# REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188



| 1. REPORT DATE (DD-MM-YYYY) | 2. REPORT TYPE | 3. DATES COVERED (From - To) |
|---|---|---|
| 03-04-2008 | Technical Report | 15-Aug-2006 - 14-Feb-2008 |

4. TITLE AND SUBTITLE
Image Science Research for Speckle-based LADAR (Speckle Research for 3D Imaging LADAR)

5a. CONTRACT NUMBER
W911NF-06-1-0371

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Nicholas George, PI

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Rochester
Office of Research & Project Administration
518 Hylan Bldg., River Campus Box 270140
Rochester, NY 14627 -

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
50480-PH.8

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
We propose a basic study of image science topics related to a new class of speckle-based laser-ranging radars (LADAR). For this imaging radar, we study two basic system configurations: a wavefront sensing configuration and an imaging configuration. Three major research projects are (1) study of speckle patterns to establish 3D qualitative features for a remote object, (2) study of performance of this compact ladar at photon counting light levels, and (3) space and wavelength dependence of speckle for a thick diffuser. A balanced research program of theory, computer simulations, and laboratory experiments is planned. These will feature low light level speckle studies with tunable/ multi-tone lasers. For the first area of

15. SUBJECT TERMS
Image Science; Speckle; Low photon level; LADAR; wavelength dependence; thick diffuser; Infrared hologram

| 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 |
| U | U | U | SAR | | 19b. TELEPHONE NUMBER<br>585-275-2417 |

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

## Report Title

Image Science Research for Speckle-based LADAR (Speckle Research for 3D Imaging LADAR)

## ABSTRACT

We propose a basic study of image science topics related to a new class of speckle-based laser-ranging radars (LADAR). For this imaging radar, we study two basic system configurations: a wavefront sensing configuration and an imaging configuration. Three major research projects are (1) study of speckle patterns to establish 3D qualitative features for a remote object, (2) study of performance of this compact ladar at photon counting light levels, and (3) space and wavelength dependence of speckle for a thick diffuser. A balanced research program of theory, computer simulations, and laboratory experiments is planned. These will feature low light level speckle studies with tunable/ multi-tone lasers. For the first area of study, we develop a new thick diffuser for studies of turbidity and imaging. The diffuser consists of three to five different polysterene spheres emmersed in agar. Additionally we have published a paper describing the first infrared hologram at 10.6 microns. It is expected to be useful for examination of silicon boules. In this study we will employ machine vision techniques and neural networks to ascertain the minimum number of photons that are required to set the boundaries or shape contours of a speckle. The study of space and wavelength dependence of speckle for a thick diffuser is important for assessing LADAR system performance in the presence of fog or smoke in the atmosphere. We seek to establish the capacity for these LADARS to see through turbulences and turbidity. Major objectives of this research are to contribute to the understanding of speckle phenomena and the feasibility of remote object classification using novel 3D-imaging means.

---

## List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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

1. Nicholas George, Kedar Khare, Wanli Chi, "Infrared holography using a microbolometer array," Applied Optics, 47, A7-A12 (2008).
2. Nien-an Chang and Nicholas George, "Speckle in the 4F optical system," Applied Optics, 47, A13-20 (2008).
3. Kedar Khare, “Sampling theorem, bandlimited integral kernels and inverse problems,” Inverse Problems 23, 1395-1416 (2007).
4. Kaiqin Chu and Nicholas George, “Correlation function for speckle size in the right-half-space,” Optics Commun. 276, 1-7 (2007).
5. Weizhen Yan, Sizing and classification of biological particles using ring-wedge detector and neural networks, Phd thesis, University of Rochester (2007).
6. Xi Chen, Gradient Fiber Array for Imaging, PhD thesis University of Rochester (1/2007).
7. Kedar Khare, "Bandpass sampling and bandpass analogures of prolate spheroidal functions," Signal Processing 86, 1550 (2006).

**Number of Papers published in peer-reviewed journals:** 7.00

---

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

Nicholas George, Kedar Khare, Wanli Chi, "Electronic holography at terrahertz and infrared frequencies," Proc. of 7th International Symp. on display holography (Wales), 117-119 (2006).

**Number of Papers published in non peer-reviewed journals:** 1.00

---

### (c) Presentations

1. Nien-An Chang, "Speckle in 4-f system," University of Rochester Industrial associate meeting (2008).
2. Nicholas George, Wanli Chi, Joel Bentley, and Kedar Khare, "Infrared holography at 10.6 microns using microbolometer array," ICO20 Capri (2007).
3. Wanli Chi and Nicholas George, "LED illumination design with a condensing sphere," OSA annual meeting, Rochester NY (2006).
4. Xi Chen and Nicholas George, "Resolution analysis of GRIN array imaging system," OSA annual meeting, Rochester NY (2006).
5. Kaiqin Chu and Nicholas George, "Speckle in the right half space," OSA
annual meeting, Rochester NY (2006).
6. Nien-an Chang and Nicholas George, "Speckle in 4-f system," OSA annual meeting, Rochester NY (2006).

**Number of Presentations:** 6.00

---

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

See Presentation section.

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):** 6

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

Invited talk at ICO20 meeting in Capri 2007 and invited talk at Symp. 7th international Symp. on holographic display (2006).

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):** 2

## (d) Manuscripts

1. Kaiqin Chu, Nicholas George, "Lensless electronic imaging under incoherent illumination," (to be submitted to Applied Optics).

2. Kaiqin Chu, Wanli Chi, Nicholas George, "Extended depth of field by 2:1 through polarization coded aperture," (to be submitted to Applied Optics).

3. Kaiqin Chu, Wanli Chi and Nicholas George, "Extended depth of field through unbalanced OPD," (to be submitted to Applied Optics).

4. Xi Chen and Nicholas George, "Aberration analysis of GRIN array imaging," (to be submitted to Applied Optics).

**Number of Manuscripts:** 4.00

**Number of Inventions:**

### Graduate Students

| NAME | PERCENT_SUPPORTED |
|---|---|
| Xi Chen | 0.30 |
| Weizhen Yan | 0.30 |
| Alice Chang | 0.50 |
| Kaiqin Chu | 0.50 |
| Joel Bentley | 0.50 |
| **FTE Equivalent:** | **2.10** |
| **Total Number:** | **5** |

### Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Wanli Chi | 0.25 |
| **FTE Equivalent:** | **0.25** |
| **Total Number:** | **1** |

### Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Nicholas George | 0.10 | No |
| **FTE Equivalent:** | **0.10** | |
| **Total Number:** | **1** | |

### 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: ...... | 0.00 |
| The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... | 0.00 |
| 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:...... | 0.00 |
| Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... | 0.00 |
| Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... | 0.00 |
| The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... | 0.00 |
| 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:...... | 0.00 |

## Names of Personnel receiving masters degrees

NAME

**Total Number:**

## Names of personnel receiving PHDs

NAME
Xi Chen
Weizhen Yan

**Total Number:** **2**

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|---|---|

**FTE Equivalent:**
**Total Number:**

## Sub Contractors (DD882)

## Inventions (DD882)

5 **Illumination with condensing sphere**

Patent Filed in US? (5d-1) N

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Wanli Chi and Nicholas George

5f-1a: University of Rochester

5f-c: 275 Hutchison Rd

Rochester NY 14627

## Technology Transfer

1. The PI participated in a visit to the Photnics Center at West Point for the purpose of reviewing their research program. In addition, he is discussing some research topics in speckle – LADAR with the Academy faculty. This is a continuing effort by the PI.

2. Both PI and Dr. Wanli Chi are actively pursuing industrial interactions with a number of companies including Hand Held Products, inc./ Minneapolis HoneyWell, and Micron inc.

## Summary of important results

1. During the past year, Micron inc. has started a major preproduction development of the logarithmic aspherical lens invented under ARO sponsorship. This development is planned to lead to major mass production starting at 1 million cell phone cameras per month and if it is successful ramping up production by 4 fold. This effort has received important technology transfer by the PI and Micron has also hired 5 graduates from U of R and RIT to staff the development. This important result is explained in detail in the attached pdf file that contains visuals.

2. A particularly significant accomplishment during the past 9 months has been the discovery by Wanli Chi of a novel new camera system that has particular application to DoD and to remote sensing. It is based on an adaptation of a concept used in X-rays and originally proposed by Princeton's R. H. Dicke. This system is in a formative state at present. It has not yet been reduced to a practical system. Each component piece of the Dicke-Chi camera is being tested or designed for later reduction to practice. This novel system is described in the attached pdf file below.

3. The field correlation of radiation of radiation from thin diffuser is studied over the whole right half hemisphere. The formulas for the speckle size are valid for nonparaxial whole half hemisphere.

4. A comprehensive review paper in which we describe speckle in the 4F optical system is published in the Applied Optics issue dedicated to Professor Emmett N. Leith. Many phenomena about speckle are explained in an accurate elegant manner by the choice of this optical system. The troublesome quadratic phase factors associated with Fresnel zone propagation are eliminated in the imaging and transform regimes. Both space and wavelength dependence are included.

5. We have developed a really practical hologram system for the 10 micron infrared wavelength. The heart of the system is the use of a microbolometer array for recording the hologram. We believe this technology will have many practical application in production of metal parts and silicon fabrication.

6. A novel approach based on sampling theorem for studying eigenvalue problems associated with bandlimited integral kernels of convolution type is studied in detail and published by Kedar Khare in the respected mathematics journal called inverse problems. Dr. Khare has accepted a position as a senior imaging scientist at the famous General Electric Research Laboratory in New York.

# INTEGRATED COMPUTATIONAL IMAGING SYSTEM FOR EXTENDED DEPTH OF FIELD:

## THE LOGARITHMIC ASPHERE +

NICHOLAS GEORGE
WANLI CHI

THE INSTITUTE OF OPTICS
UNIVERSITY OF ROCHESTER

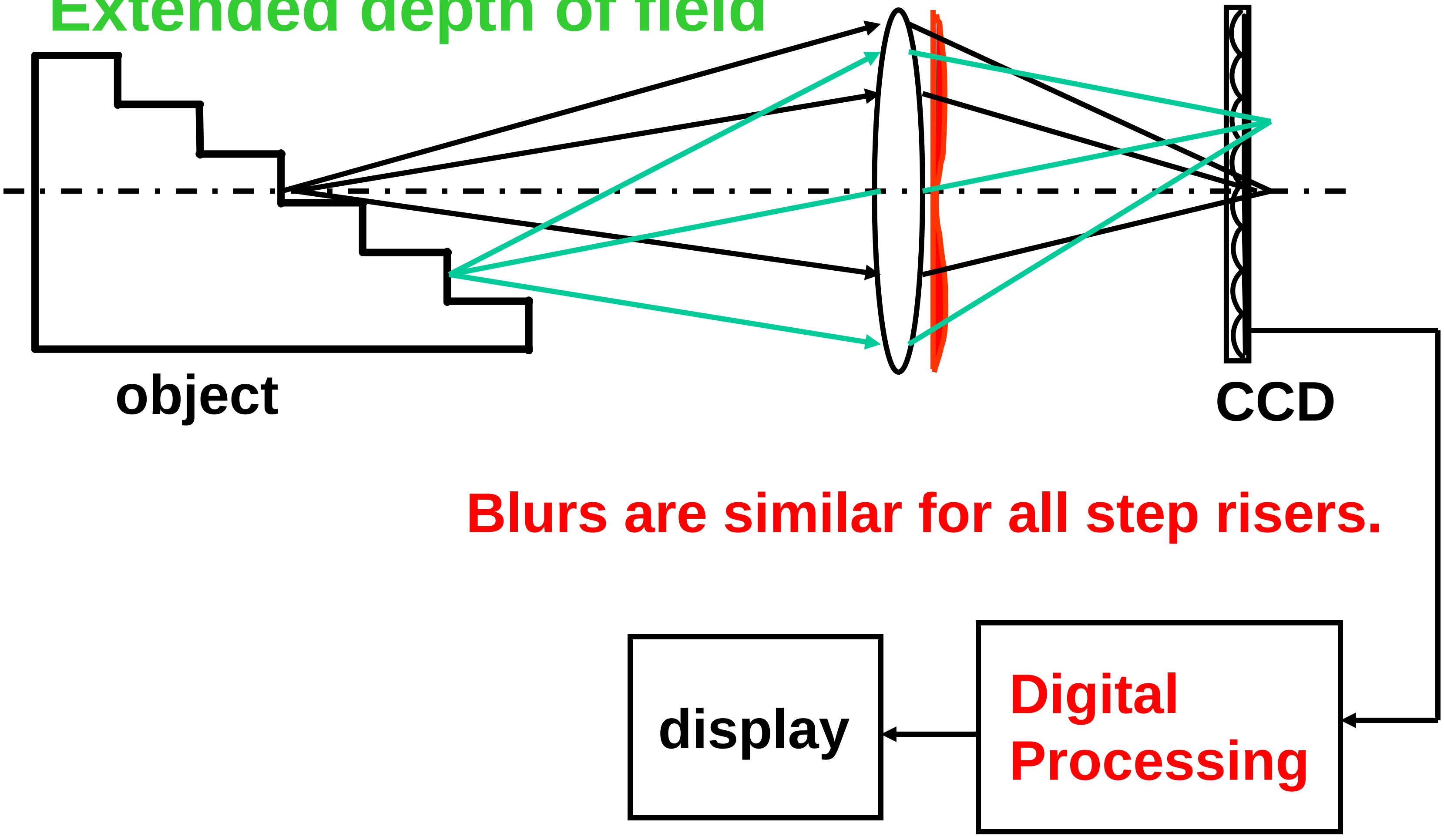
March 2008

+ RESEARCH SUPPORTED BY ARO (PHYSICS – R. HAMMOND)

# INTEGRATED COMPUTATIONAL IMAGING SYSTEM: CONCEPT



## Extended depth of field

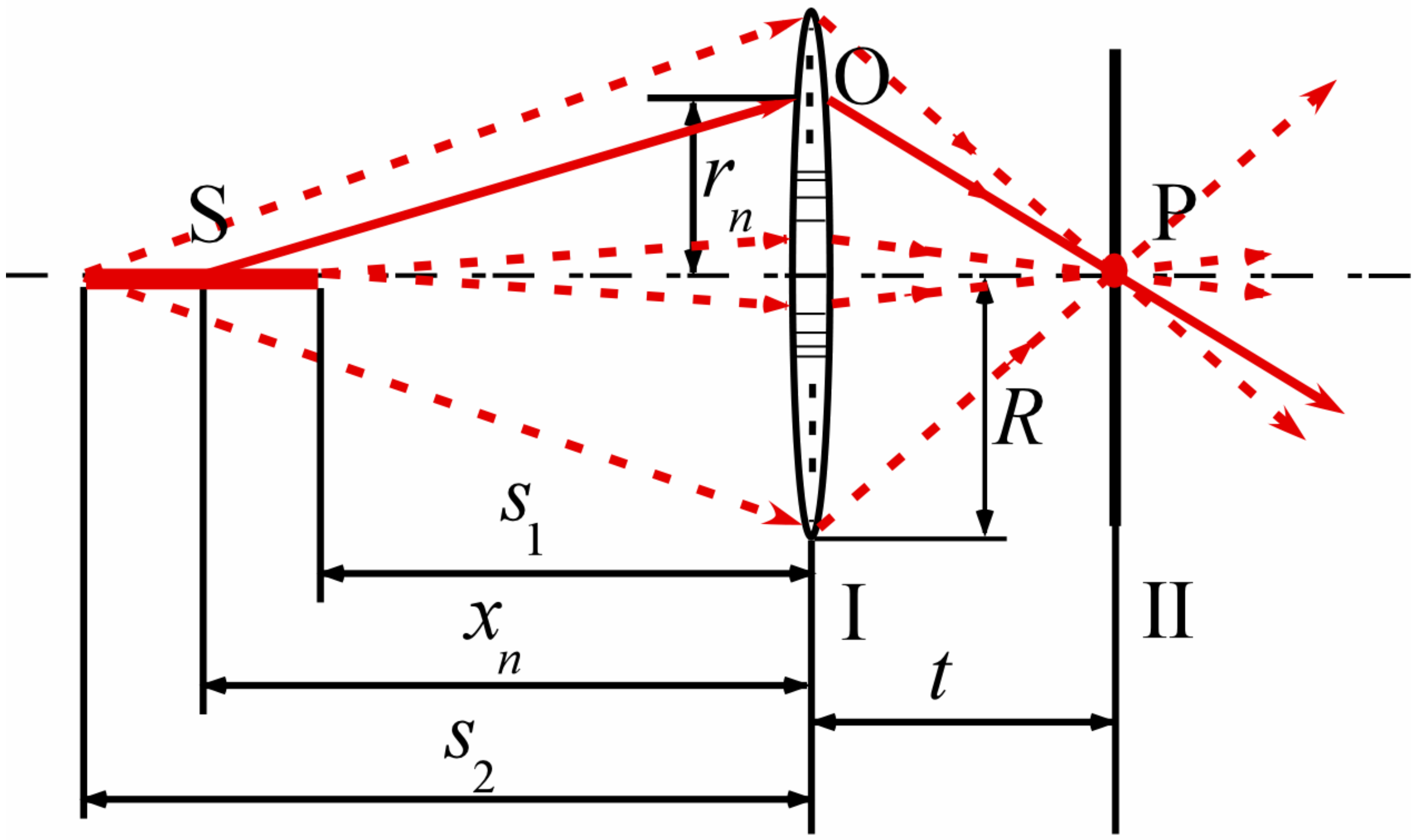



**Concept explained by Dr George in our group meeting, 1999**

# NEXT STEP: logarithmic asphere ($\alpha$ lens)



- PHYSICAL CONCEPT-FERMAT'S PRINCIPLE




- PHASE TRANSMISSION

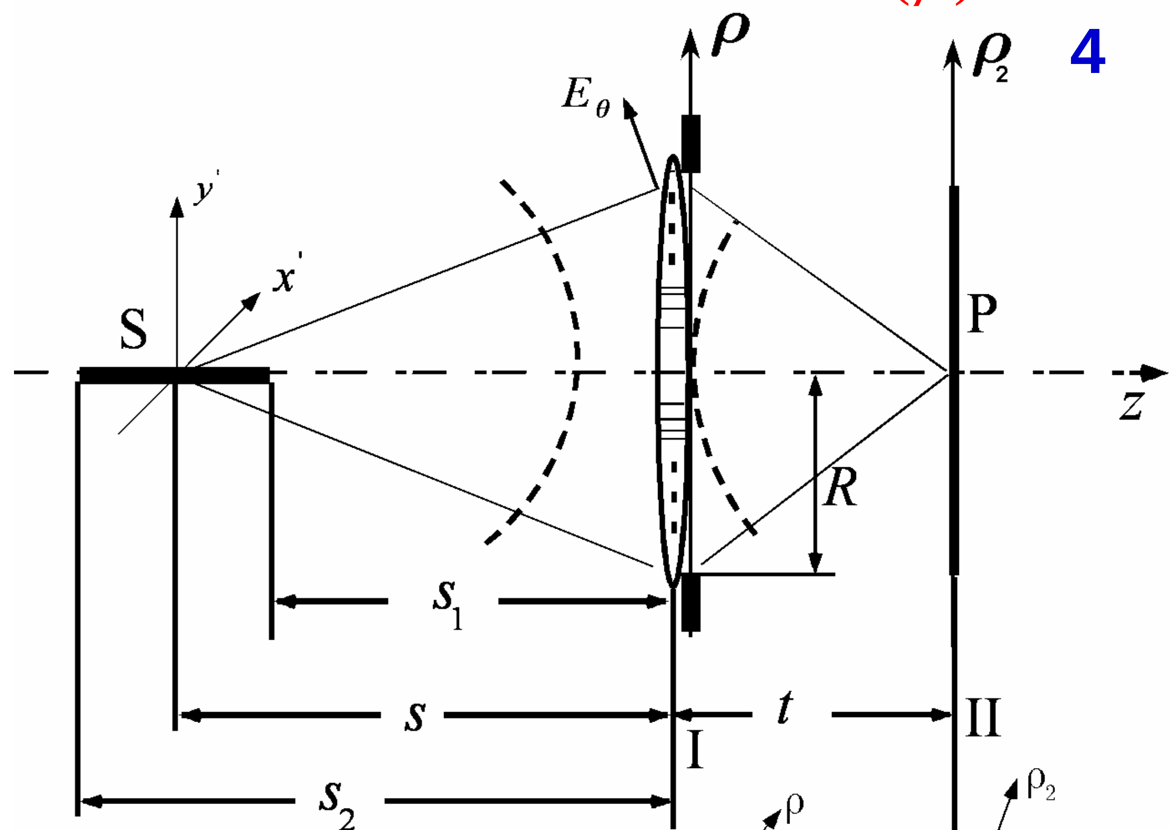
$$\phi(r) = -\frac{2\pi}{\lambda_0}\int_0^r \{\frac{r}{\sqrt{r^2+t^2}} + \frac{r}{\sqrt{r^2+[s_1+(s_2-s_1)r^2/R^2]^2}}\}dr$$

CHI AND GEORGE, OPTICS LETTERS 26, 875 (2001).

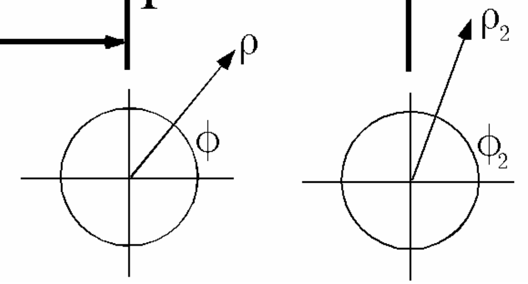
# GENERALIZED THEORY FOR THE LOGARITHMIC ASPHERE $t(\rho)=e^{-i\phi(\rho)}$

## IMPULSE RESPONSE (PSF)

4



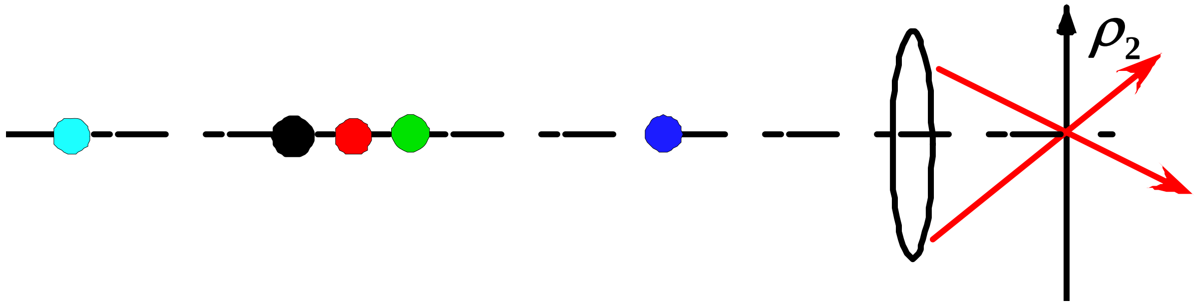

$$I(\rho_2;s)=\left|\int_{\delta R}^{R}\rho d\rho\int_0^{2\pi}d\phi\frac{i}{\lambda_0}\frac{A}{\sqrt{\rho^2+s^2}}\frac{i}{\lambda_0}\frac{t}{[(\rho\cos\phi-\rho_2\cos\phi_2)^2+(\rho\sin\phi-\rho_2\sin\phi_2)^2+t^2]^{1/2}}\right.$$
$$\left.e^{-i\frac{2\pi}{\lambda_0}\sqrt{\rho^2+s^2}}e^{-i\phi(\rho)}e^{-i\frac{2\pi}{\lambda_0}\sqrt{(\rho\cos\phi-\rho_2\cos\phi_2)^2+(\rho\sin\phi-\rho_2\sin\phi_2)^2+t^2}}\right|^2$$

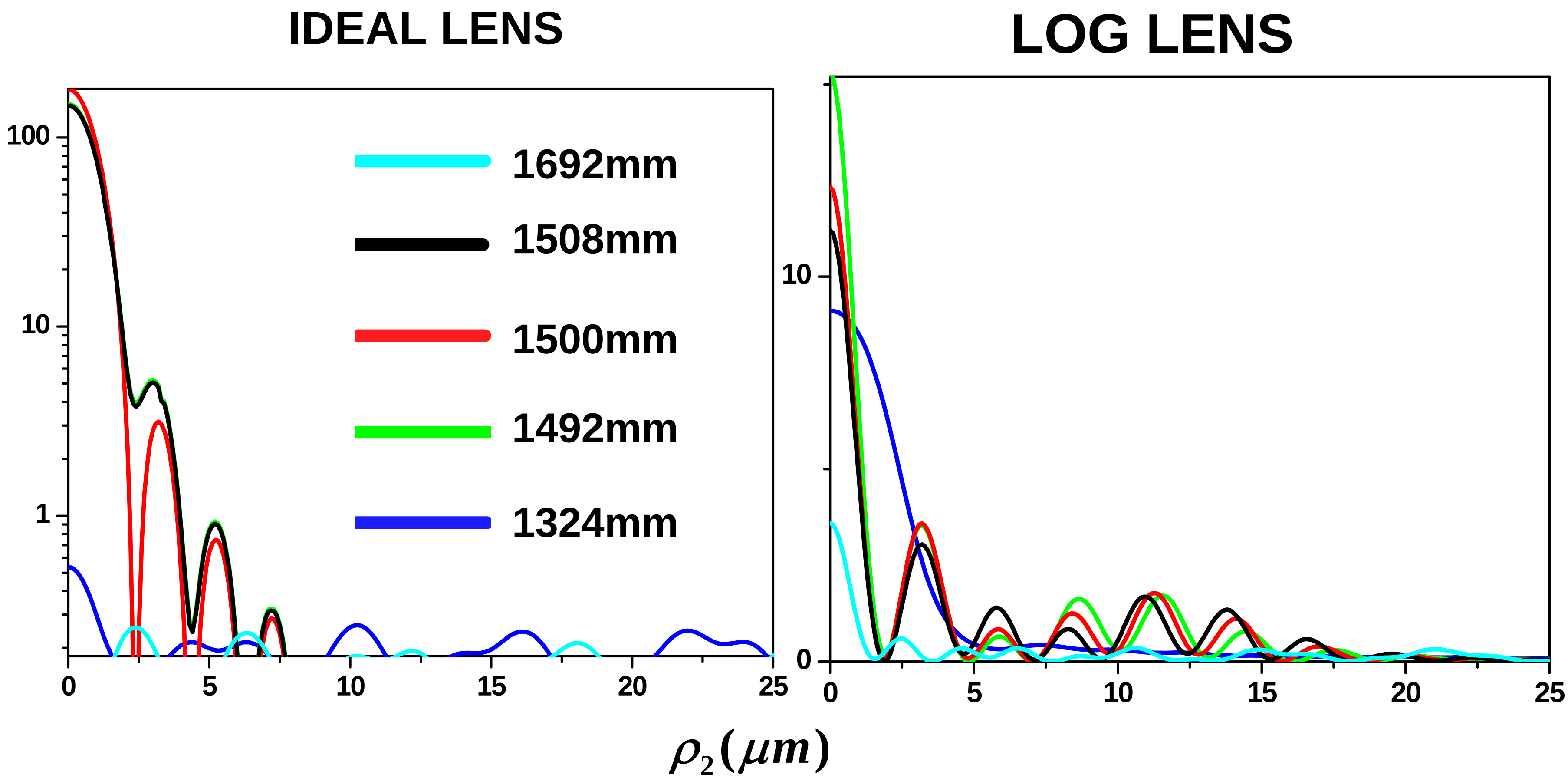



$$I(\rho_2;s)\simeq\left|\int_0^R d\rho 2\pi\rho J_0\left(\frac{2\pi\rho\rho_2}{\lambda_0\sqrt{t^2+\rho^2}}\right)\frac{e^{-i\frac{2\pi}{\lambda_0}\sqrt{s^2+\rho^2}-i\phi(\rho)-i\frac{2\pi}{\lambda_0}\sqrt{t^2+\rho^2}}}{\sqrt{s^2+\rho^2}\sqrt{t^2+\rho^2}}\right|^2$$

# POINT SPREAD FUNCTIONS FOR VARIOUS OBJECT POINTS





# COMPARISON OF MAXIMUM ENTROPY METHODS †

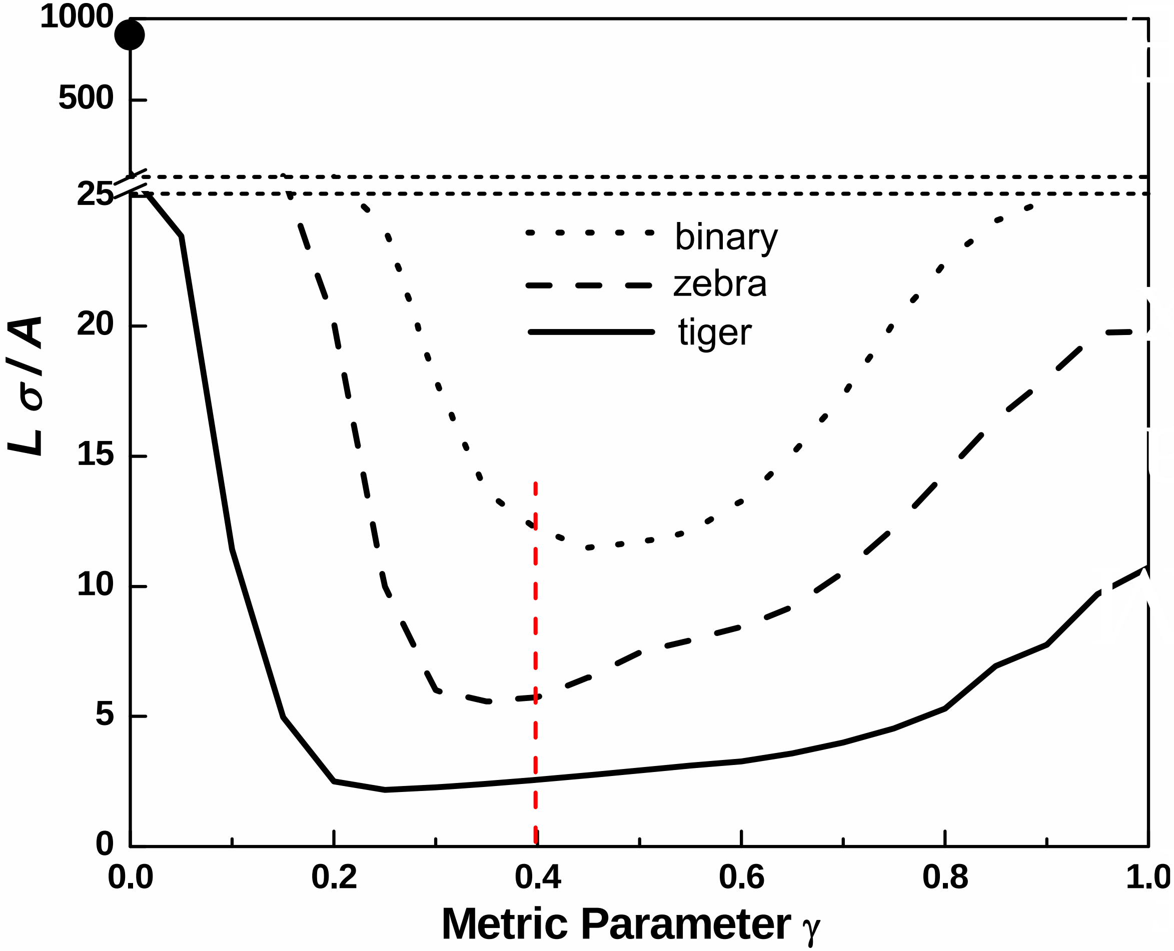


*L* **Loops needed**

*σ* **Noise deviation**

*A* **Area of PSF**

*γ* **New parameter**



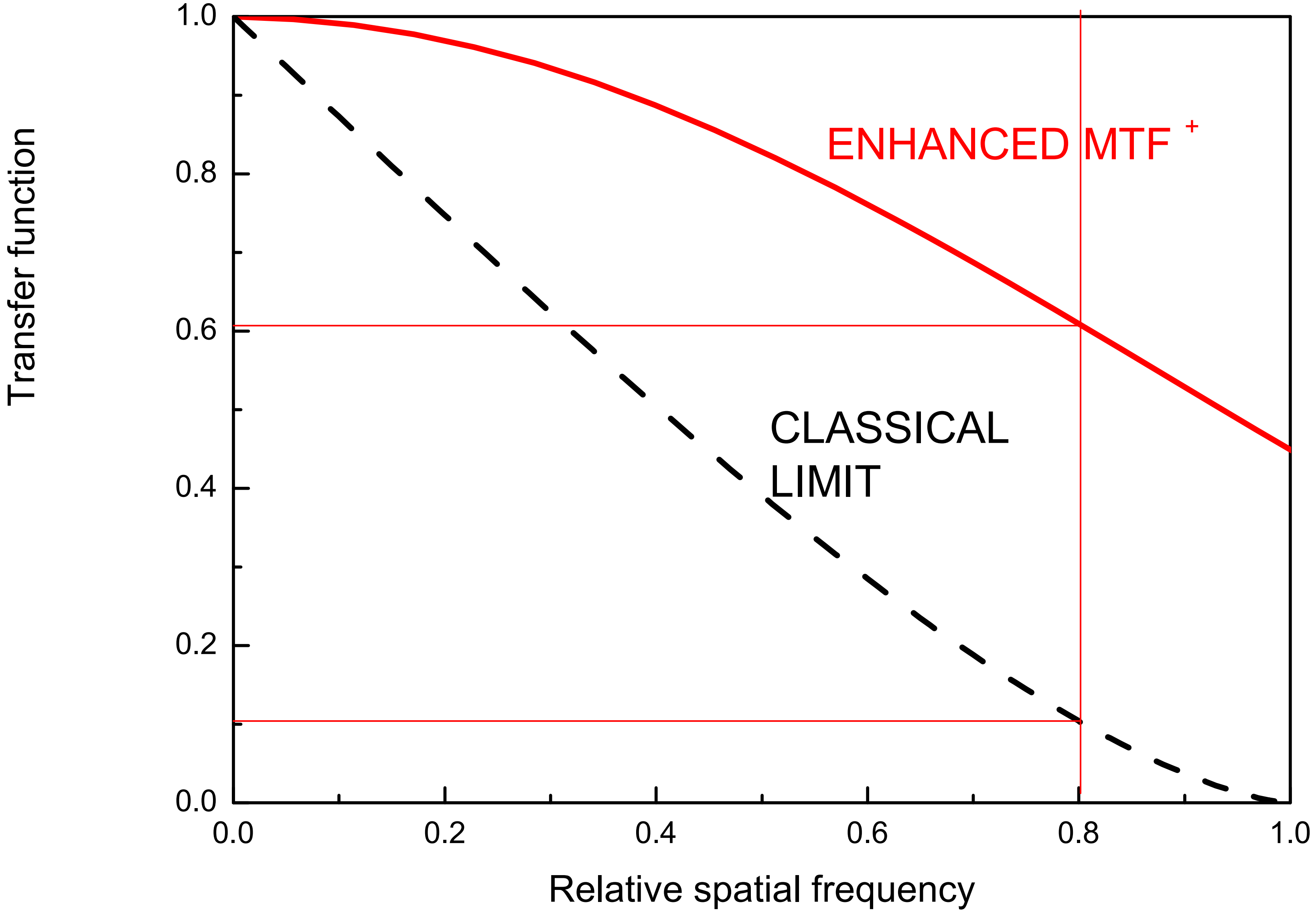

γ=0, steepest ascent;

γ=1, Burch, Skilling, Gull;

† W. CHI AND N. GEORGE, JOSA (2003).

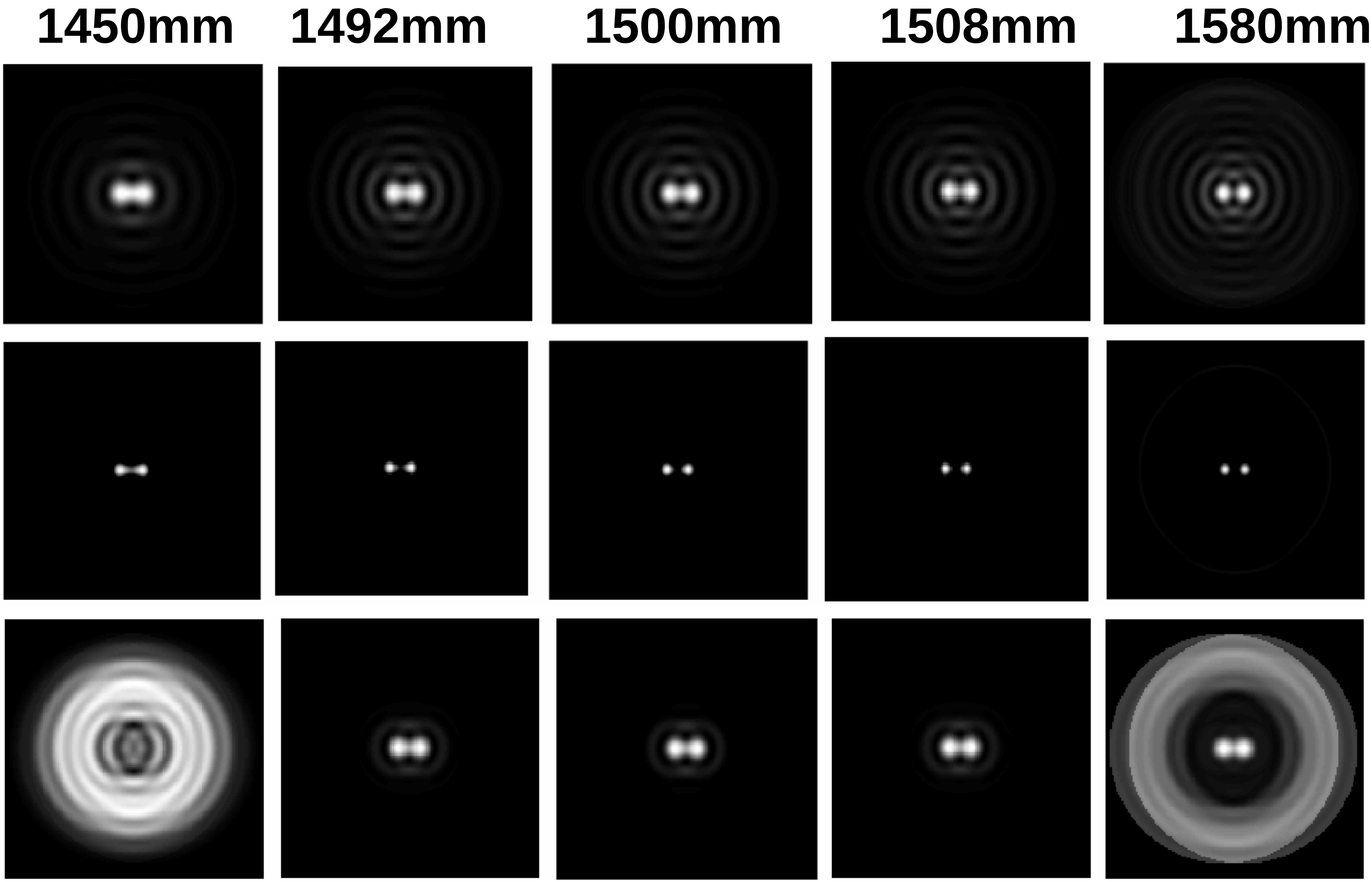
# OVERALL TRANSFER FUNCTION: Optics+Digital






**+ NEW DISCOVERY IMPORTANT FOR INFRARED IMAGING**

# M.E. Recovery of a Two-Point Object




## Diffraction Limited Performance

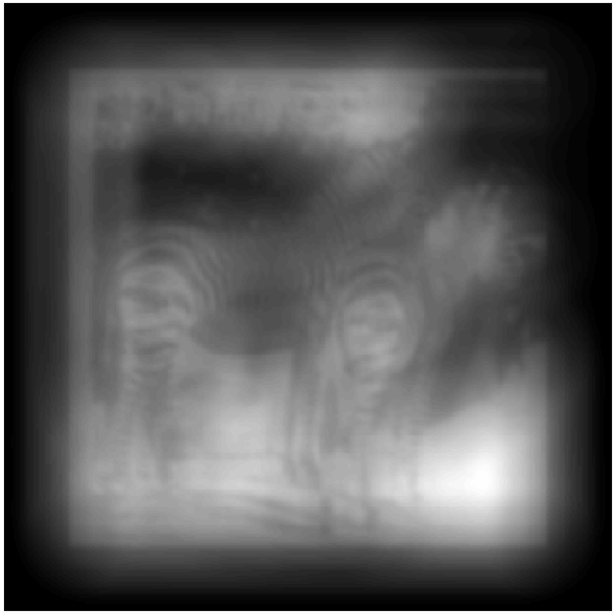
## 8 x EXTENDED DEPTH OF FIELD

# M.E. Recovery of a Picture Blurred by Log Lens

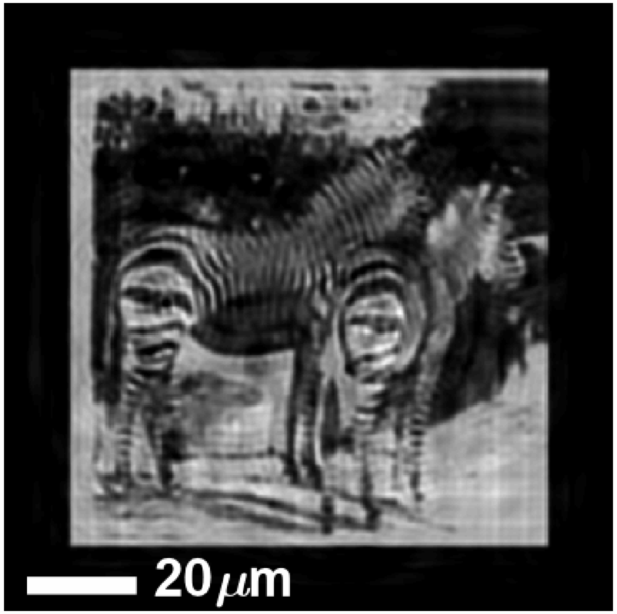
## Object distance at 1580mm

**(Best focus plane at 1500mm)**

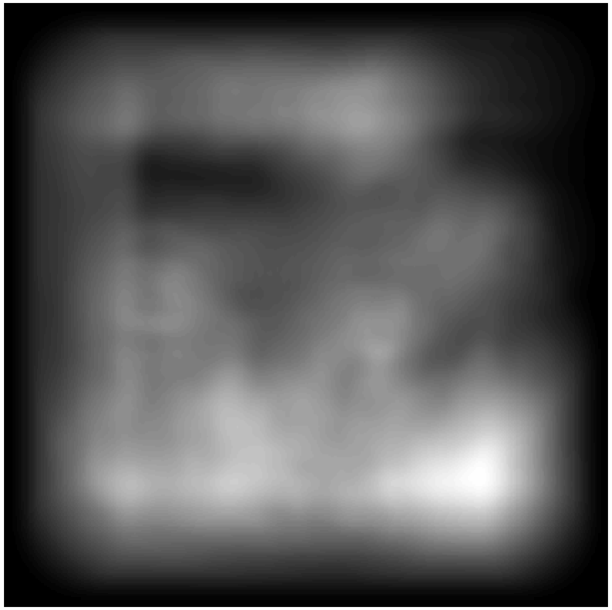
**Blur by Log lens**



**Recovery**




**Blur by ideal lens**



Chi and George, JOSA 2003.

# EXTENDED DEPTH OF FIELD
# MAJOR FINDINGS UNDER ARO SPONSORSHIP

| TOPIC | MAJOR RESULTS |
| --- | --- |
| EXTENDED DEPTH OF FIELD | 8 TO 10x CLASSICAL LIMIT (Pat 1) |
| MAXIMUM ENTROPY – METRIC PARAMETER FORM | PROVIDES SUPERIOR IMAGE RECOVERY (Patent 2)<br>. THE RINGING IS LOW<br>. THE MTF IS BETTER THAN THE CLASSICAL LIMIT<br>. INFRARED TELESCOPE |

CONSTRAST ENHANCEMENT OF INFRARED IMAGERY IS SUPERIOR THIS FACT NEEDS TO BE COUPLED TO NIGHT VISION LAB AND TO HOMELAND SECURITY

# TECHNOLOGY TRANSFER EDoF PROJECT SUMMARY 

APPLICATION

STARTUP CORPORATIONS

GG & C / CMPS, INC.

INFRARED TELESCOPE STTR & HARDENED BOILER ENVIRONMENT

PATENTS: 2 GRANTED, 2 PENDING

(U.S. Pat. Nos. 6927922 B2; 7336430 B2)

---

MAJOR INDUSTRIAL PARTICIPANTS

- HANDHELD PRODUCTS, INC

  DIVISION OF MINNEAPOLIS/HONEYWELL

BARCODE SCANNER

- MICRON IMAGING CORPORATION

CELLPHONE CAMERA

# UNCONVENTIONAL INTEGRATED IMAGING AND COMPUTING SYSTEMS

**NICHOLAS GEORGE, ngeorge@troi.cc.rochester.edu**
**Wilson Professor of Electronic Imaging**

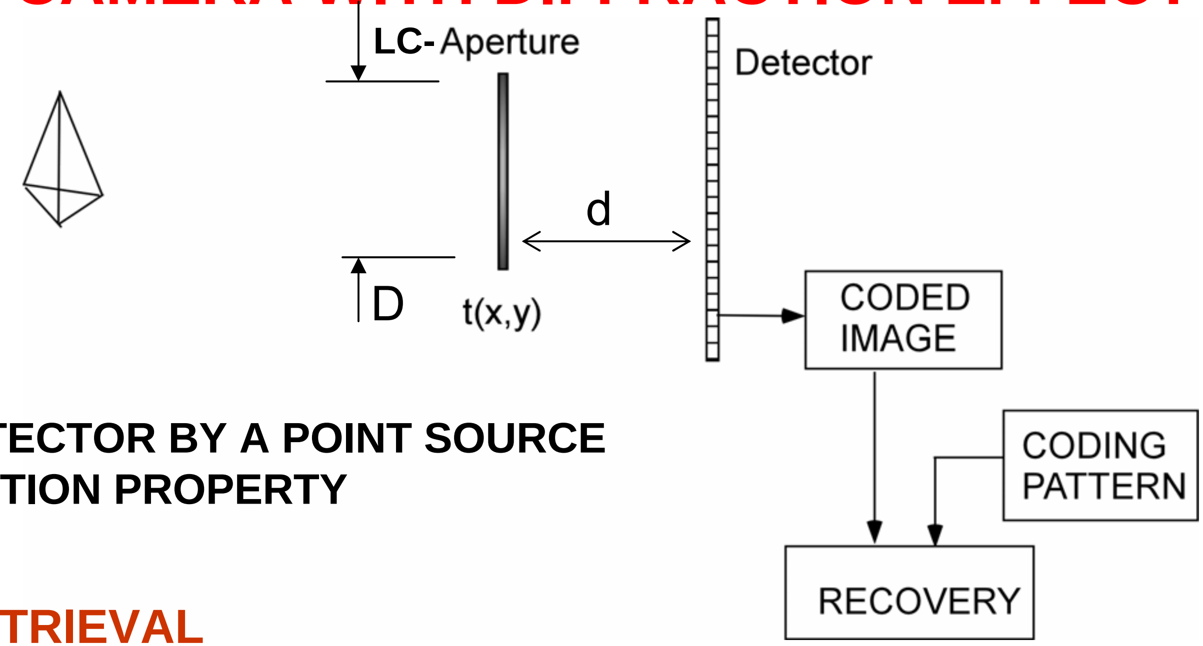
**WANLI CHI, chiw@optics.rochster.edu**
**Assistant Professor of Optics (Research)**

**THE INSTITUTE OF OPTICS**
**UNIVERSITY OF ROCHESTER**

**March 2008**

**Prepublication Data**
**Research Supported by ARO (Physics --- R. Hammond)**

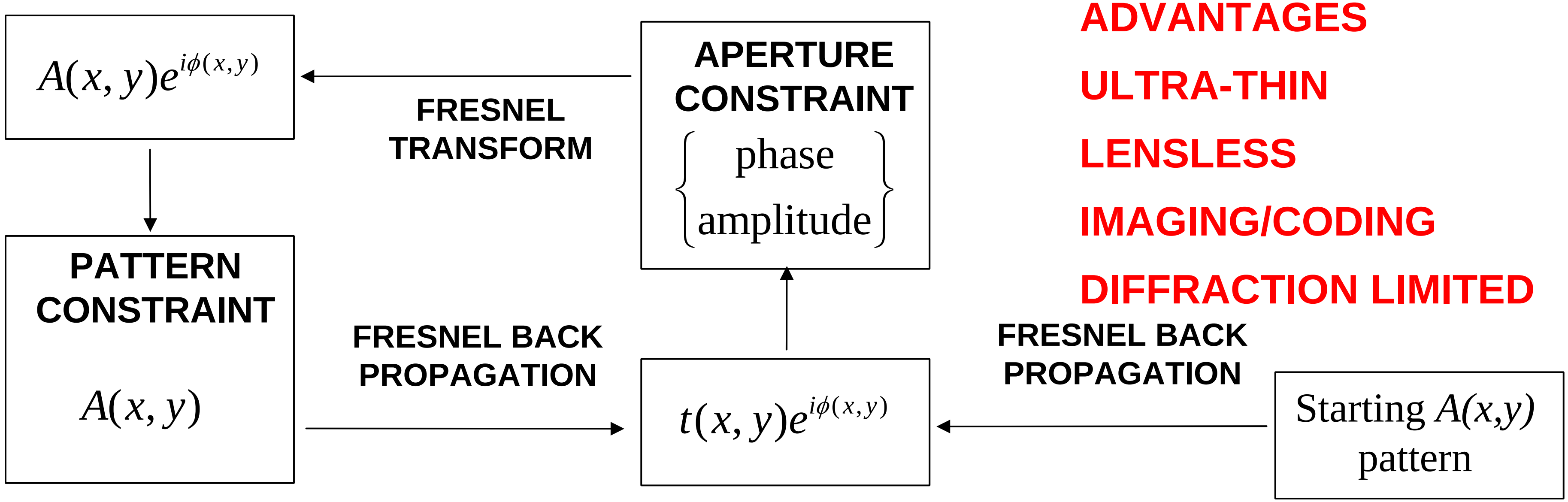
# MODIFIED DICKE CAMERA WITH DIFFRACTION EFFECT




## APERTURE REQUIREMENT

**PATTERN GENERATED ON DETECTOR BY A POINT SOURCE HAS OPTIMUM AUTOCORRELATION PROPERTY**

## t(x,y) calculation:
## FRESNEL ZONE PHASE RETRIEVAL




## ADVANTAGES

**ULTRA-THIN**

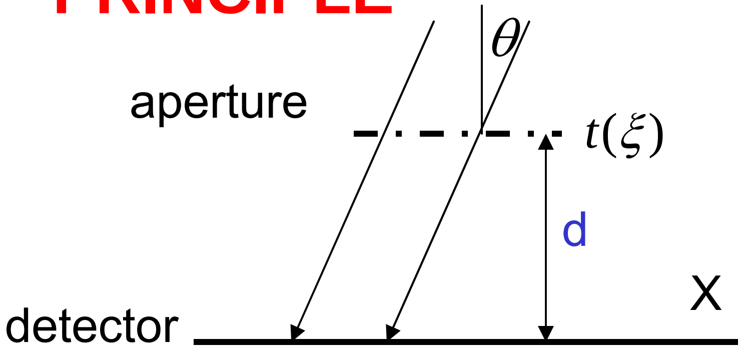
**LENSLESS**

**IMAGING/CODING**

**DIFFRACTION LIMITED**

# DICKE CAMERA

## PRINCIPLE




- **IMAGING**

$$I(x) = \int O(\xi/d) \cdot t(x-\xi) d\xi$$

- **PROCESSING**

$$\hat{O}(-x/d) = \int t(x') \cdot I(x'-x) dx'$$

$$= \int \left[ \int t(x') \cdot t(x'-x-\xi) dx' \right] O(\xi/d) d\xi$$

- **APERTURE, "RANDOM" PINHOLE**

$$\int t(x') \cdot t(x'-x-\xi) dx' = \delta(x+\xi) + \ldots$$

$$\hat{O}(-x/d) \rightarrow O(-x/d) + \ldots$$

## RESEARCH AREAS

- **APERTURE DESIGN**

  **(PERFECT δ AUTOCORRELATION FUNCTION IS OPTIMUM)**

  - **FRESNEL ZONE PLATE**

    **MERTZ AND YOUNG**

  - **SCATTER-HOLE ARRAY**

    **DICKE**

  - **UNIFORM REDUNDANT ARRAY**

    **FENIMORE AND CANNON**

  - **PHASE RETRIEVAL (DIFFRACTION)**

    **CHI AND GEORGE**

- **PROCESSING (OPTICAL & DIGITAL)**

  - **CROSS CORRELATION**
  - **PHOTON TAGGING (BACK PROJECTION)**
  - **LINEAR FILTER**
  - **MAXIMUM ENTROPY**
  - **ITERATIVE REMOVAL OF SOURCES**

# APERTURE DESIGN (CYCLIC DIFFERENCE SET)

$\{a_1, a_2, \cdots, a_s\}$ is CDS if $0 \le a_1 < n$

Either case i) all $\boxed{(a_i - a_j)\cdot \bmod n}$ are different for $i \ne j$

or case ii) for any $\boxed{m \cdot \bmod n}$ there are $z$ pairs $\{a_i, a_j\}$, $(m = a_i - a_j)$

**EXAMPLE:** i) $\{0, \quad 5, \quad 6, \quad 9, \quad 19\}$ $\quad n = 21$

ii) $\{0, \quad 1, \quad 2, \quad 4\}$ $\quad n = 7, \quad z = 2$

$\quad a_1 \quad a_2 \quad a_3 \quad a_4$

Ex. $m \cdot \bmod n = 5$, the pairs are $\{0,2\}$ $\{2,4\}$

$\cdots \quad = 1, \quad \cdots \quad \cdots \quad \{1,0\}$ $\{2,1\}$

$\vdots \qquad \vdots \qquad \vdots$

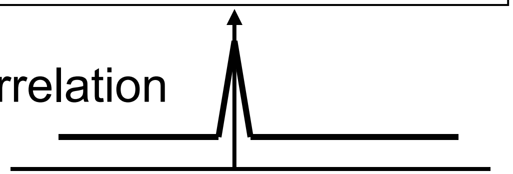
Mask from ii)

| 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 1 | 0 | 0 |

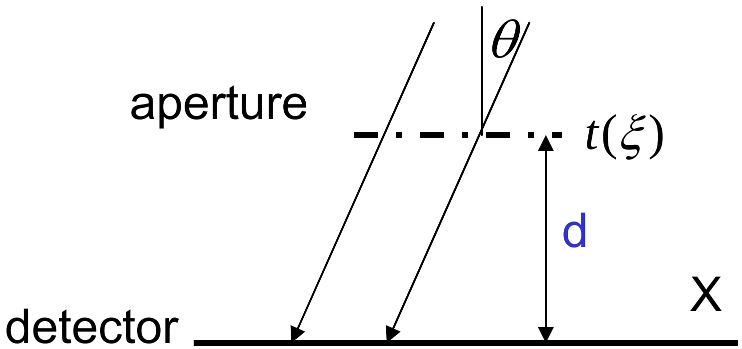
from i)

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

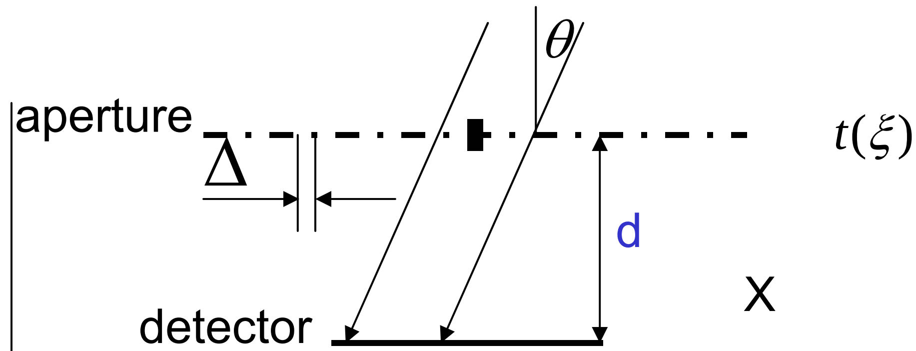
Cyclic autocorrelation



# TWO SYSTEM REALIZATIONS (COMPLETE CODING)




**EACH SOURCE FORMS SAME PATTERN BUT SHIFTED AT DETECTOR**




**EACH SOURCE FORMS DIFFERENT PATTERN (CYCLIC SHIFTED)**

**RECOVERY: CROSS CORRELATION WITH APERTURE (REPEATED APERTURE) GENERATES THE SOURCE DISTRIBUTION**

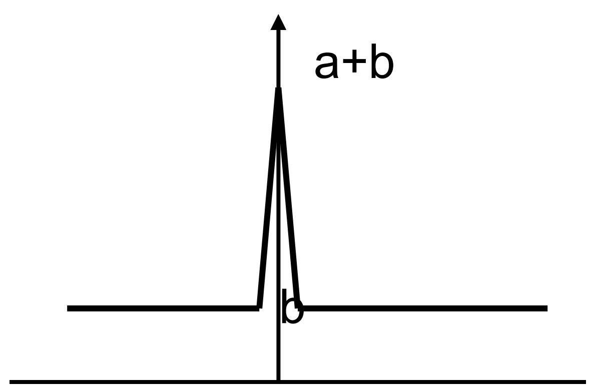
**RECOVERY: CYCLIC CROSS CORRELATION WITH APERTURE GENERATES SOURCE DISTRIBUTION**

**RESOLUTION** $\delta\theta = \Delta / d$

**APERTURES SATISFY THE OPTIMUM CONDITION**

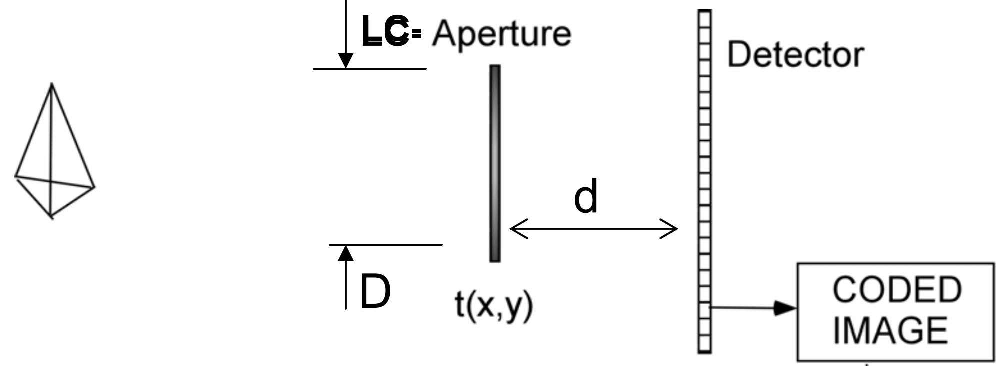
**APERTURE FUNCTION** $t(n) = \begin{Bmatrix} 0 \\ 1 \end{Bmatrix}$

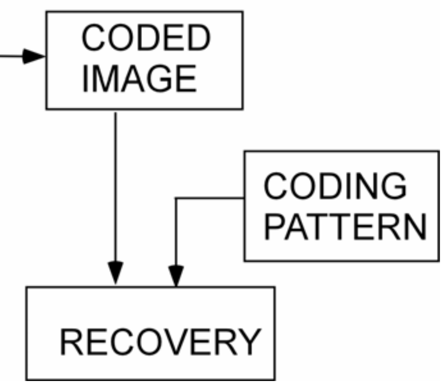
$$\sum_{m=0}^{N} t(n)\cdot t[(n-m)\cdot \mathrm{mod}\, N] = a\cdot\delta_{nm} + b$$



# MODIFIED DICKE CAMERA WITH DIFFRACTION EFFECT






## APERTURE REQUIREMENT

**PATTERN GENERATED ON DETECTOR BY A POINT SOURCE HAS OPTIMUM AUTOCORRELATION PROPERTY**

## t(x,y) calculation:
## FRESNEL ZONE PHASE RETRIEVAL

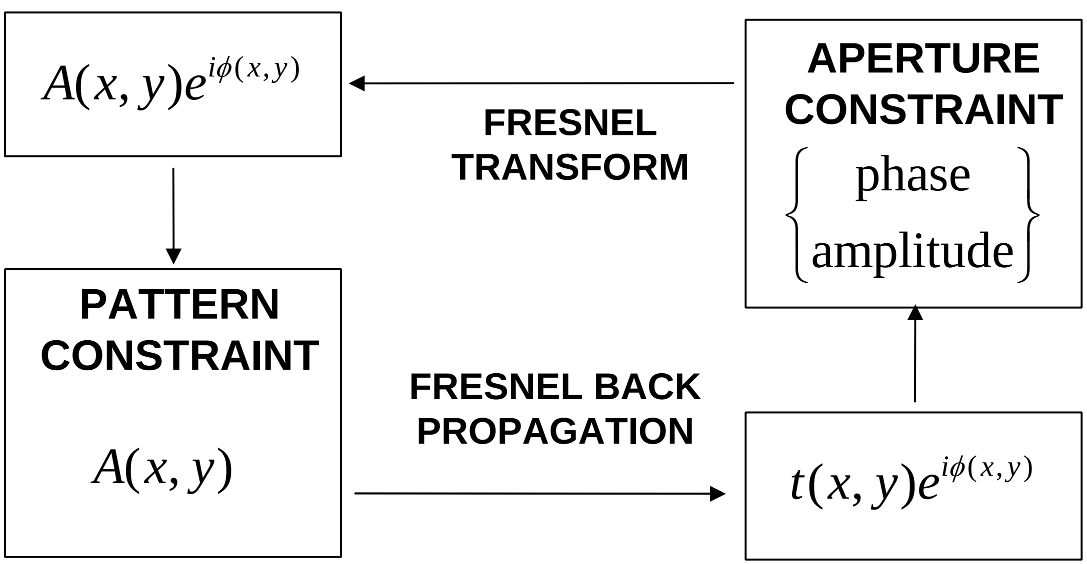
## ADVANTAGES

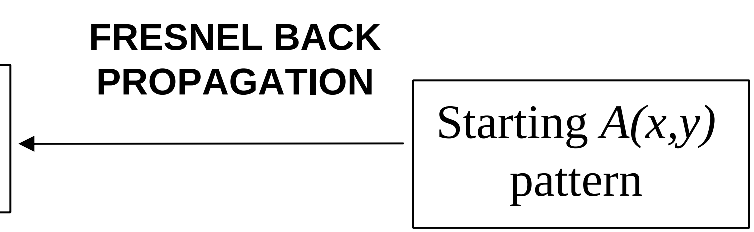
## ULTRA-THIN

## LENSLESS

## IMAGING/CODING

## DIFFRACTION LIMITED



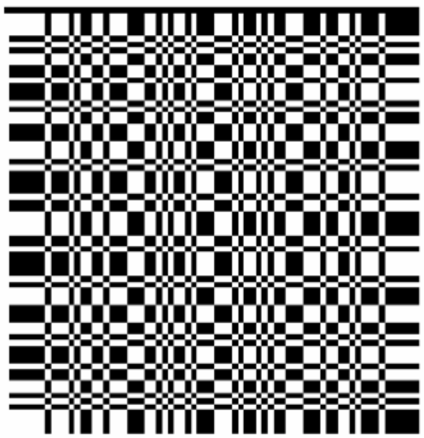




**APERTURE CONSTRAINT CAN BE EITHER AMPLITUDE OR PHASE CONSTRAINT**

# MODIFIED DICKE CAMERA



PSF



OBJECT

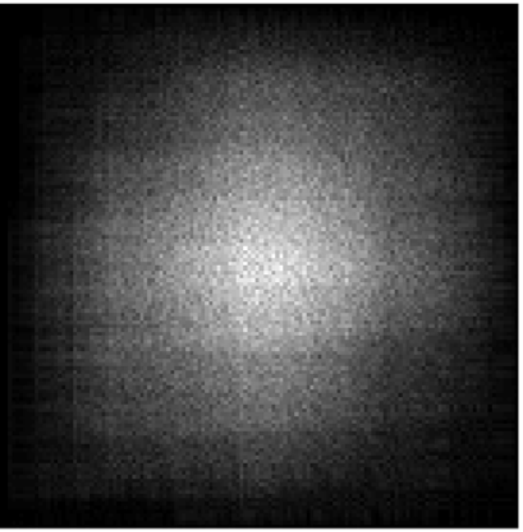
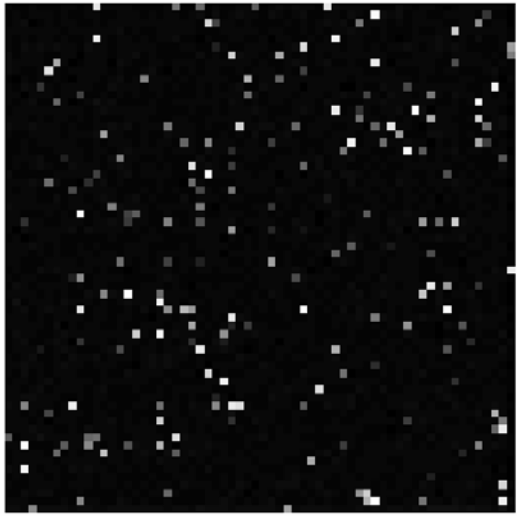


IMAGE (Noise 1%)



RECOVERY
(CROSS-CORRELATION)

**ADVANTAGES**

**ULTRA-THIN**

**LENSLESS**

**IMAGING/CODING**

**DIFFRACTION LIMITED**

---

**RESEARCH TOPICS**

2007-2009 W CHI

**APERTURE DESIGN**
**PHASE RETREVAL**
**R G B COLOR**

**IMAGE PROCESSING**
**MAX ENTROPY**

**3-D IMAGING & DOF**

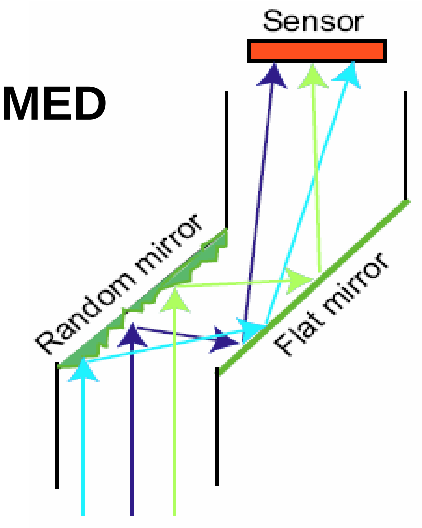
# RELATED WORK:



## RANDOM LENS IMAGING+

**PRINCIPLE:**

RANDOM PATTERN FORMED ON DETECTOR FOR A SINGLE POINT SOURCE



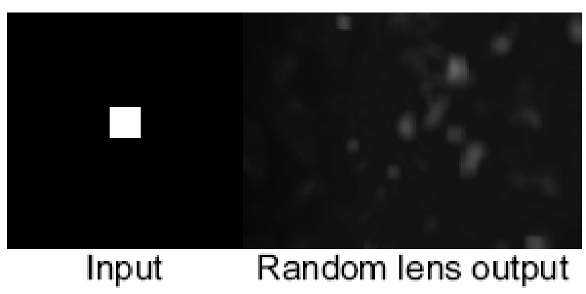

**DECODING:**

i) SPACE-VARIANT

MAP DETECTOR PATTERN FOR EACH POINT IN OBJECT SPACE

ii) SPACE-INVARIANT

DEBLURRING PROBLEM




IMPULSE RESPONSE

**RESEARCH TOPICS:**

- PSEUDO RANDOM LENS
- DIGITAL PROCESSING

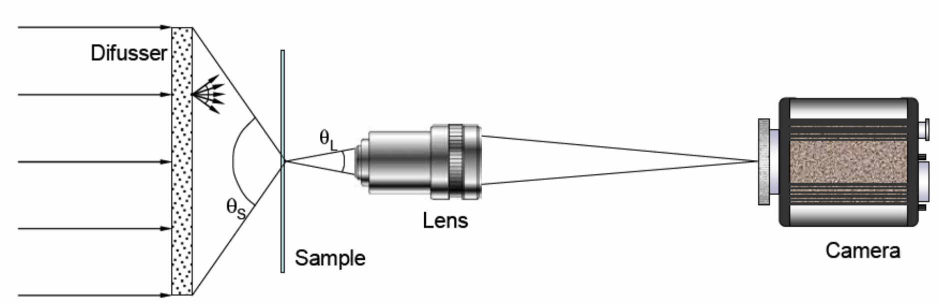
**RELATED CODED APERTURE TOPICS:**

- CYCLIC DIFFERENCE SET
- PHASE RETRIEVAL

+ FERGUS, TORRALBA, AND FREEMAN. MIT-CSAIL-TR-2006-058

# RELATED WORK:
# STRUCTURED ILLUMINATION / SUPERRESOLUTION

- **SPECKLE PATTERN ILLUMINATION**




- **RECORDING**

$$O_{\xi}(x) = [g(x) \cdot S(x-\xi)] * h(x)$$

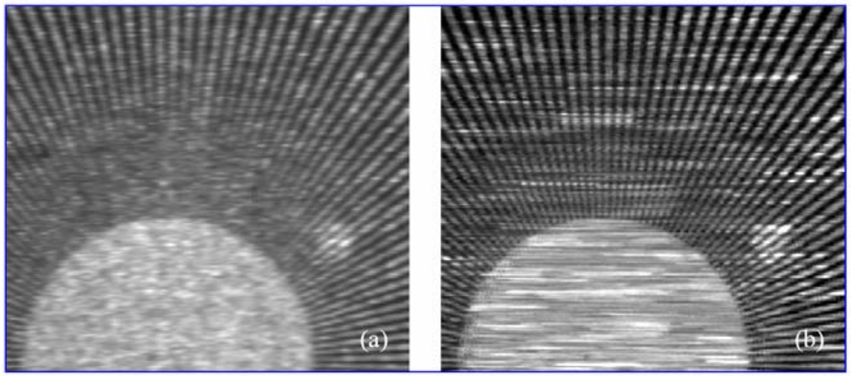
**A SET OF IMAGES ARE COLLECTED**

- **DECODING**

$$O(x) = \int O_{\xi}(x) \cdot S(x-\xi) d\xi = g(x) * [h(x) \cdot \gamma(x)]$$

$$\gamma(x) = \int S(\xi) \cdot S(x+\xi) d\xi$$

- **RESULTS**




**ONE SAMPLE LOW RESOLUTION IMAGE** | **DECODED FROM A SET OF IMAGES**

- **RESEARCH TOPICS**

**ILLUMINATION PATTERN**

- **CYCLIC DIFFERENCE SET**
- **REMOVAL OF IRREGULARITIES**

GARCIA, ZALEVSKY, AND FIXLER. OPT. EXP. 13, 6073 (2005)

# TWO DIMENSIONAL UNIFORMLY REDUNDANT ARRAY



## URA: Ideal cyclic auto-correlation property

A(i,j) is a uniformly redundant array of size RXS
R, S are two prime numbers, R-S=2.

$$A(i,j) = \begin{cases} 0 & \text{if } i=0 \\ 1 & \text{if } j=0 \ \& \ i \neq 0 \\ 1 & \text{if } C_R(i) C_S(j) = 1 \\ 0 & \text{Otherwise,} \end{cases}$$

where

$$C_R(i) = \begin{cases} 1 & \text{if there exists an integer } x,\ 1 \leq x < R \text{ such that } i = (x^2) \cdot \mathrm{mod}\, R \\ -1 & \text{Otherwise} \end{cases}$$

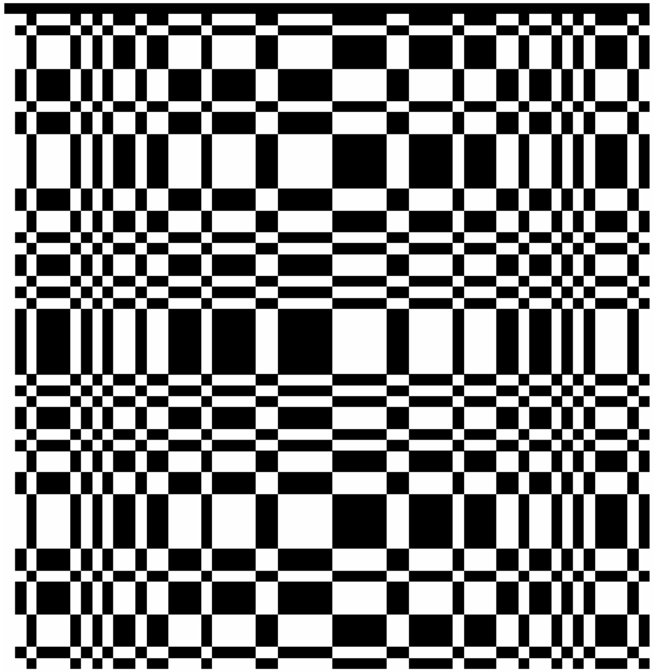
and

$$C_S(i) = \begin{cases} 1 & \text{if there exists an integer } x,\ 1 \leq x < S \text{ such that } i = (x^2) \cdot \mathrm{mod}\, S \\ -1 & \text{Otherwise.} \end{cases}$$

**Examples**

$$5 \times 3 \quad \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

$$61 \times 59$$



**Research Topic:**

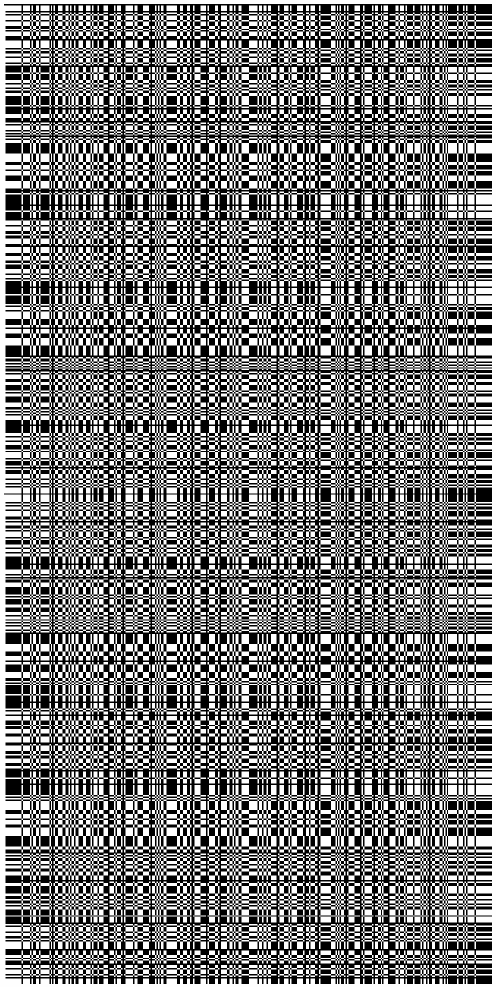
**Three or more 2-D arrays for color imaging**

First applied to coded aperture by Fennimore and Cannon

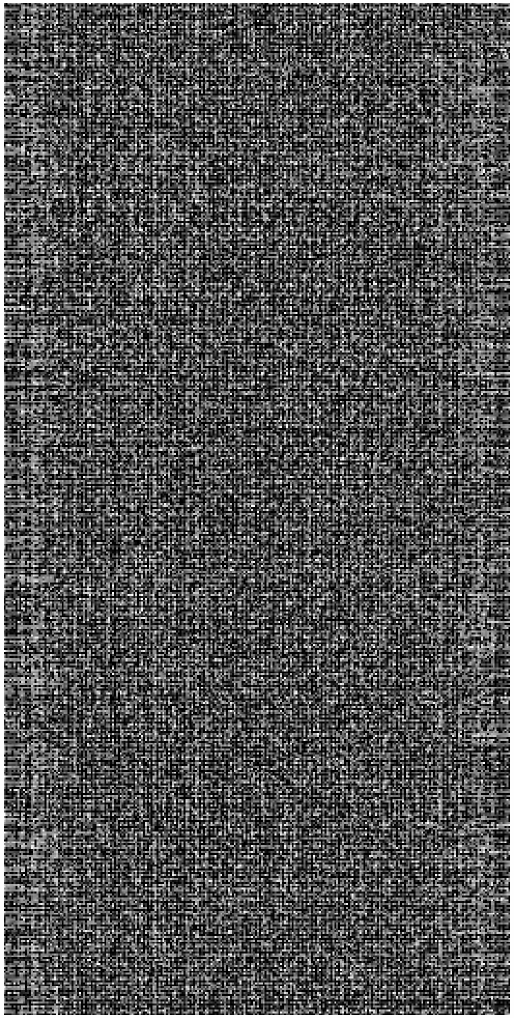
# PHASE SCREEN PATTERN: PHASE RETRIEVAL



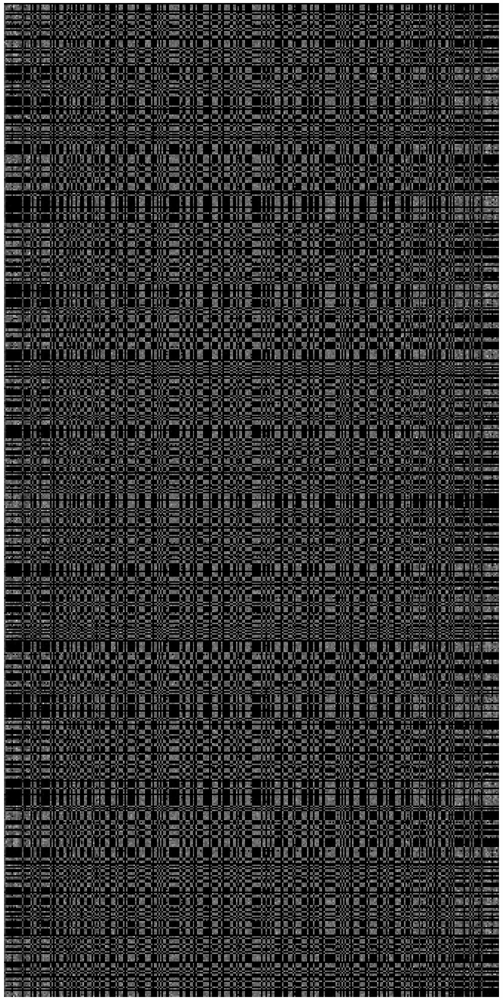
Ideal detector pattern



Phase screen



Actual detector pattern



**Limiting factor: the pixel size of phase screen (RESEARCH TOPIC)**

**Negligible effect on image quality**

# IMAGING SIMULATION: IDEAL AND ACTUAL PHASE SCREEN

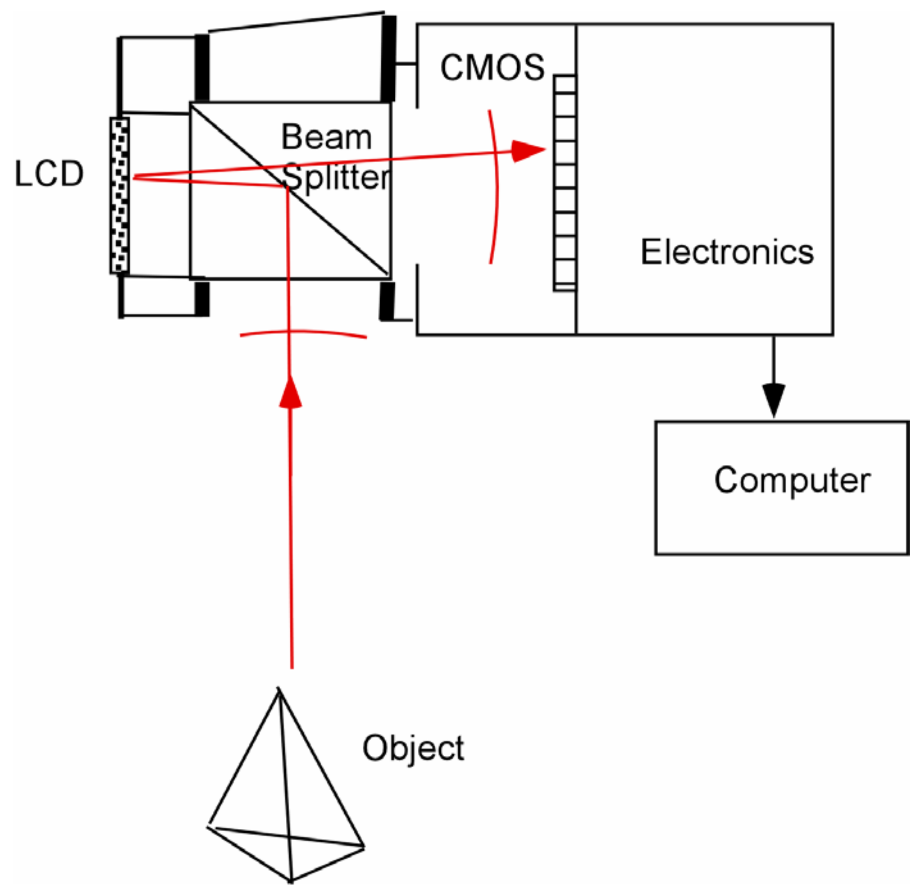
**OBJECT**

**RECOVERY (IDEAL)**

**RECOVERY (LCD PIXEL 8 MICRONS)**

- In the case of 8μm pixel phase screen, the actual detector pattern is used for imaging, and the ideal detector pattern is used for recovery.
- A simple cross-correlation method is used.
- Negligible deleterious effect on image quality is observed in actual 8μm pixel screen compared to ideal theoretic one.

# NOVEL DICKE-CHI CAMERA




**PRELIMINARY DESIGN (MONOCHROMATIC ILLUMINATION)**

**LCD screen**

- **Reflective phase type**
- **1920X1080 pixels**
- **Pixel size 8.1μm**

**CMOS**

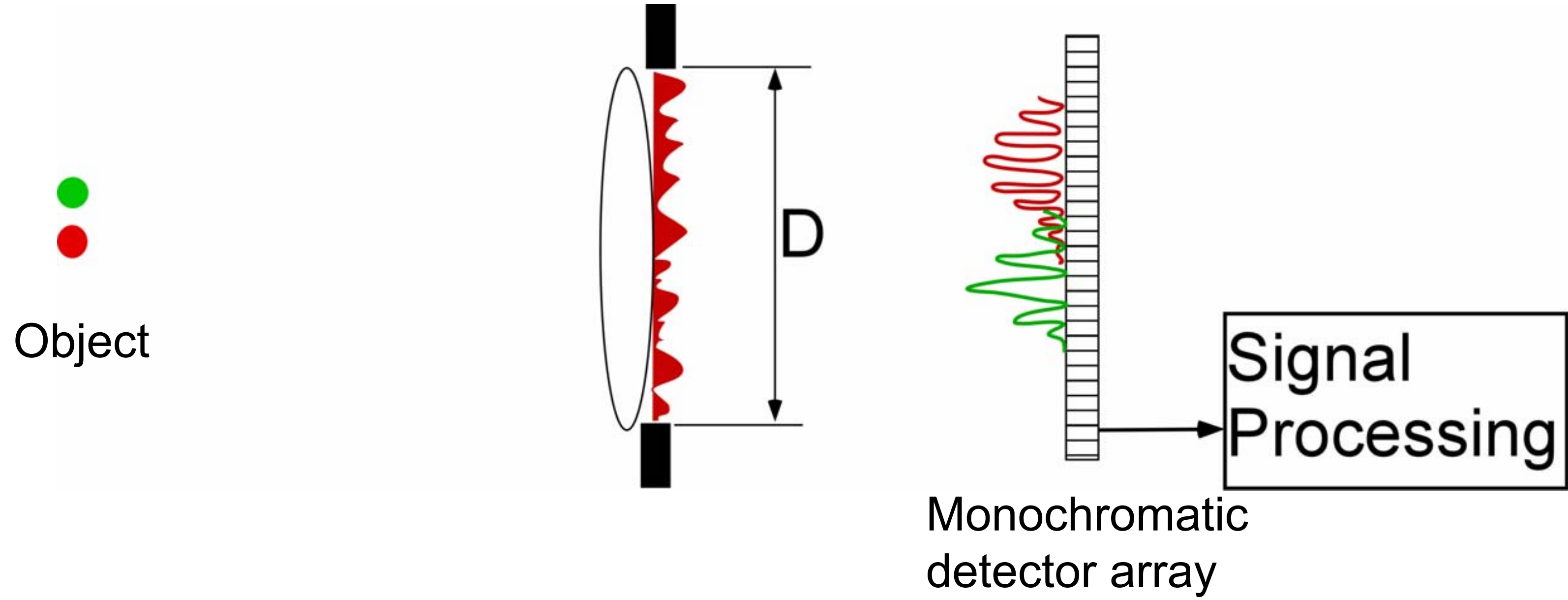
- **1024X1024 pixels**
- **pixel size 10μm**

**Current Status**

- **Theory finished (Monochromatic illumination)**
- **Successful computer simulations completed (2/2008) in first contract**

# PROPOSAL on CODED APERTURE IMAGING SPECTROMETER






- Dicke camera in optical regime
  - Cross-correlation signal processing (Repeat for all wavelength)
- Spectral resolution $$\Delta\lambda = \frac{\lambda^2}{2\pi(n-1)\sigma_h}$$
- Can be lensless
- Color imaging without Bayer's filter
  - Better color rendition than R G B
- Research Topics: aperture pattern & contrast; digital processing