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6. AUTHORS
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5f. WORK UNIT NUMBER

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Rochester, NY 14627 -0140

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14. ABSTRACT
In the rapidly emerging field of coded-aperture imaging, research is underway to improve the scope and quality of images in the visible and the infrared. In this research one needs to integrate the system design so as to enhance the combined effect of the “lens” and the digital processing. In this research we are studying a new camera system employing what we call “correlation imaging”. We have adapted the X-ray coded aperture imaging system of Dicke (1968) and others so that it is operative in the visible and infrared, where diffraction effects need to be taken into account. This novel optical system includes a phase-only screen followed by a detector array. A band-limited

15. SUBJECT TERMS
Coded Imaging; Correlation; Phase-coding; Thick-Diffusesr; Speckle; Multi-spectral; Hyperspectral

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Nicholas George
UU	UU	UU	UU		19b. TELEPHONE NUMBER 585-275-2417

Report Title

Final Report: Novel correlation imaging and multispectral camera in the visible and infrared spectrum

ABSTRACT

In the rapidly emerging field of coded-aperture imaging, research is underway to improve the scope and quality of images in the visible and the infrared. In this research one needs to integrate the system design so as to enhance the combined effect of the "lens" and the digital processing. In this research we are studying a new camera system employing what we call "correlation imaging". We have adapted the X-ray coded aperture imaging system of Dicke (1968) and others so that it is operative in the visible and infrared, where diffraction effects need to be taken into account. This novel optical system includes a phase-only screen followed by a detector array. A band-limited uniformly redundant array diffraction pattern is formed when the phase screen is illuminated by a point source in object space. Correlation-type image processing is applied to recover the object. Excellent imaging results of both binary and continuous tone objects can be obtained. In this research program, we are also conducting a separate, but related study of speckle since it is important in the development of the phase screen. Also in image science there remains some fundamental question as to the possibility of imaging through a dilute turbid atmosphere and we are conducting research studies on this topic.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
05/24/2016 14.00	Kaiqin Chu, Nicholas George, Wanli Chi. Incoherently combining logarithmic asphericlenses for extended depth of field, Applied Optics, (10 2009): 5371. doi:
TOTAL:	**1**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
10/29/2012	6.00	Nicholas George, Wanli Chi, Nian-An Chang. Wavelength deccorelation of speckle in propagation through a thick diffuser, J. Opt. Soc Am. A, (02 2011): 245. doi:
10/29/2012	8.00	Nicholas George, Paul Zavattero. Remotely measuring a thin dielectric coating on a metallic cylinder, Optics Express, (12 2011): 26684. doi:
10/29/2012	11.00	Nicholas George, Xi Chen. Extended depth-of-field lenses and methods for their design, optimization and manufacturing, United States Patent Application Publication, Pub. No.: US 2010/0002310 A1, (01 2010): 0. doi:
10/29/2012	12.00	Wanli Chi, Nicholas George. Optical Element, Device, Method, and Applications, United States Patent Application Publication, Pub. No.: US 2011/0085051 A1, (04 2011): 0. doi:
10/29/2012	13.00	Wanli Chi, Nicholals George. Phase-coded aperture for optical imaging, Optics Communications, (06 2009): 2110. doi:
TOTAL:		**5**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Wanli Chi, “Correlation type imaging systems,” National University of Ireland, Galway (2009). Invited Seminar.
2. Wanli Chi, “Integrated imaging system for extended depth of field,” National University of Ireland, Galway (2009) Invited Seminar.
3. Nicholas George, "Computational imaging and extended-depth-of-field in digital camera systems," Institute of Optics Graduate Seminar, University of Rochester, Rochester, NY.
4. Nicholas George and Wanli Chi, “Emerging electronic imaging systems,” Optical Society of American Annual Meeting (2009). Invited Talk.
5. Kaiqin Chu, Nicholas George and Wanli Chi, “Extended depth of field through aperture partitioning,” Optical Society of American Annual Meeting (2009).
6. Nicholas George, “Design and performance of EDOF digital cameras,” OSA Optics and Photonics Congress. 01-JUL-12.
7. Nienan Chang, Nicholas George, and Wanli Chi, “Propagation through a thick diffuser with small particles,” Fronties in Optics 2010, OSA Annual Meeting, Rochester, NY
8. Nicholas George, Xi Chen, Wanli Chi, “Illustrative EDOF topics in Fourier optics,” SPIE Annual Meeting, Tribute to Joseph W. Goodman 75th year. 21-AUG-11.

Number of Presentations: 8.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
10/29/2012	9.00	Nicholas George, Xi Chen, Wanli Chi. Illustrative EDOF topics in Fourier otics, SPIE Annual Meeting, Tribute to Joseph W. Goodman 75th year. 21-AUG-11, . : ,
10/29/2012	10.00	Nicholas George. Design and performance of EDOF digital cameras, OSA Optics and Photonics Congress. 01-JUL-12, . : ,
TOTAL:	**2**	

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper
TOTAL:	

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

1. Wanli Chi, Nicholas George. Optical Element, Device, Method, and Applications, United States Patent Application Publication, Pub. No.: US 2011/0085051 A1, (04 2011).
2. Nicholas George, Xi Chen. Extended depth-of-field lenses and methods for their design, optimization and manufacturing, United States Patent Application Publication, Pub. No.: US 2010/0002310 A1, (01 2010).

Patents Awarded

1. Nicholas George and Wanli Chi, "Extended depth of field using a multi-focal length lens with a controlled range of spherical aberration and a centrally obscured aperture," US Patent 7,336,430 (February 26, 2008).
2. Nicholas George and Wanli Chi, “Apparatus and method for extended depth of field imaging,” US Patent 7,511,895 (March 31, 2009).
3. Nicholas George and Wanli Chi, “Imaging using a multifocal aspheric lens to obtain extended depth of field,” US Patent 7,554,750 (June 30, 2009), rewrite of 922.
4. Nicholas George and Wanli Chi, “Apparatus and method for extended depth of field imaging,” US Patent 7,593,161 (September 22, 2009).

Awards

N/A

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Nien-An Chang	1.00	
Kaiqin Chu	1.00	
FTE Equivalent:	**2.00**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Nien-An Chang	0.20
FTE Equivalent:	**0.20**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Nicholas George	0.40	
Wanli Chi	1.00	
FTE Equivalent:	**1.40**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: .....

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):.....

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:.....

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense .....

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: .....

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Nien-An Chang
Kaiqin Chu
Total Number: 2

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Scientific progress and accomplishments (Descriptioin should include significant theoretical or experimental advances)

(1) Aperture design using a uniformly redundant array: With the completion of the first design, there are now two main issues relative to the topic: Aperture. It is now possible to provide accurate computer simulation of the operation of the camera. Secondly, we are now preparing separate laboratory experiments as well. The details of aperture design are explained in Section 4 of our Optics Communications paper. We start with a bandlimited version of uniformly redundant array at detector plane, and then working it backward to calculate the aperture function using phase retrieval algorithm. The results in the paper indicate the effectiveness of such a designed system in optical imaging. The success of the imaging results is due to perfect cyclic correlation property of the uniformly redundant array (Eq. (8) in the Opt. Comm. paper). No extra noise is introduced in the correlation type processing as opposed to the original Dicke proposal (1968), which uses a random pattern as aperture for X-ray.

(2) Phase retrieval studies to devise a computer simulation model for the lossless aperture that replaces a conventional lens: This software is set up so that specific coded correlation apertures can be design for different cameras. Study of this topic is continuing, especially we are studying a phase retrieval algorithm with multiple intensity pattern constraint.

(3) Fabrication for laboratory tests of the aperture in Fig. 1 included as pdf in Attachments: (i) liquid crystal for first trials and (ii) fabrication using laser writing on photoresist of "refractive" elements as novel technology vs. diamond turning. We have built a laboratory setup with Holoeye liquid crystal as phase screen. The diagram of setup is shown in Fig. 3. In this laboratory model, we use a reflective phase screen so a beam splitter is used to send light to the detector plane. Our experiment shows that this new correlation imaging is a promising concept. We attached a few unpublished experimental data in the report. We also finished a design and fabrication of a new transmissive phase plate. Experimental results can be expected in several months. Presently we are operating with an 8 micron liquid crystal device and a 13 micron detector array. As shown in preliminary data, some artifacts appear. We are now fully understand these artifacts, the major reason is due to this nonmatach of pixel sizes between liquid crystal and detector. We expect a much better result using RPC component in several months. We also studied the depth of field effect as shown in the attached slides.

(4) Color / Multi-wavelength studies: This camera is capable of color imaging with monochrome detector, thus eliminating the need of Beyer's filter array and color cross talk problem. If in the design we choose the thickness of phase screen in a way that RGB patterns at the detector are uncorrelated so that in digital processing, three different patterns are used for correlation processing to recover the corresponding RGB data. An extremely important feature of this camera is that there is virtually no color cross talk. We are presently working on a quantitative value for the cross-talk in a speckle equivalent of the coded aperture screen. We anticipate an exciting improvement over the present RGB Beyer's mask and also over Carver Mead's semiconductor stack. Now that reduction-to-noise has been demonstrated literally, we have filed a patent application for the University crediting ARO-Physics support funding.

(5) Speckle theory and experiments: As mentioned in the Abstract of this report, we have been working on some basic topics in the field of speckle that are related to the development of the phase screen for our novel camera. To broaden the scope of this speckle research, we have set a long-term goal to establish the practicality of imaging through a turbid medium. While excellent prior research over the past twenty years, particularly that of Leith and separately Alfano, has centered on rather dense media (such as chicken breast), it is our plan to start with very dilute turbidity where we are certain of some success. Starting with dilute diffusers, fabricated using speckle thinking, we will develop the digital processing. Then we plan to increase the turbidity, quantitatively, until the image transmission is poor. In this manner, one can establish practical limitations to the image quality that is attainable.

(6) We have completed the first phase of this speckle study. The results are a PhD thesis, an OSA talk, and a forthcoming JOSA paper on the subject of "The Thick Diffuser." The theory provides accurate results for the wavelength de-correlation of speckle in propagation through a thick, dilute diffuser. This diffuser consists of polystyrene spheres embedded in a gelatin. These diffusers will be used as the building blocks in our later, planned imaging experiments. This research is continuing.

(7) Milestones and Schedule for Novel correlation imaging system:

Milestones: T = Theory / E = Experiment	**Start Date**	**Duration**
1. Concept	(T) 12/2008	1 month
2. Math on URA; bandlimited	(T) 12/2008	1 month
3. Phase retrieval for single intensity constraint	(T) 12/2008	6 months; continuing
4. Image processing, study on detection noise effect	(T) 7/2009	3 months
5. Experimental setup using liquid crystal (see figure in Attachment)	(E) 10/2009	3 months; continuing
6. Accurate determination of distance from liquid crystal to detector plane	(E) 10/2009	less than 1 month
7. Experimental study of monchromatic imaging point; letter; pattern; depth of field	(E) 10/2010	continuing
8. Design of transmissive screen	(E) 7/2010	1 month
9. Experiment using RPC fabricated screen	(E) 11/2010	planned 3 months
10. 2^{nd} phase plate design and experiment	(T/E) 1/2011	6 months
11. Specific application: Telescope	(T/E) 7/2011	1 year
12. Field of view and depth of field study	(T/E) 10/2010	continuing
13. Phase retrieval algorithm for multiple intensity constraint	(T) 10/2010	Long term project
14. Color study	(E) 1/2012	Planned
15. Design of phase plate for color imaging	(T/E) 1/2013	
16. Color experiment	(E) 7/2014	

(8) References

Wanli Chi and Nicholas George, “Phase-coded aperture for optical imaging,” Optics Commun. 282, 2110-2117 (2009).

Kaiqin Chu, Nicholas George, and Wanli Chi, “Incoherently combining logarithmic aspheric lenses for extended depth of field,” Appl. Opt. 48, 5371-5379 (2009).

Nien-An Chang, Nicholas George and Wanli Chi, “Wavelength decorrelation of speckle in propagation through a thick diffuser,” under review, Journal of the Optical Society of America.

Nien-An Chang, "Speckle in a Thick DIffuser," PhD Thesis, Advisor: Dr. Nicholas George, University of Rochester, Rochester, NY (2009).

Kaiqin Chu, "Partition Lenses for Extended Depth of Field," PhD Thesis, Advisor: Dr. Nicholas George, University of Rochester, Rochester, NY (2009).

Nicholas George and Wanli Chi, “Emerging electronic imaging systems,” Optical Society of American Annual Meeting (2009). Invited Talk.

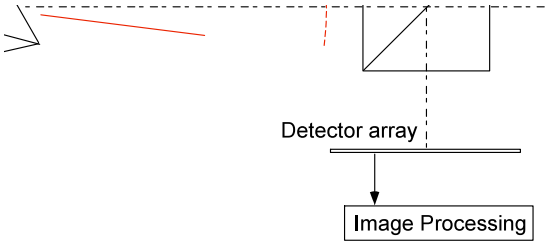
Kaiqin Chu, Nicholas George and Wanli Chi, “Extended depth of field through aperture partitioning,” Optical Society of American Annual Meeting (2009).

Wanli Chi, “Correlation type imaging systems,” National University of Ireland, Galway (2009). Invited Seminar.

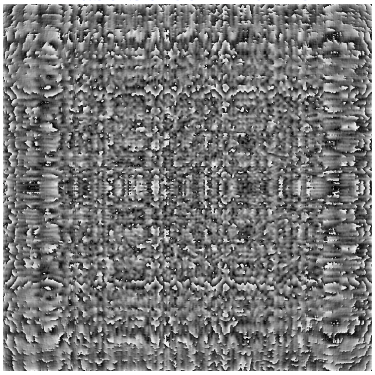
Wanli Chi, “Integrated imaging system for extended depth of field,” National University of Ireland, Galway (2009). Invited Seminar.

(9) Preliminary Experimental Data on Correlation Imaging Using Liquid Crystal Screen

Experimental Setup



Phase Screen Profile



Spatial light modulator

Pixel 8μm; fill factor 85%;

0-2π phase modulation @0.633μm.

Detector Pixel 13 μm.

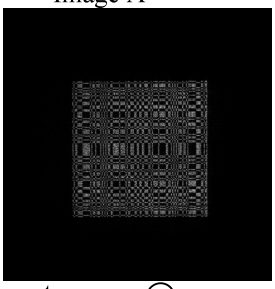
Distances Object to Phase screen 1275mm;

Phase screen to Detector 204.4mm.

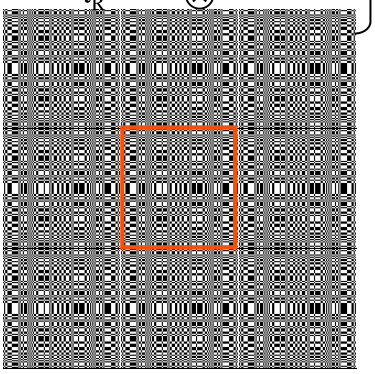
Aperture 5.5mmX5.5mm.

IMAGE AND RECOVERY: Point Source

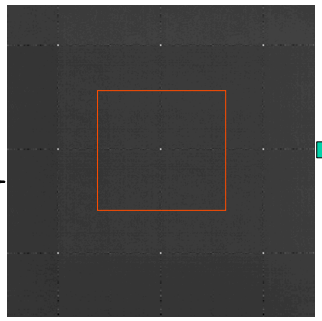
Image A



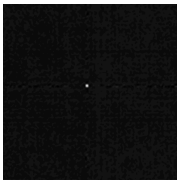
t_R ⊗

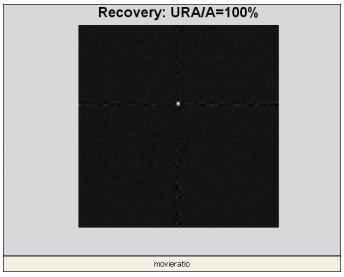


Cross correlation

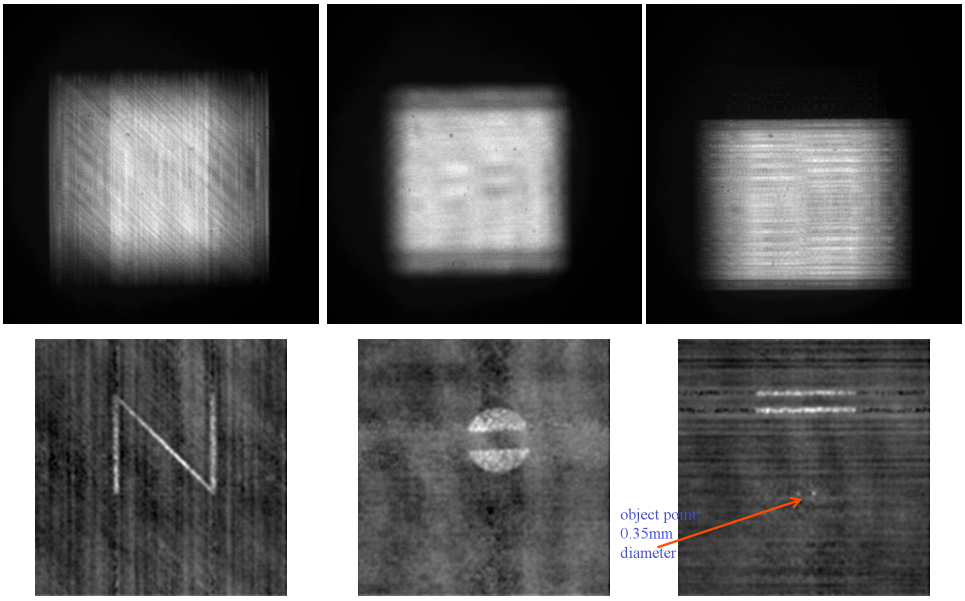


Recovered image is half the size of intermediate image.



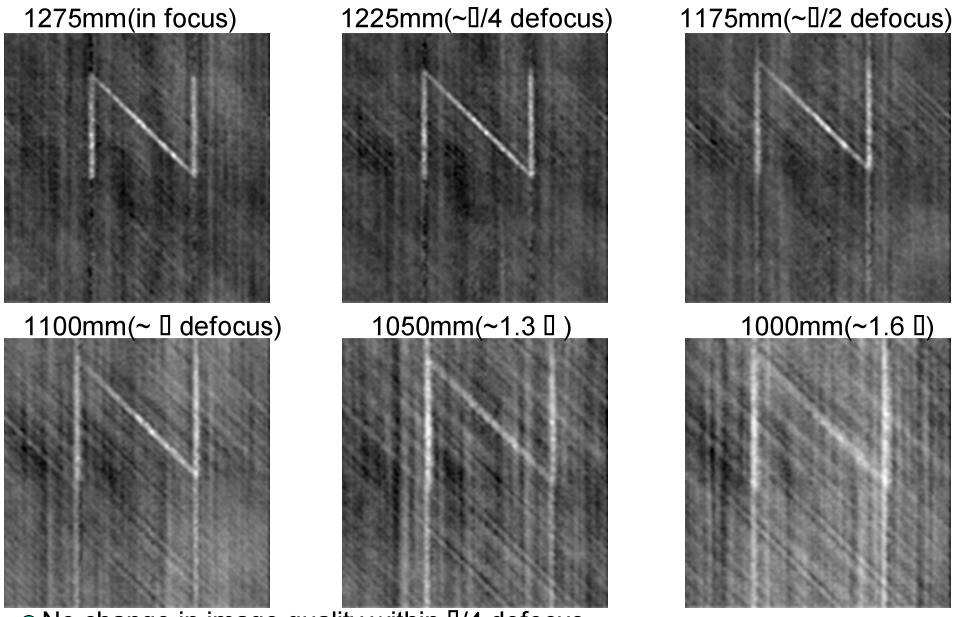


MORE IMAGES AND RECOVERY



Optical imaging is possible with phase coded aperture & correlation processing.

DEPTH OF FIELD STUDY

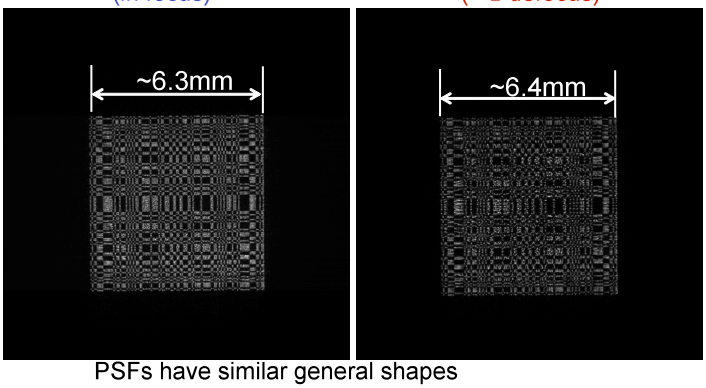


- No change in image quality within λ/4 defocus.
- Different defocus blur compared to conventional lens imaging.

DEFOCUS EFFECTS for PSF

PSF Point@1275mm
(in focus)

PSF Point@1100mm
(~ □ defocus)



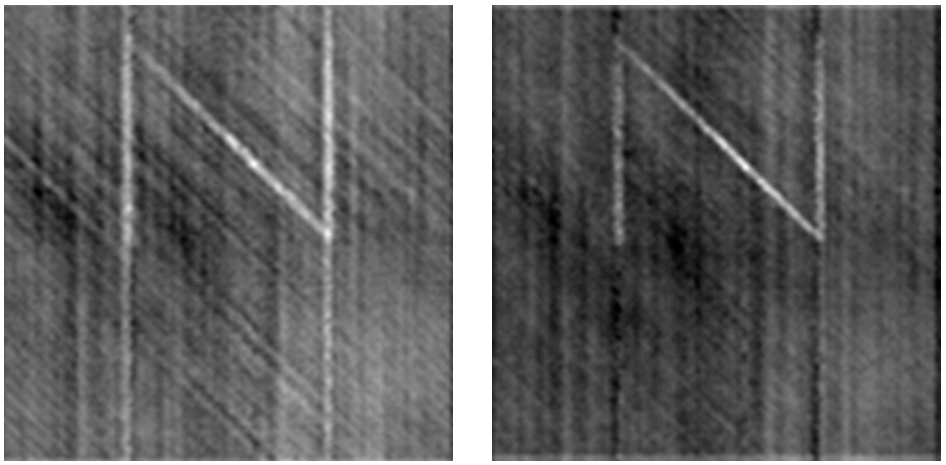
PSFs have similar general shapes

BUT: 1. fine details change at defocused position
2. scale different (bigger PSF for closer point source)

RECOVERY USING SCALED URA PATTERNS (N @1100mm)

Scaled URA has the size of ~6.3mm

Scaled URA has the same size as PSF@1100mm (~6.4mm).



Cause of line artifact: PSF size ≠ URA size
Appropriate scaling or re-sampling of URA is important in recovery.