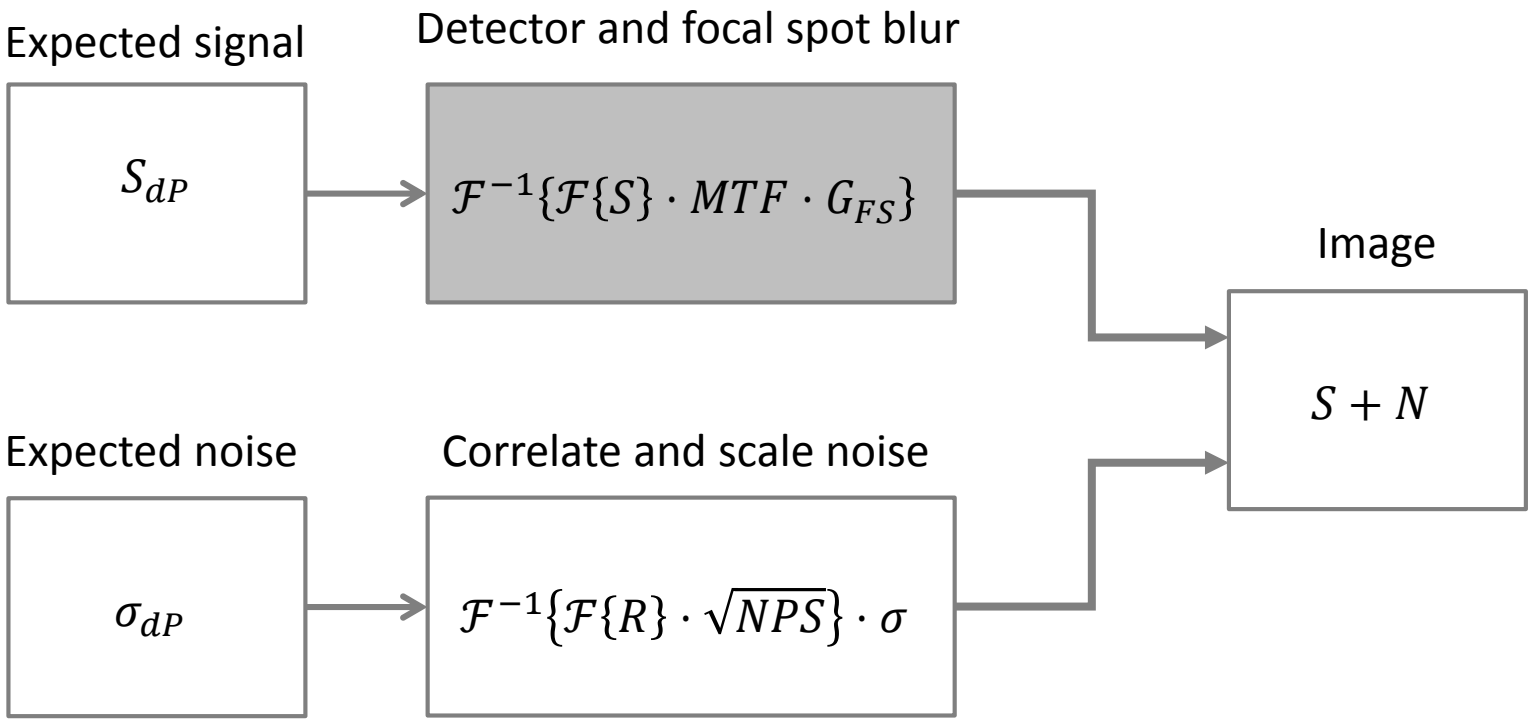
HYBRID IMAGE MODELLING

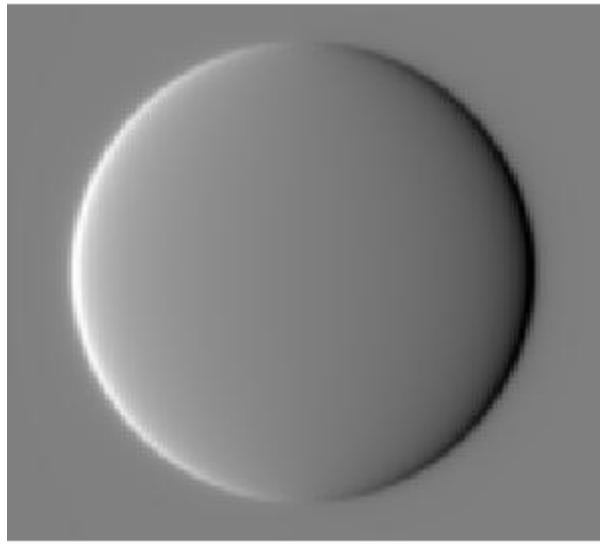




$$S_{dP} = \frac{\boldsymbol{2\pi d}}{\boldsymbol{p_2}} \tan\left(\frac{\partial \delta t}{\partial x}\right)$$

HYBRID IMAGE MODELLING





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Correlate and scale noise

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Image

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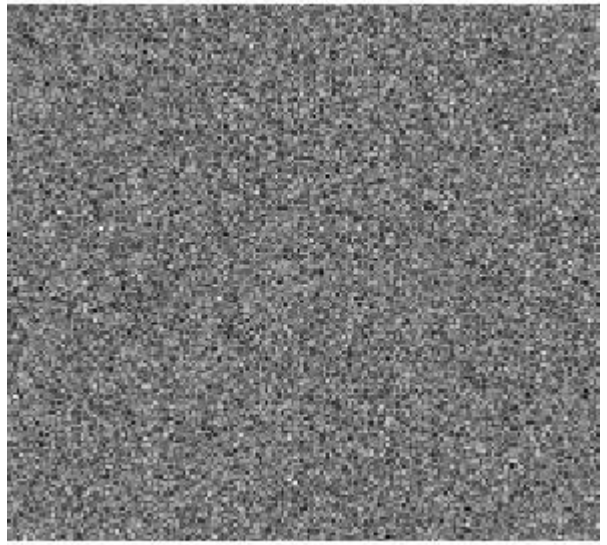

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HYBRID IMAGE MODELLING

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S_{dP}

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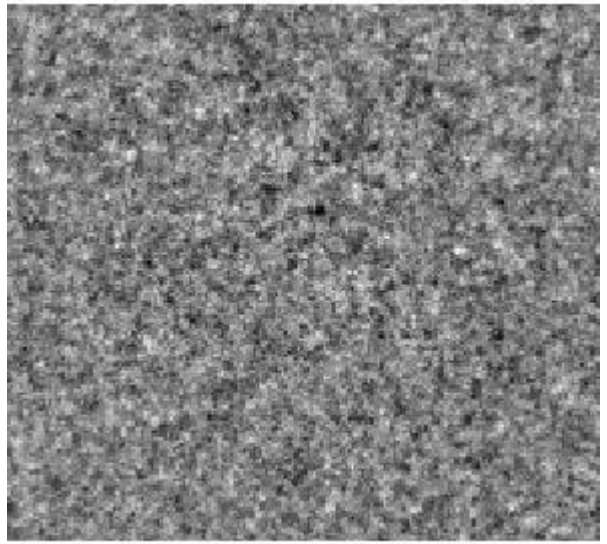
Image

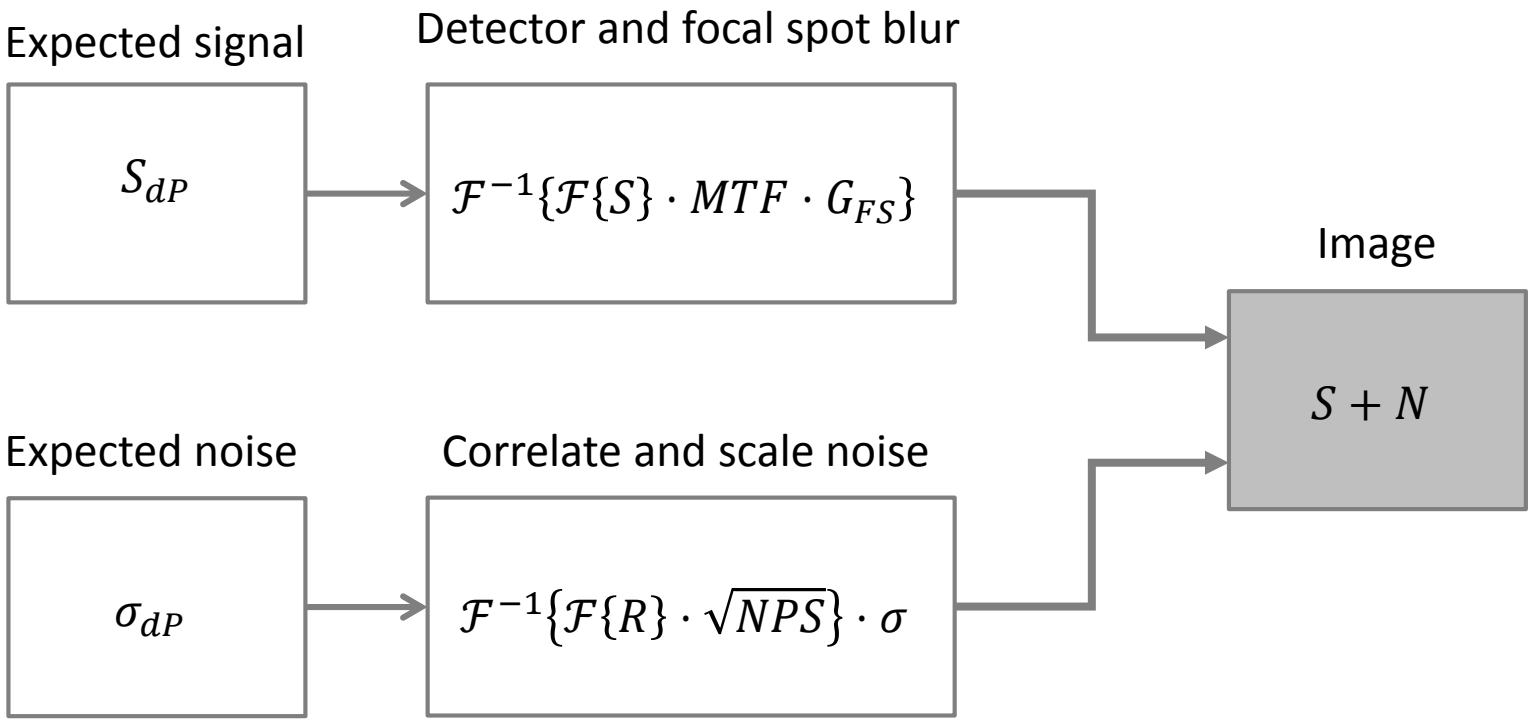
$S + N$

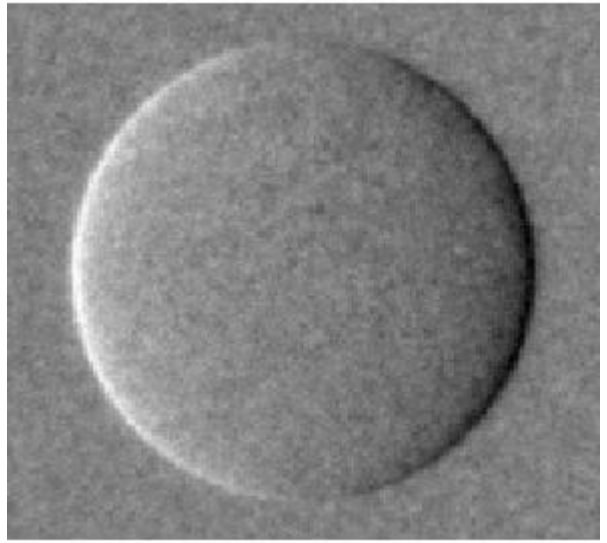


$$\sigma_{dP} = \frac{S_{Tr}}{\sqrt{\boldsymbol{PV}}} \sqrt{\frac{2}{\boldsymbol{v}^2}\left(1 + \frac{1}{S_{Tr}}\right)\left(1 + \frac{1}{S_{Tr}D^2}\right)}$$

NPS : measured
PV: measured
v : measured

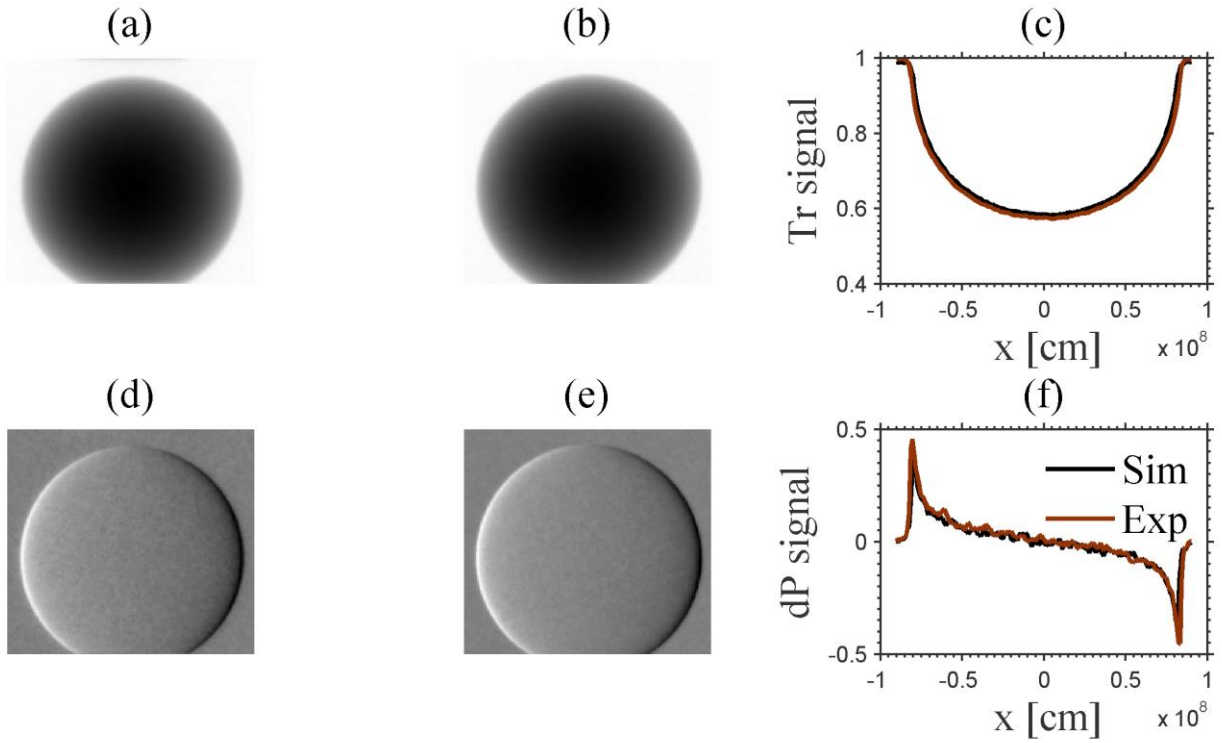
HYBRID IMAGE MODELLING





HYBRID IMAGE MODELLING

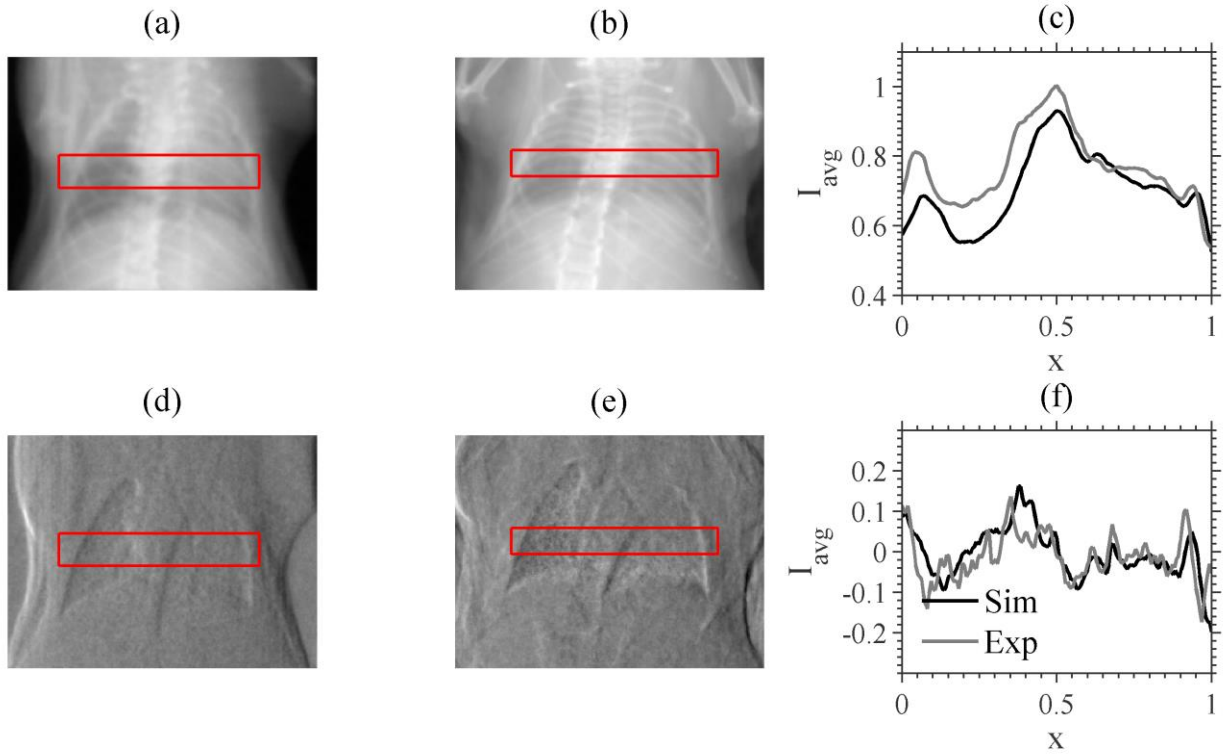
PMMA sphere



HYBRID IMAGE MODELLING

In vivo scan mouse

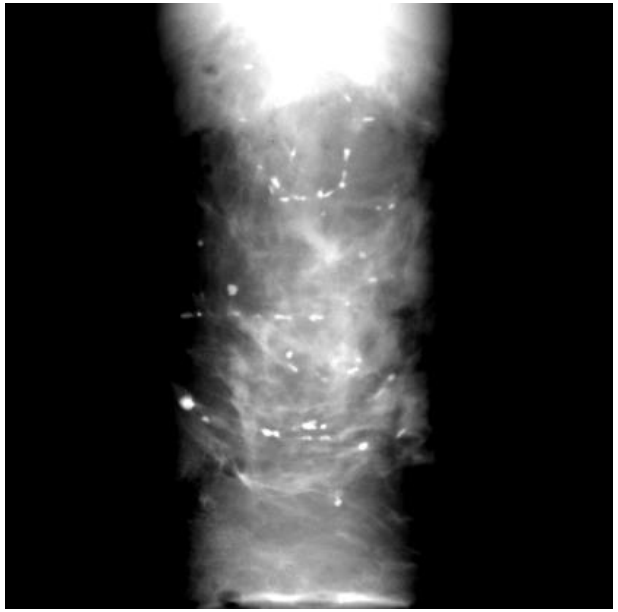
Model is based on segmented uCT data



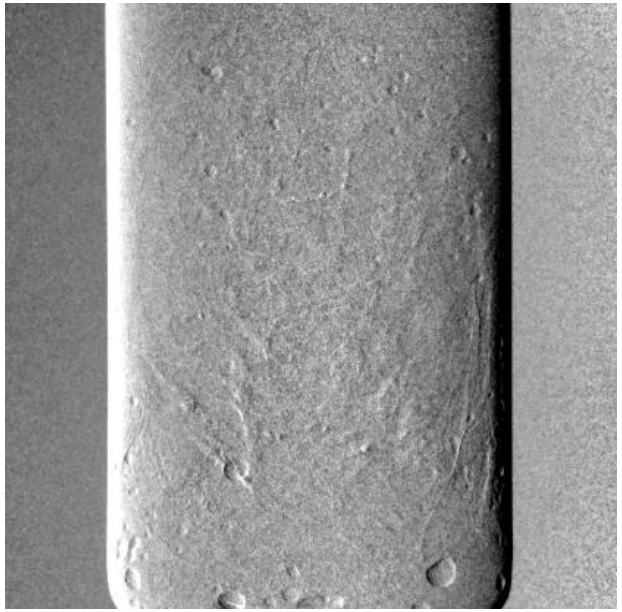
RESEARCH QUESTION

How to quantitatively compare Tr and dP imaging?

Transmission Image



Differential phase Image



OUTLINE

- Talbot-Lau interferometry
- A hybrid simulation framework
  - generate ‘realistic’ imagines that match those of a TLI scanner
- **A detectability study**
  - a task-based study
  - human reader studies (4-AFC)
- Application: mammography

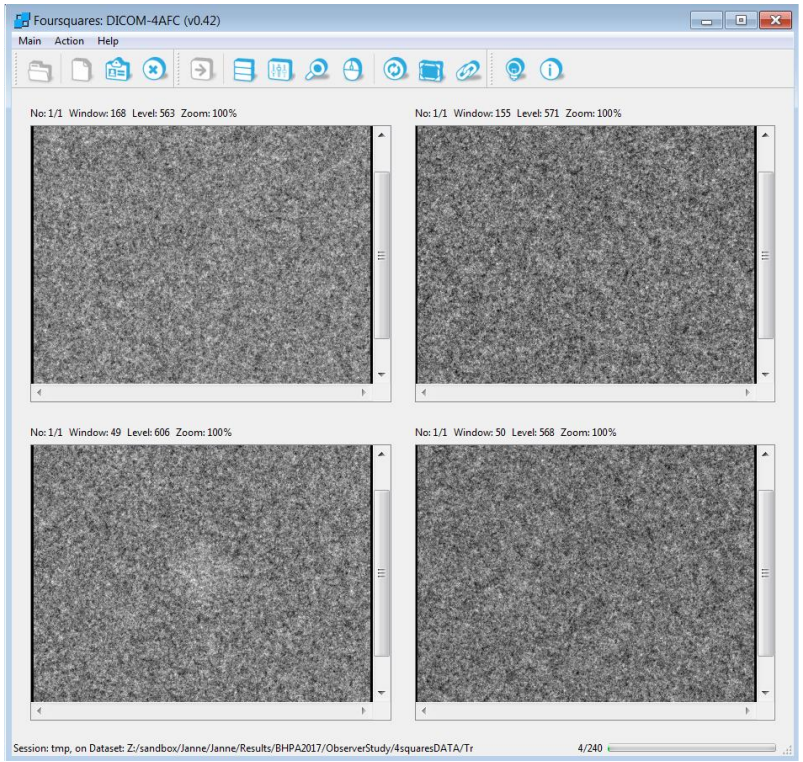
TASK BASED DETECTABILITY STUDY

Relative dose required for a lesion to be detectable

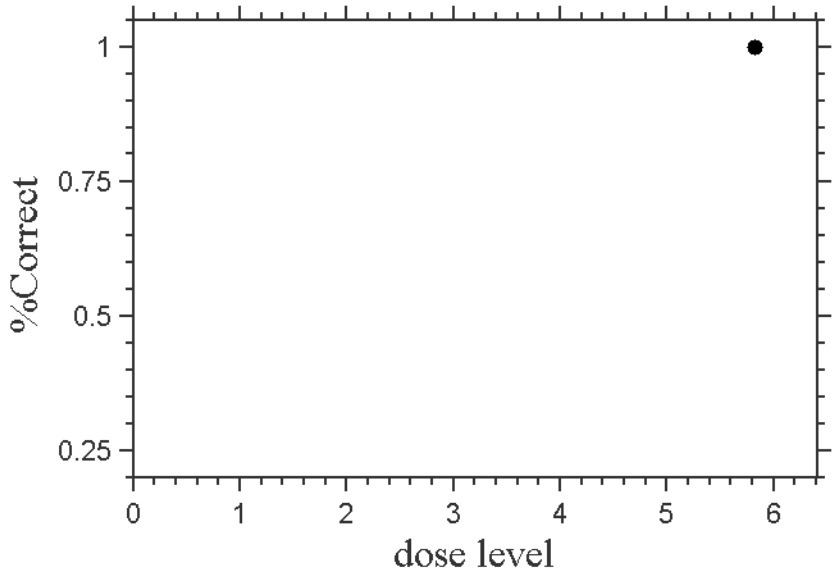
= measure of relative performance

Via a four alternative forced choice study

Four alternative forced choice (4-AFC)

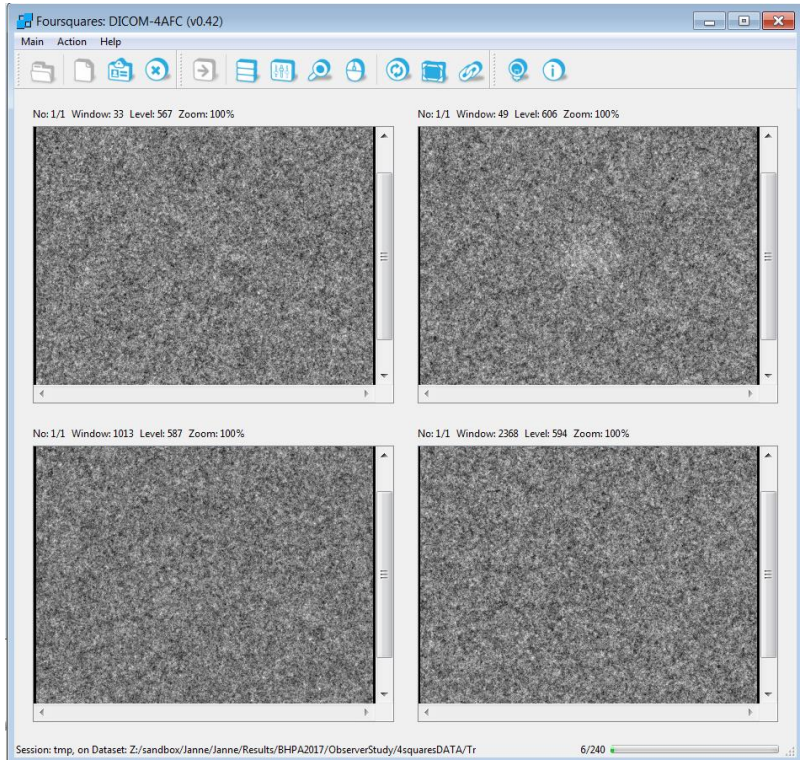


Zhang et al., SPIE proceedings (2016)

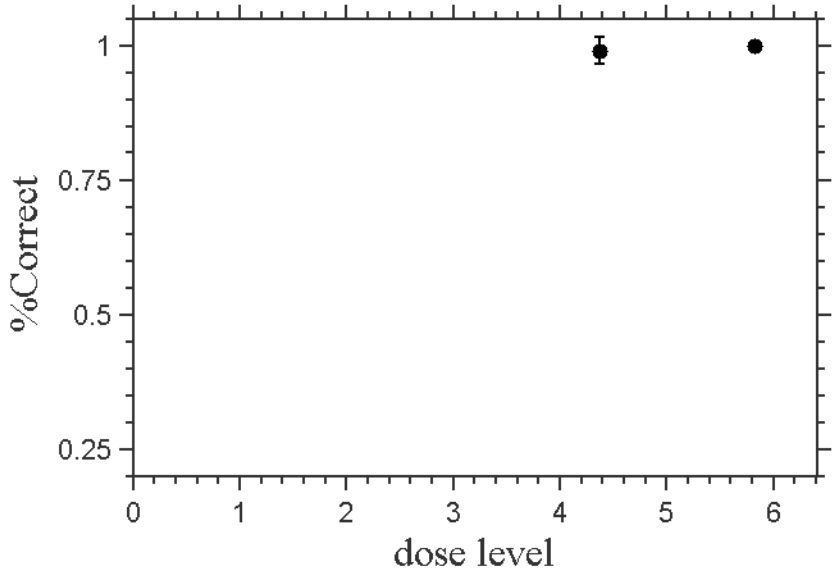


4-AFC

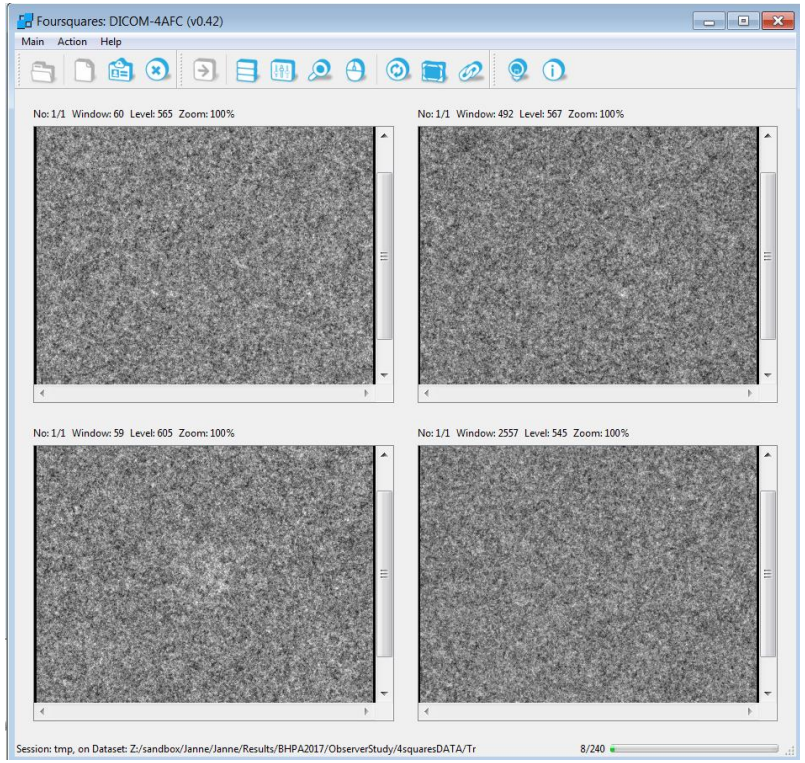
Four alternative forced choice (4-AFC)



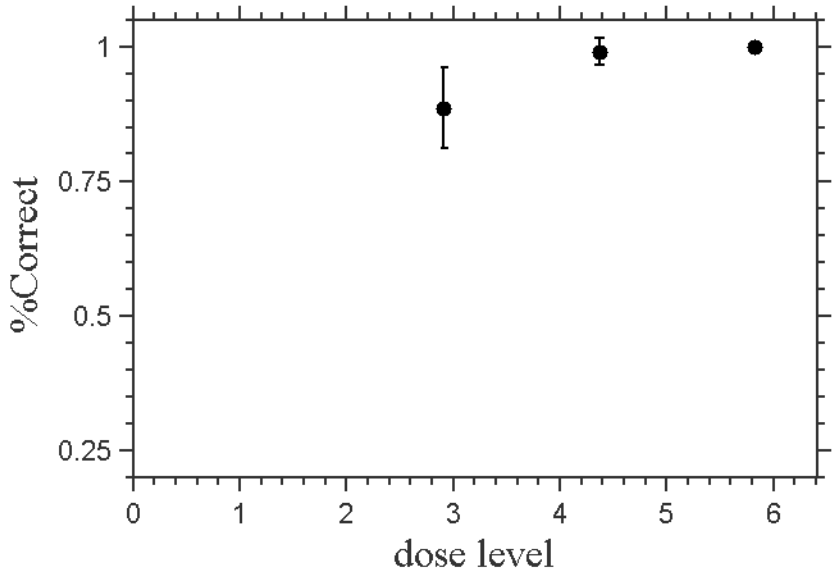
Zhang et al., SPIE proceedings (2016)



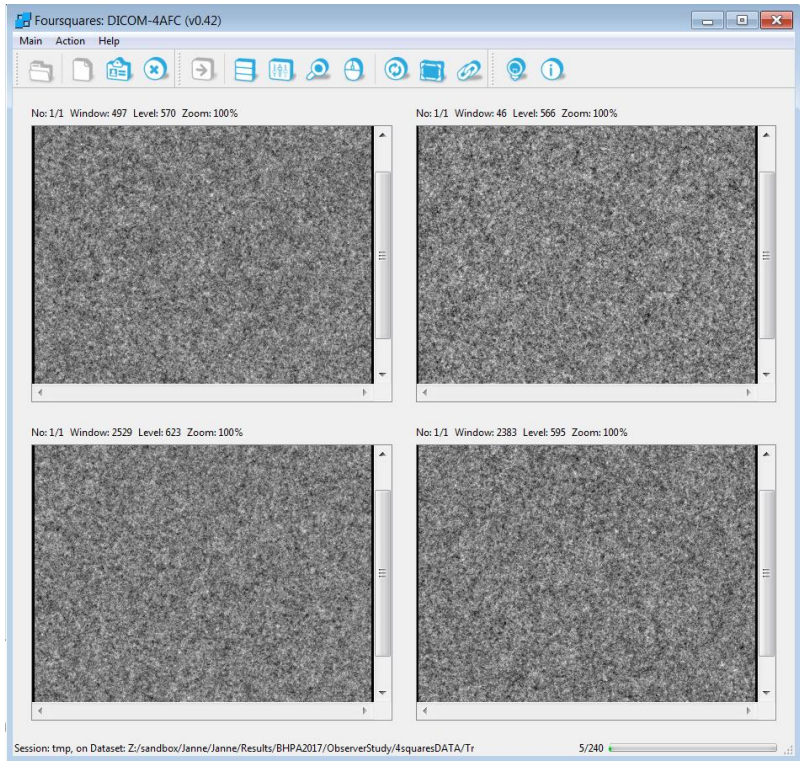
Four alternative forced choice (4-AFC)



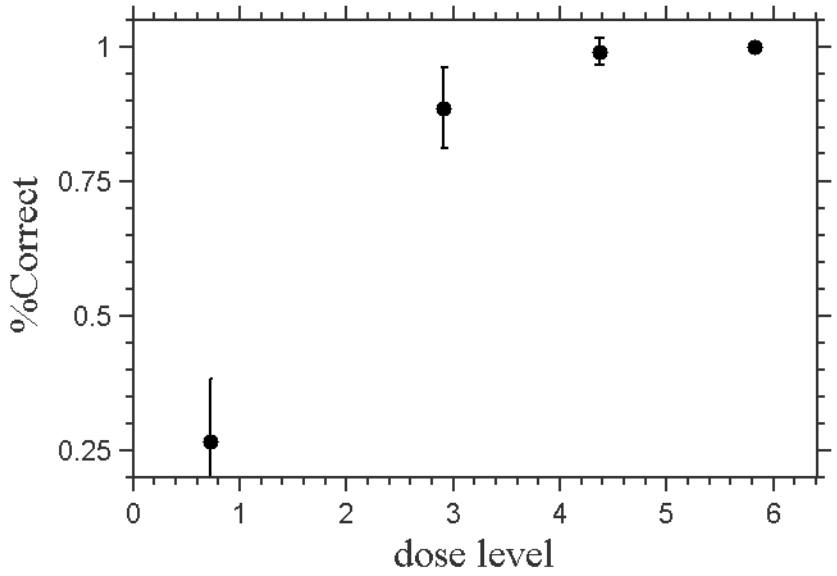
Zhang et al., SPIE proceedings (2016)



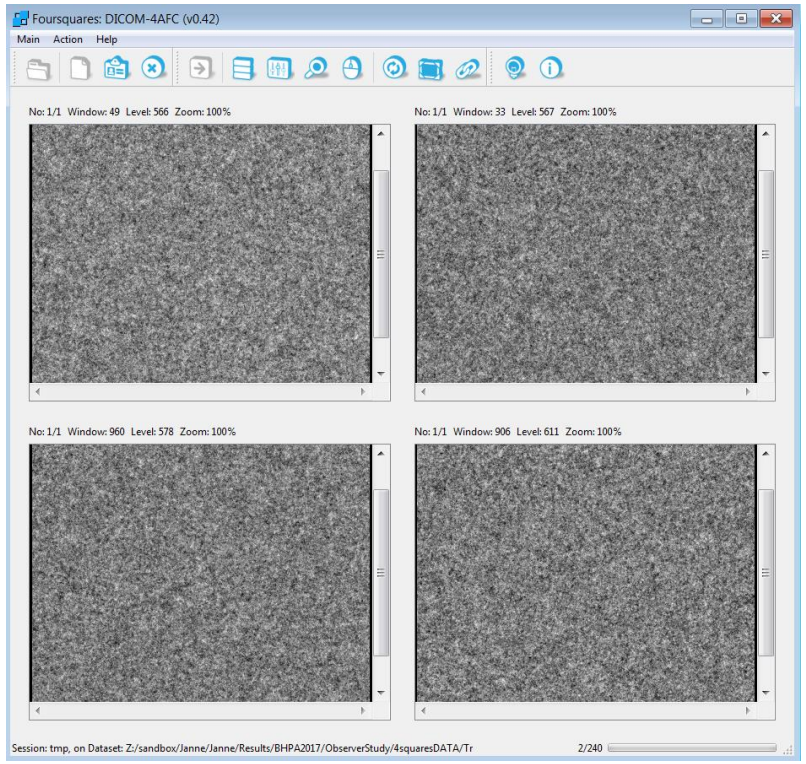
Four alternative forced choice (4-AFC)



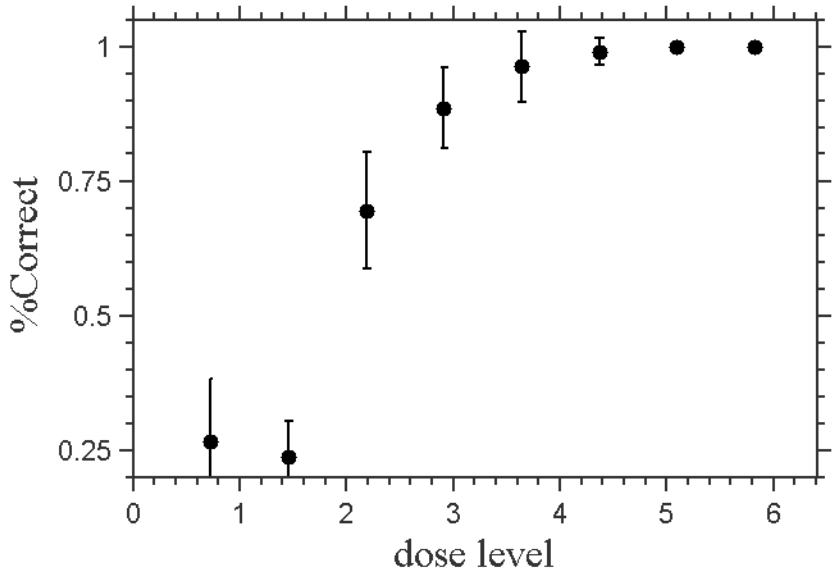
Zhang et al., SPIE proceedings (2016)



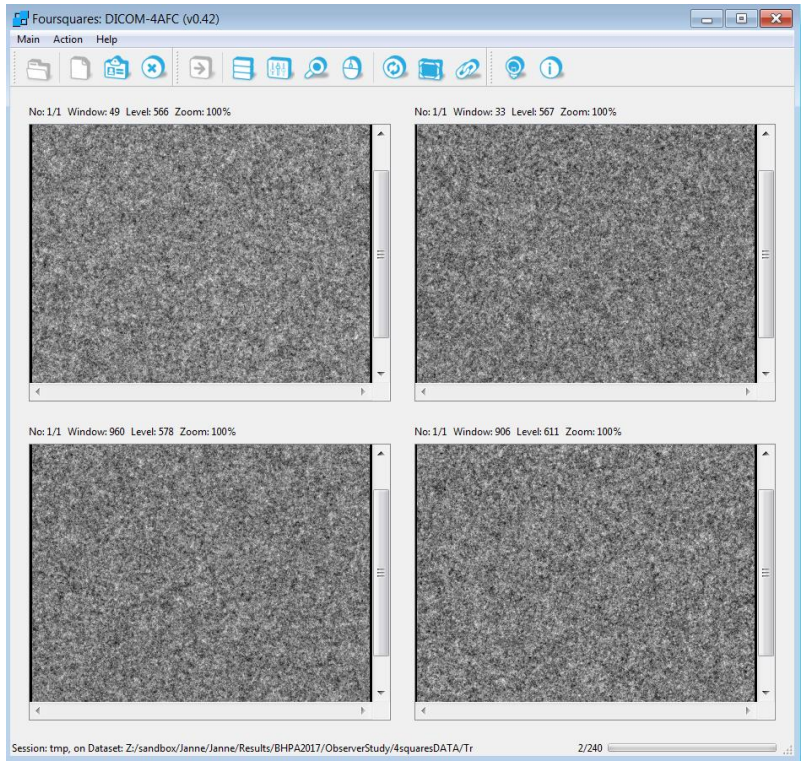
Four alternative forced choice (4-AFC)



Zhang et al., SPIE proceedings (2016)

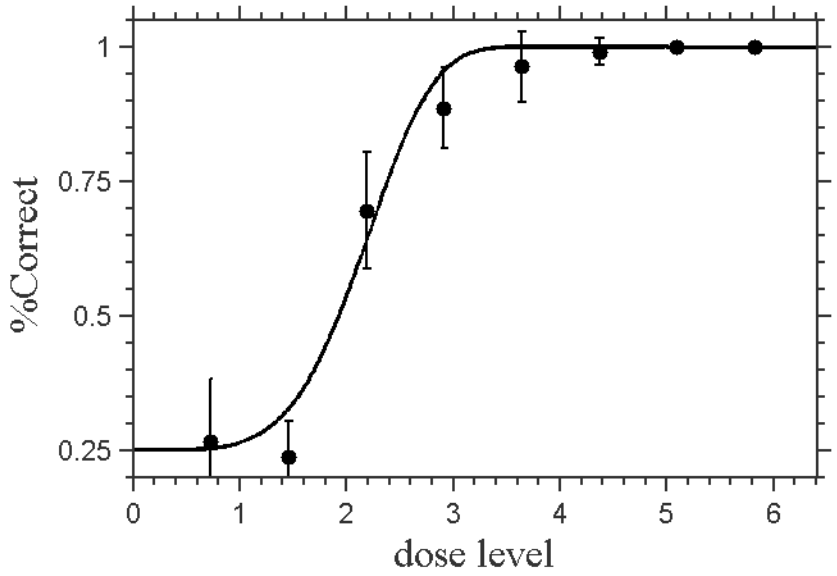


Four alternative forced choice (4-AFC)



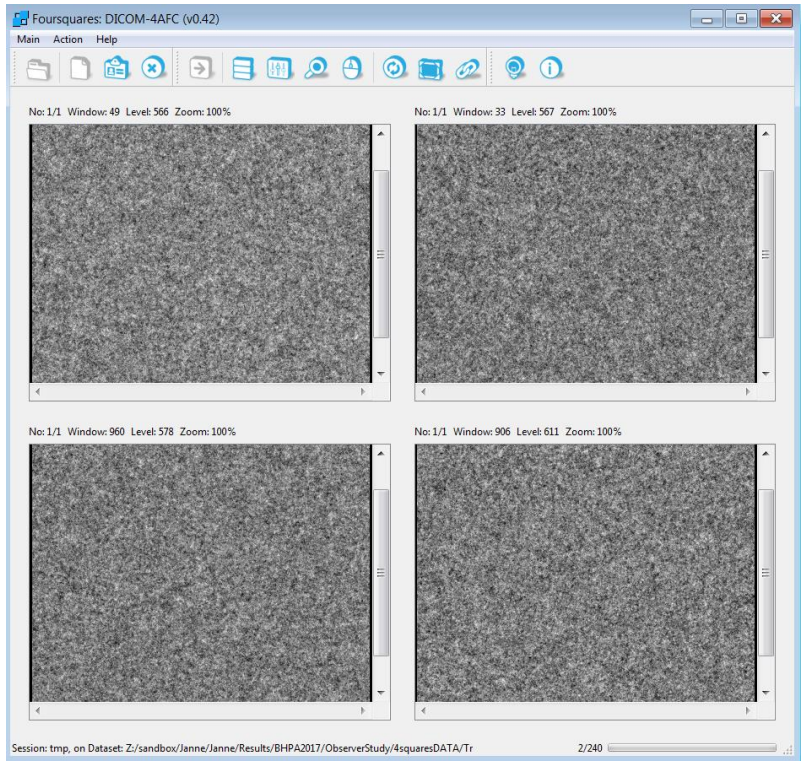
Zhang et al., SPIE proceedings (2016)

Psychometric curve fit



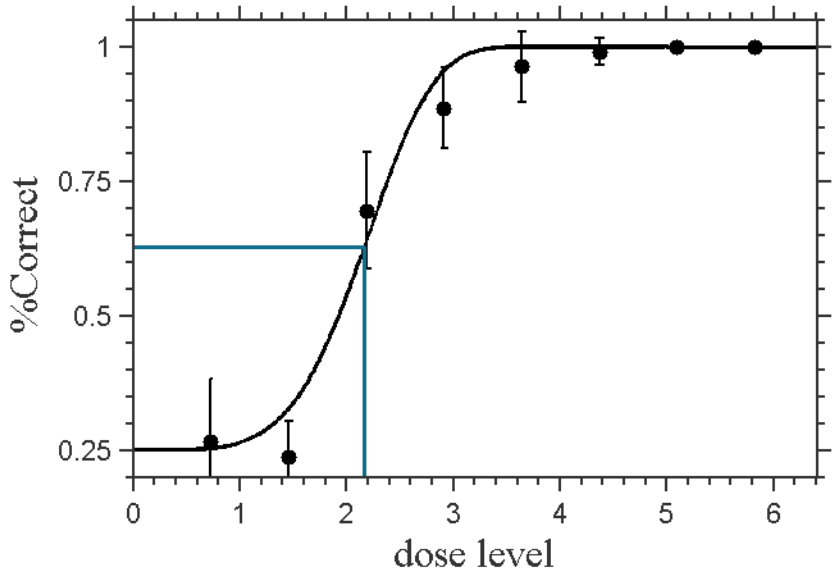
$$\%Corr = 1 - 0.75 \cdot \exp\left(-\left(\frac{dose}{a}\right)^{b}\right)$$

Four alternative forced choice (4-AFC)



Zhang et al., SPIE proceedings (2016)

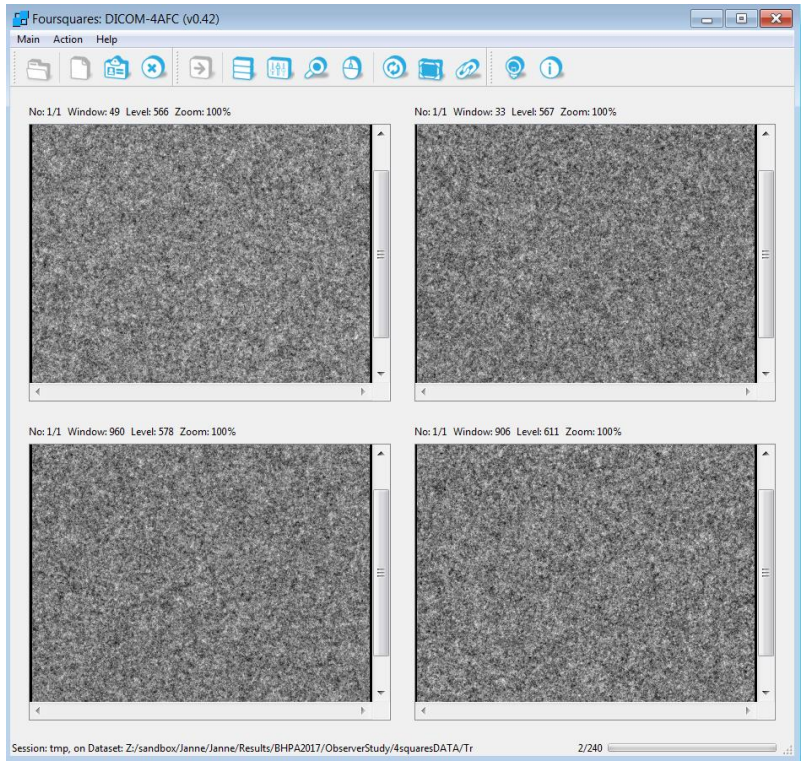
Psychometric curve fit – threshold at 62.5%



$$\%Corr = 1 - 0.75 \cdot \exp\left(-\left(\frac{dose}{a}\right)^{b}\right)$$

4-AFC

Four alternative forced choice (4-AFC)



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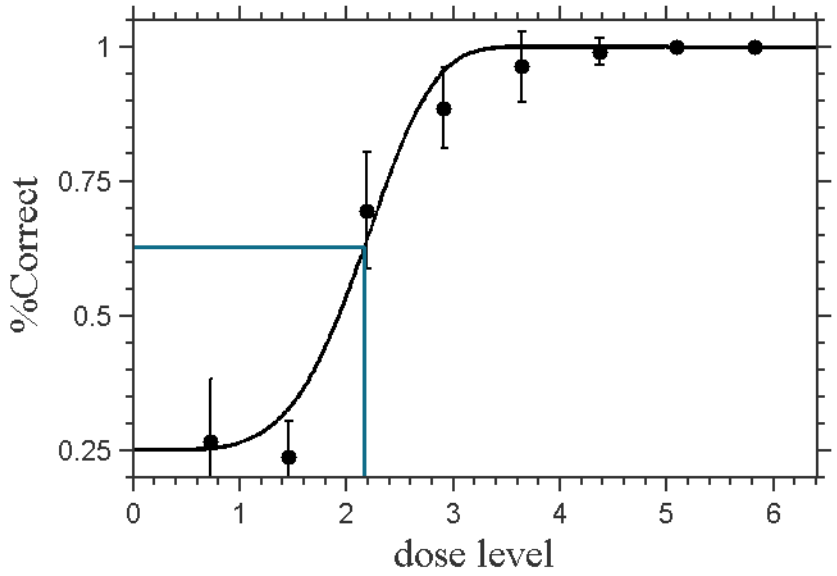
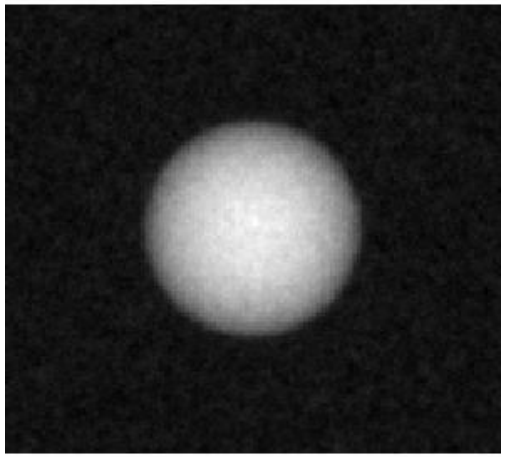


$$\%Corr = 1 - 0.75 \cdot \exp\left(-\left(\frac{dose}{a}\right)^{b}\right)$$

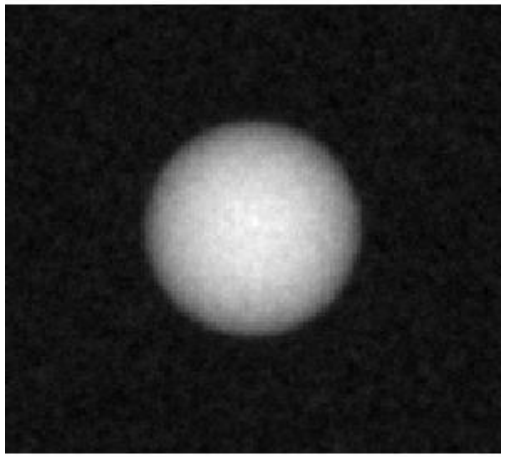
If you want to do this for every task it is very time consuming. Make it more general.

GENERALIZED TASK BASED DETECTABILITY STUDY

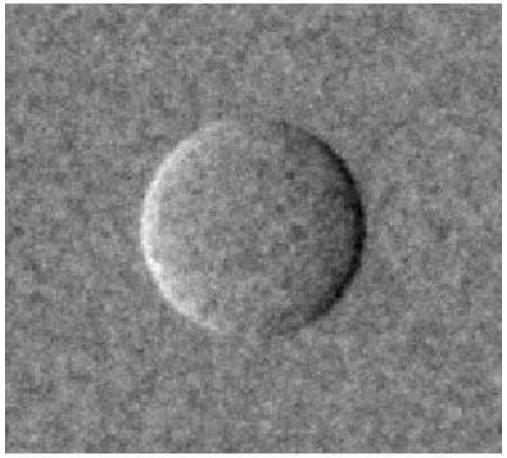
Liver in adipose bg with radiation dose of *x*



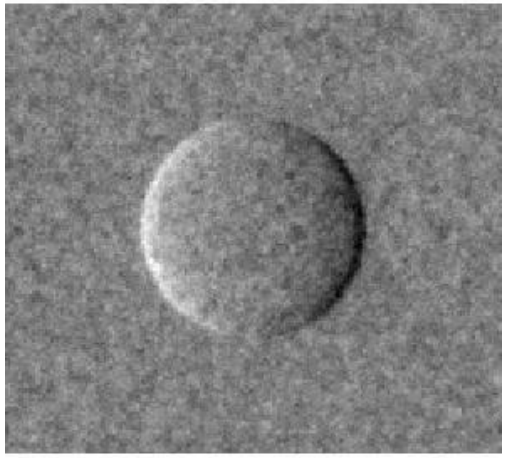
blood in muscle bg with radiation dose of *y*



Liver in adipose bg with radiation dose of *w*



blood in muscle bg with radiation dose of *z*



Definitions FOM

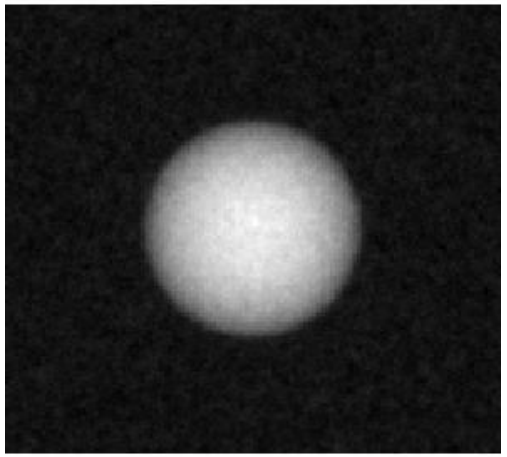
$$FOM_{Tr} = \frac{\min(I_{Tr}) - \max(I_{Tr})}{\sigma_{Tr}}$$

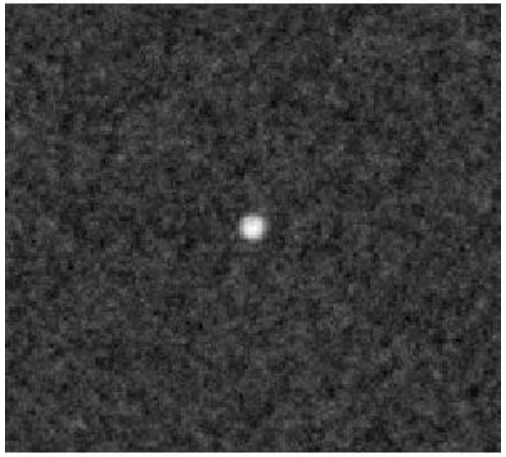
$$FOM_{dP} = \frac{\max(\int |S_{dP}| dx)}{\sigma_{dP}}$$

Should scale with detectability

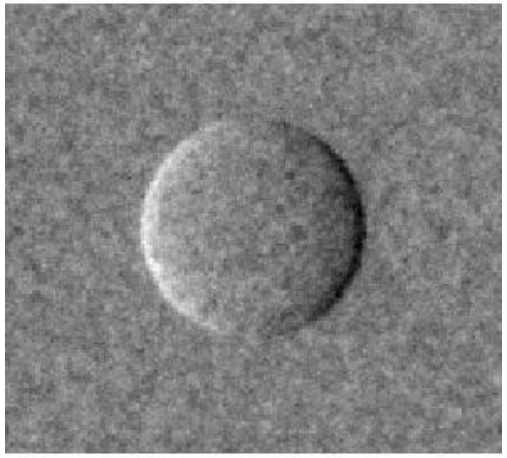
GENERALIZED TASK BASED DETECTABILITY STUDY

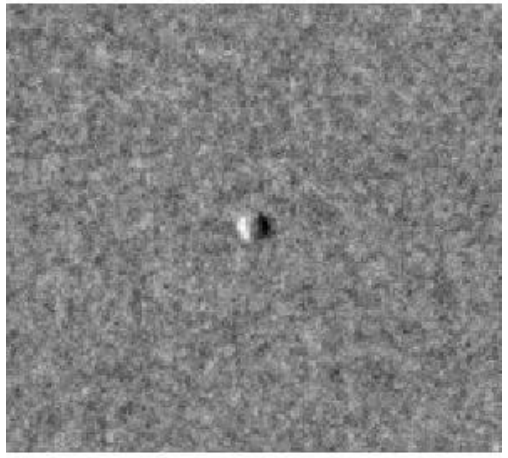
Liver in adipose bg with radiation dose of *x*





Liver in adipose bg with radiation dose of *w*





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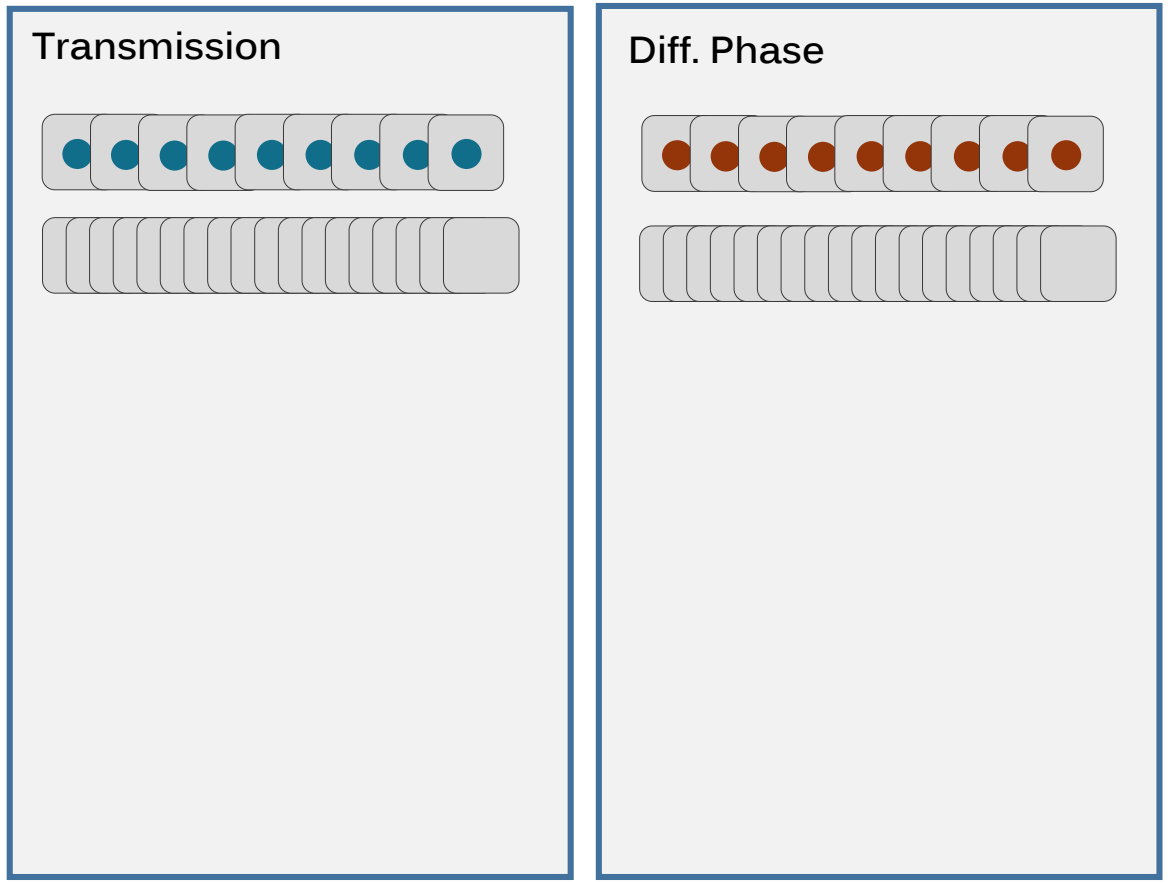
$$FOM_{dP} = \frac{\max(\int |S_{dP}| dx)}{\sigma_{dP}}$$

Should scale with detectability

Only valid for same task shape!

GENERALIZED TASK BASED DETECTABILITY STUDY

For a certain task shape

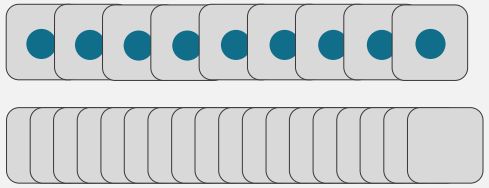


1. **Simulate**. Simulate set of Tr and dP images (bg and obj) with signal and noise combinations ranging between undetectable to detectable
2. FOM.
3. 4AFC.
4. Thresholds.
5. EAK(62.5%).
6. RP.

GENERALIZED TASK BASED DETECTABILITY STUDY

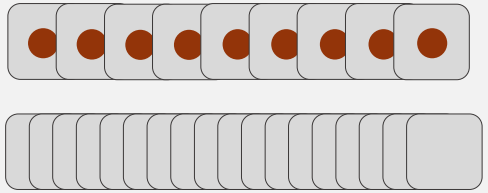
For a certain task shape

Transmission



$$FOM_{Tr} = \frac{\min(I_{Tr}) - \max(I_{Tr})}{\sigma_{Tr}}$$

Diff. Phase



$$FOM_{dP} = \frac{\max(\int |S_{dP}|dx)}{\sigma_{dP}}$$

1. **Simulate**. Simulate set of Tr and dP images (bg and obj) with signal and noise combinations ranging between undetectable to detectable
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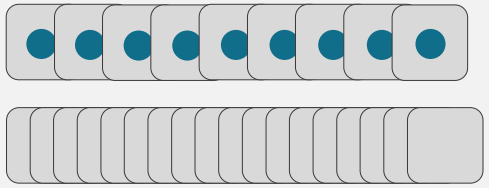
5. **EAK(62.5%).**
6. **RP.**

GENERALIZED TASK BASED DETECTABILITY STUDY

For a certain task shape

Transmission



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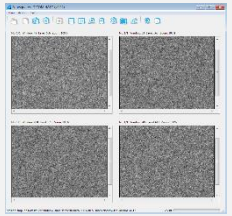
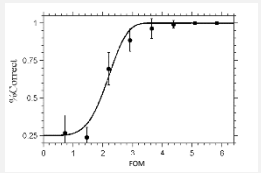
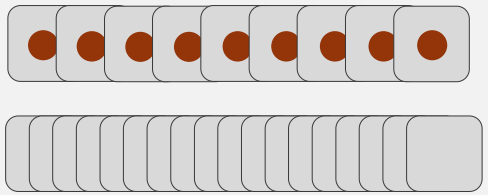
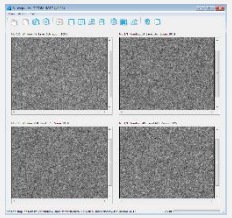


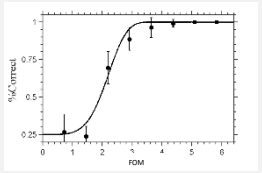


Diff. Phase



$$FOM_{dP} = \frac{\max(\int |S_{dP}|dx)}{\sigma_{dP}}$$





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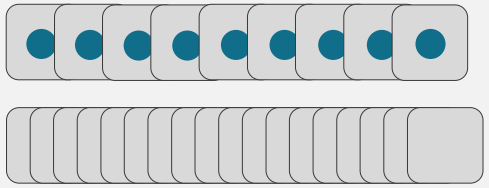
6. **RP.**

GENERALIZED TASK BASED DETECTABILITY STUDY

For a certain task shape

Transmission



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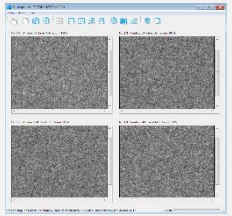
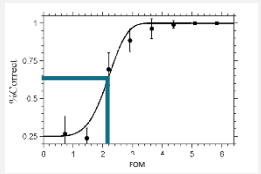
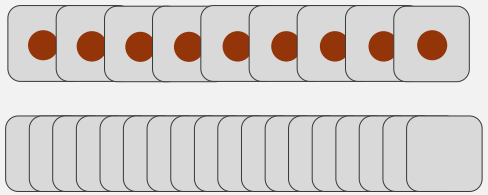
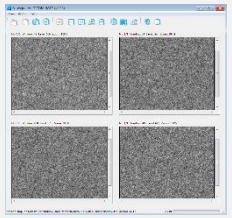


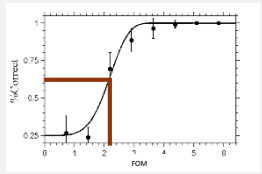


Diff. Phase



$$FOM_{dP} = \frac{\max(\int |S_{dP}|dx)}{\sigma_{dP}}$$





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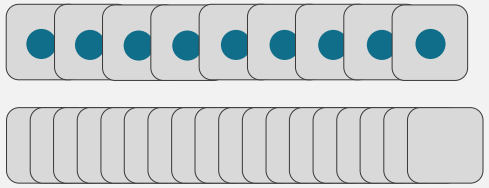
GENERALIZED TASK BASED DETECTABILITY STUDY

For a certain task shape

Transmission



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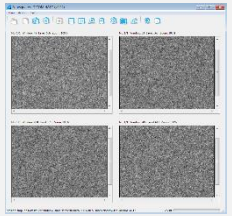
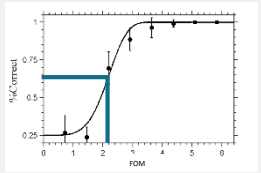
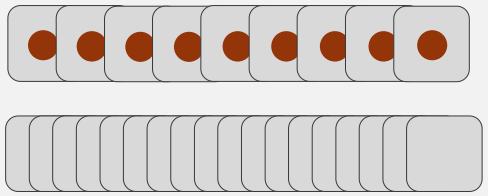




e.g. for tumor lesion in adipose tissue which EAK required to reach $FOM_{Tr} = FOM_{Tr62.5\%}$

Diff. Phase



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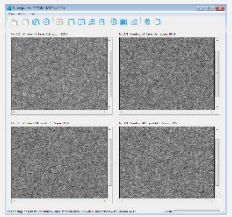

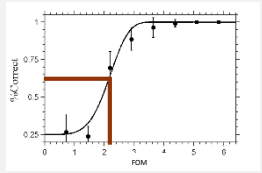

e.g. for tumor lesion in adipose tissue which EAK required to reach $FOM_{dP} = FOM_{dP62.5\%}$

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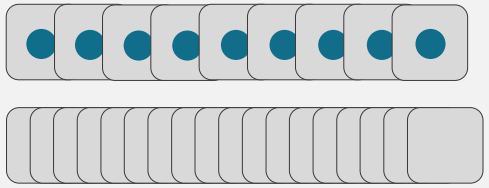
6. **RP.**

GENERALIZED TASK BASED DETECTABILITY STUDY

For a certain task shape

Transmission



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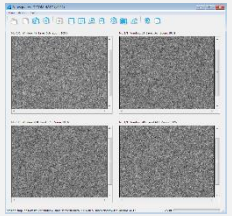
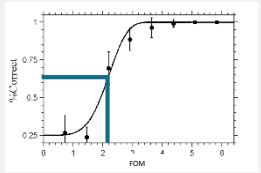
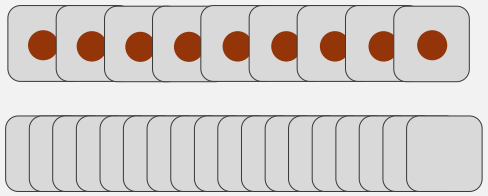




e.g. for tumor lesion in adipose tissue which EAK required to reach $FOM_{Tr} = FOM_{Tr62.5\%}$

Diff. Phase



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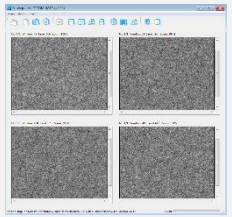

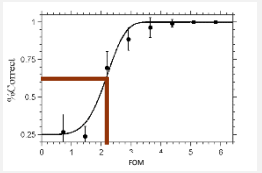

e.g. for tumor lesion in adipose tissue which EAK required to reach $FOM_{dP} = FOM_{dP62.5\%}$

$$RP = \frac{EAK_{Tr}(62.5\%)}{EAK_{dP}(62.5\%)}$$

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5. **EAK(62.5%).** Calculate the EAK_{Tr} and EAK_{dP} for a given application (combination of bg and obj materials) to reach respectively the FOMTr and FOMdP
6. **RP.** The relative performance of an application = EAK_{Tr}/EAK_{dP}

OUTLINE

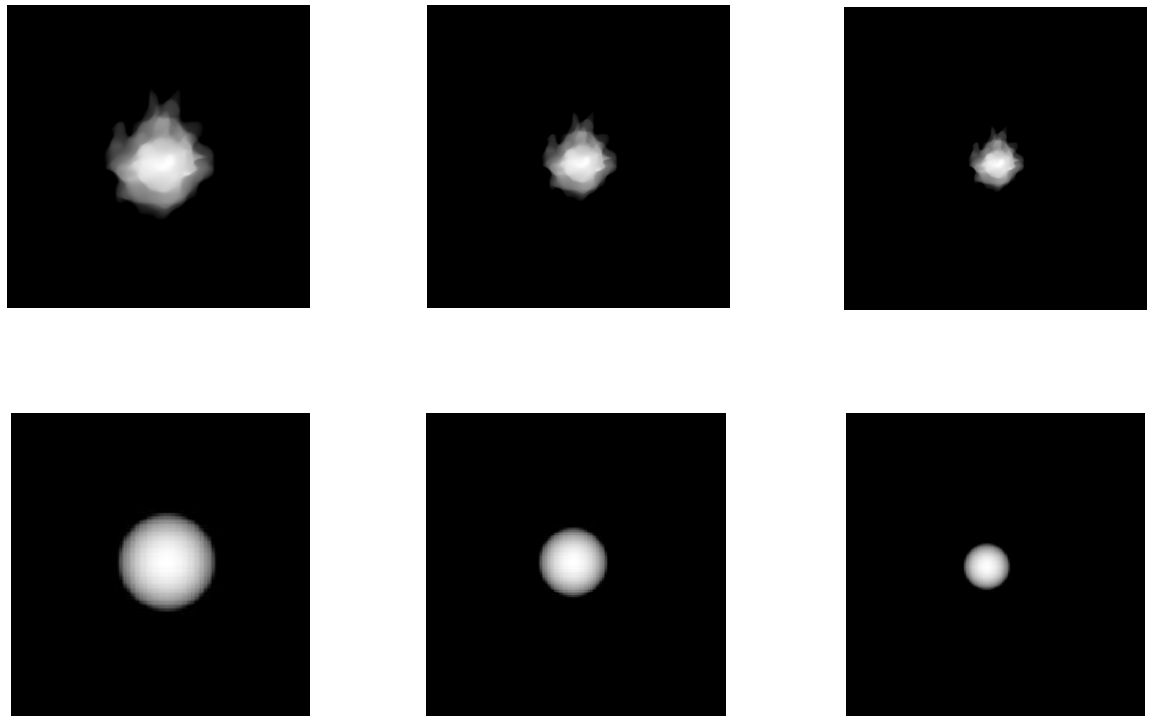
- Talbot-Lau interferometry
- A hybrid simulation framework
  - generate ‘realistic’ imagines that match those of a TLI scanner
- A detectability study
  - a task-based study
  - human reader studies (4-AFC)
- **Application: mammography**

Application 1. Sphere/lesions of different sizes

5.3 mm diam

2.6 mm diam

1.3 mm diam

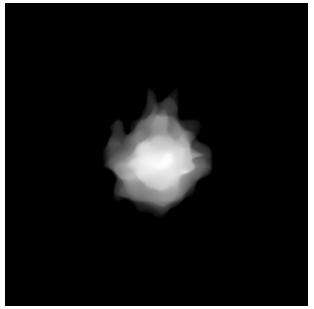


Lesion

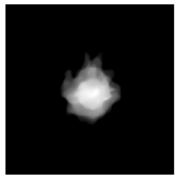
Shaheen E. et al. , Med. Phys. 41(8), 2014

Application 1. Sphere/lesions of different sizes

5.3 mm diam



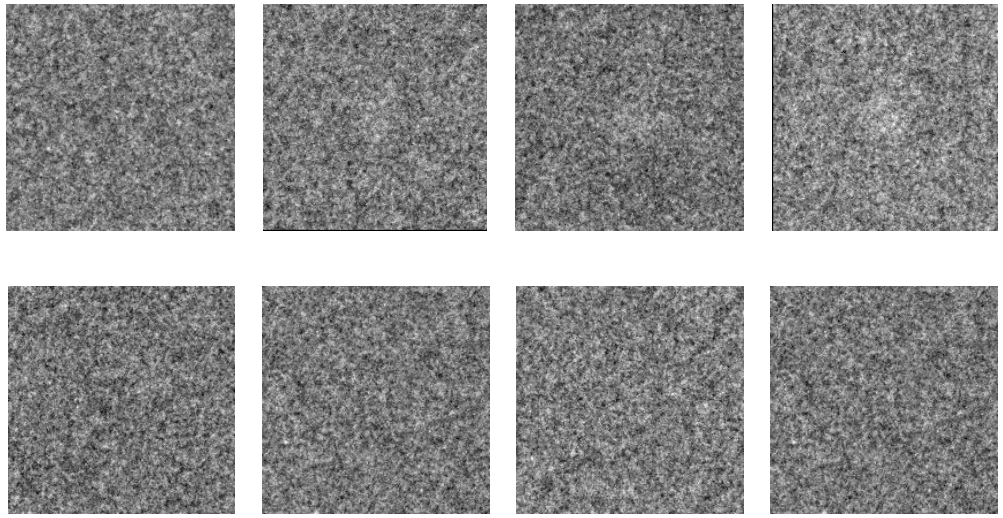
APPLICATIONS: HOMOGENEOUS BG



Application 1. Sphere/lesions of different sizes

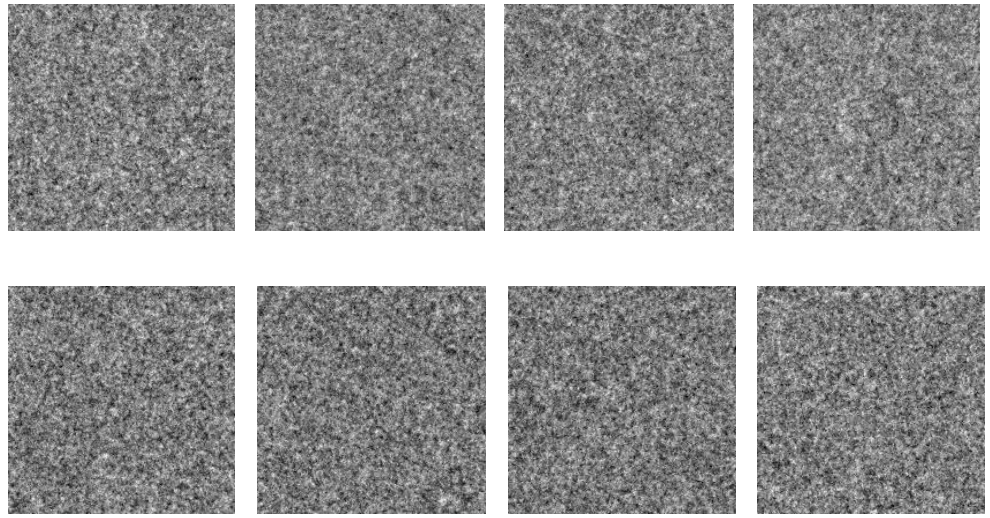
1. **Simulate**.
2. FOM.
3. 4AFC.
4. Thresholds.
5. EAK(62.5%).
6. RP.

Transmission



8 different FOM values
15 signal present & 45 signal absent per dose

Differential phase



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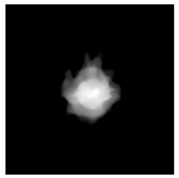
APPLICATIONS: HOMOGENEOUS BG



Application 1. Sphere/lesions of different sizes

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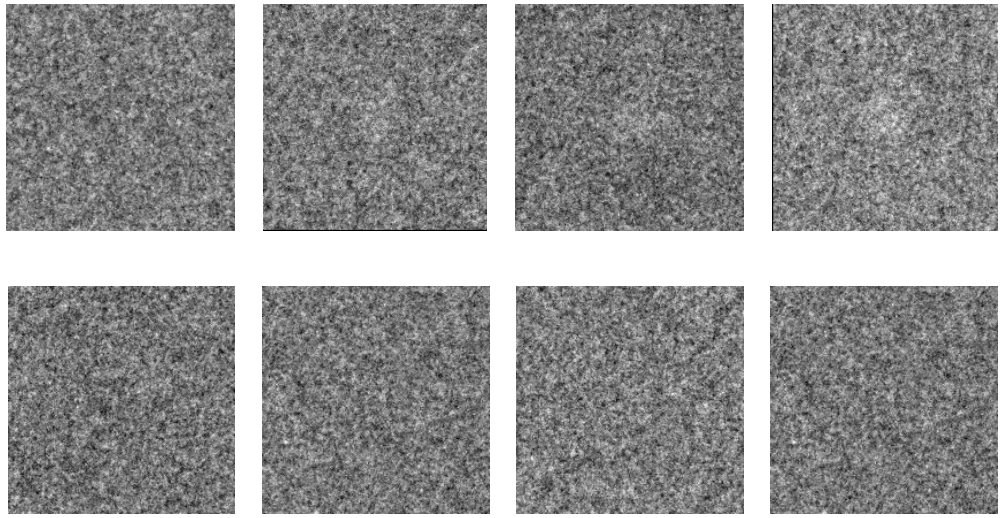
5. EAK(62.5%).
6. RP.

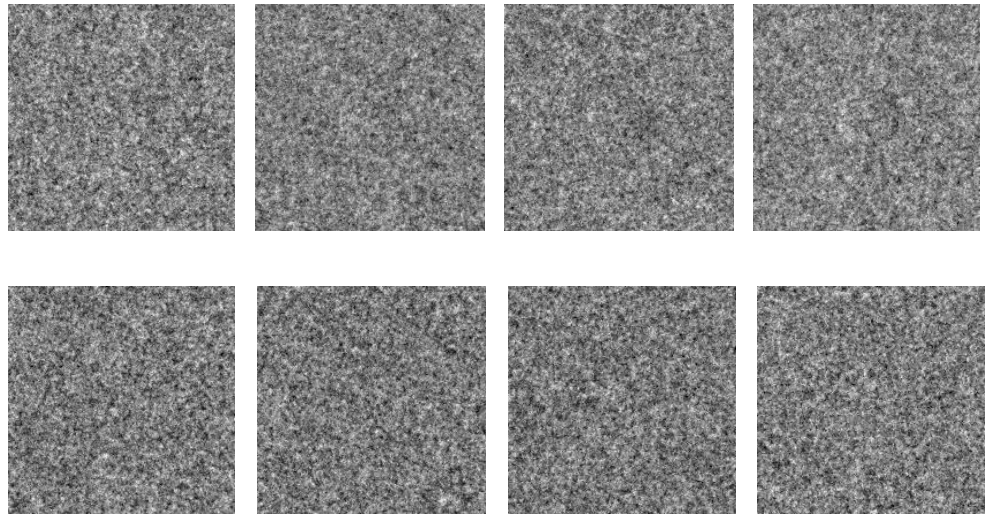
Transmission FOM_{Tr}

= 0.2 = 0.37 = 0.53 = 0.7



Differential phase FOM_{dP}

= 1.45 = 3.03 = 4.61 = 6.2



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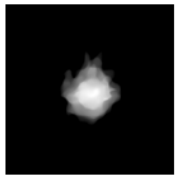

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1. Simulate.
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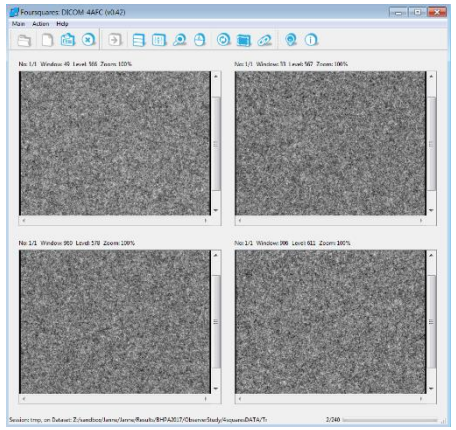
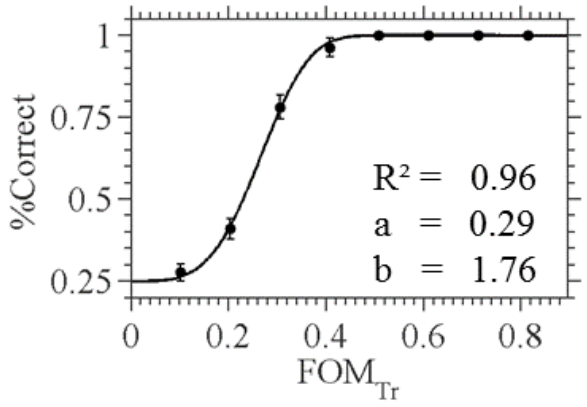
Transmission

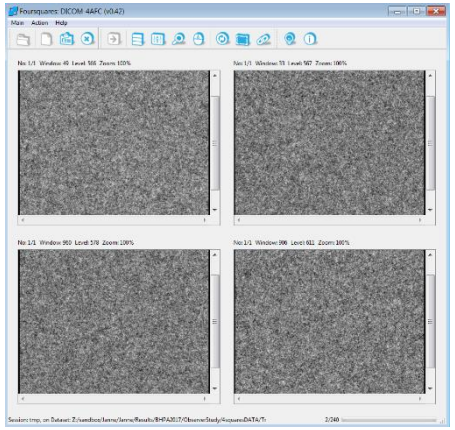
7 trained readers

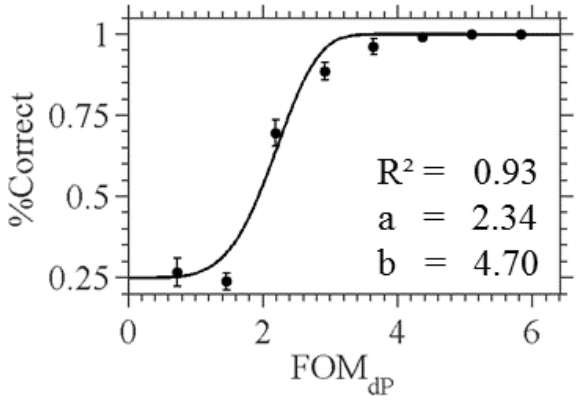




Differential phase

7 trained readers





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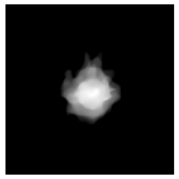

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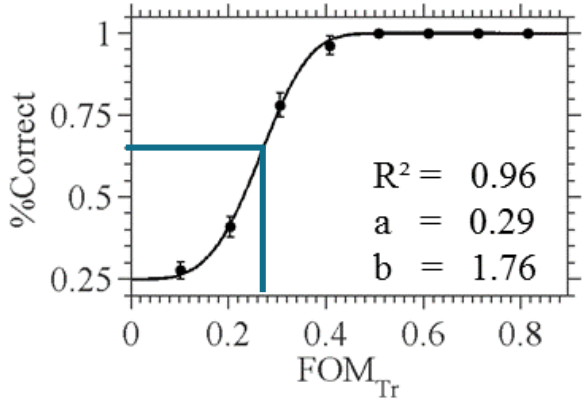
3. 4AFC.
4. **Thresholds**.
5. EAK(62.5%).
6. RP.

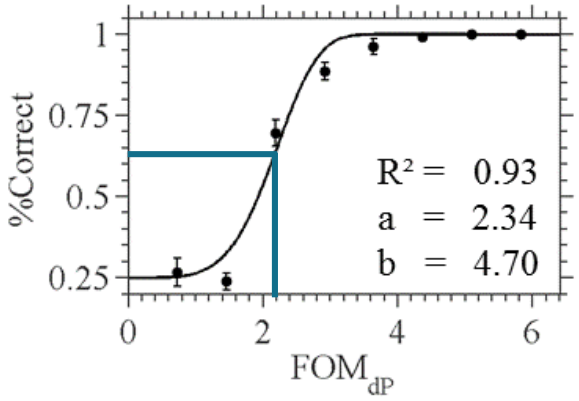
Transmission

$FOM_{Tr}(62.5\%) = 0.34$



Differential phase

$FOM_{dP}(62.5\%) = 2.16$



APPLICATIONS: HOMOGENEOUS BG

5.3 mm diam

Compositions

Hammerstein G. et al., Rad., **130**, 1979

Johns P.C., Yaffe M.J. , Phys. Med. Biol. **32**(675), 1987

Application 1. Sphere/lesions of different sizes

1. Simulate.
2. FOM.
3. 4AFC.
4. Thresholds.
5. **EAK(62.5%).**
6. RP.

Transmission

$$FOM_{Tr}(62.5\%) = 0.34$$

$$FOM_{Tr} = \frac{\min(I_{Tr}) - \max(I_{Tr})}{\sigma_{Tr}}$$

Background	lesion	EAK(62.5%) [mGy]
adipose	tumour	0.007(1)
Glandular	tumour	0.030(4)

Differential phase

$$FOM_{dP}(62.5\%) = 2.16$$

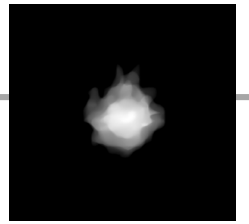
$$FOM_{dP} = \frac{\max(\int |S_{dP}|dx)}{\sigma_{dP}}$$

Background	lesion	EAK(62.5%) [mGy]
adipose	tumour	0.71(6)
Glandular	tumour	6.7(5)

APPLICATIONS: HOMOGENEOUS BG

Application 1. Sphere/lesions of different sizes

5.3 mm diam



1. Simulate.
2. FOM.
3. 4AFC.
4. Thresholds.
5. EAK(62.5%).
6. **RP**.

Transmission

Background	lesion	RP
adipose	tumour	0.0010(2)
Glandular	tumour	0.0045(7)

Background	lesion	EAK(62.5%) [mGy]
adipose	tumour	0.007(1)
Glandular	tumour	0.030(4)

Differential phase

Background	lesion	EAK(62.5%) [mGy]
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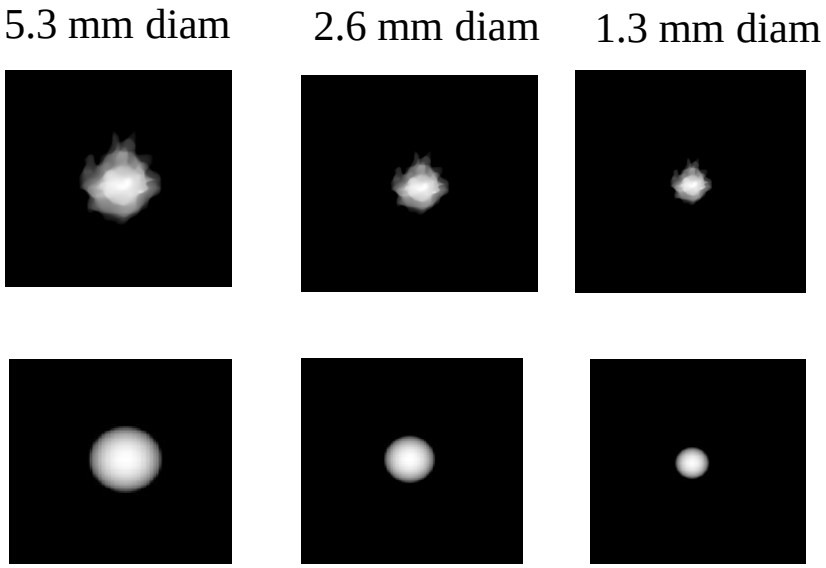
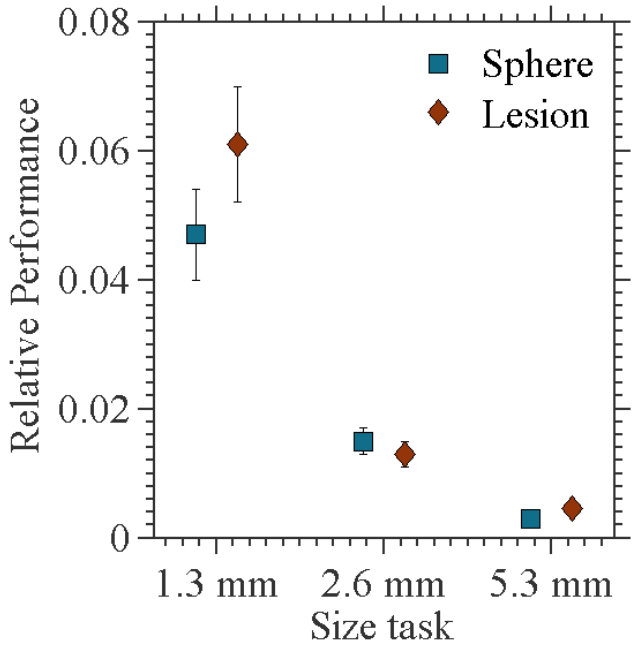
APPLICATIONS: HOMOGENEOUS BG

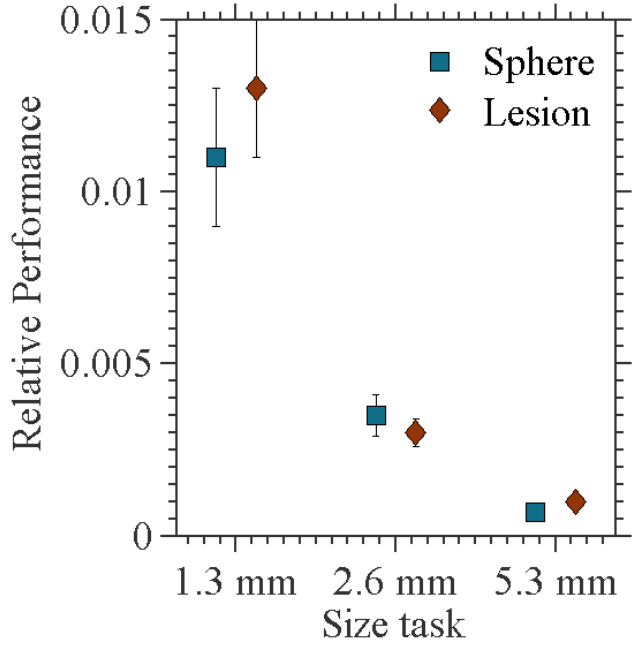
Application 1. Sphere/lesions of different sizes



Glandular



Adipose

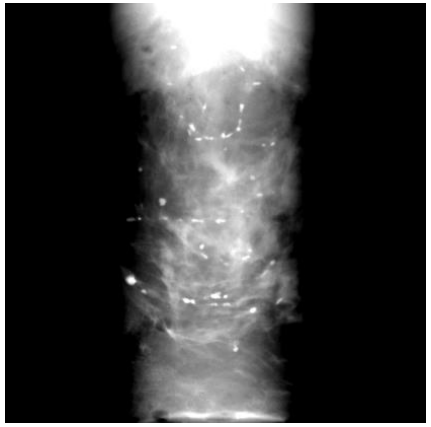


For our system, we do not expect dP to outperform Tr imaging for these tasks

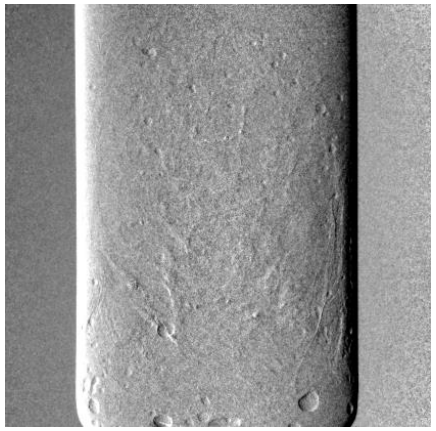
APPLICATIONS: HOMOGENEOUS BG

Application 1. Sphere/lesions of different sizes

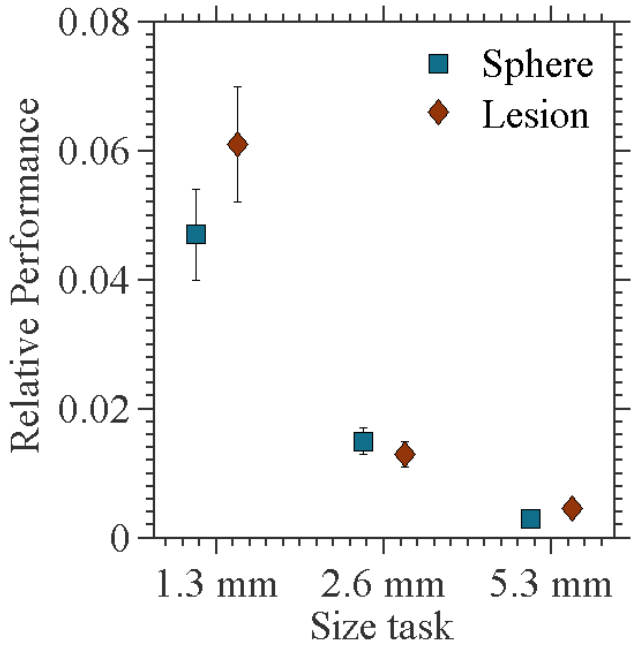
Tr Image



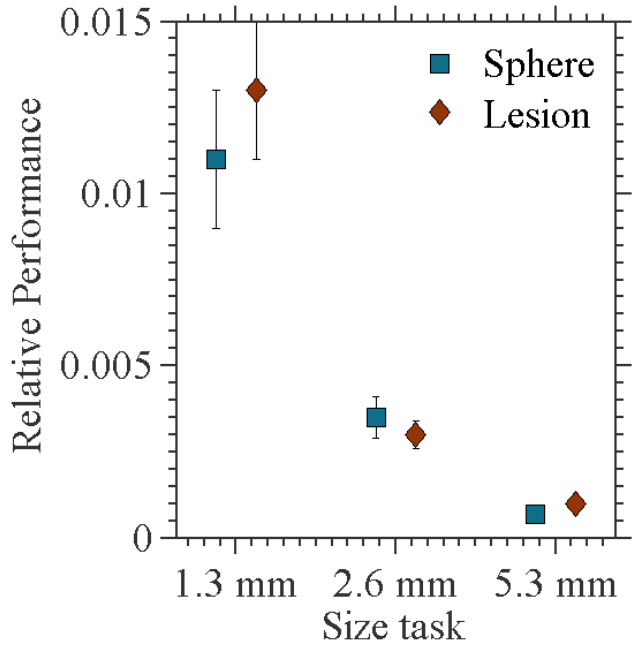
dPImage



Glandular

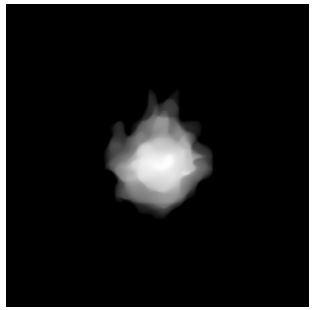


Adipose



For our system, we do not expect dP to outperform Tr imaging for these tasks

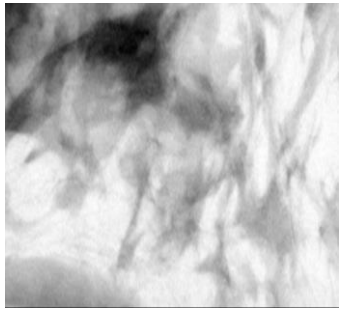
Application 2. Mammo



5.3 mm diam

glandular

adipose

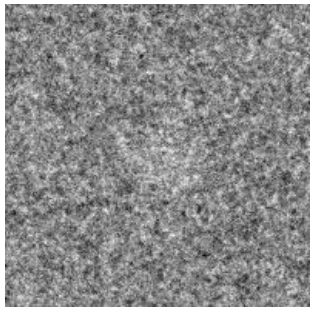


mammographic

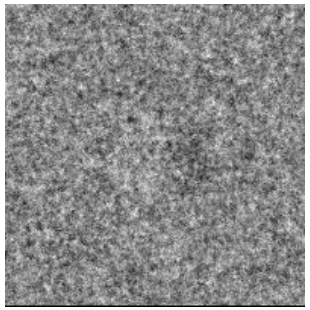
Mammographic background

1. μCT data of mastectomy
2. Thresholding glandular and adipose tissue
3. Selecting appropriate ROI's

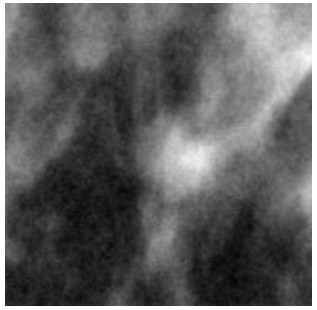
Tr



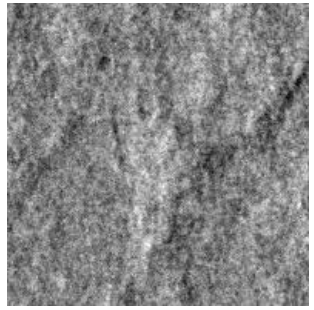
dP



Tr

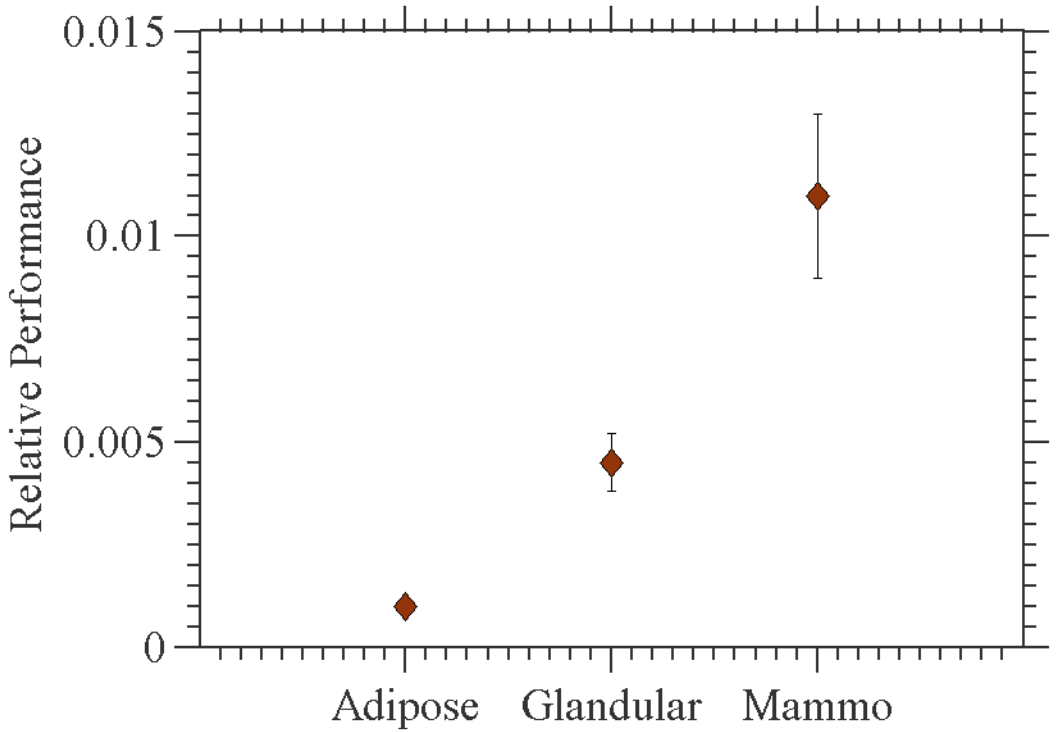


dP



Application 2. Mammo

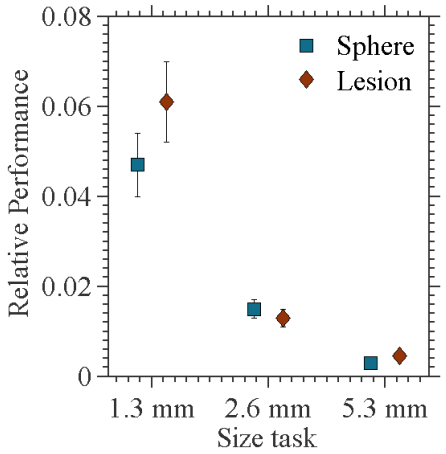
	Uniform		Mammographic
	Adipose	glandular	background
EAK_{Tr}	0.0007(1)	0.030(4)	0.032(4)
EAK_{dP}	0.71(6)	6.7(5)	3.1(2)
RP	0.0010(2)	0.0045(7)	0.011(2)



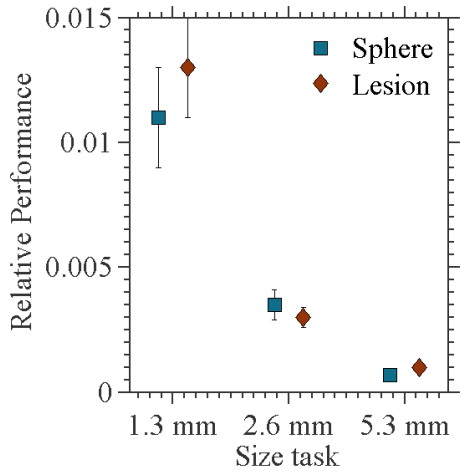
Application 1 & 2. Discussion

Diff Phase imaging does not outperform Tr imaging for our system setup.

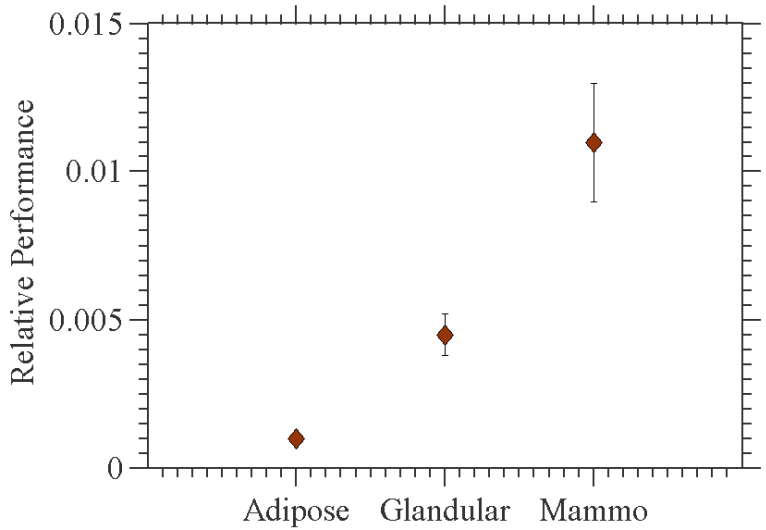
Glandular



Adipose



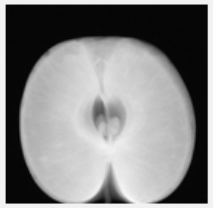
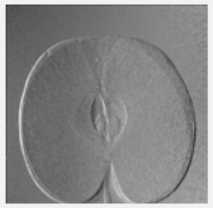
5.3 mm lesion



But our system is not the state of the art system

Application 1 & 2. Discussion

Diff Phase imaging does not outperform Tr imaging for our system setup.

	 Transmission (Tr)	 Differential phase (dP)
Signal	$S_{Tr} = \exp(-\mu t) = \exp(-2k\beta t)$	$S_{dP} = \frac{2\pi d}{p_2} \tan\left(\frac{\partial \delta t}{\partial x}\right)$
Noise	$\sigma_{Tr} \propto \frac{1}{\sqrt{PV}}$	$\sigma_{dP} \propto \frac{1}{\sqrt{PV}} \cdot \frac{1}{v}$

$$RP \propto \left(\frac{d}{p_2} \cdot v\right)^2$$

But our system is not the state of the art system

Application 1 & 2. Discussion

Diff Phase imaging does not outperform Tr imaging for our system setup.

System	CH-TLI	Birnbacher *et al.* [2016]	Michel *et al.* [2013]
d [cm]	4.35	85.7	15.9
p_2 [μm]	2	5.4	2.4
Sensitivity [10^5]	1.37	9.97	4.16
Visibility	22%	38.7%	20.7%
$(S_s \cdot v)_{rel}$	1.00	12.8	2.90
α_{min}	$1.64 \cdot 10^{-7}$	$1.7 \cdot 10^{-8}$ rad	-

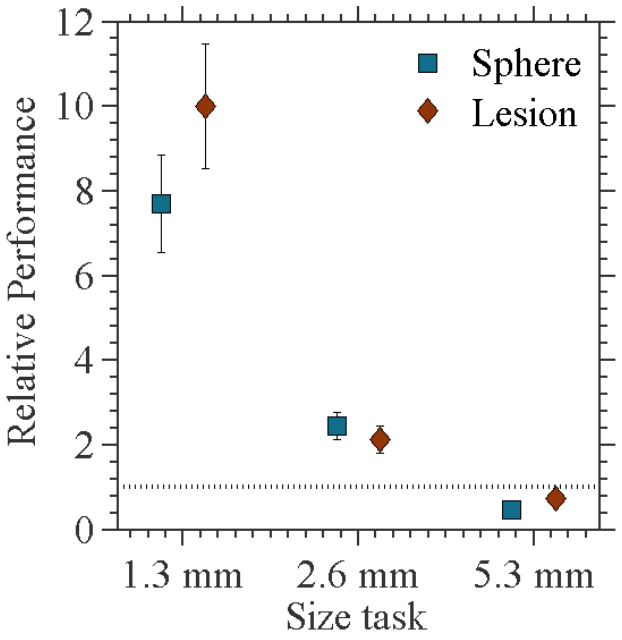
$$RP \propto \left(\frac{d}{p_2} \cdot v\right)^2$$

But our system is not the state of the art system

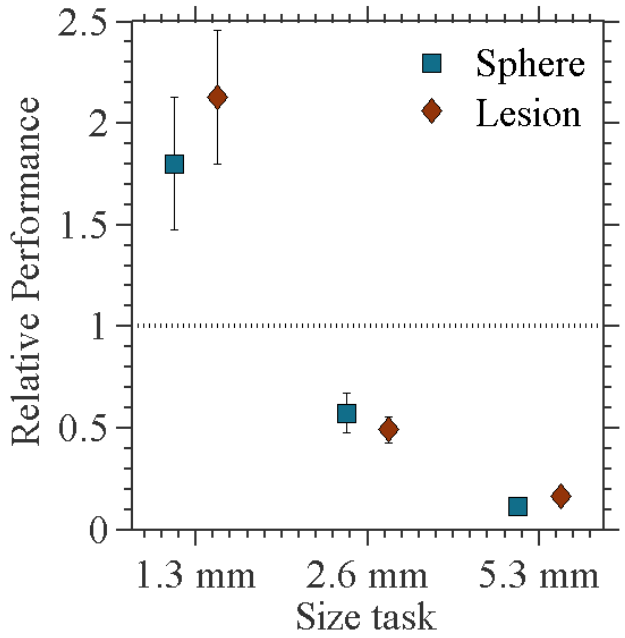
Application 1 & 2. Discussion

With reasonable system optimization dP outperforms Tr for some tasks!

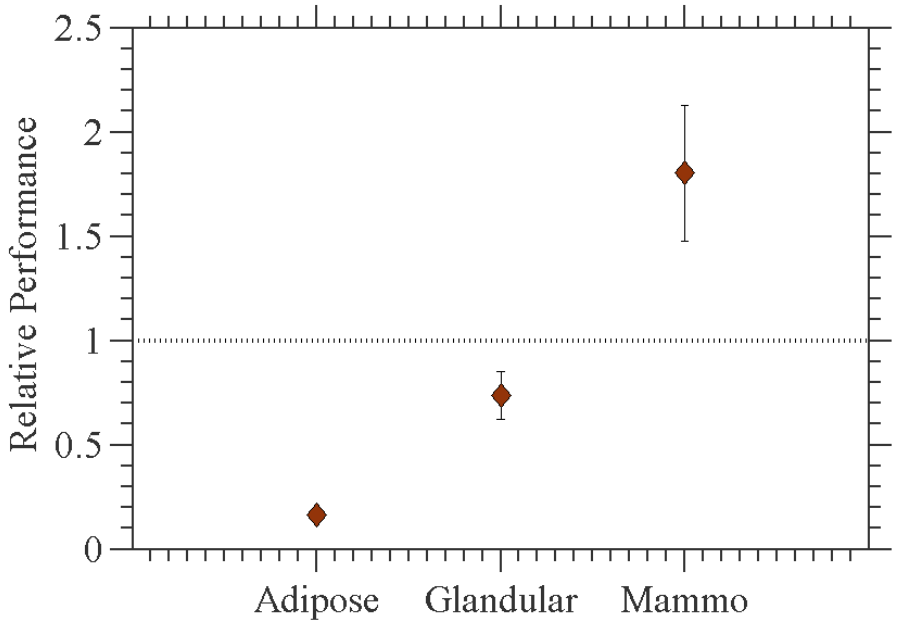
Glandular



Adipose



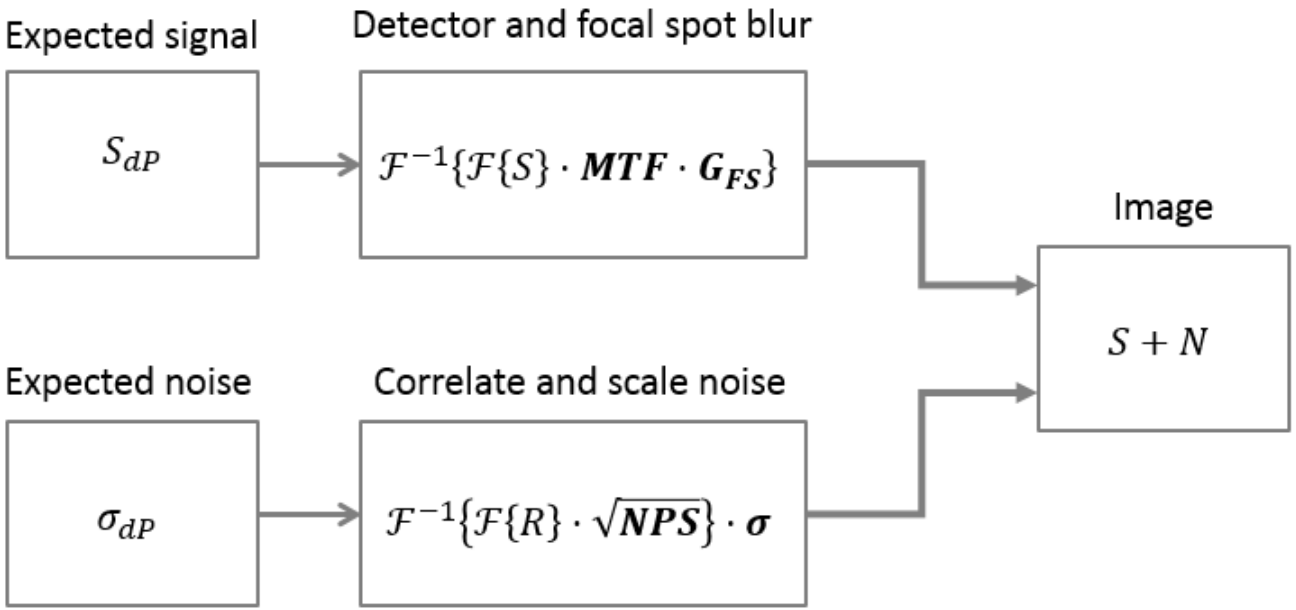
5.3 mm lesion

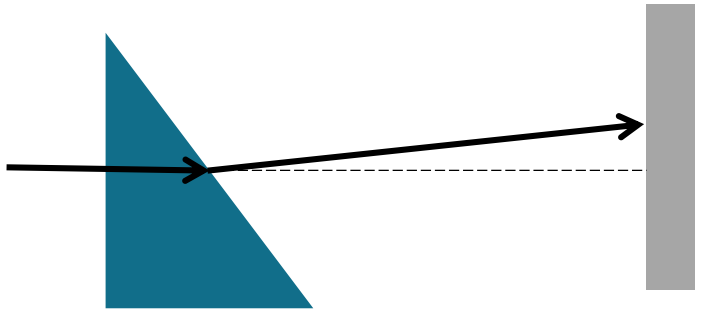


Diff phase is specifically promising to detect small lesions in a complex background

Application 1 & 2. Discussion

With reasonable system optimization dP outperforms Tr for some tasks! **However, this is only an approximation**





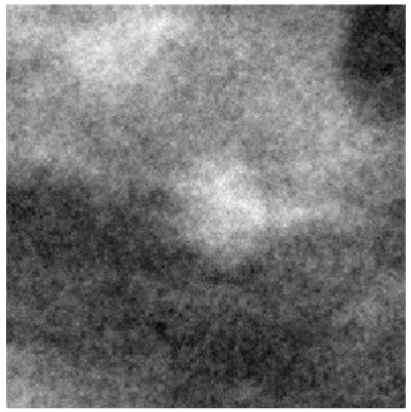
Magnification, different detector and source properties,...

Application 1 & 2. Discussion

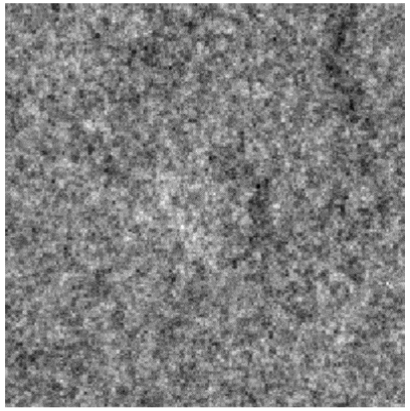
Orientation background affects dP performance

$$S_{dP} = \frac{2\pi d}{p_2} \tan\left(\frac{\partial \delta t}{\partial x}\right)$$

Tr

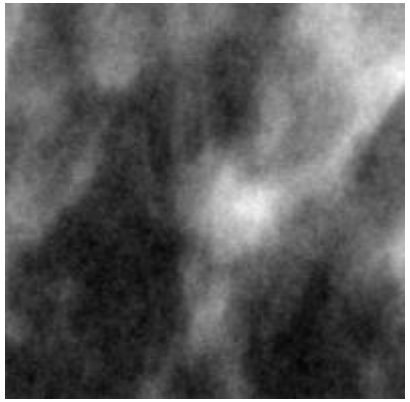


dP

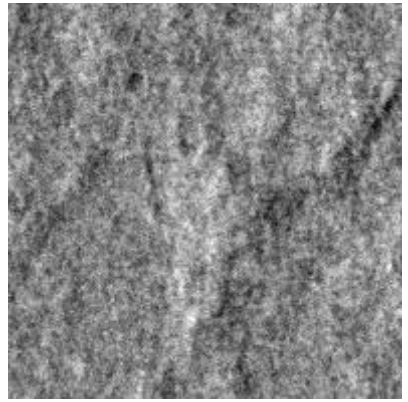


Horizontal oriented bg

Tr



dP

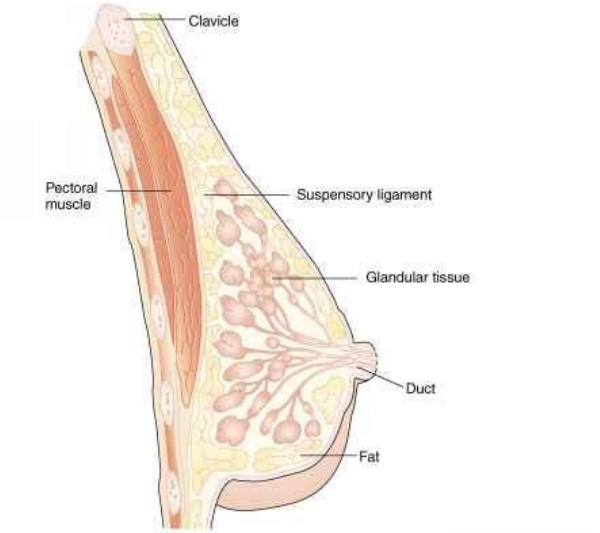


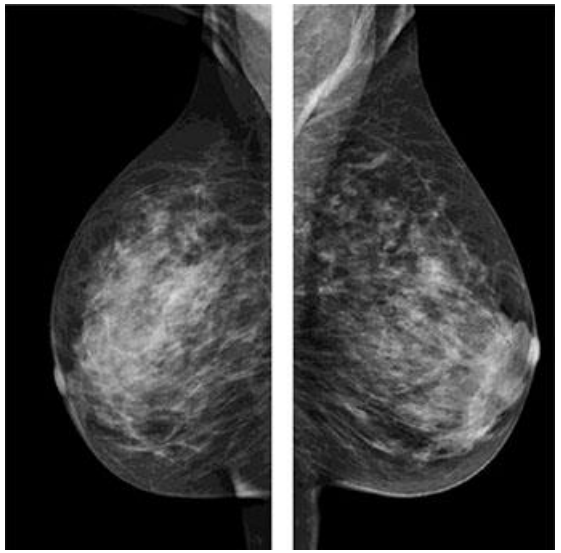
Vertical oriented bg

Horizontal structures are not detected in dP

Application 1 & 2. Discussion

Orientation background affects dP performance





Exploit this feature when developing TLI mammo systems because human breast has inherent orientation?

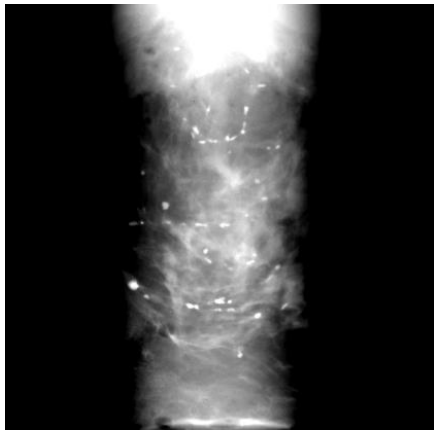
Application 1 & 2. Conclusion

CH-TLI system not good enough, but other systems in the literature might have sufficient system quality for dP to outperform Tr

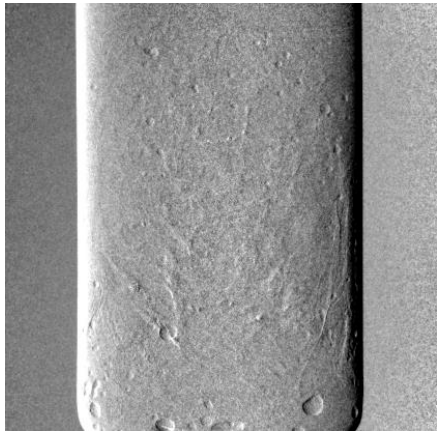
But TLI is a promising tool for the detection of small lesions in a complex background

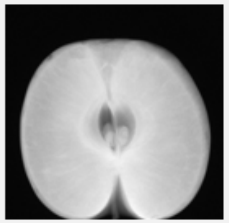
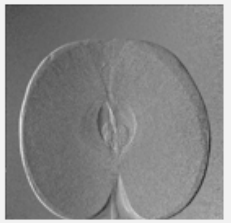
DISCUSSION AND CONCLUSION

Tr Image



dPImage



	 Transmission (Tr)	 Differential phase (dP)
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Noise	$\sigma_{Tr} \propto \frac{1}{\sqrt{PV}}$	$\sigma_{dP} \propto \frac{1}{\sqrt{PV}} \cdot \frac{1}{v}$

Computer simulations can be used to quantitatively estimate the feasibility of applications and/or to estimate the required system quality in TLI