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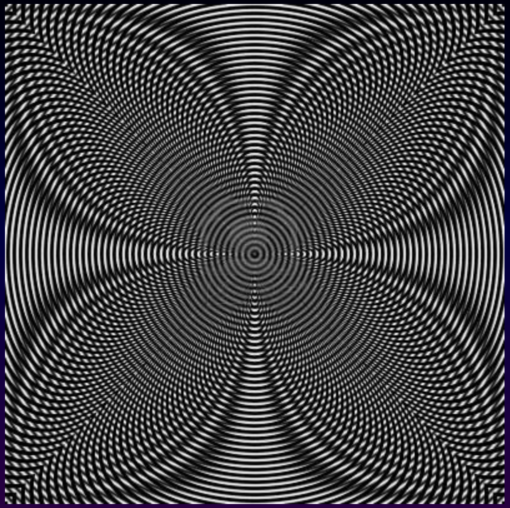

2D Sampling: characteristics, difficulties and applications

José Manuel Rebordão

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Summary

Sampling is a fundamental part of any measurement, one of the "arts" of physics. Within the signal (one-dimensional, 1D, typically time) sampling is a well-controlled process. At two spatial dimensions (images, 2D) and at three dimensions (volumes, 3D), one is often confronted with unknown objects or symmetry-shaped objects that become evident as spatial resolution increases, and it is possible to obtain results of the measurement that can either describe reality or can be artifacts generated by the measurement process.

On the other hand, we are increasingly dealing with information presented to us through displays of various technologies, or generated through dynamic scanning processes. Due to their periodic or quasi-periodic nature, such mathematical objects do not always make possible the natural application of Shannon's theorem, confronting us with the need to perform other forms of analysis.

The aim of this seminar is to draw attention - without major formal elaborations - to a wide range of artifacts that typically arise in image manipulation, and from which various applications derive, using either their stability or their unique nature and instability.

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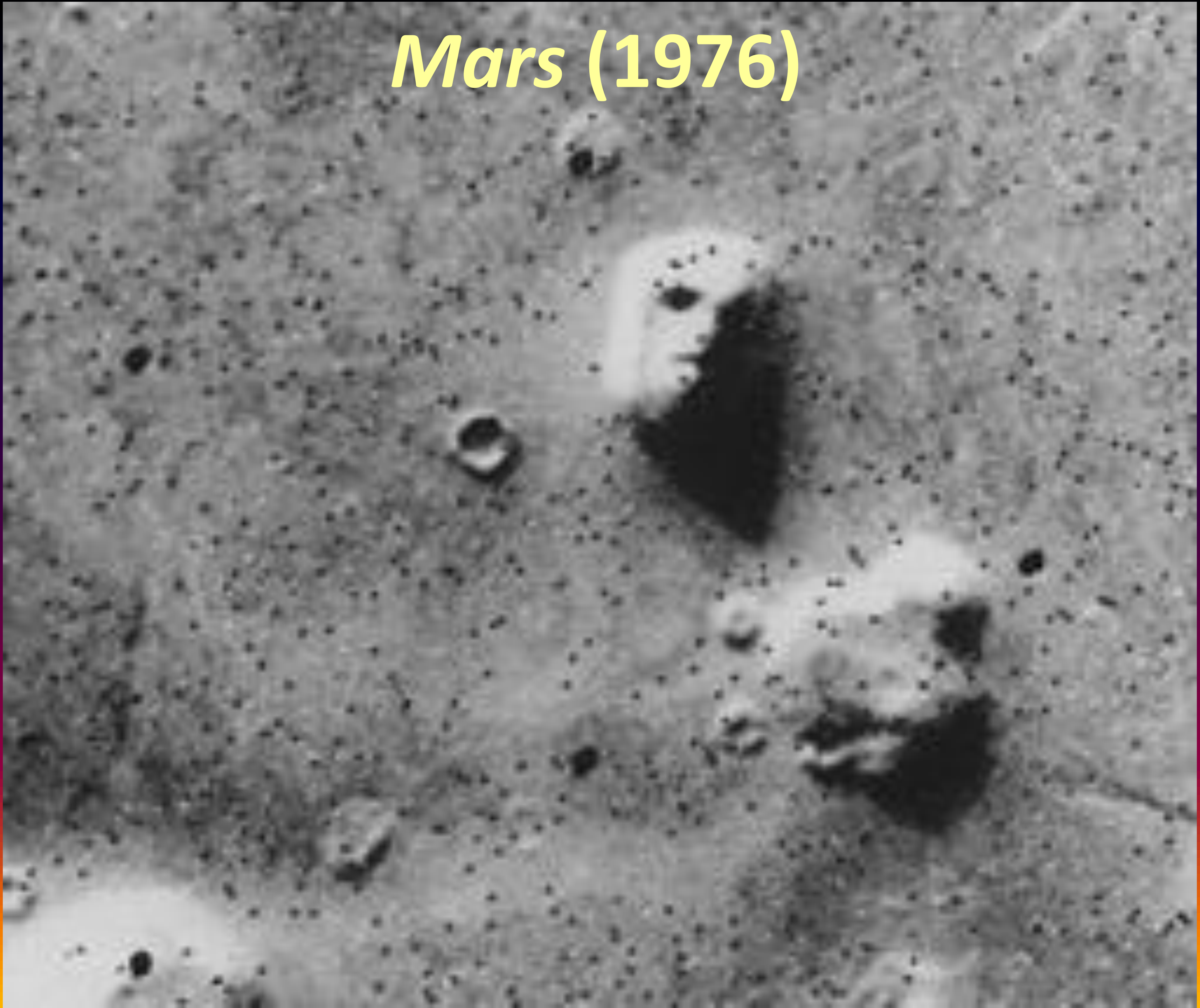
Sumário

As estratégias de amostragem constituem uma parte fundamental de qualquer processo de medição, uma das "artes" da Física. No âmbito do sinal (unidimensional, 1D, tipicamente o tempo), a amostragem é um processo bem controlado. A duas dimensões espaciais (imagens, 2D) e a 3 dimensões (volumes, 3D), é-se muitas vezes confrontado com objectos desconhecidos ou possuidores de formas de simetria que se põem em evidência à medida que a resolução espacial aumenta, e não é difícil obterem-se resultados do processo de medida que tanto podem descrever a realidade como podem perfeitamente ser artefactos gerados pelo processo de medida.

Por outro lado, cada vez mais lidamos com informação que nos é apresentada através de "displays" de diversas tecnologias, ou gerada através de processos dinâmicos de varrimento. Pela sua natureza periódica ou quase-periódica, tais objectos matemáticos nem sempre viabilizam a aplicação natural do teorema de Shannon, confrontando-nos com a necessidade de recorrer a outras formas de análise.

Este seminário tem assim como objectivo chamar a atenção - sem grandes elaborações formais - para uma gama variada de artefactos que tipicamente surgem na manipulação de imagens, e das quais decorrem aplicações diversas que beneficiam quer da sua estabilidade, quer da sua natureza singular e instabilidade.

Mars (1976)



Common points among ...


PS

TV

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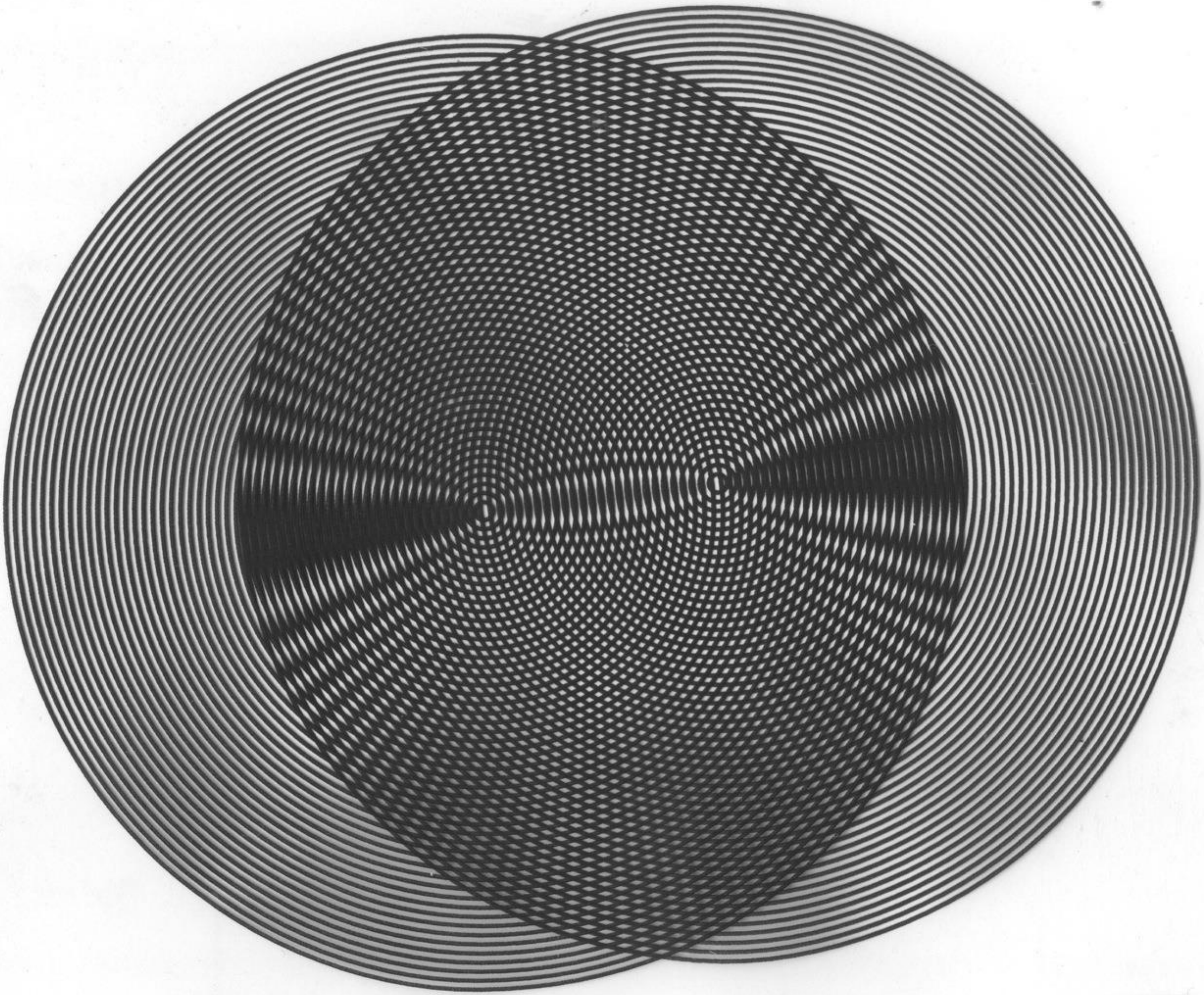
Yankee stadium in Bronx, New York

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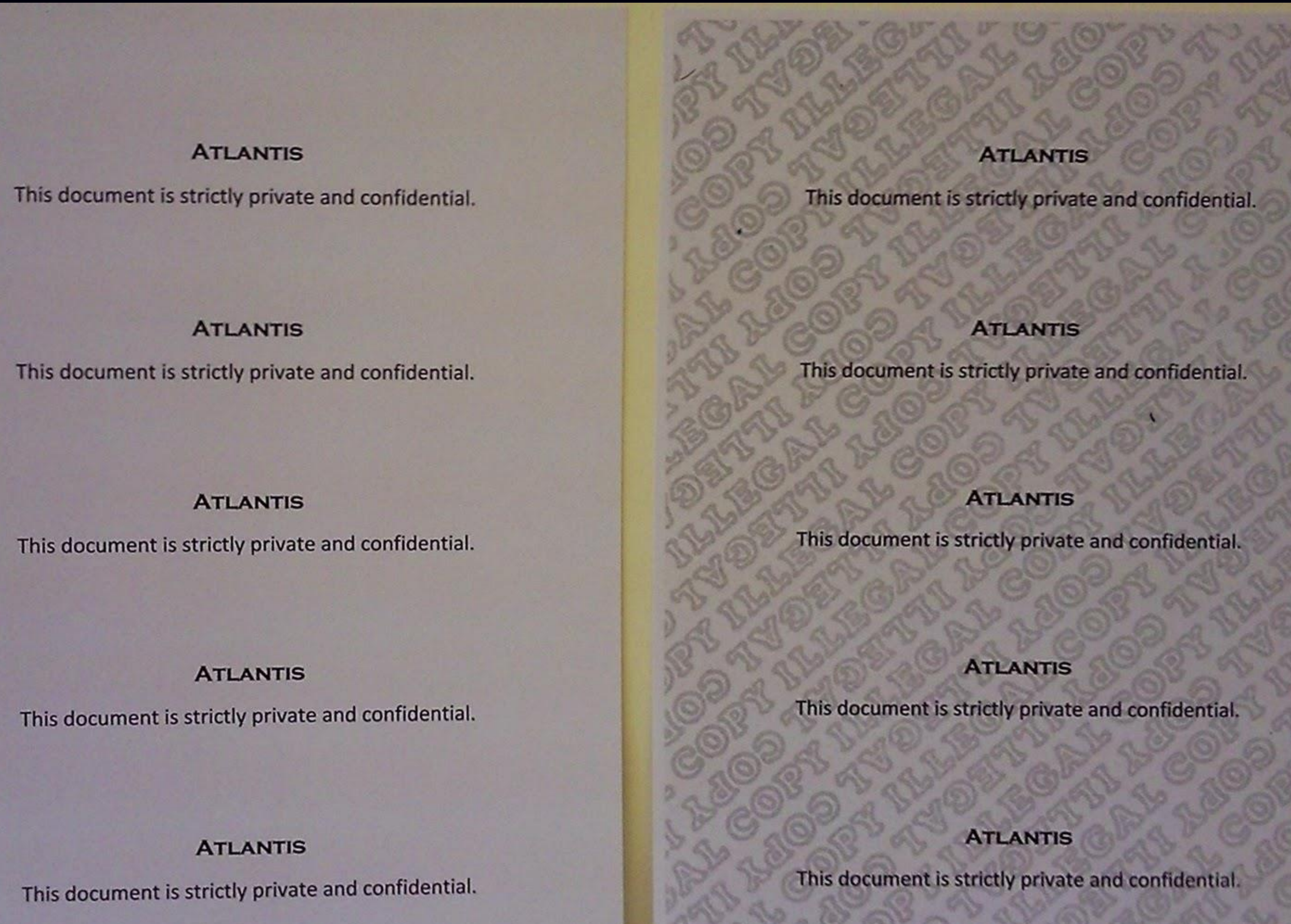

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In common, previously:

- Handling periodic or quasi-periodic patterns
- General sampling theory in 1D, 2D (3D)

- 2D / 3D sampling
  - Representation / Interpolation
- Metrology and measurement
  - Matrix sensors
  - Matricial scanning
  - Measurement: a filtered “reality”
  - New measurement measurement (Moiré, …)
    - All scales, from nano to macro
- *Displays , scanners* & copiers
  - Artifacts
- Sistems
  - Alignement (integrated circuits, offset printing)
- Security
  - Protection / Coding / Decoding / Zoom / …

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2D models

- A 2D image / pattern (monochromatic) can be represented by:
  - Reflectance function, $r_i(x,y)$
  - Transmitance function
- Image **superposition** can be modelled:
  - **Multiplicative**
  - Additive

$$r(x,y) = r_1(x,y) \cdot \ldots \cdot r_m(x,y)$$

↓ Fourier transform

$$R(u,v) = R_1(u,v) ** \ldots ** R_m(u,v)$$

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** → Convolution

- Convolution:

$$f(x,y) ** \; g(x,y) = \iint_{-\infty}^{+\infty} f(u,v)g(x-u,y-v)dudv$$

- Different from Correlation:

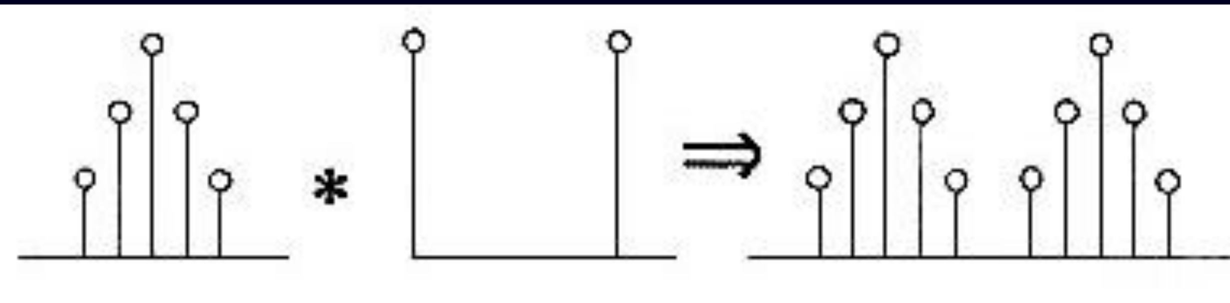
$$f(x,y) \otimes\otimes g(x,y) = \iint_{-\infty}^{+\infty} f(u,v)g(u-x,v-y)dudv$$

- Convolution theorem:

h = f ** g → TF(h) = TF(f) . TF(g)

h = f . g → TF(h) = TF(f) ** TF(g)

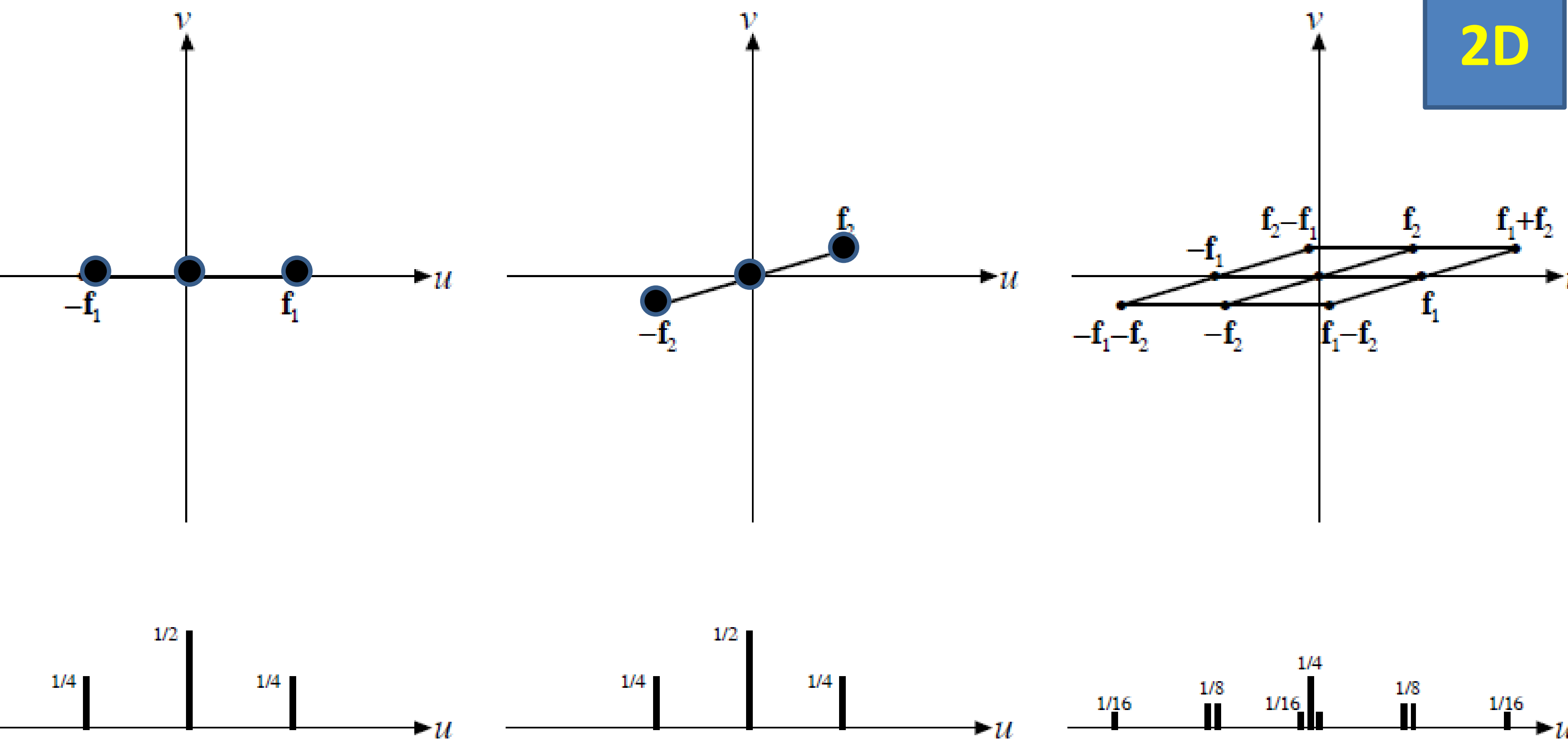
** → Convolution



$$f(x,y) ** g(x,y) = \iint_{-\infty}^{+\infty} f(u,v)\, g(x-u, y-v)\, du\, dv$$

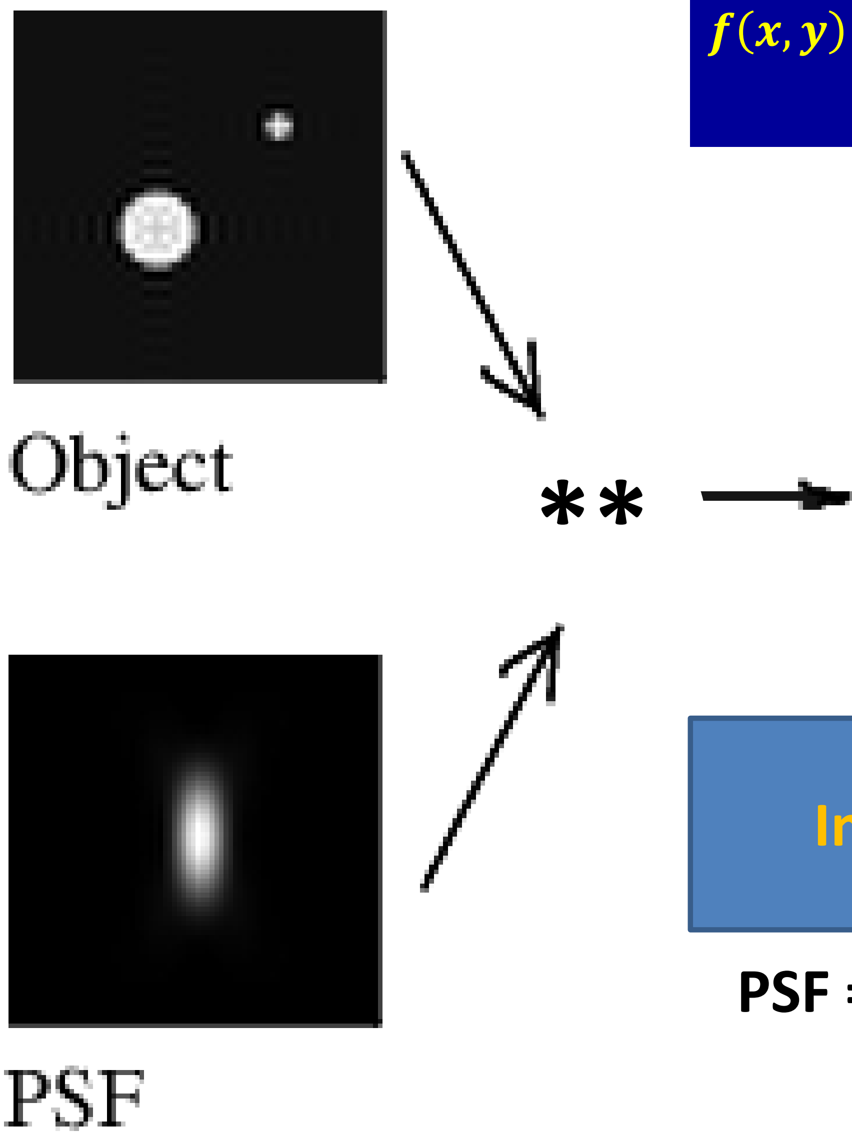
1D

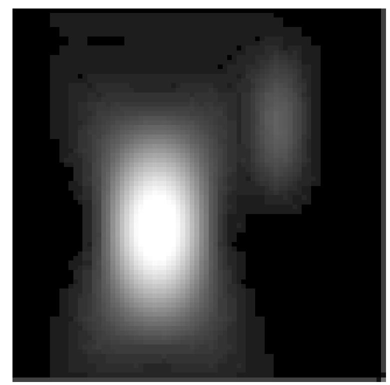
2D



** → Convolution in 2D

$$f(x,y) ** g(x,y) = \iint_{-\infty}^{+\infty} f(u,v)g(x-u,y-v)\,du\,dv$$





2D

**

Image = Object ** PSF

PSF = Point Spread Function

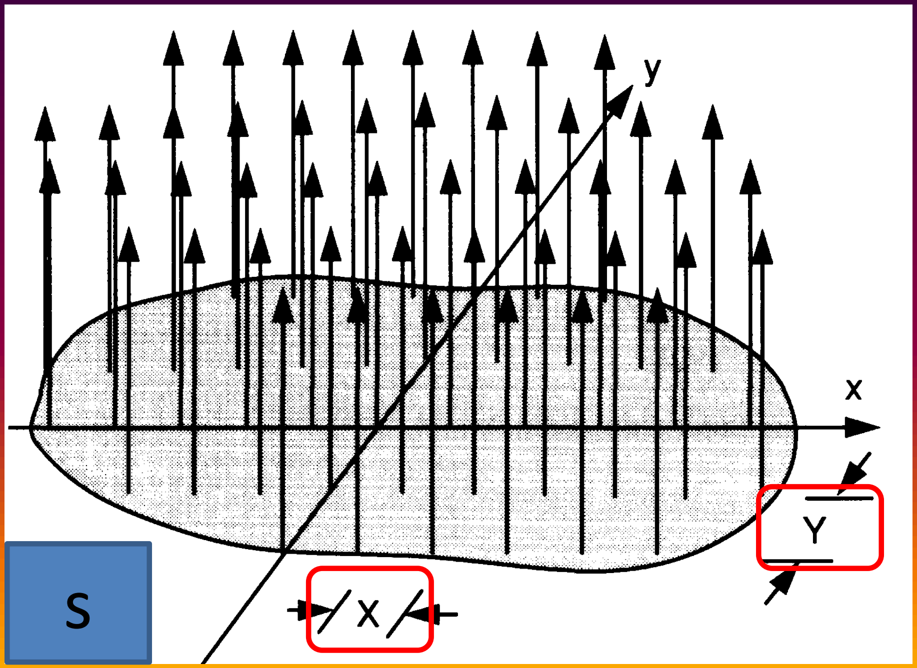
Sampling

Point sampling is a multiplicative process:

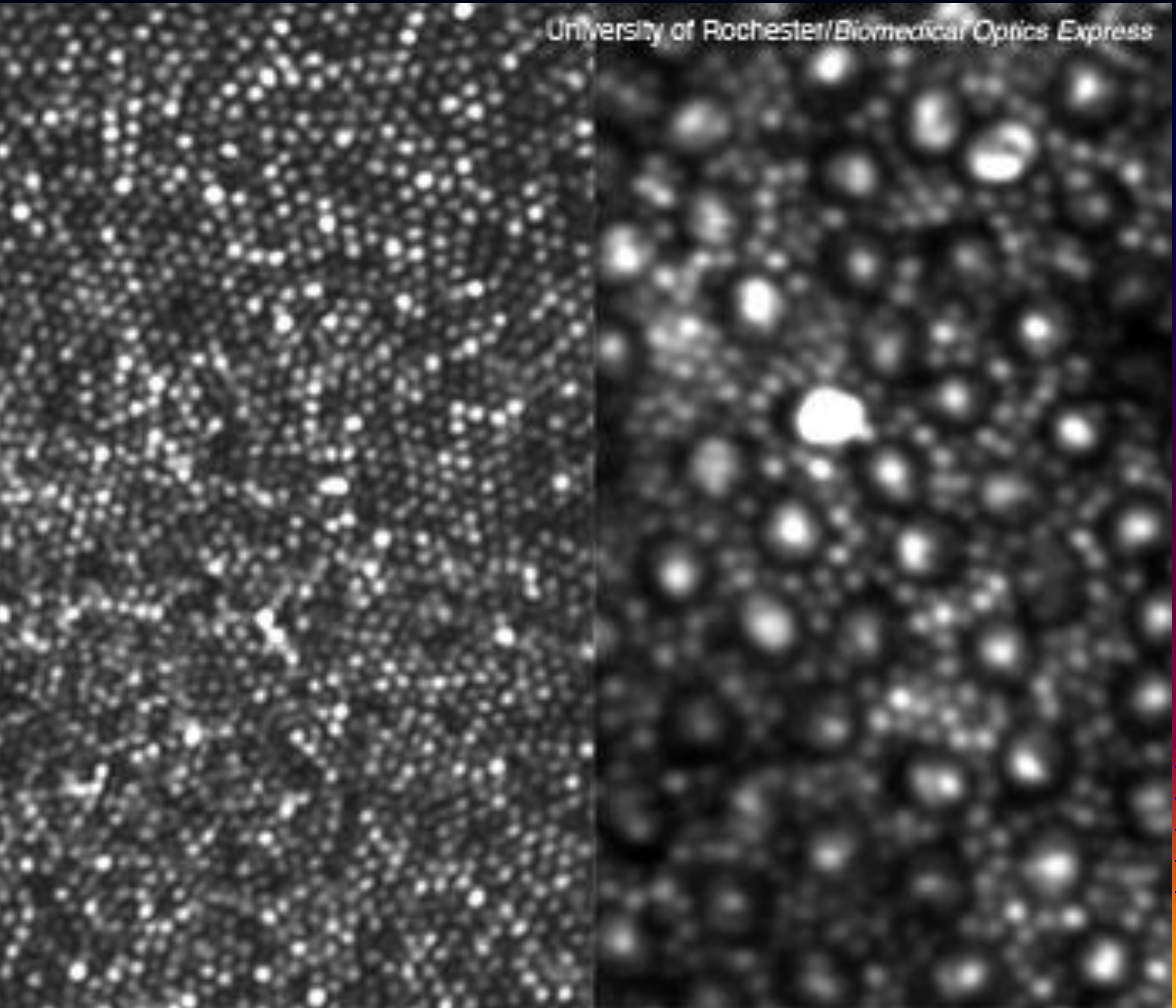
$$g_S\ (x,y) = g\ (x,y)\ .\ s\ (x,y)$$

with:

- **g (x,y)** : continuous description of the signal
- **s (x,y)** : **2D sampling function** **(steps X, Y – not necessarily constant…→)**



Non-uniform sampling - example



Left

Cones in the centre of the retina (fovea)

Right:

Cones, bigger, with dark rings.

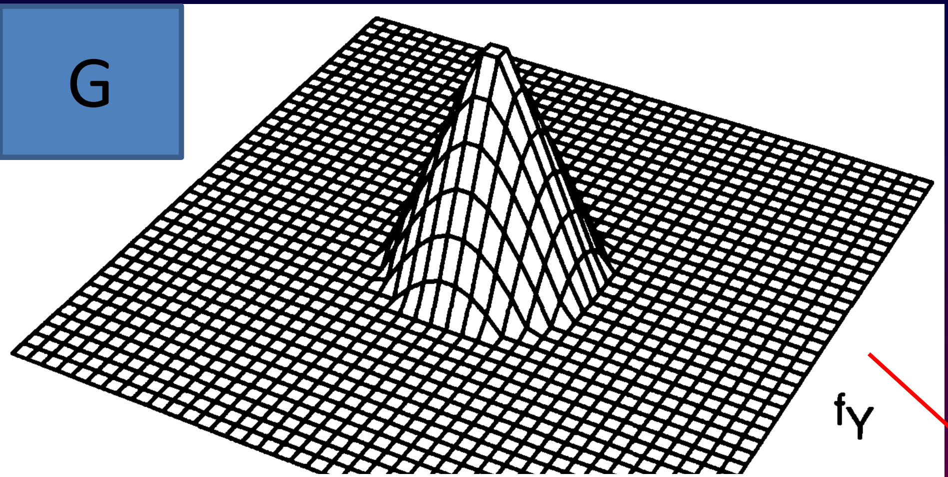
Rods, large numbers, smaller, around cones.

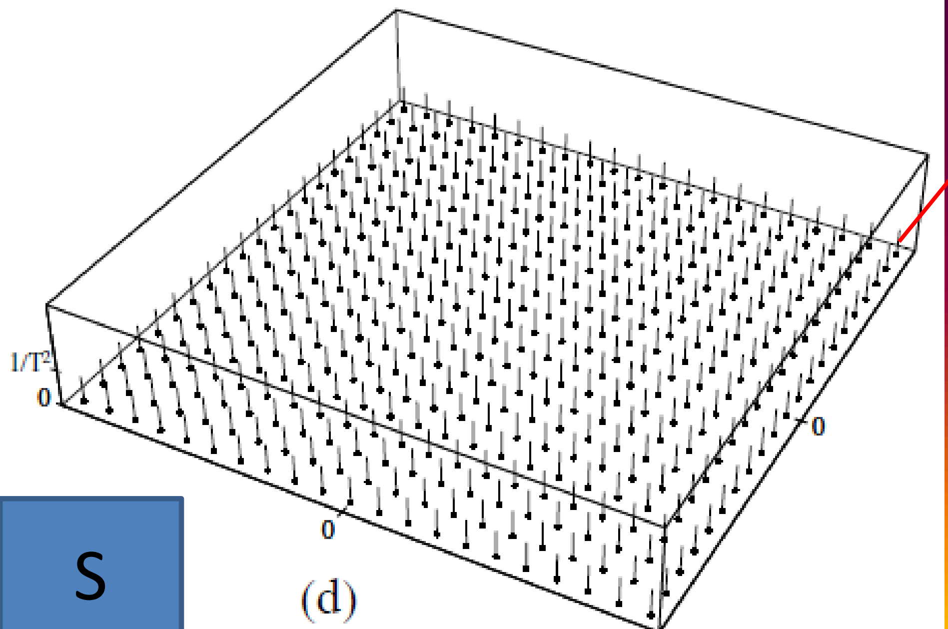
Scientists Image Rods in the Living Eye

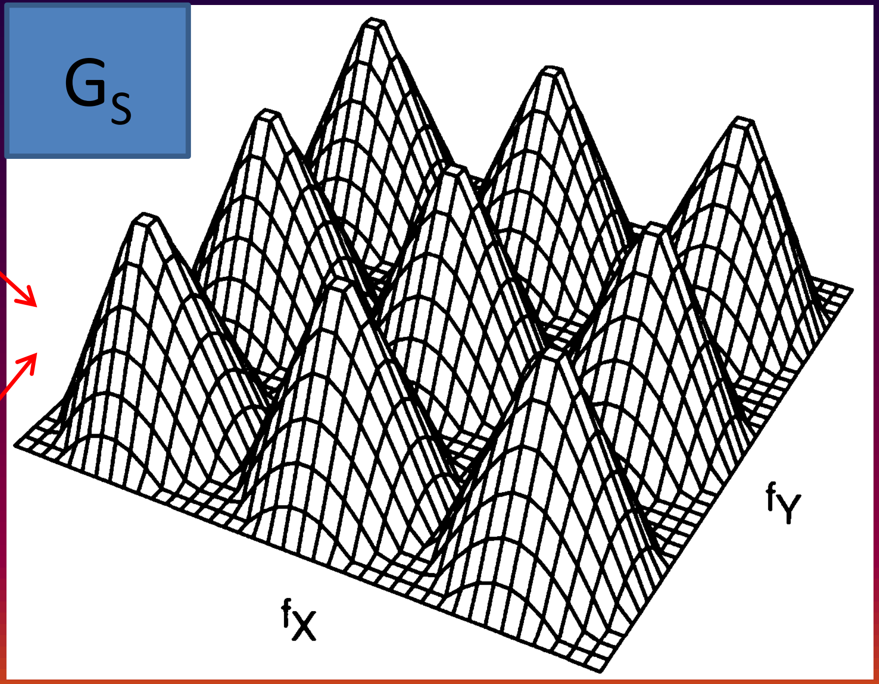
[Biomed. Opt. Express **2**, 1864, 2011; doi:10.1364/BOE.2.001864]

2D point sampling

$g_S(x,y) = g(x,y) \cdot s(x,y) \rightarrow G_S(f_x,f_y) = G(f_x,f_y) ** S(f_x,f_y)$





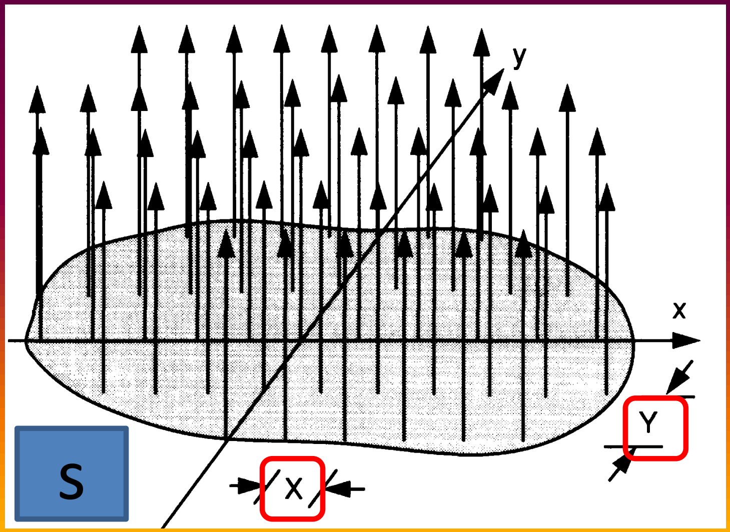


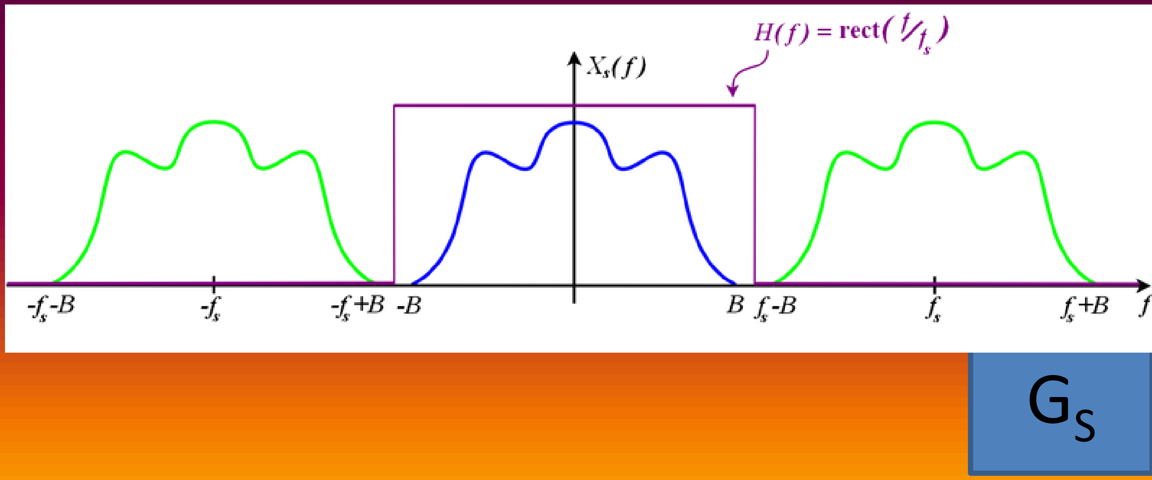
2D sampling

If the function is band LIMITED $|f_{X,Y}| < B$, the sampling step in (X, Y) can always be chosen in order to ensure that the repetitions of G_S do not overlap:

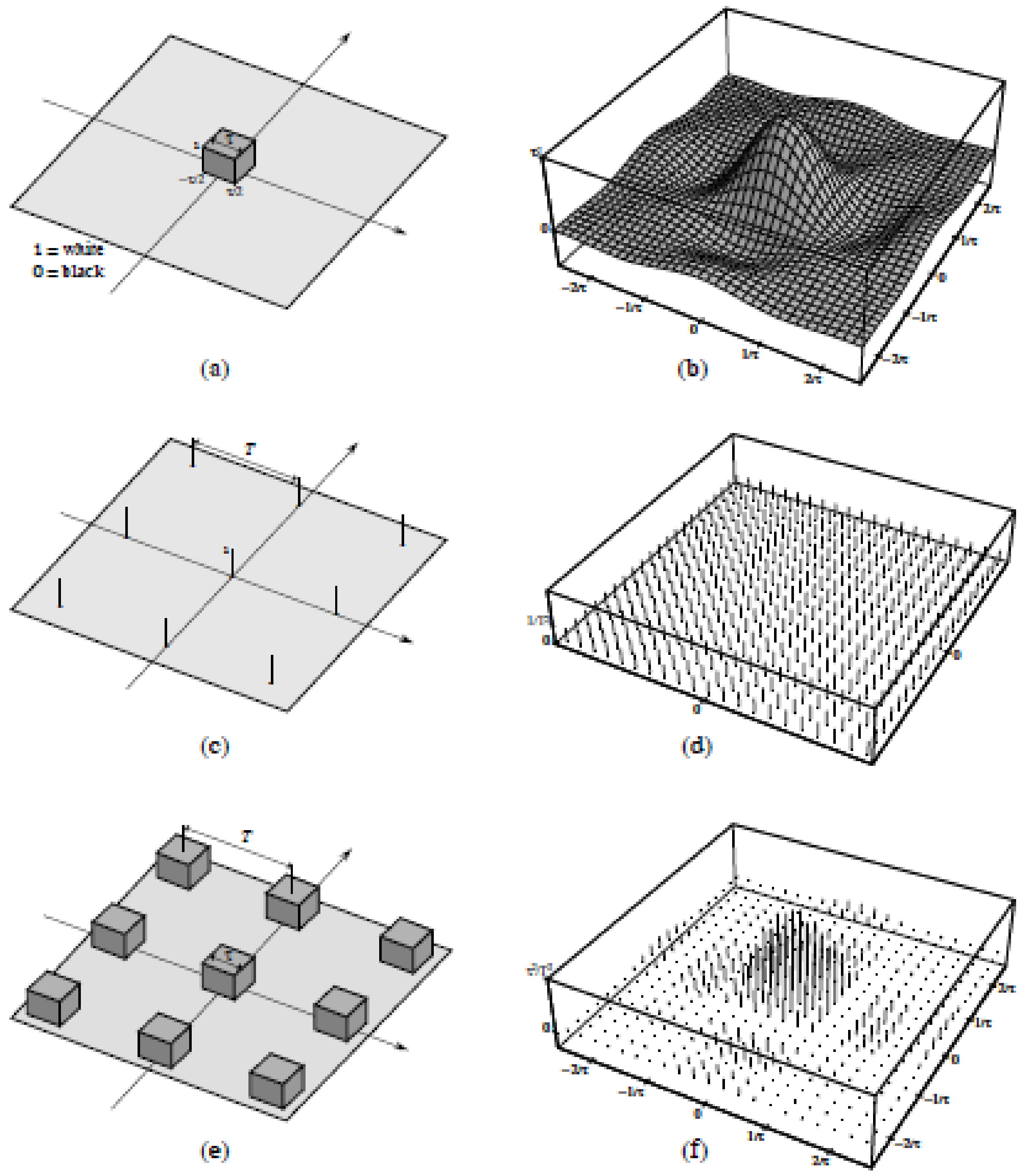
$$X \leq \frac{1}{2B_X} \qquad\qquad Y \leq \frac{1}{2B_Y}$$

- The minimum value of $2B_{X,Y}$ of the sampling frequency is the Nyquist frequency





Dot Screens

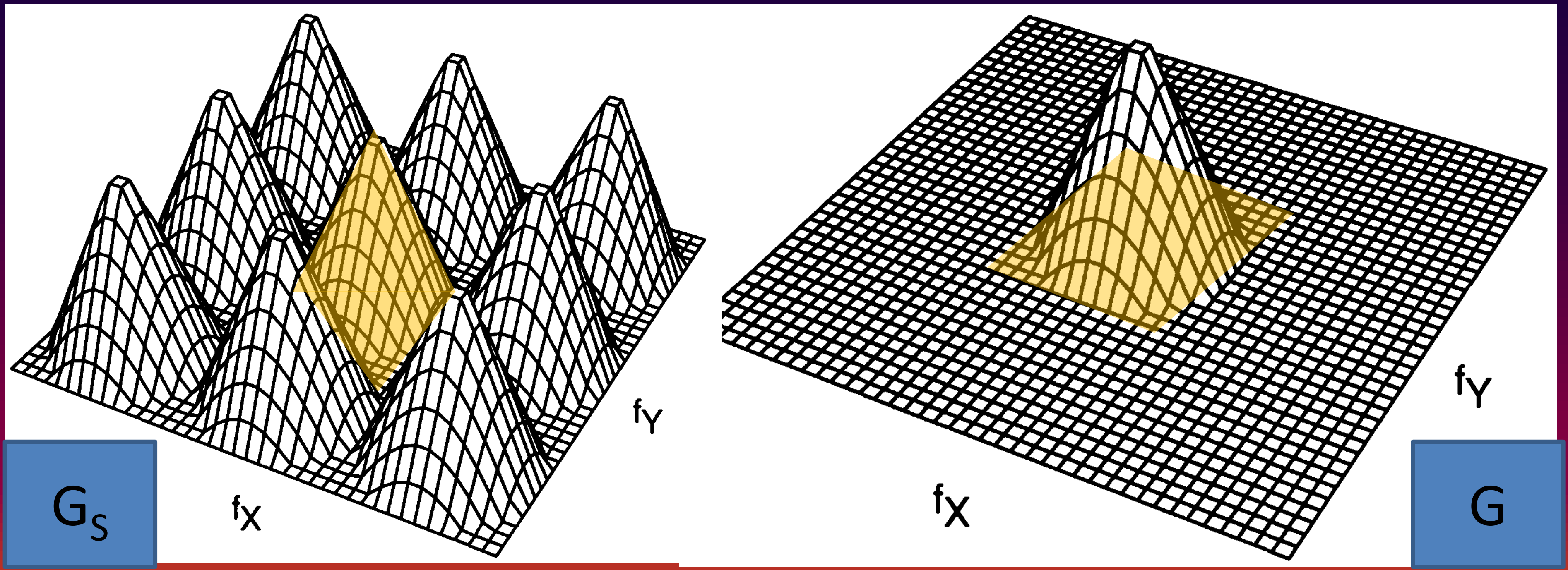


(a) A square white dot $d(x,y)$ with side τ; (b) its continuous spectrum $D(u,v) = \tau^2 \,\mathrm{sinc}(\tau u)\,\mathrm{sinc}(\tau v)$. (c) A nailbed with period T and amplitude 1; (d) its spectrum is a nailbed with period $1/T$ and amplitude $1/T^2$. (e) A screen of square white dots is the convolution of (a) and (c); (f) the spectrum of this screen is the product of (b) and (d): a nailbed that samples the "envelope" (b) at intervals of $1/T$, scaling its amplitude by $1/T^2$. Note that the impulses in (f) represent the coefficients of the 2D Fourier series development of (e).

2D sampling: low pass filtering

If the function is band LIMITED and $|f_{X,Y}| < B_{X,Y}$, the true spectrum of g, **G** , can always be extracted from G_S by filtering:

$G_S(f_x,f_y) = G(f_x,f_y) ** S(f_x,f_y)$ → $G(f_x,f_y) = \mathrm{rect}(f_x/2B_X, f_y/2B_Y) \cdot G_S(f_x,f_y)$



By inverse FT, we can retrieve g(x,y) from its samples:

$$g(x,y) = TF^{-1}\, G(f_x,f_y)$$

2D sampling

If a function g (x,y) IS BAND LIMITED, $|f_{X,Y}| < B_{X,Y}$, below the Nyquist frequency:

$$g_S(x,y) = g(x,y) \cdot s(x,y)$$

Point sampling: $p(x,y) = \delta(x,y)$

$$G_S(f_x,f_y) = G(f_x,f_y) ** S(f_x,f_y)$$

$$G(f_x,f_y) = \text{rect}(f_x/2B_X, f_y/2B_Y) \cdot G_S(f_x,f_y)$$

$$g(x,y) = TF^{-1}\, G(f_x,f_y)$$

$$g(x, y) = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} g\left(\frac{n}{2B_X}, \frac{m}{2B_Y}\right) \operatorname{sinc}\left[2B_X\left(x - \frac{n}{2B_X}\right)\right] \operatorname{sinc}\left[2B_Y\left(y - \frac{m}{2B_Y}\right)\right]$$

$$\operatorname{sinc} x = \frac{\sin(\pi x)}{\pi x}$$

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2D sampling – other factors…

Degrading the signal, **g**: aberrations, low-pass anti-aliasing filter, …

$$g(x,y) \rightarrow g(x,y) * h(x,y)$$

Integrating the signal with a finite aperture sensors, $\mathbf{p_S}$

$$g(x,y) \rightarrow g(x,y) * h(x,y) * p_S(x,y)$$

Sampling the degraded signal

$$g_S(x,y) = [g(x,y) * h(x,y) * p_S(x,y)] \,.\, s(x,y)$$

$$G_S(f_x,f_y) = [G(f_x,f_y).\, H(f_x,f_y).P_S(f_x,f_y)] * S(f_x,f_y)$$

Displaying the sampled signal (periodic array of display pixels, $\mathbf{p_D}$) … → …

$$g_V(x,y) = \{[g(x,y) * h(x,y) * p_S(x,y)] \,.\, s(x,y)\} * p_D(x,y)$$

$$G_V(f_x,f_y) = \{ [G(f_x,f_y).\, H(f_x,f_y).P_S(f_x,f_y)] * S(f_x,f_y)\} \,.\, P_D(f_x,f_y)$$

What if the function is NOT band LIMITED?

Shannon theory is no longer applicable!

Nyquist requirements cannot be satisfied

- **The object is unknown or dynamic**
- **Technical or technological impossibility**

The signal is not band limited / very large bandwidth

- **Periodic or quasi-periodic signals**

  Printed or digital documents, displays, ...

The multiplicative model is not applicable

- **n components multiplicative model (colour)**
- **Non-multiplicative model**

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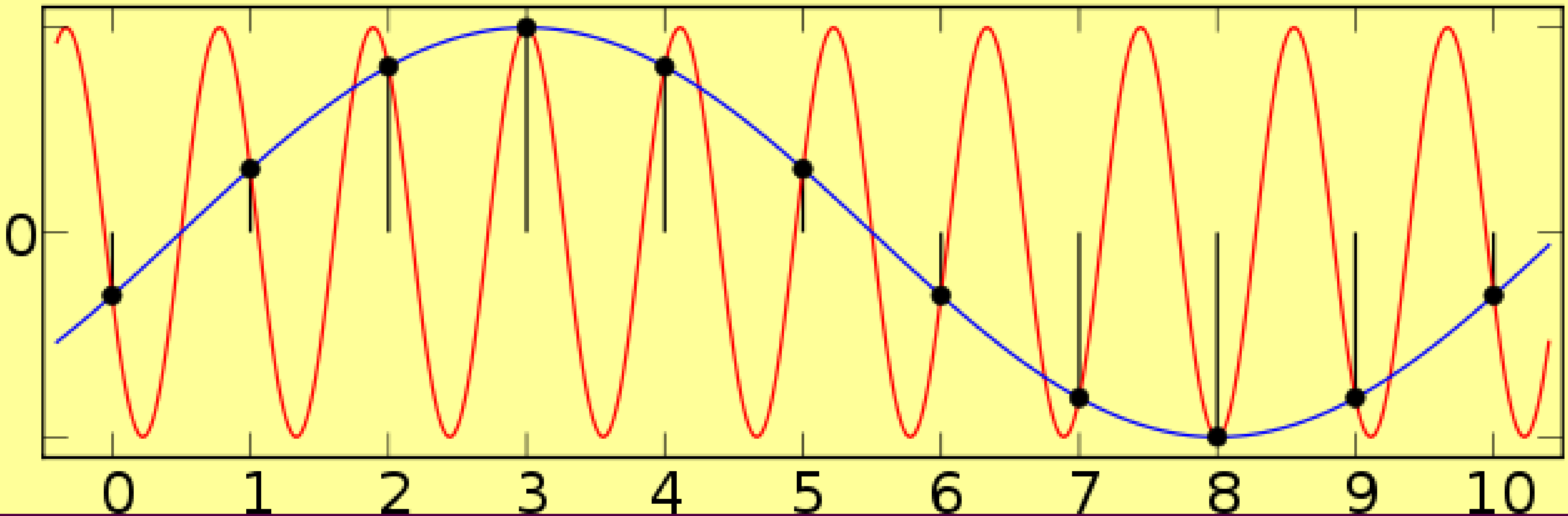
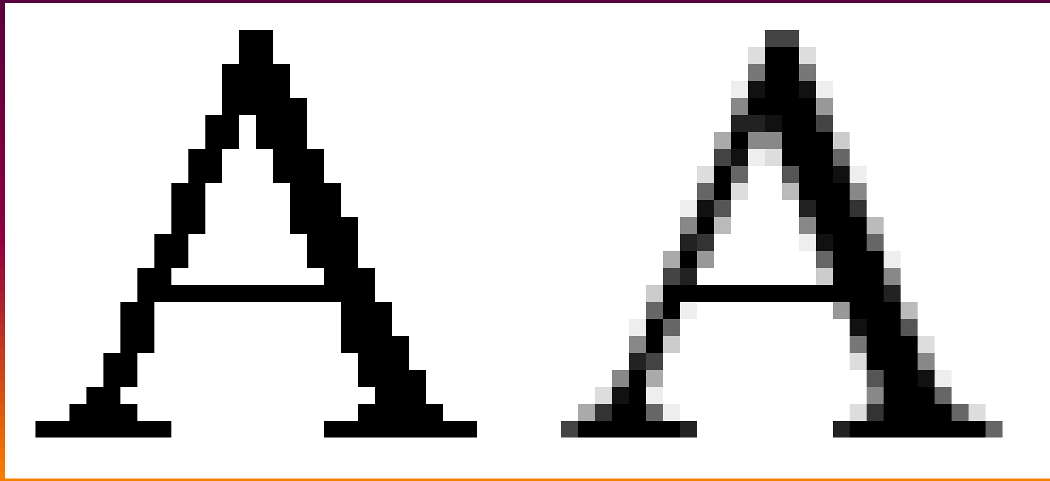
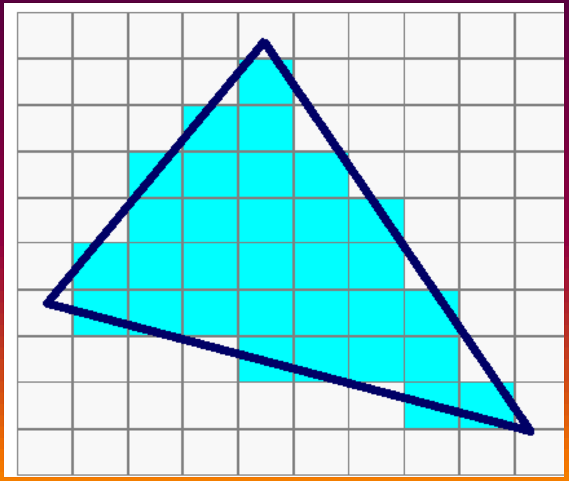
→ **Artifacts** **appear:** ***Aliasing,*** **stroboscopic effect, Moiré, ...**

Artifacts ...







Artifacts

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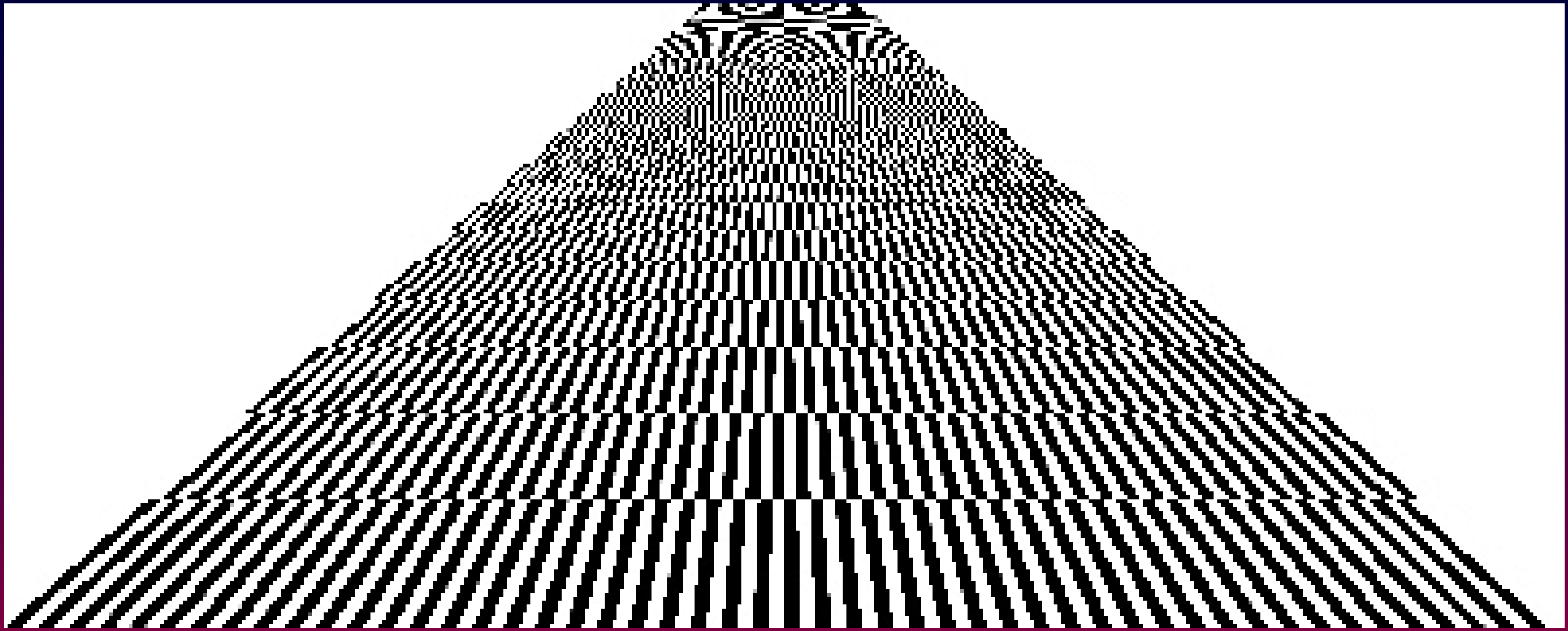
Artifacts ...



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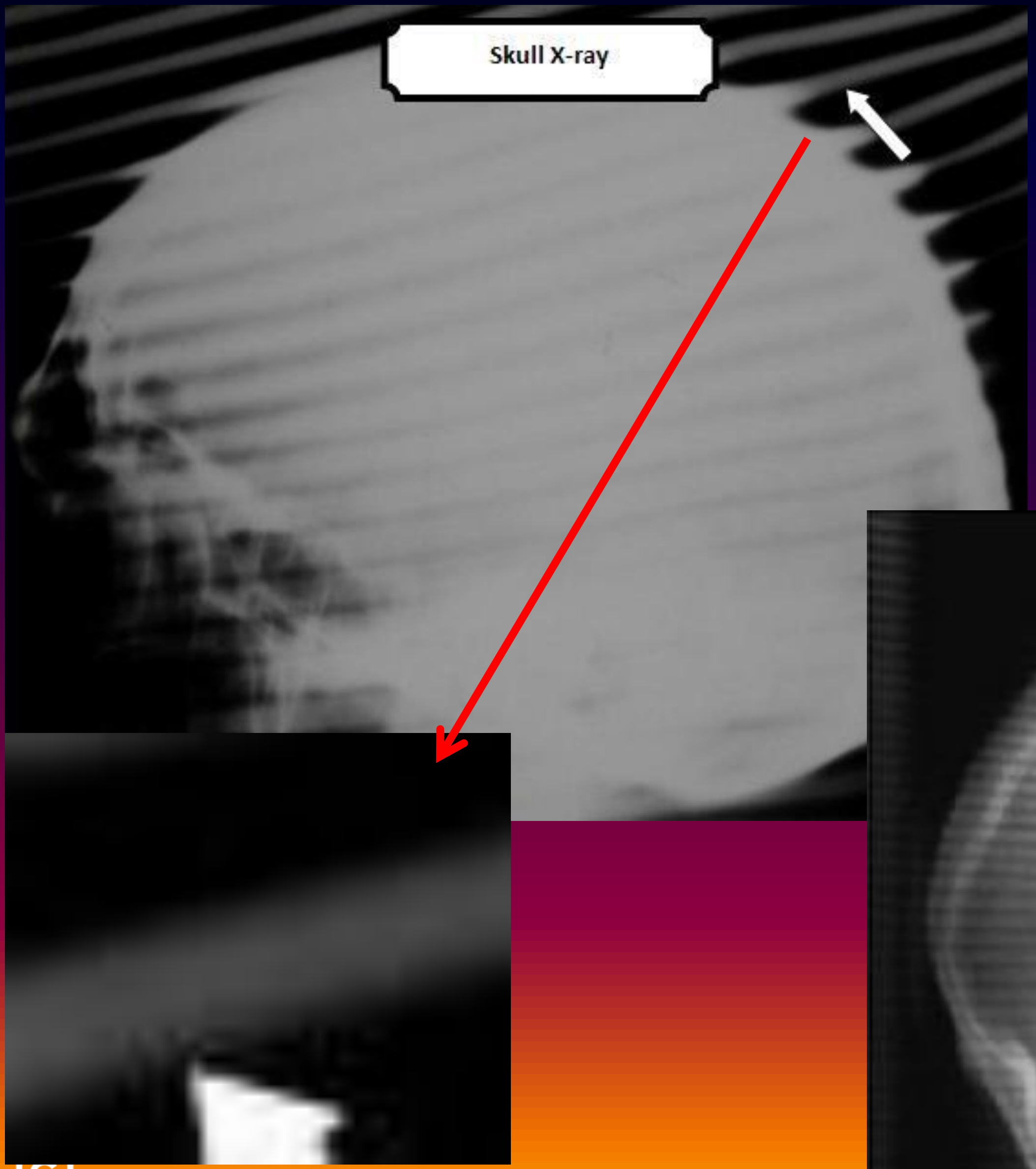
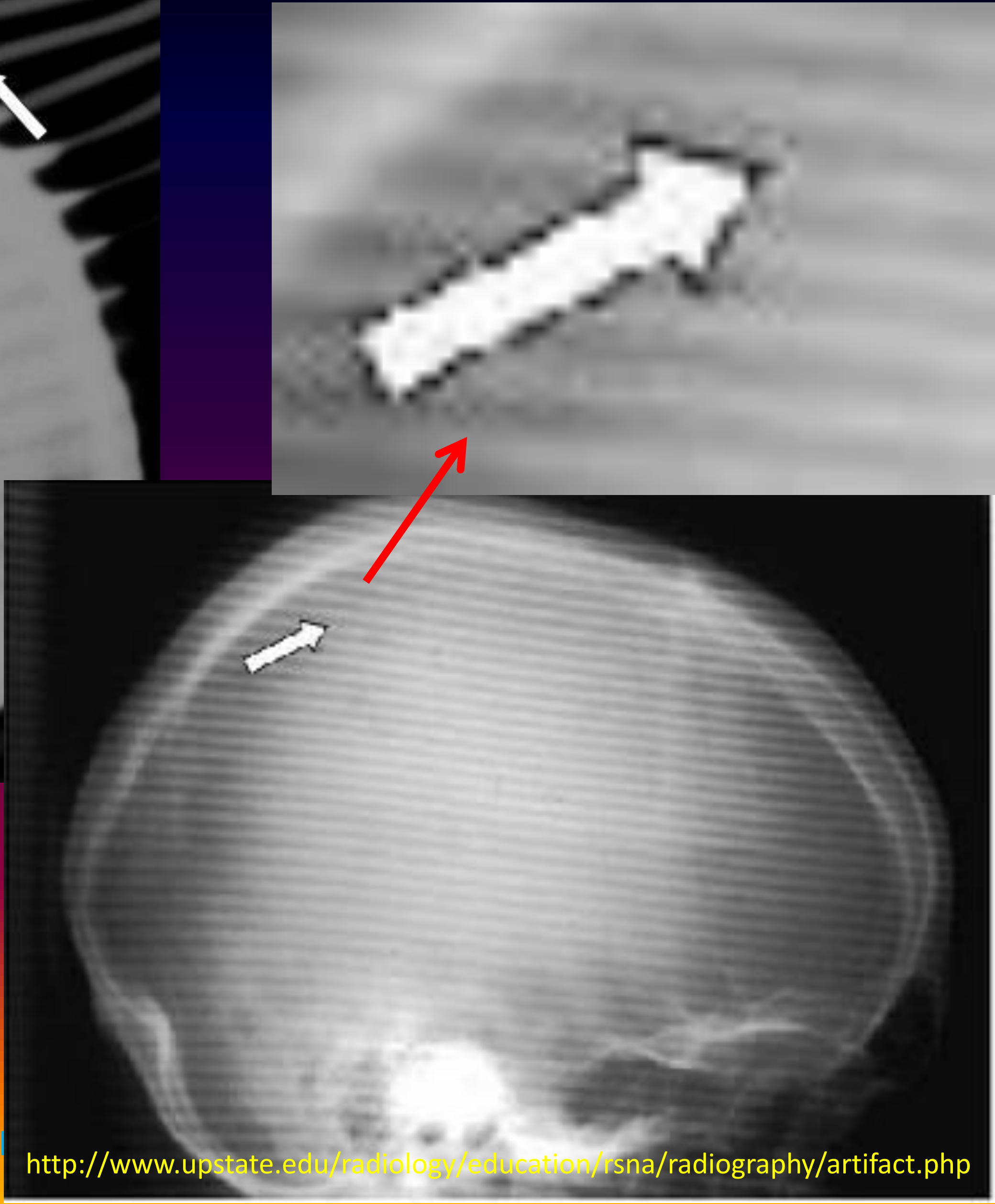
Artifacts …… in digital radiography



http://www.uospacs.com/eAtlas/artifact-with-blac



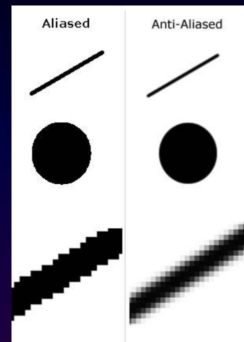
http://www.upstate.edu/radiology/education/rsna/radiography/artifact.php

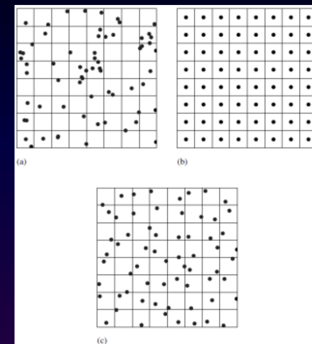
Artifacts …

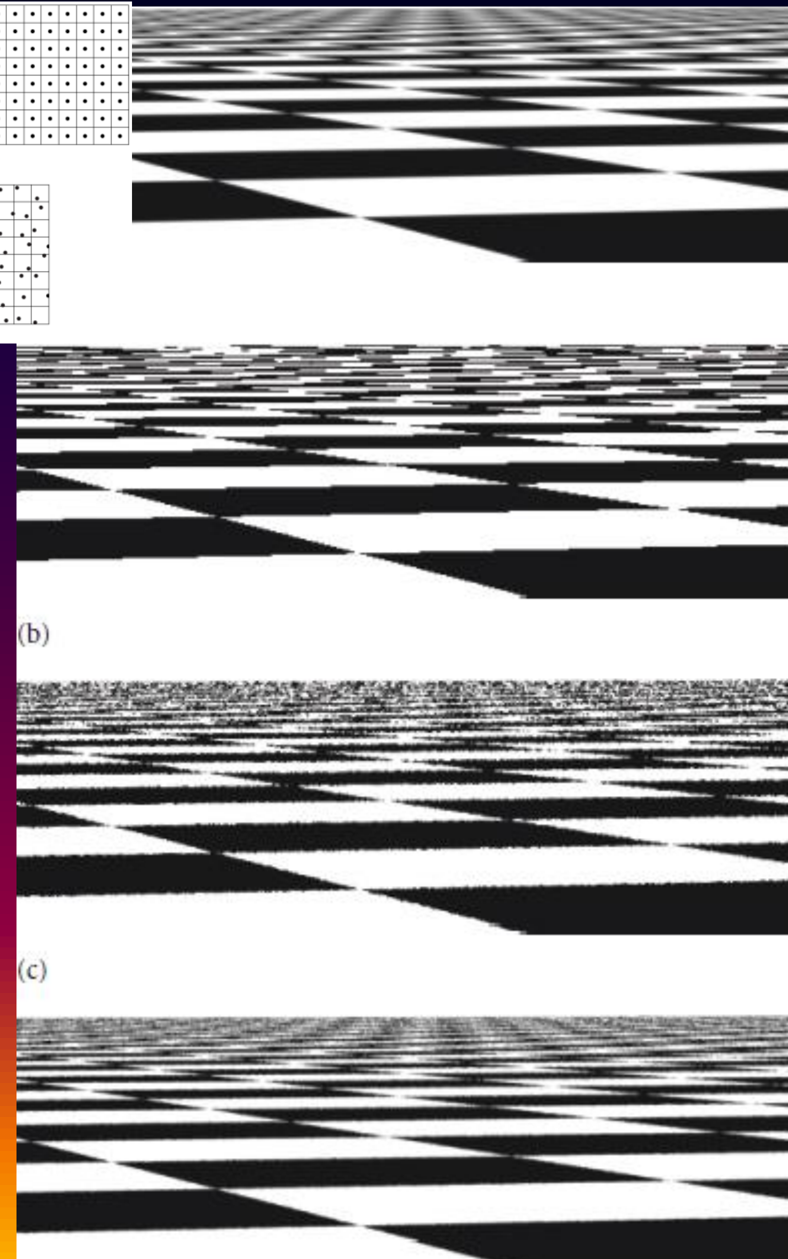
Aliasing → anti-aliasing

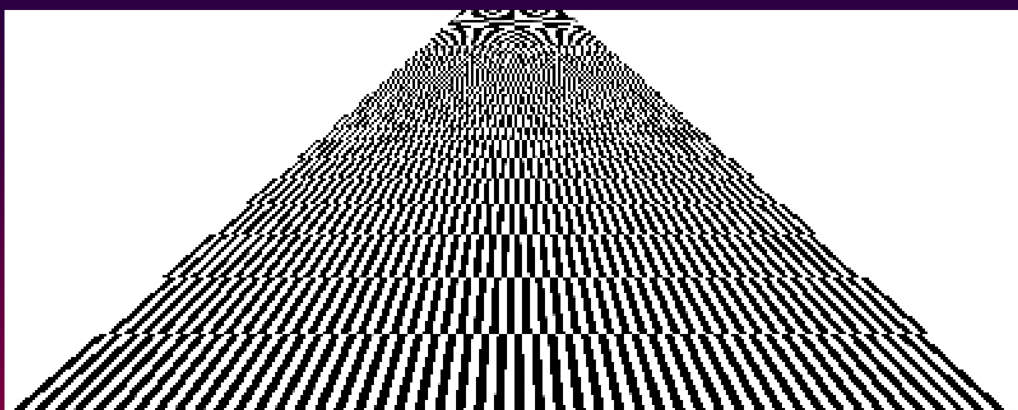
Sampling

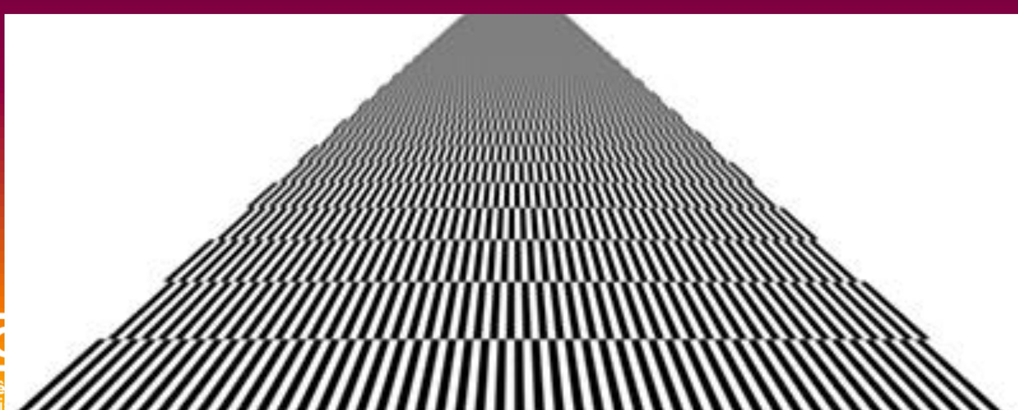
- Non-uniform
  - Stratified
- Adaptive
- Previous / later low-pass filtering











Aliasing → anti-aliasing

Sampling

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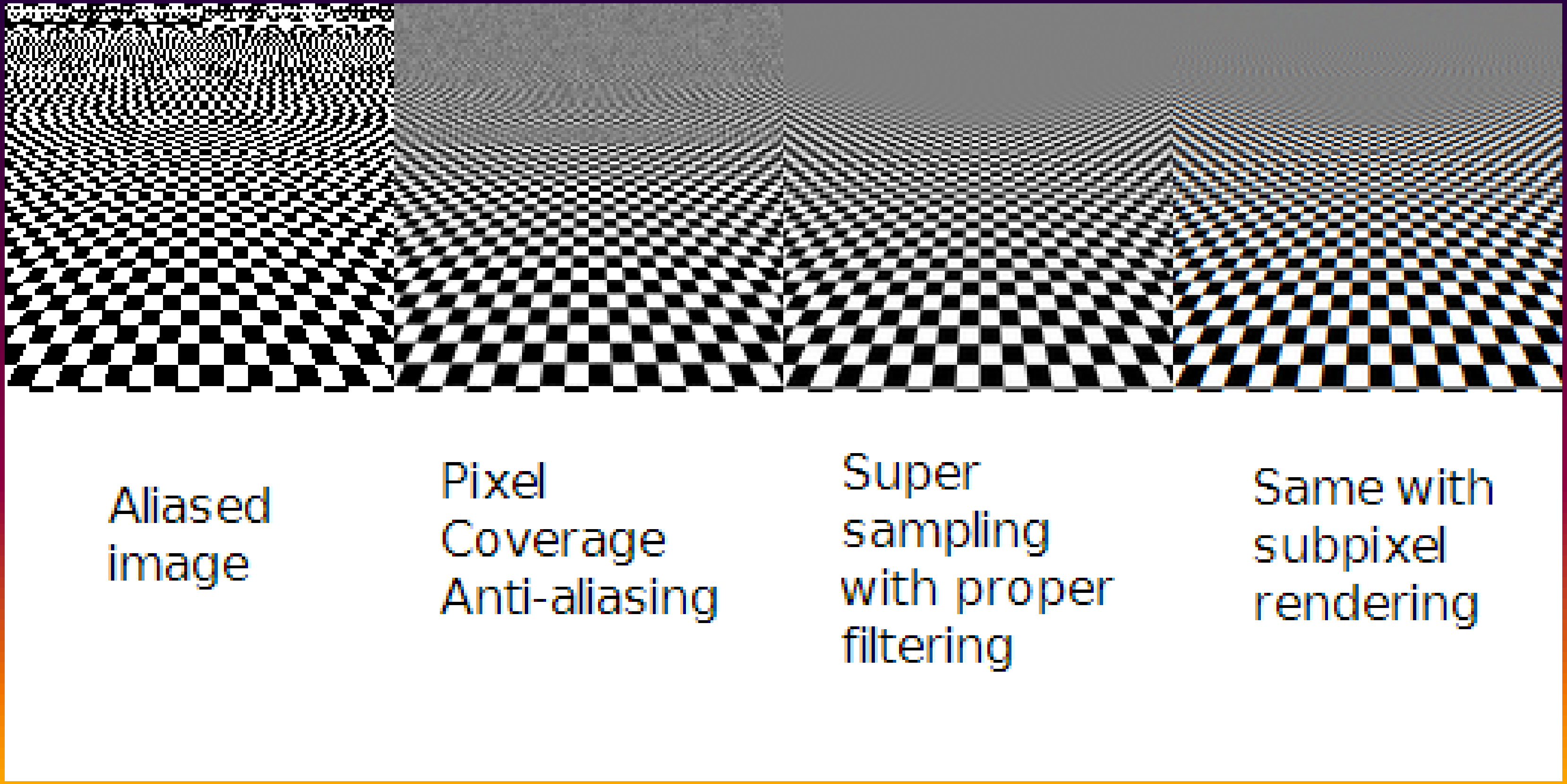

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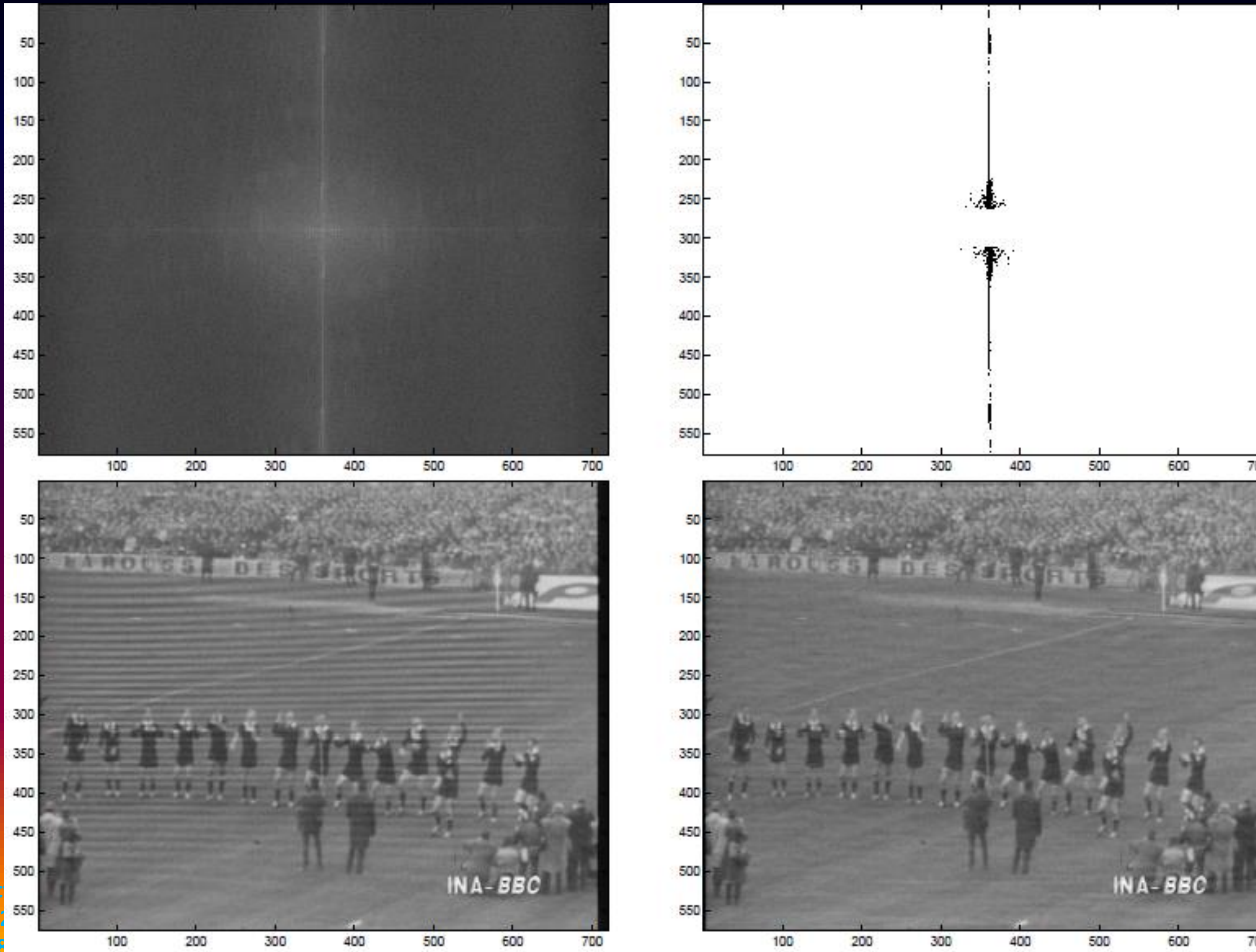
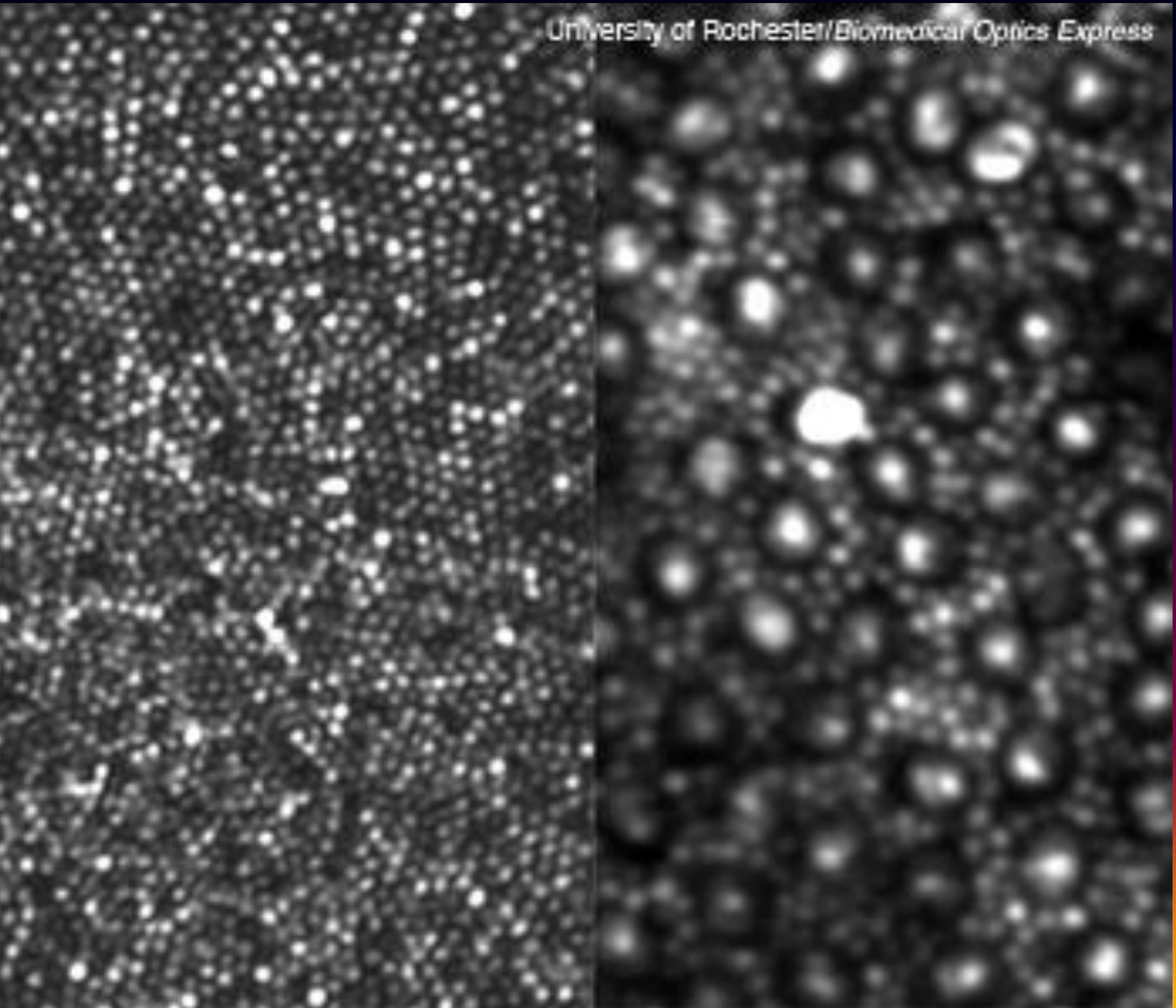
Low pass filtering – TV transmission



Retina sensors: non-uniform sensor network



Left

Cones in the centre of the retina (fovea)

Right:

Cones, bigger, with dark rings.

Rods, large numbers, smaller, around cones.

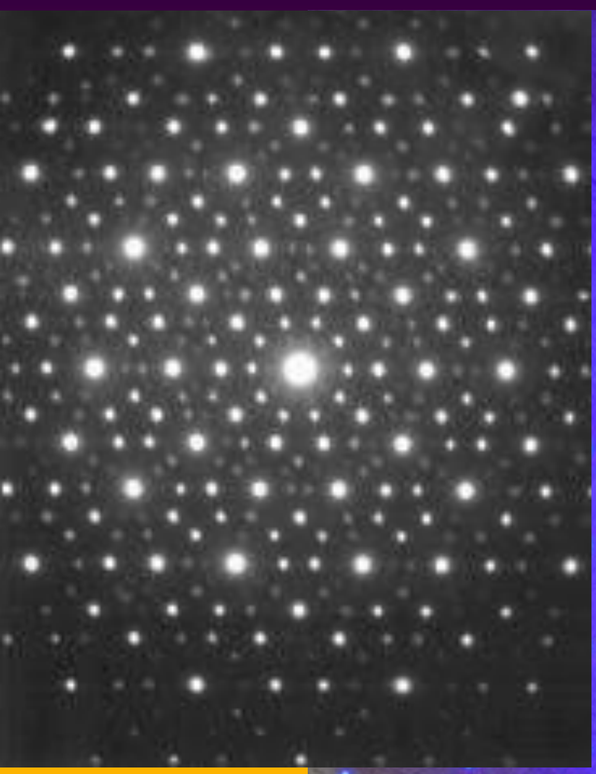
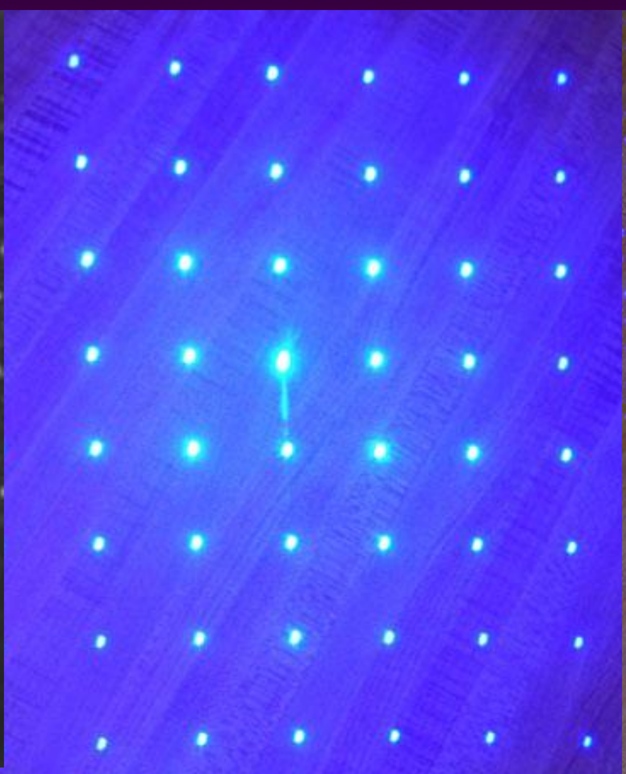
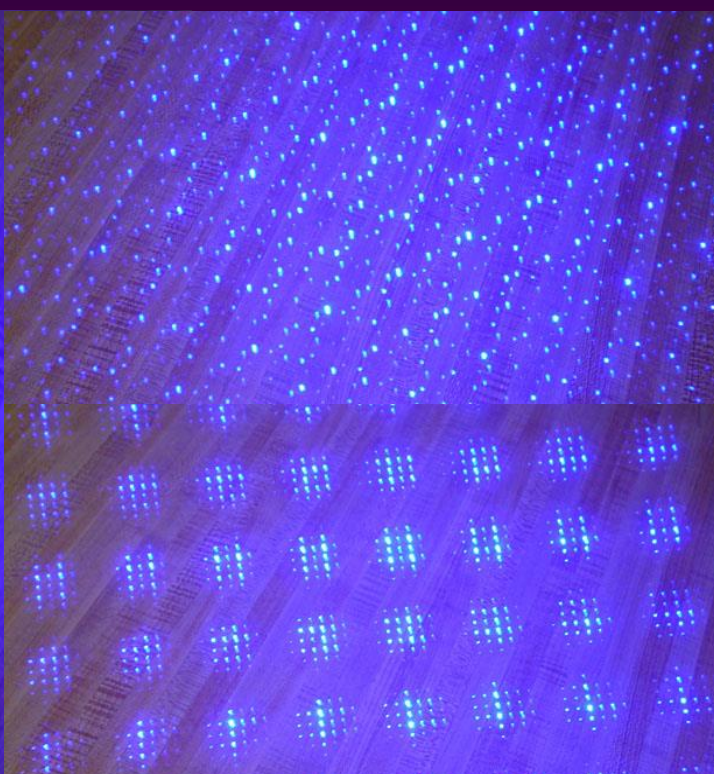
Scientists Image Rods in the Living Eye

Biomed. Opt. Express **2**, 1864, 2011; doi:10.1364/BOE.2.001864

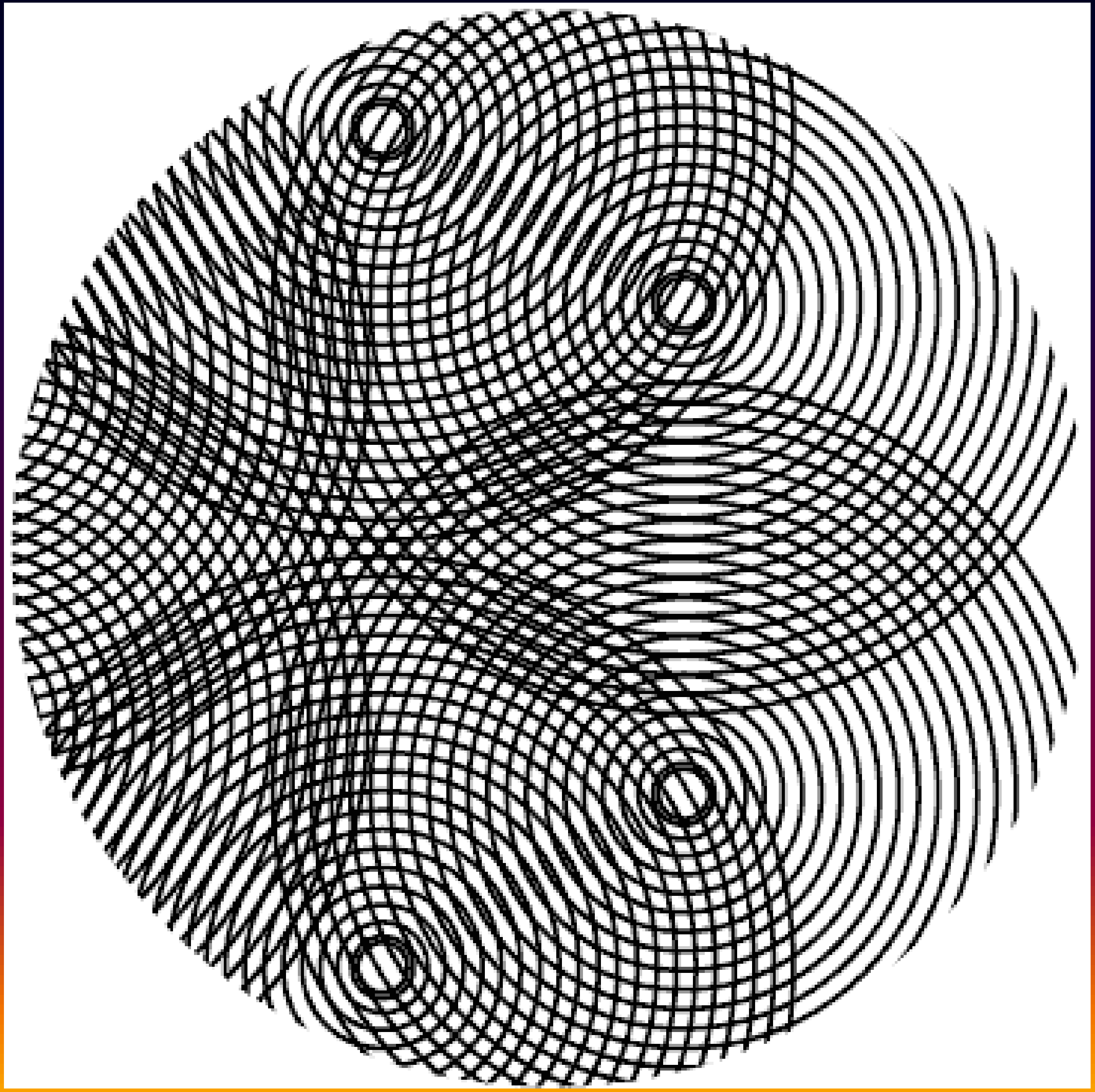
Artifacts do exist ... What now?

How to go beyond Shannon theory?

How to handle periodic objects → Large bandwidth Fourier spectra, quasi-periodic, with intense pulses in a regular pattern, with modulated intensity

X Superposition of 5 periodic objects?



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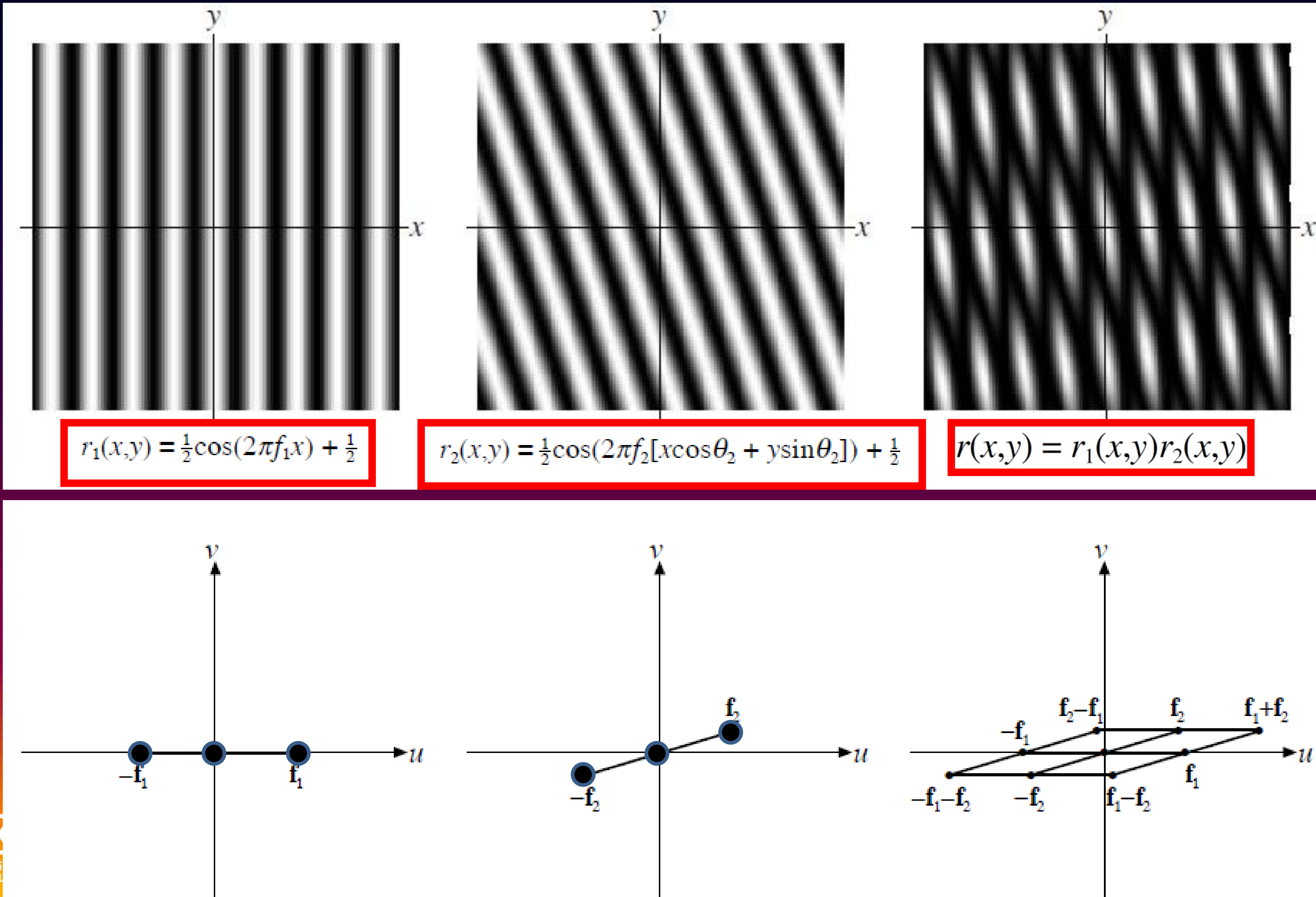
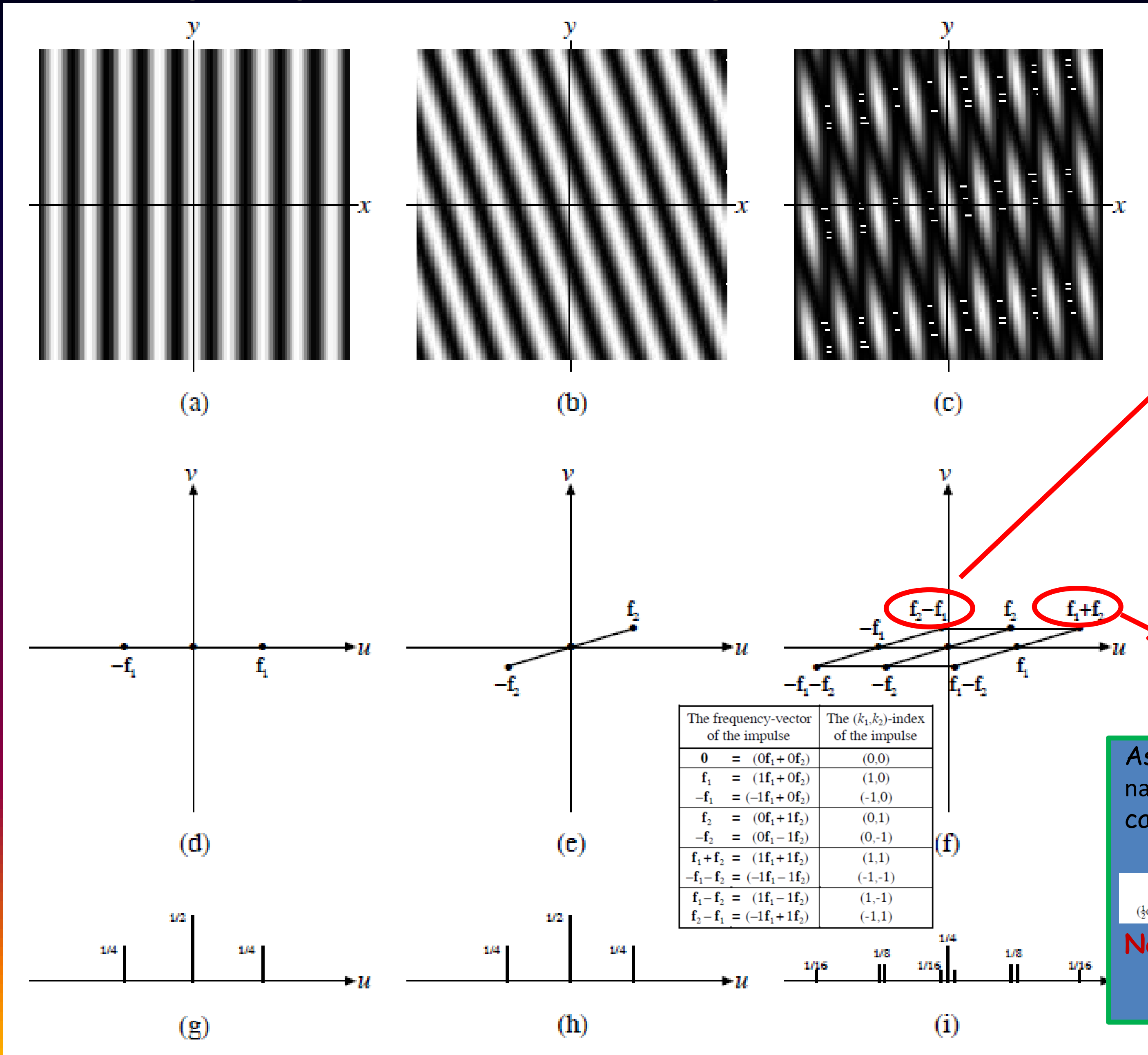
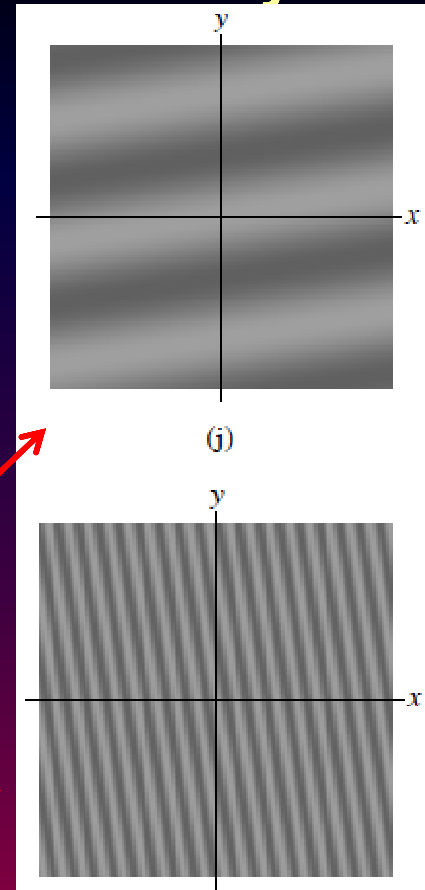
Exemple: X Superposition of 2 periodic harmonic objects



X Superposition of 2 periodic harmonic objects



The frequency-vector of the impulse	The (k_1,k_2)-index of the impulse
$\mathbf{0} = (0\mathbf{f}_1 + 0\mathbf{f}_2)$	(0,0)
$\mathbf{f}_1 = (1\mathbf{f}_1 + 0\mathbf{f}_2)$	(1,0)
$-\mathbf{f}_1 = (-1\mathbf{f}_1 + 0\mathbf{f}_2)$	(-1,0)
$\mathbf{f}_2 = (0\mathbf{f}_1 + 1\mathbf{f}_2)$	(0,1)
$-\mathbf{f}_2 = (0\mathbf{f}_1 - 1\mathbf{f}_2)$	(0,-1)
$\mathbf{f}_1+\mathbf{f}_2 = (1\mathbf{f}_1 + 1\mathbf{f}_2)$	(1,1)
$-\mathbf{f}_1-\mathbf{f}_2 = (-1\mathbf{f}_1 - 1\mathbf{f}_2)$	(-1,-1)
$\mathbf{f}_1-\mathbf{f}_2 = (1\mathbf{f}_1 - 1\mathbf{f}_2)$	(1,-1)
$\mathbf{f}_2-\mathbf{f}_1 = (-1\mathbf{f}_1 + 1\mathbf{f}_2)$	(-1,1)



(j)

As frequências $\mathbf{f_1}$ e $\mathbf{f_2}$ só existem na imagem de sobreposição por causa dos termos DC em r_1 e r_2:

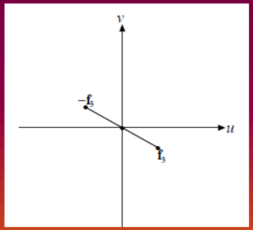
$$\cos\alpha \cos\beta = \tfrac{1}{2}\cos(\alpha-\beta) + \tfrac{1}{2}\cos(\alpha+\beta)$$

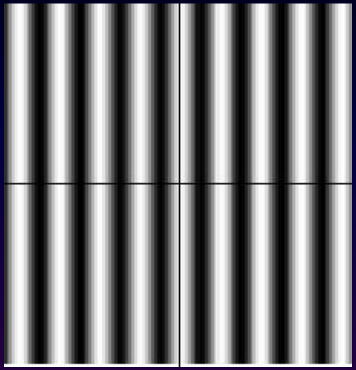
$$(\tfrac{1}{2}\cos\alpha + \tfrac{1}{2})(\tfrac{1}{2}\cos\beta + \tfrac{1}{2}) = \tfrac{1}{4} + \tfrac{1}{4}\cos\alpha + \tfrac{1}{4}\cos\beta + \tfrac{1}{8}\cos(\alpha-\beta) + \tfrac{1}{8}\cos(\alpha+\beta)$$

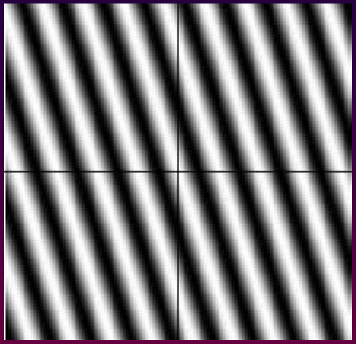
Notação (para 2 redes):

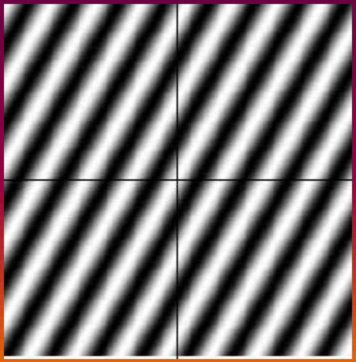
$\mathbf{f} = n\,\mathbf{f_1} + m\,\mathbf{f_2} \rightarrow (n,m)$

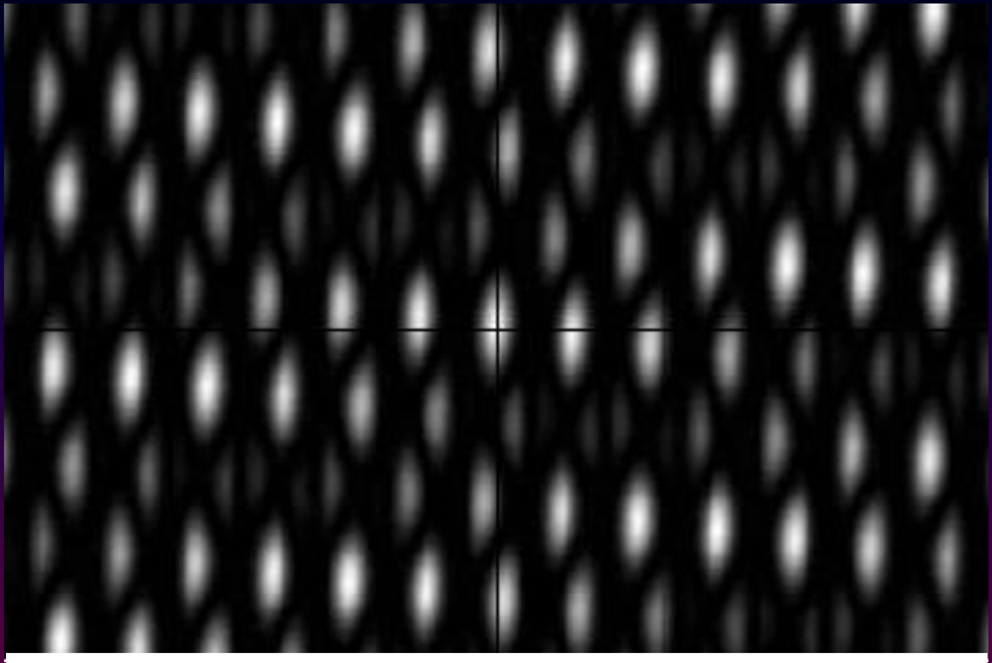
X Superposition of 3 periodic harmonic objects

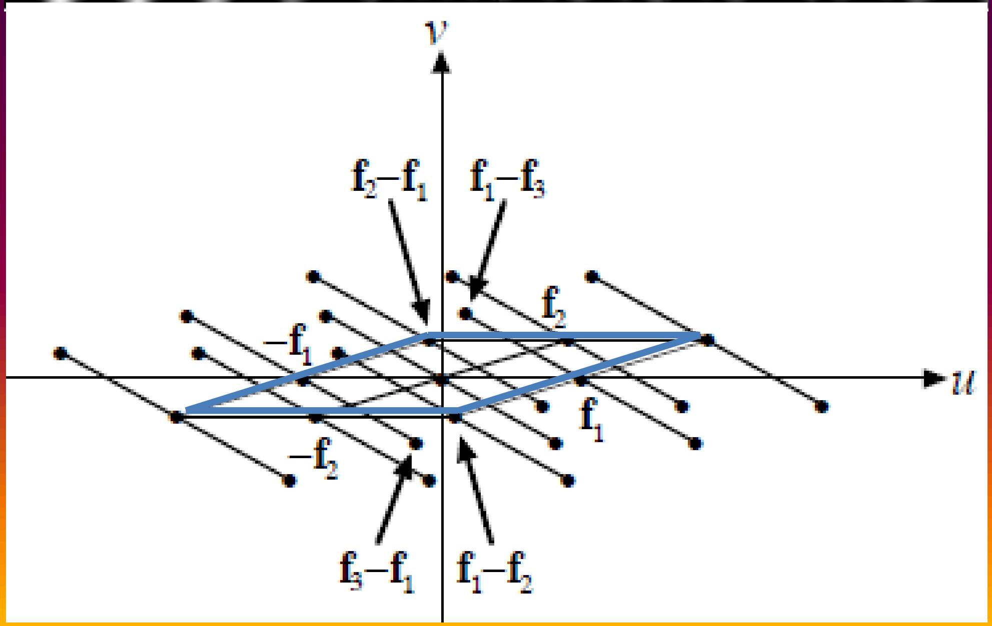




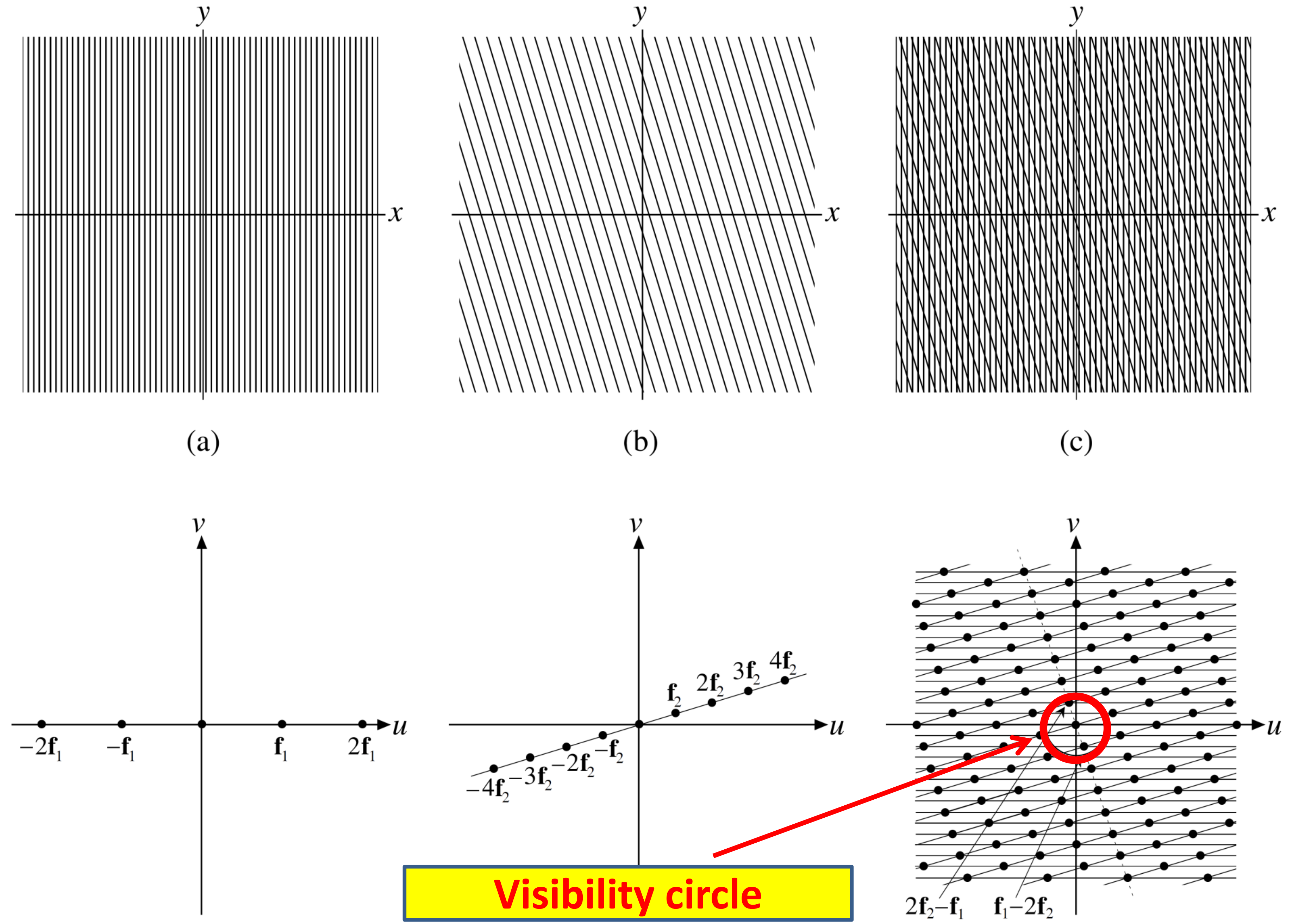






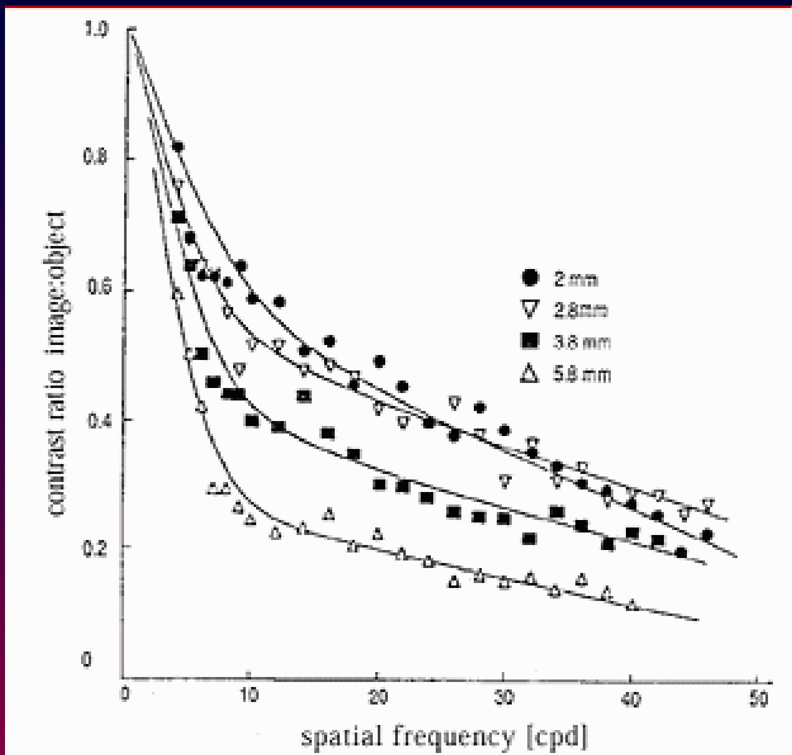


Superposition of non-harmonic periodic objects

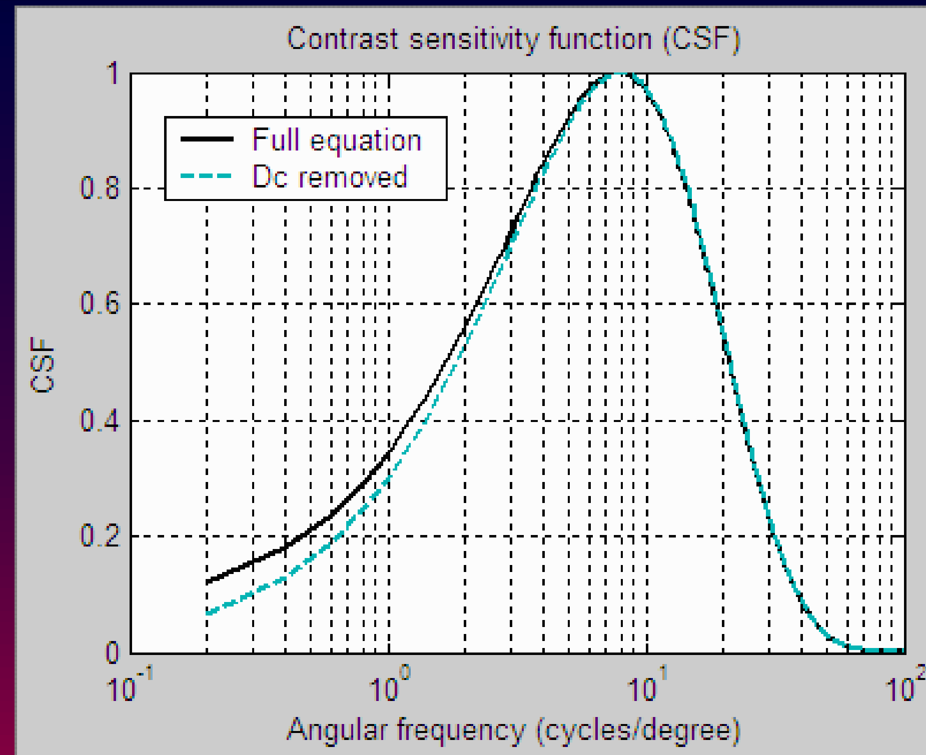


Visual band

MTF



CSF



Cutoff frequency: 60 cycles/º (2 mm pupil)

~ 250 dpi @ 30 cm (~ 0.1 mm @ 30 cm)

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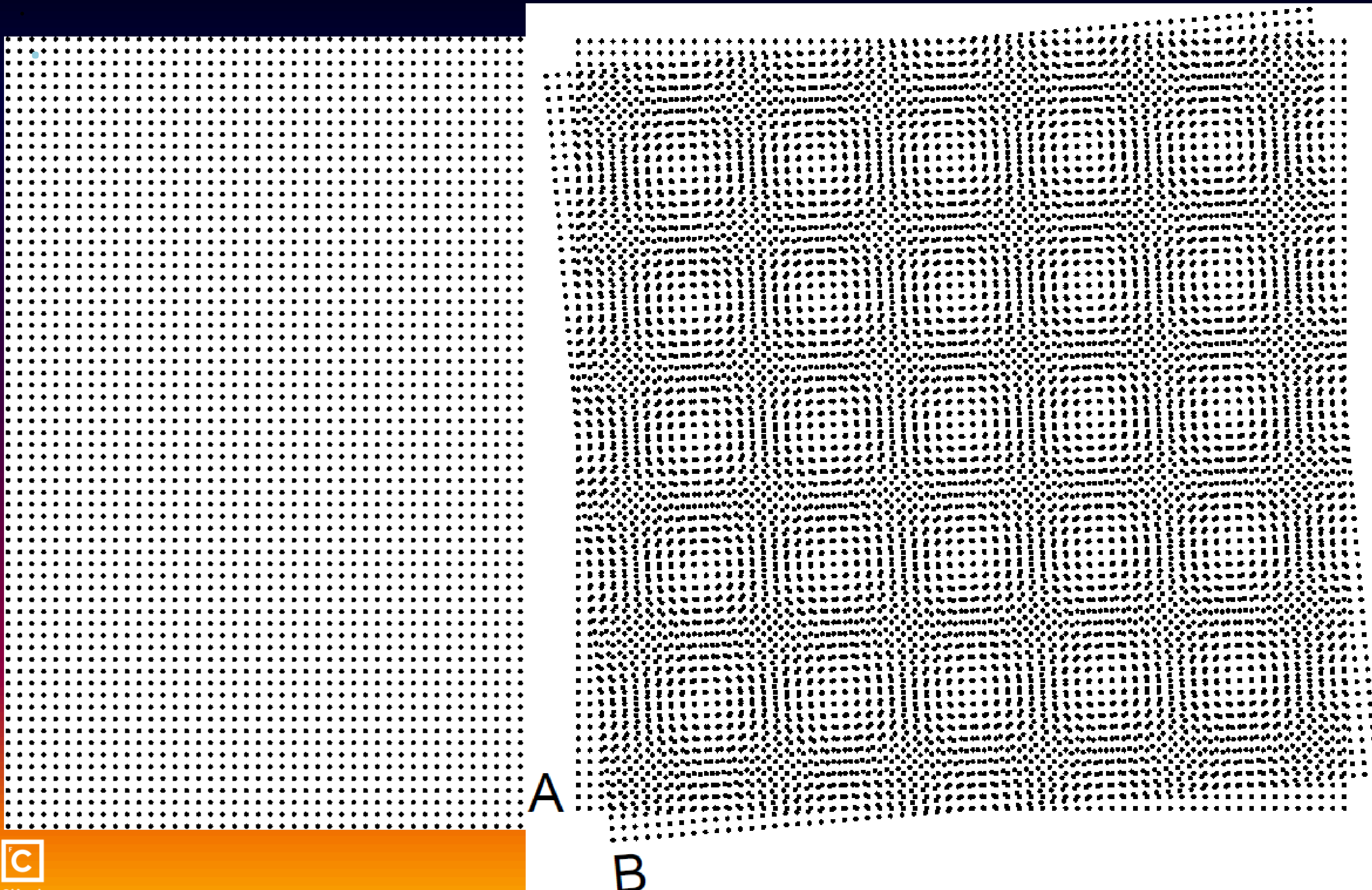
Superposition (X) of periodic 2D objects



Ciências
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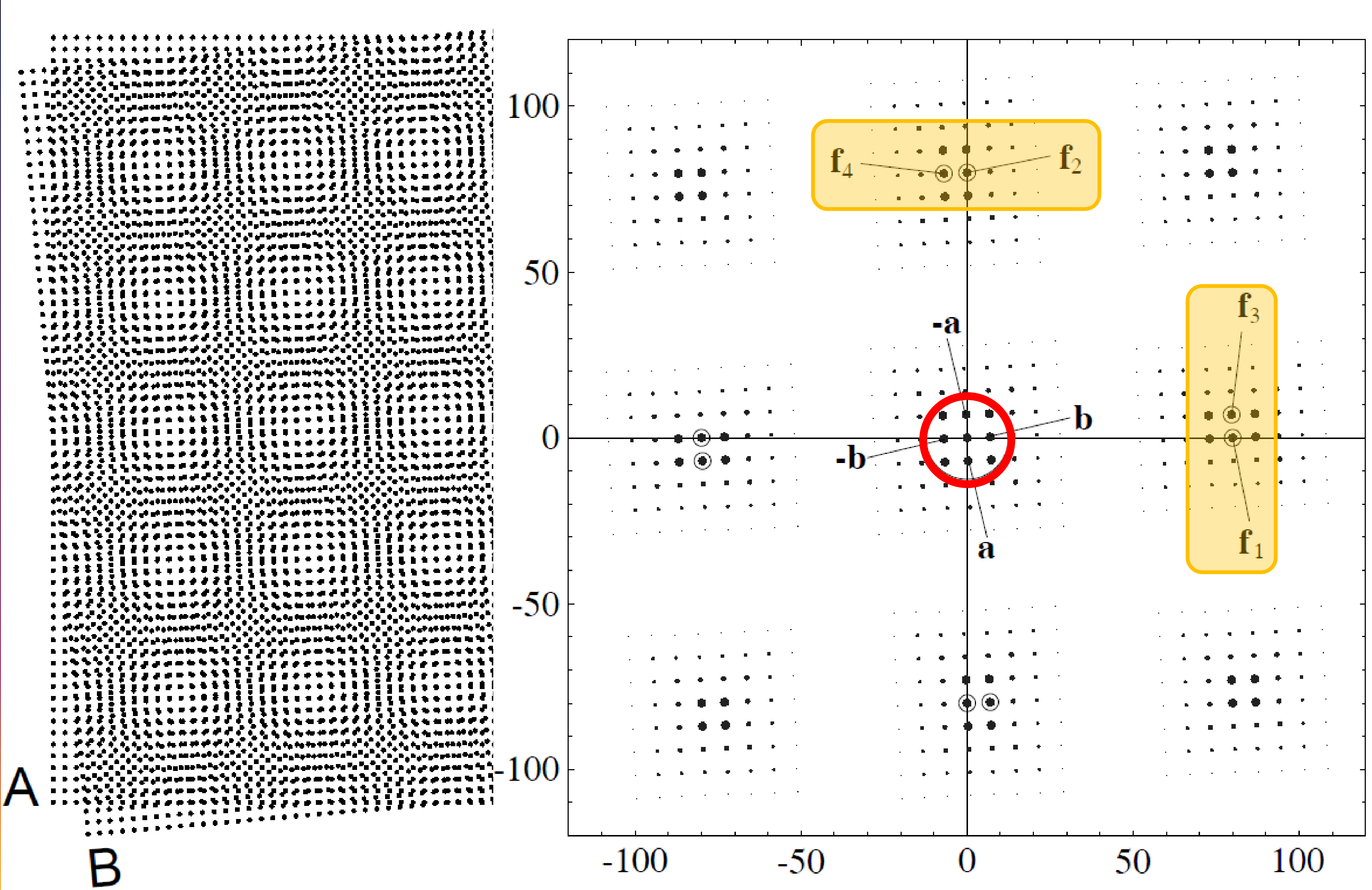
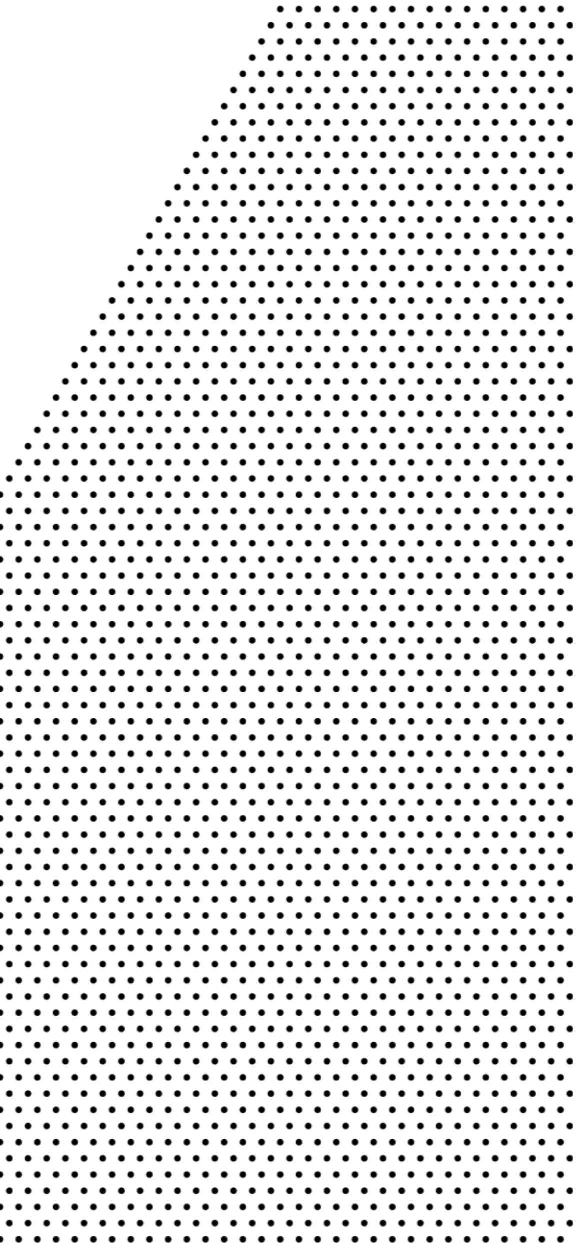
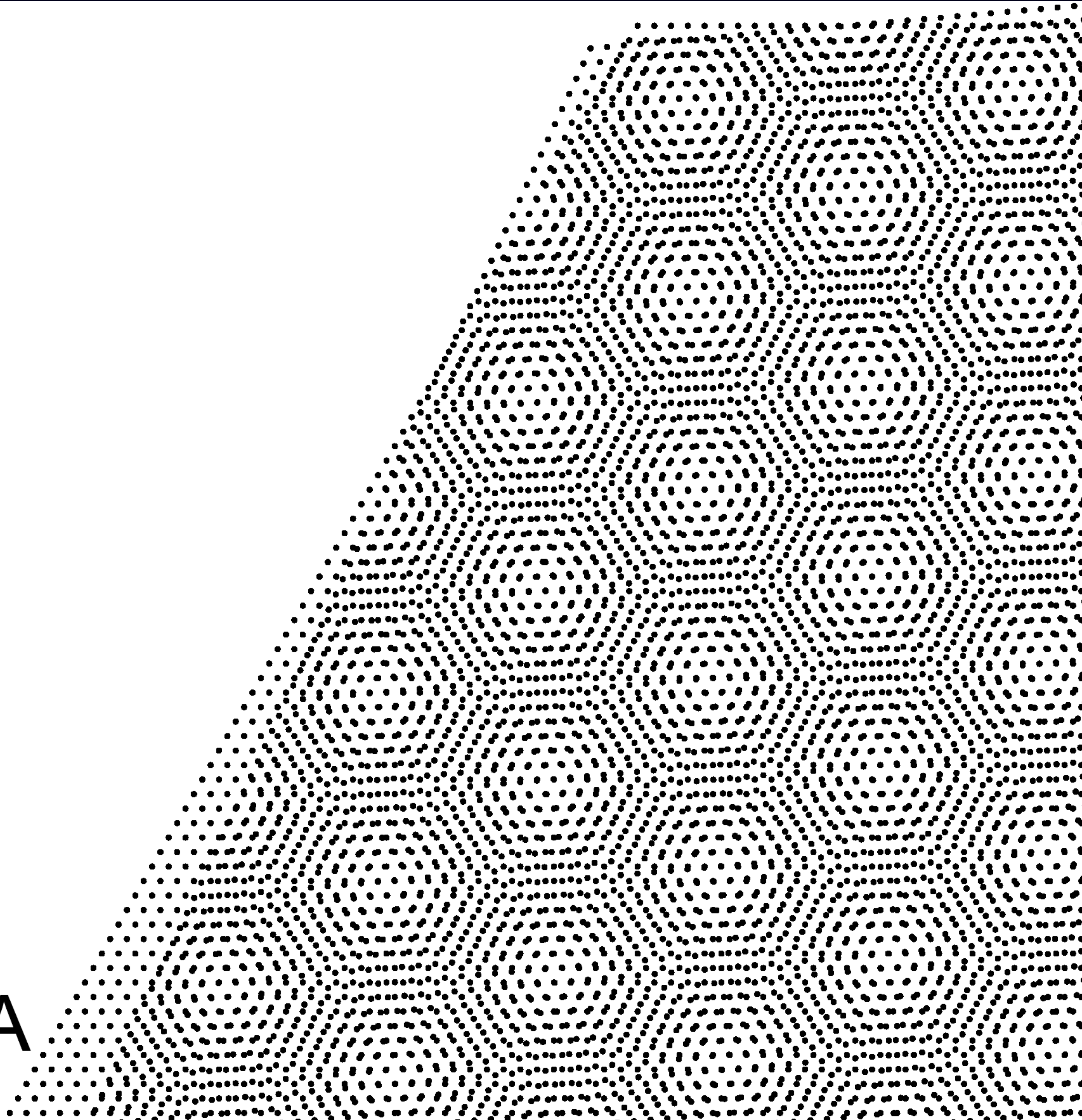
Superposition (X) of periodic 2D objects



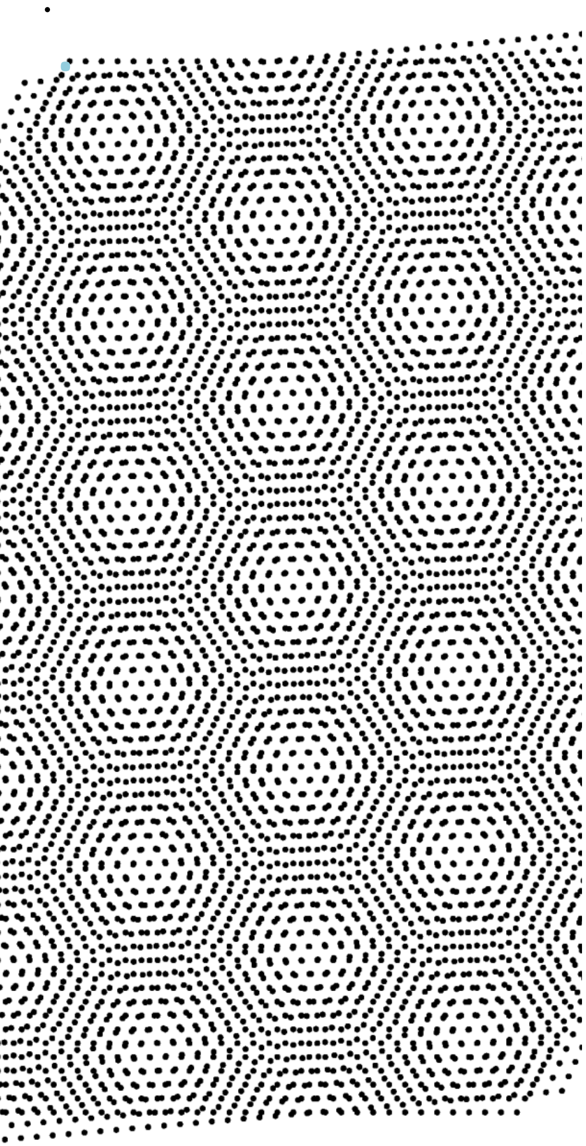
Superposition (X) of periodic 2D objects (hexagonal)

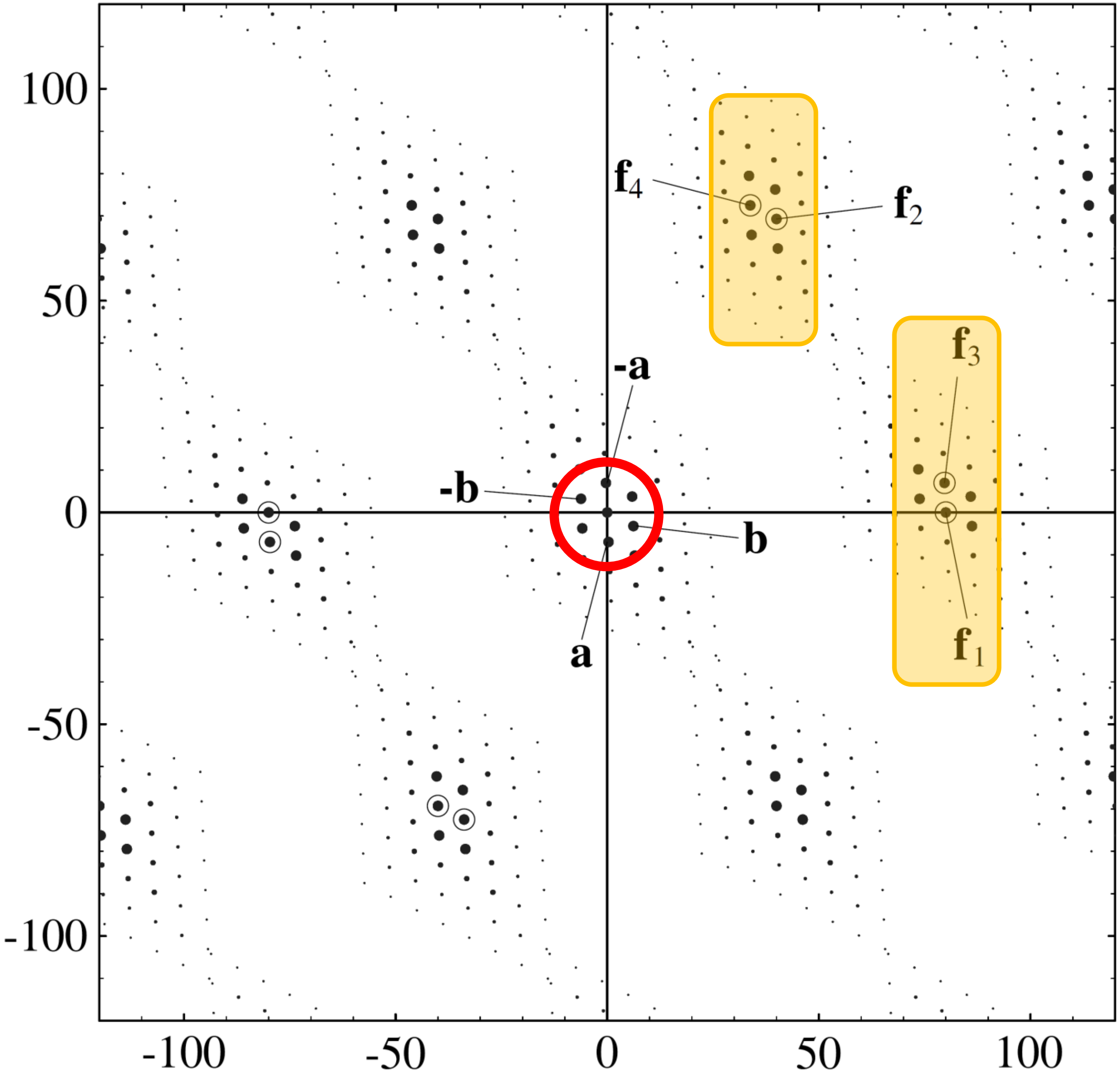




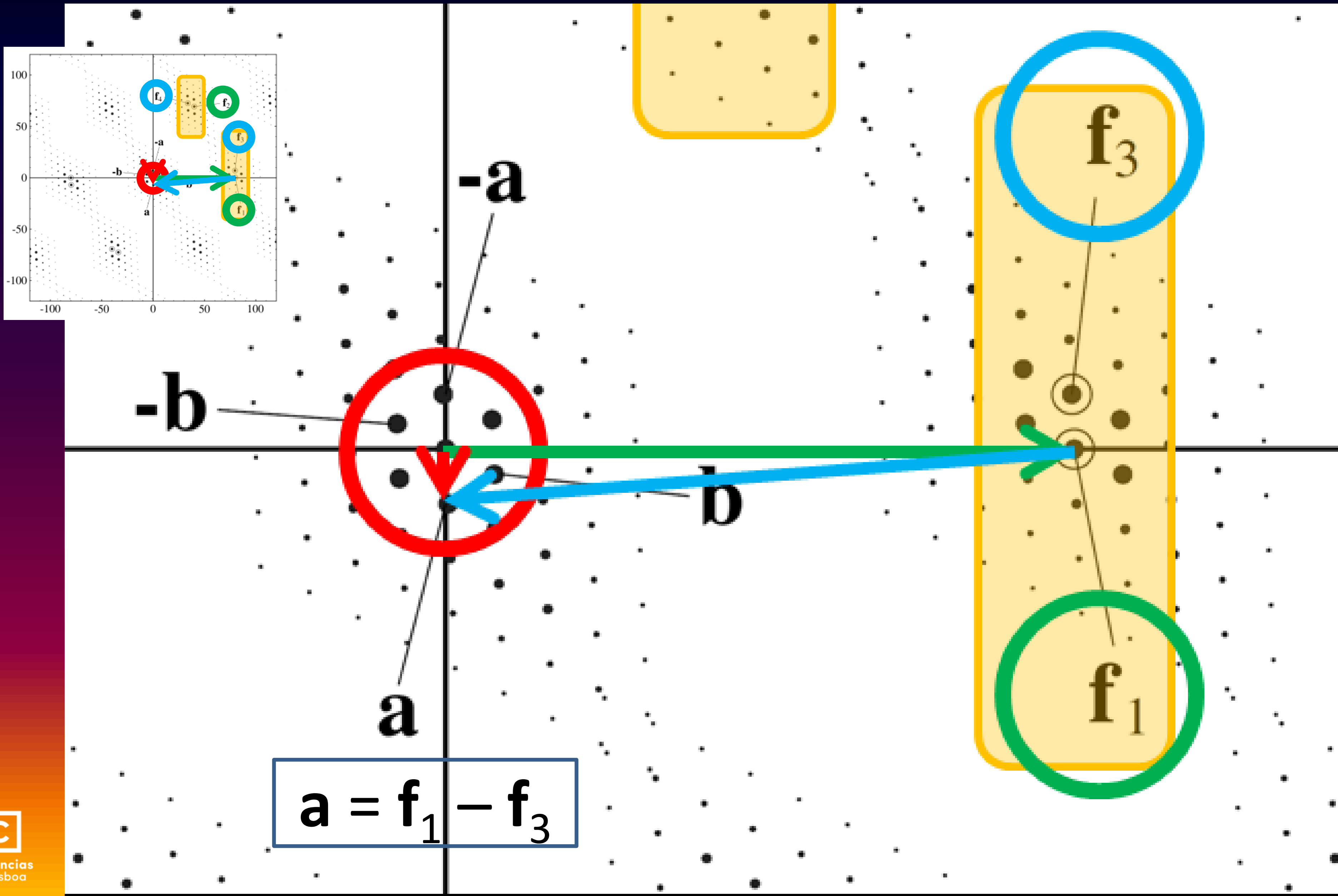
A

Superposition (X) of periodic 2D objects





Superposition (X) of periodic 2D objects



$a = f_1 - f_3$

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Very important!

Generating low frequencies within the visibility circle, from non-visible high frequencies (100,000 dpi → 0.25 μm), enables applications in:

- **In document security**
  - ***Scrambled indicia,*** **hidden images, modulations, digital watermarking, …**
- **In image or video coding**

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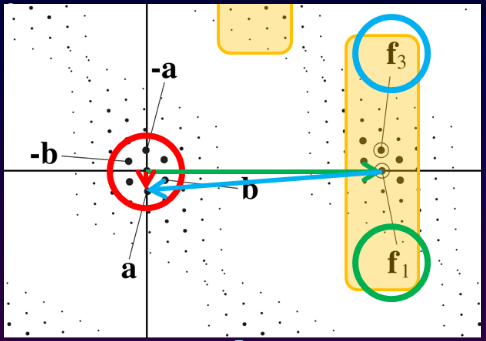
In general:

Anywhere – and also within the **visibility circle**:



$$\mathbf{f} = \sum_{i=1}^{m} k_i \, \mathbf{f}_i$$

In particular, it may happen that, from the combination of frequencies, a **singular state** appears:

$$\mathbf{f} = \sum_{i=1}^{m} k_i \, \mathbf{f}_i = \mathbf{0}$$

Distinguishing stable from unstable or singular states is of utmost importance for Moiré applications or to mitigate Moiré effects.

Unstable states ...?

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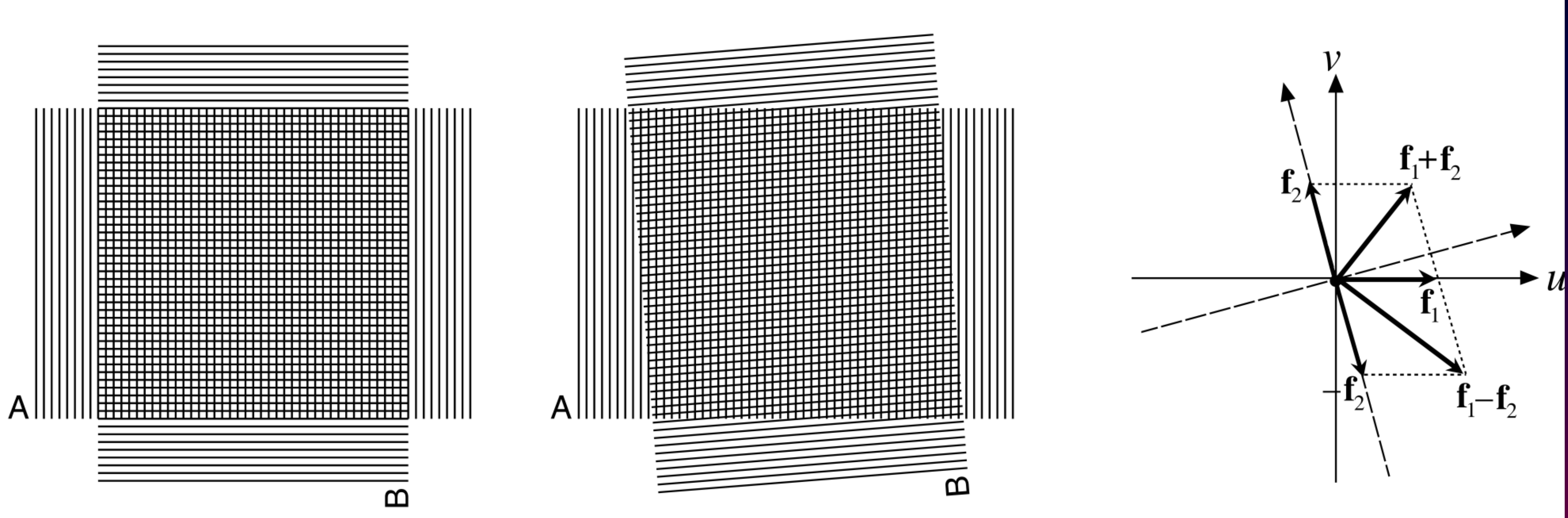
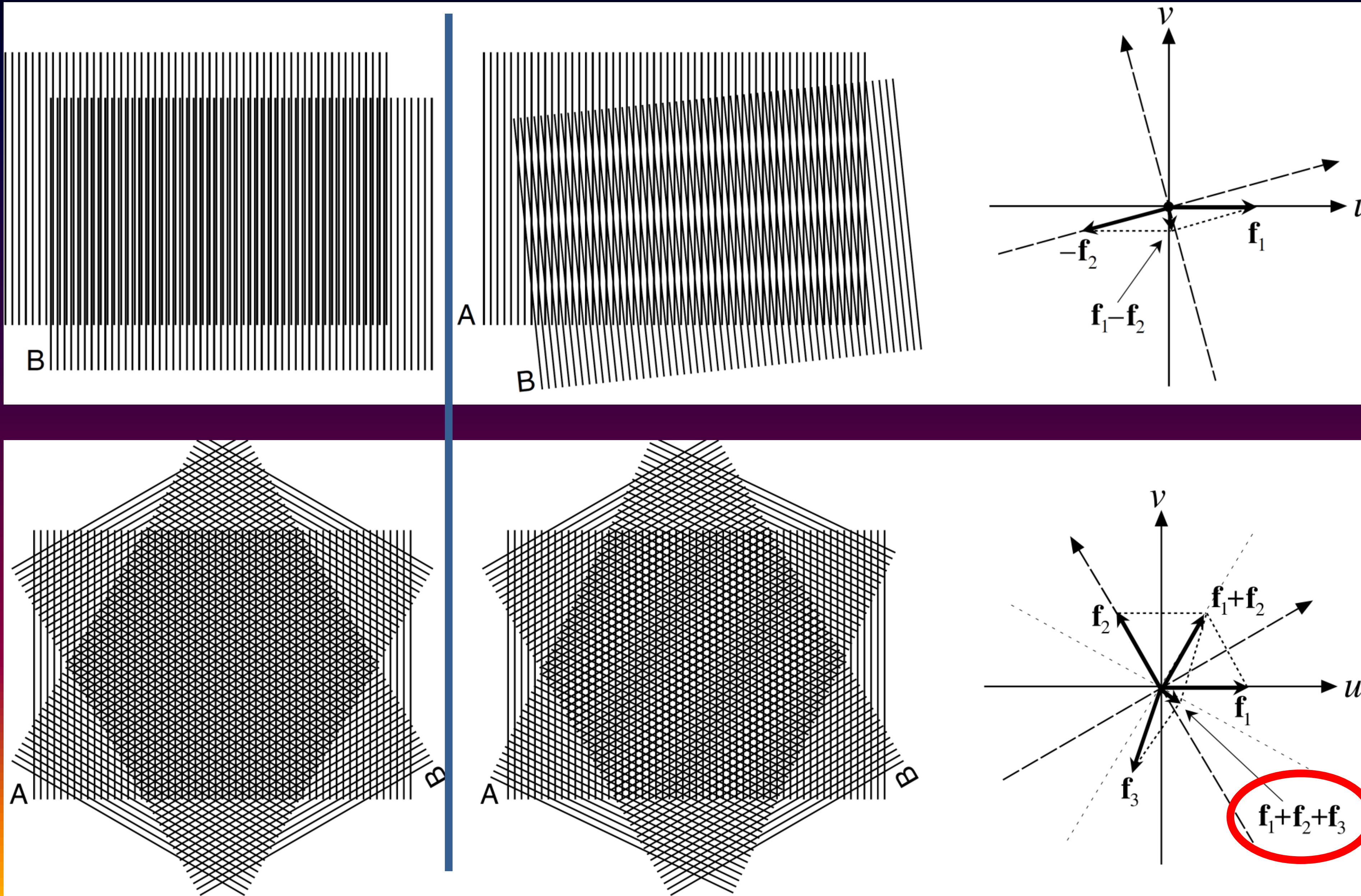
Stability

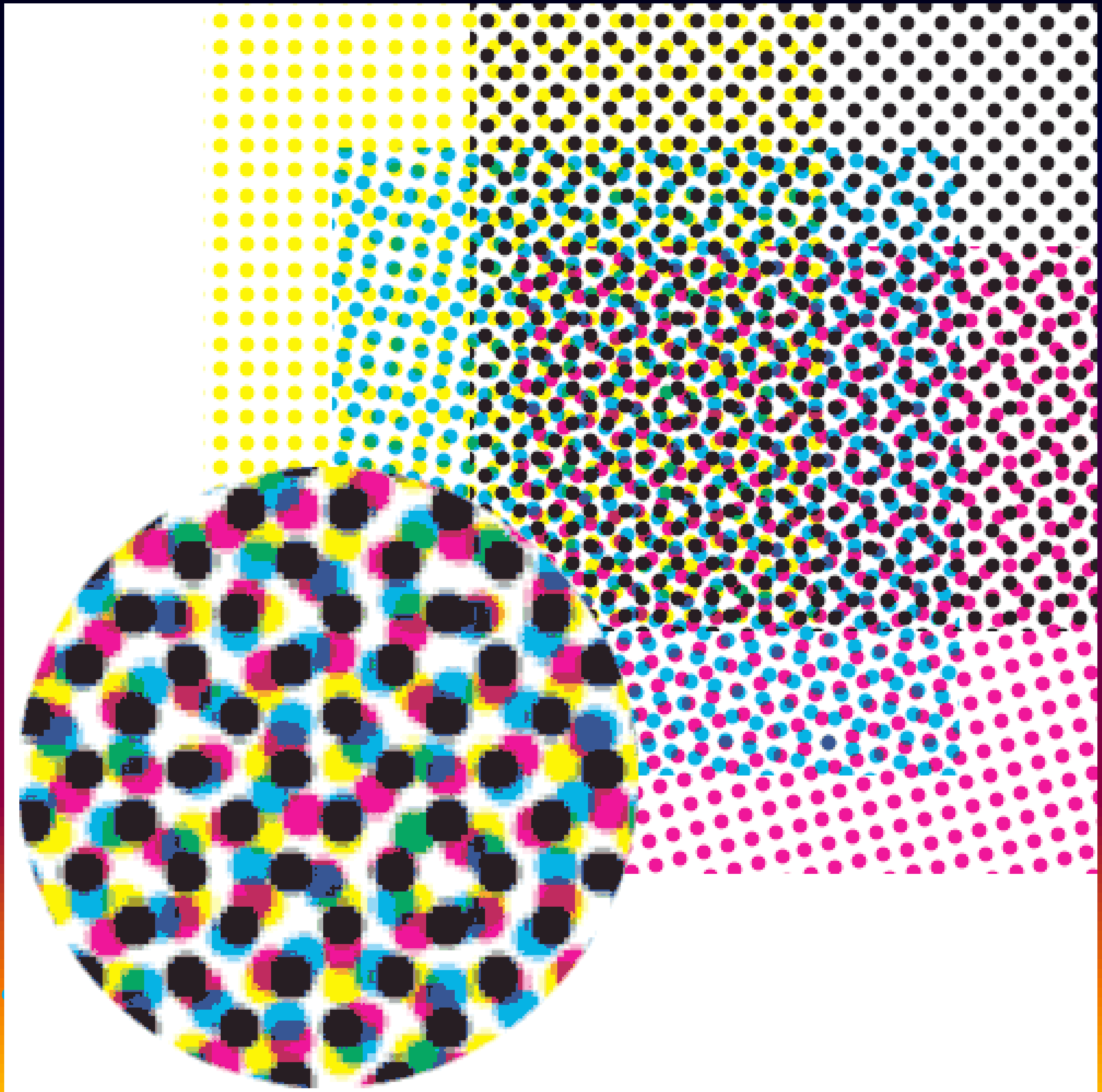


A
B
A
B
v
u
$\mathbf{f}_1+\mathbf{f}_2$
$\mathbf{f}_2$
$\mathbf{f}_1$
$-\mathbf{f}_2$
$\mathbf{f}_1-\mathbf{f}_2$

Instability



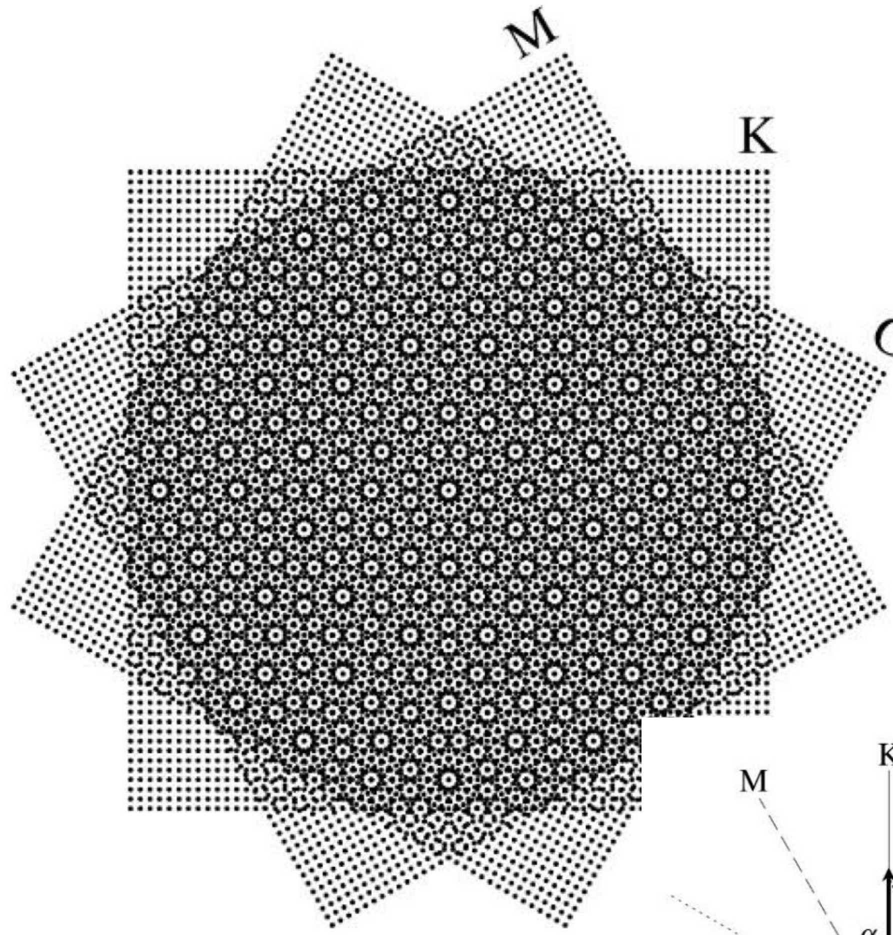
Printing: 4 meshes, singular state unstable

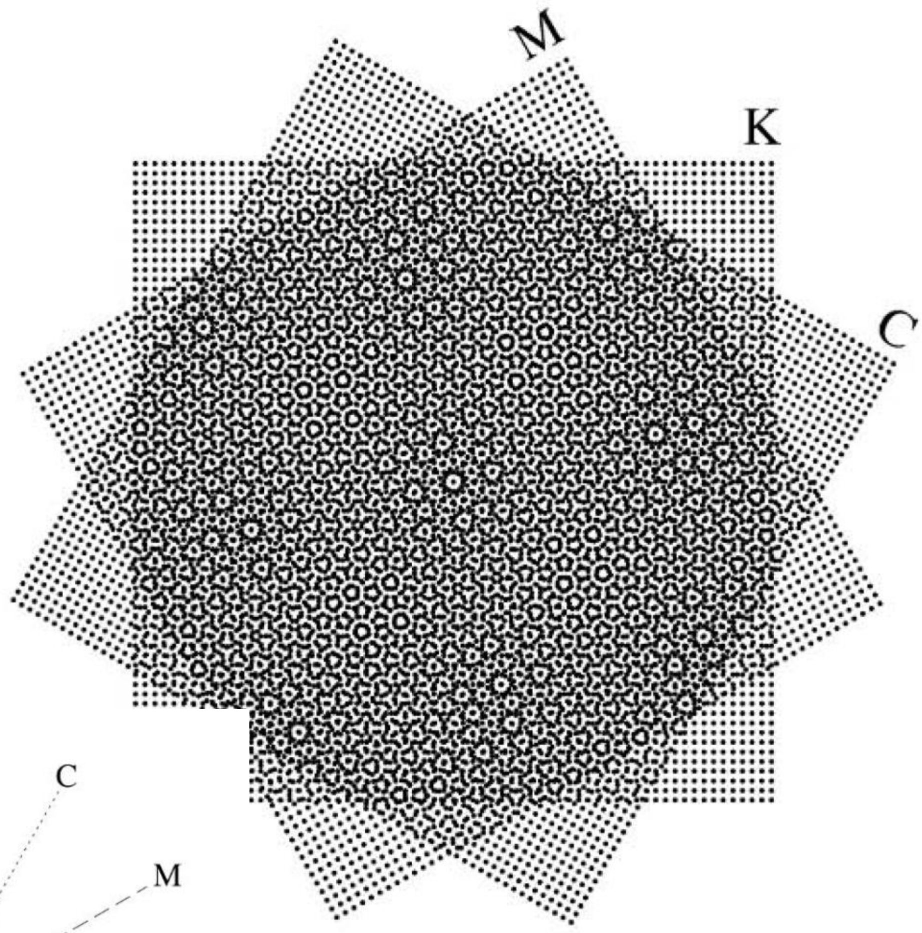


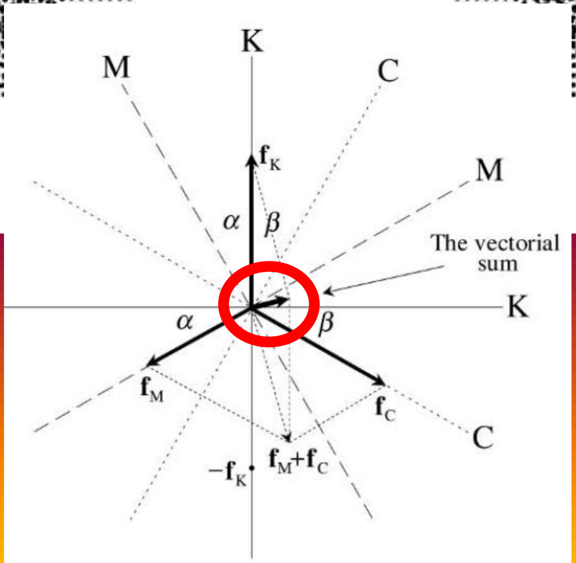
http://3.bp.blogspot.

Ciências ULisboa

Printing: 4 meshes, singular state unstable







Currently, in industry:
M, K, C a 30º

Other solution →

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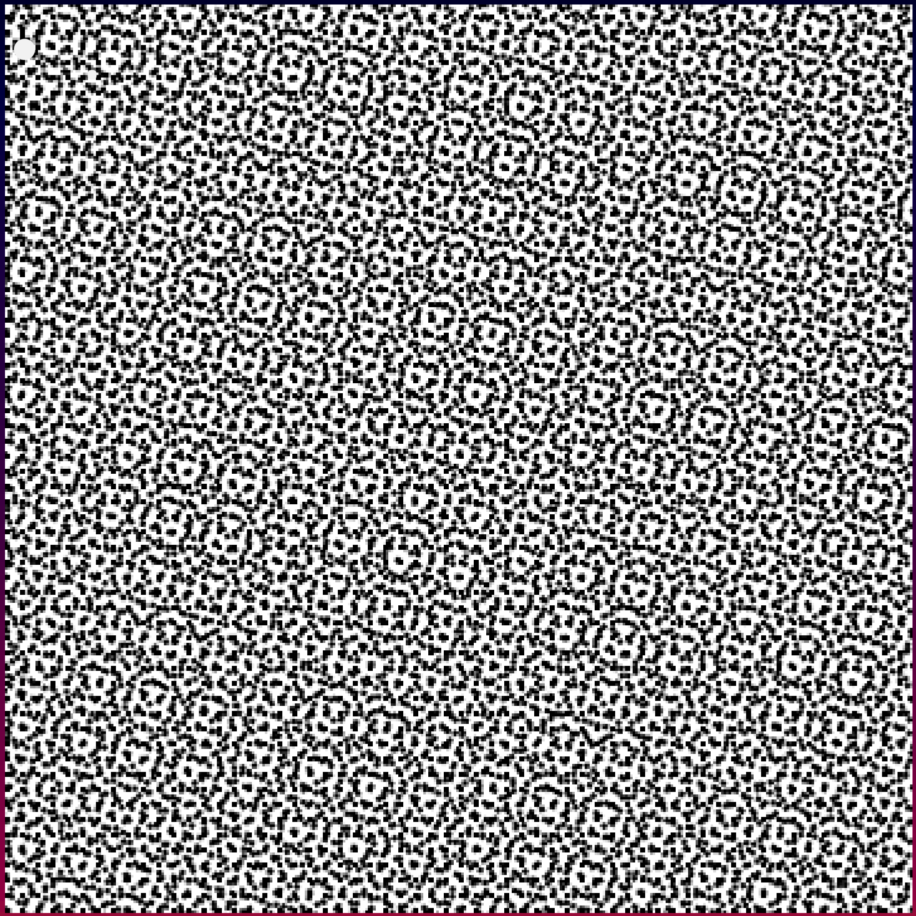
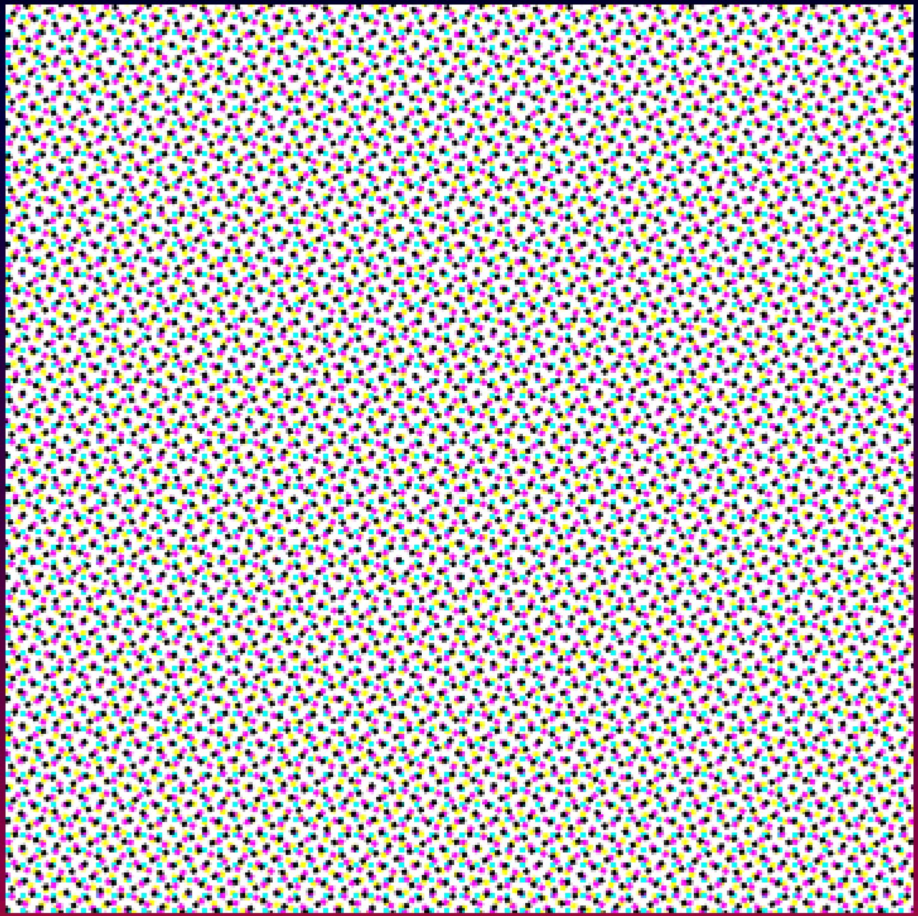
Printing: 4 meshes, stability point

http://www.wasatch.com/moire.html





M, K, C at 30º
Y at 15º

Final result, CMYK

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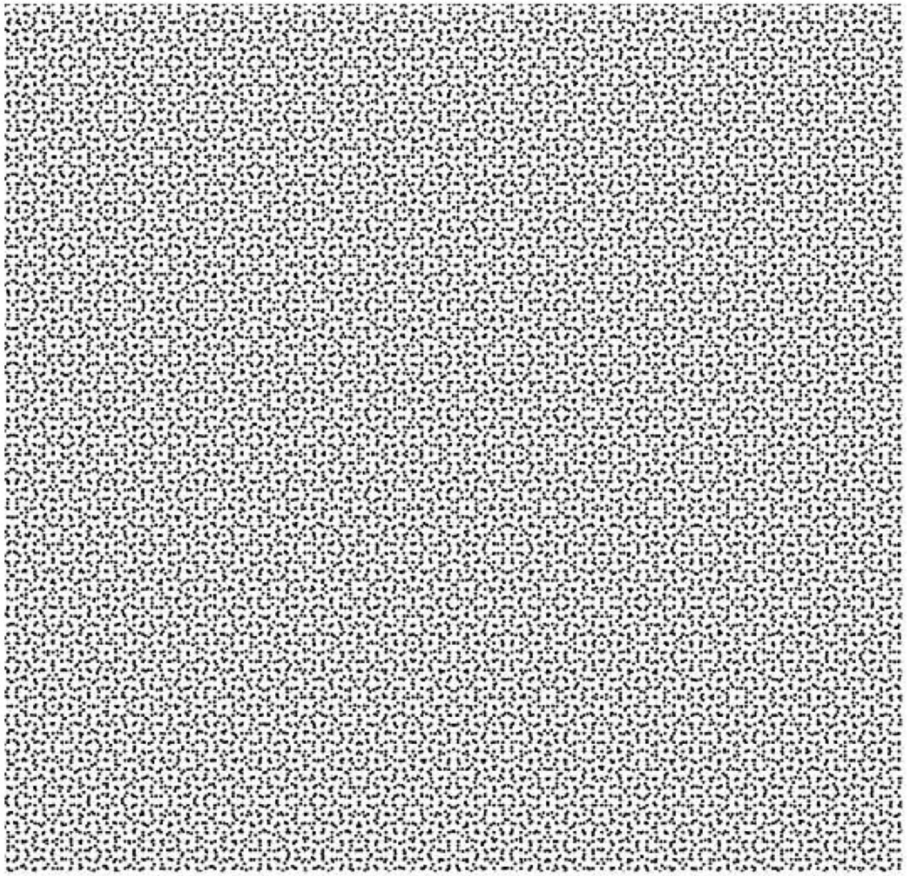
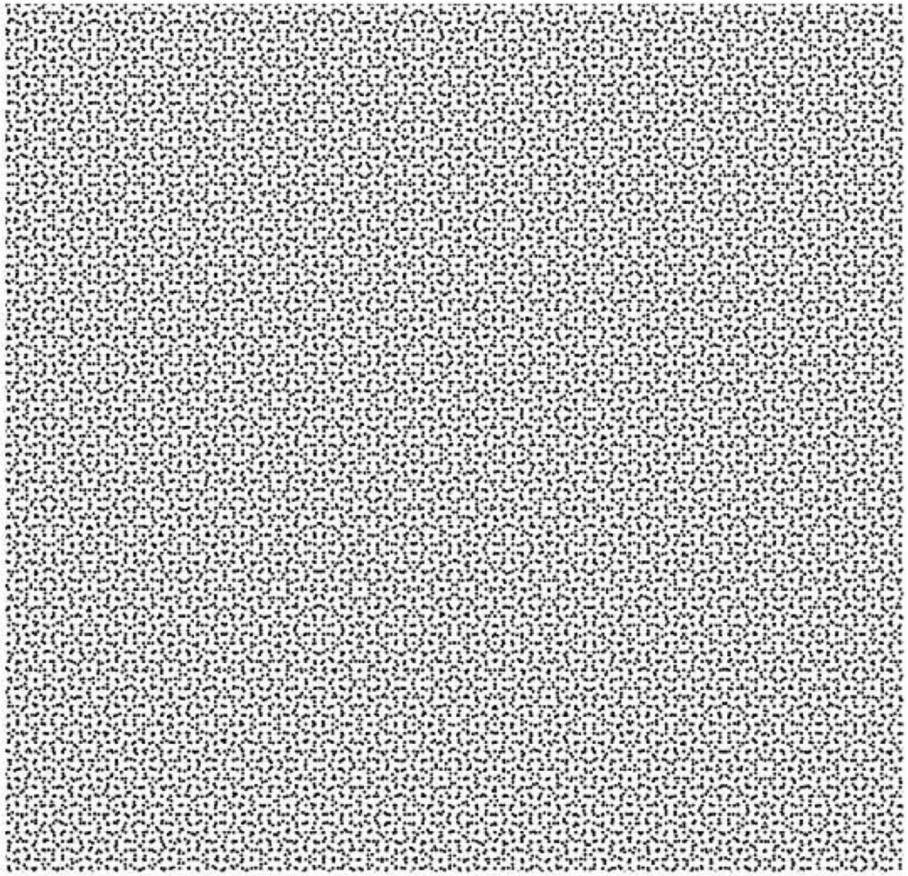
Other solution →

Printing: 4 meshes, stability point





Stable point

M, K, C at 23.5º, 24º,

$q_{MK}=q_{CK}=0.833º$

Perturbations

Tiny visual differences

Ciências
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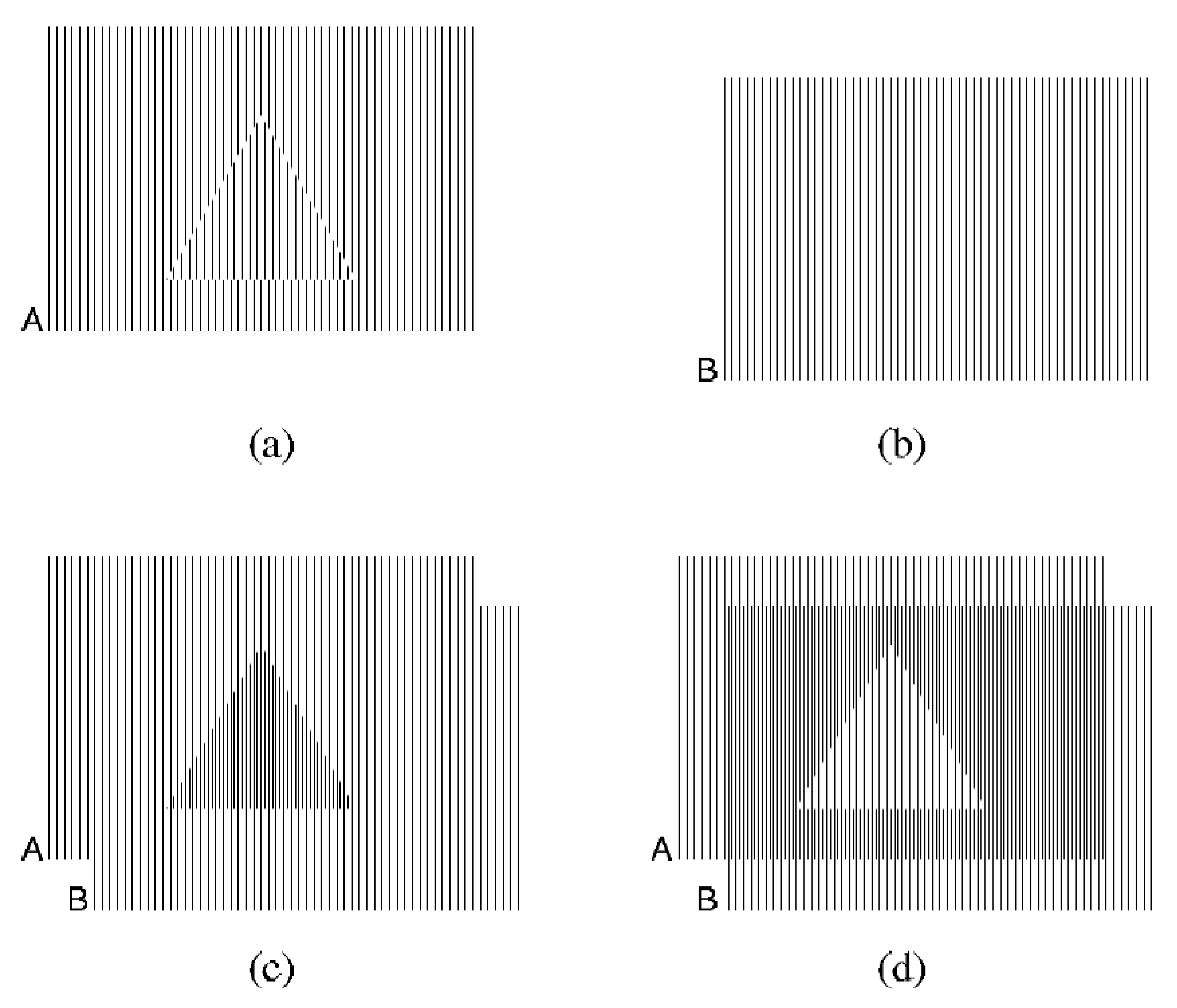
Security

http://iopscience.iop.org/1742-6596/77/1/012001/pdf/jpconf7_77_012001.pdf



Security – *Scrambled indicia*

http://sites.google.com/site/stamphiddenimages/Home/stamp-images

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Security – *Scrambled indicia* *(Estónia)*

http://seguridaddocumental.blogspot.com/2009/10/imagen-encriptada-scrambled-indicia.html

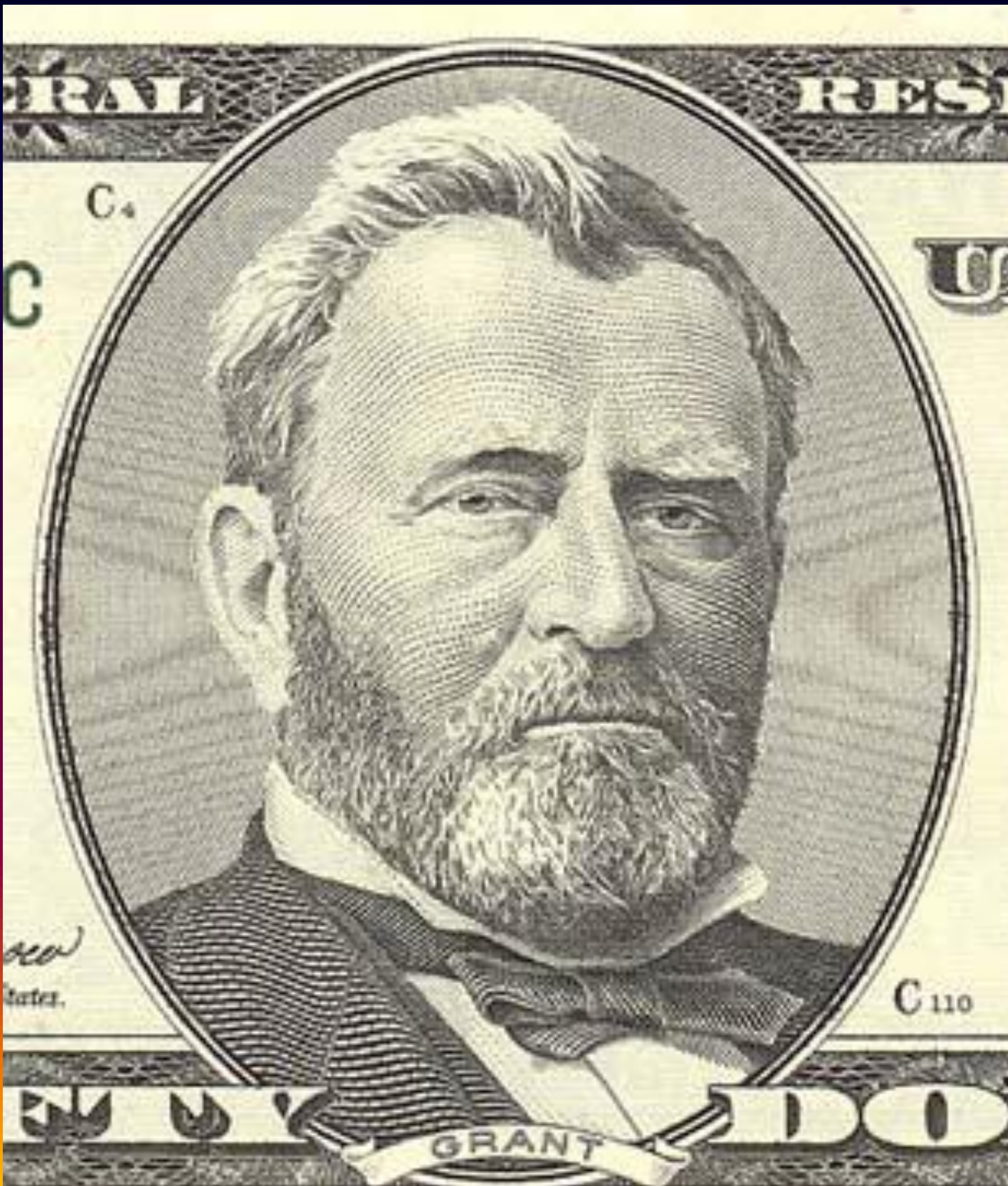
Ciências ULisboa

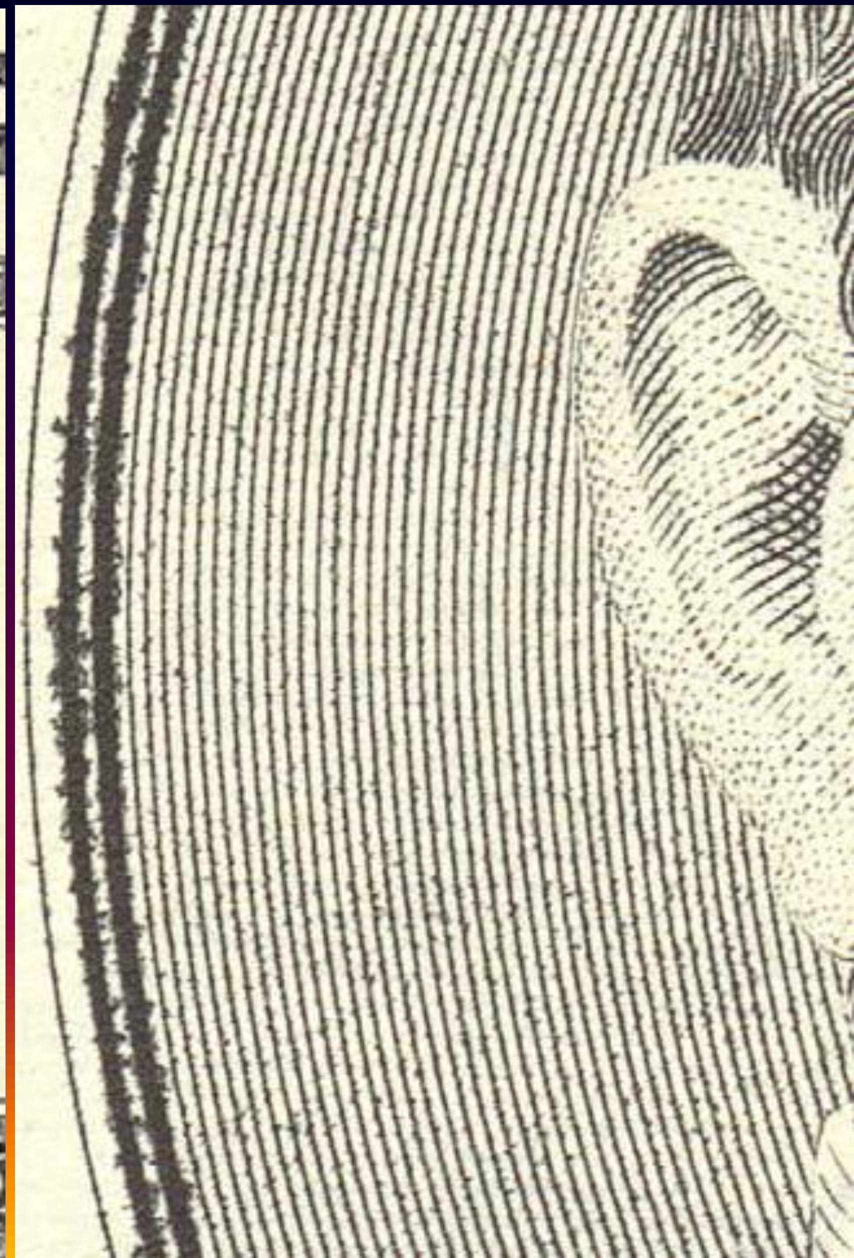
Security – *Scrambled indicia* *(Estónia)*

http://seguridaddocumental.blogspot.com/2009/10/imagen-encriptada-scrambled-indicia.html

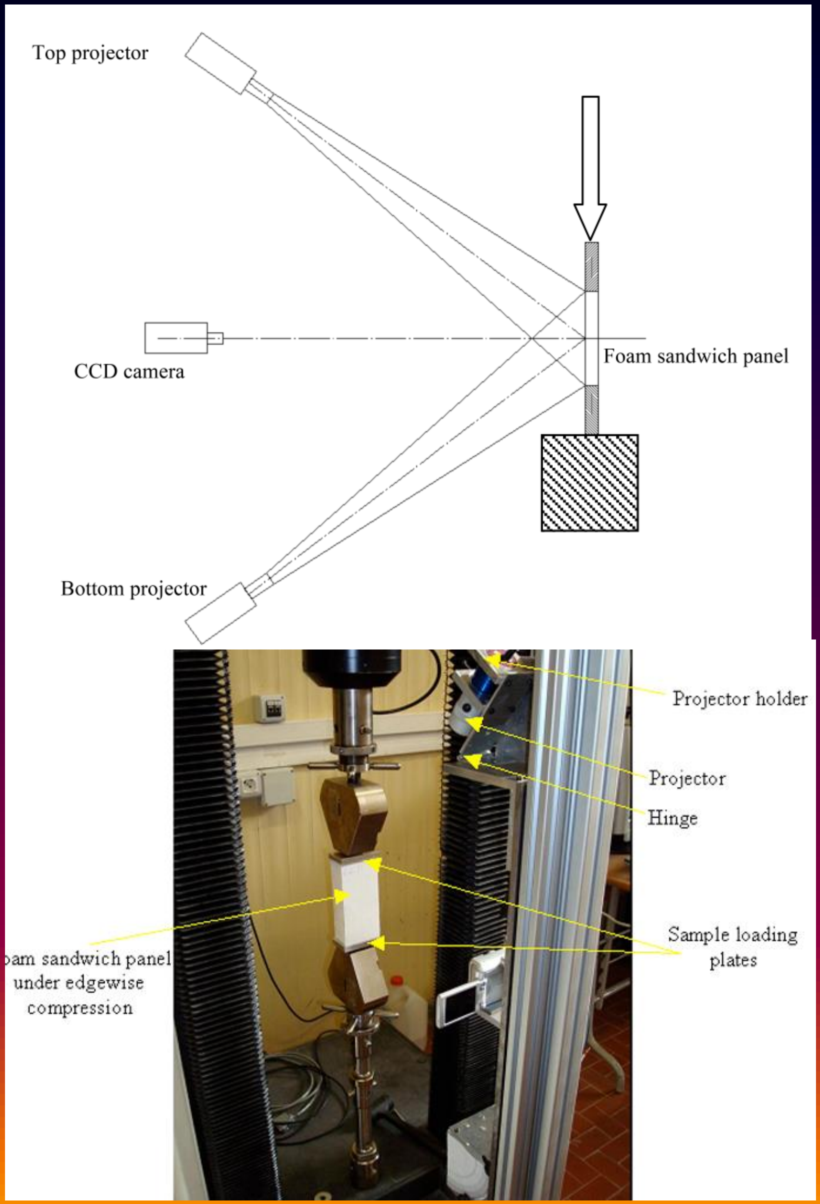
Security – *Screen / scan trap*

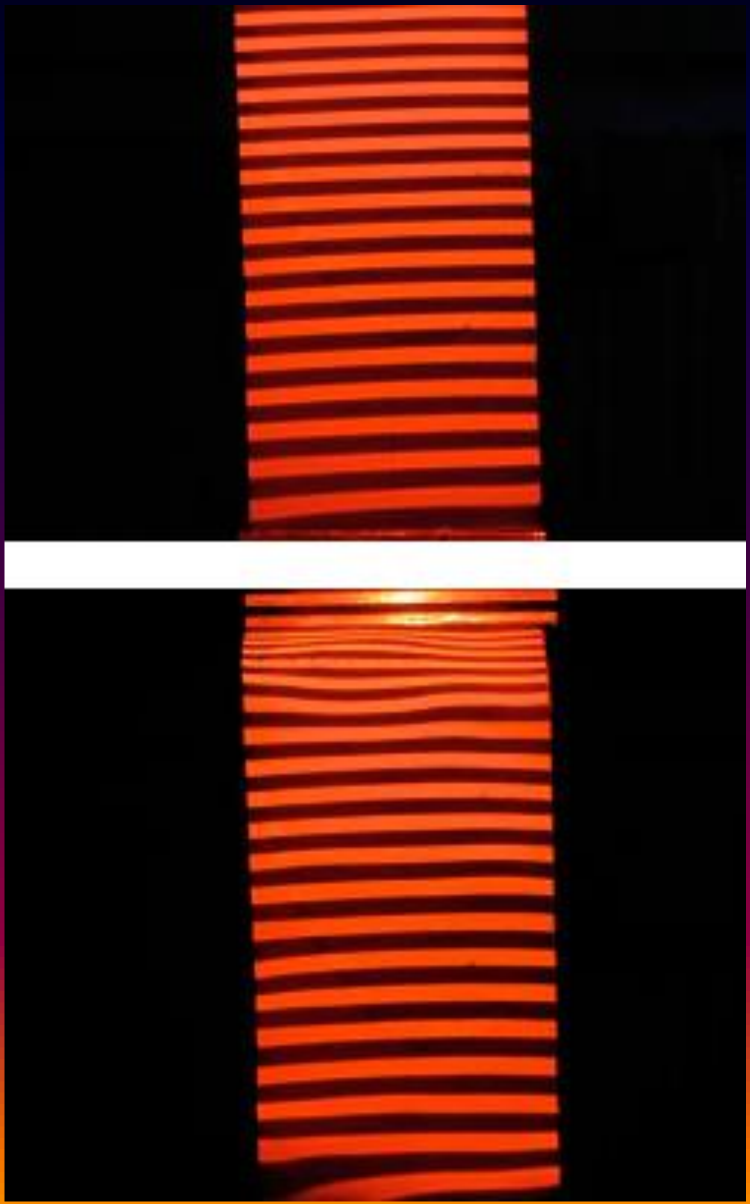
(USD, President Ulysses S. Grant, 1869-1877)





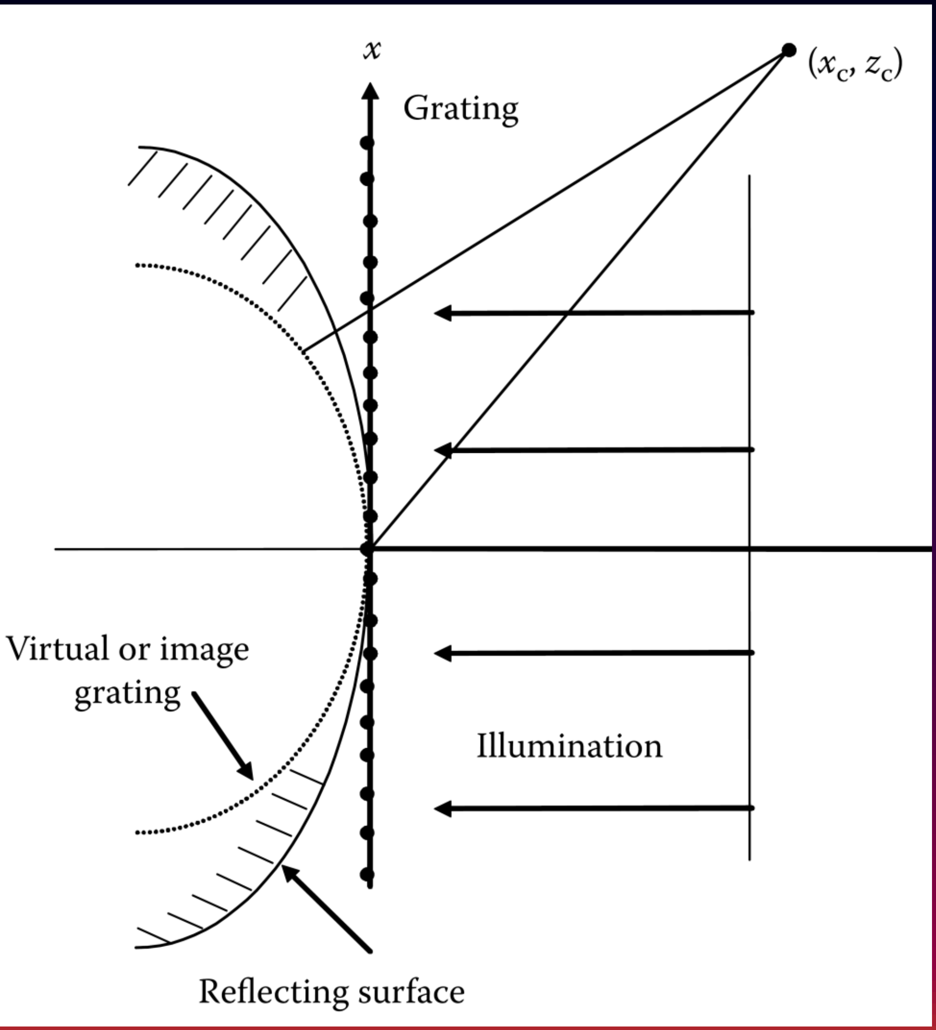
Moiré – metrology

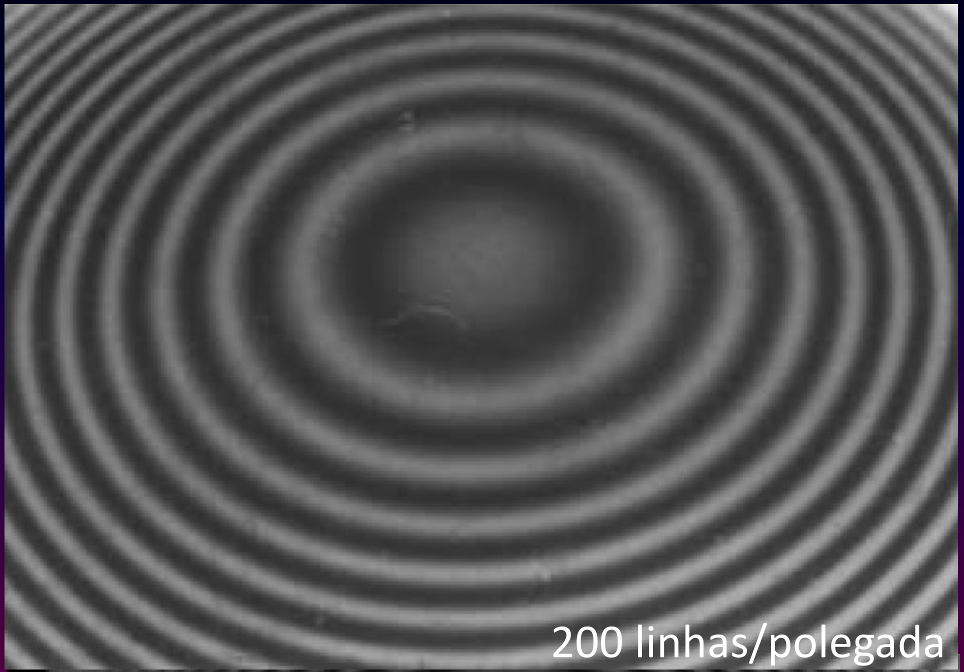


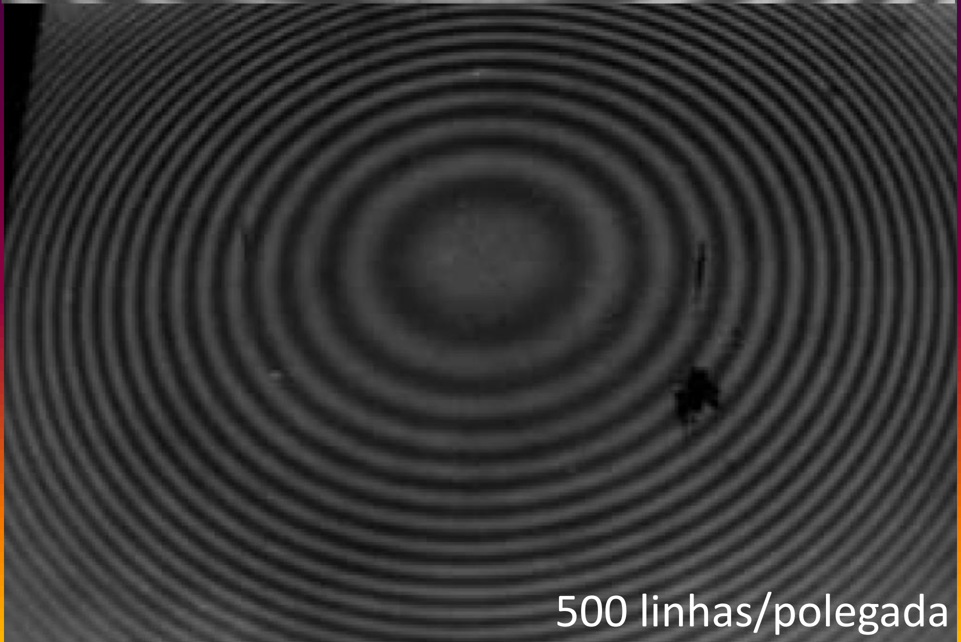


Optical Measurements, Modeling, and Metrology, Vol. 5, Proulx T., Springer 2011

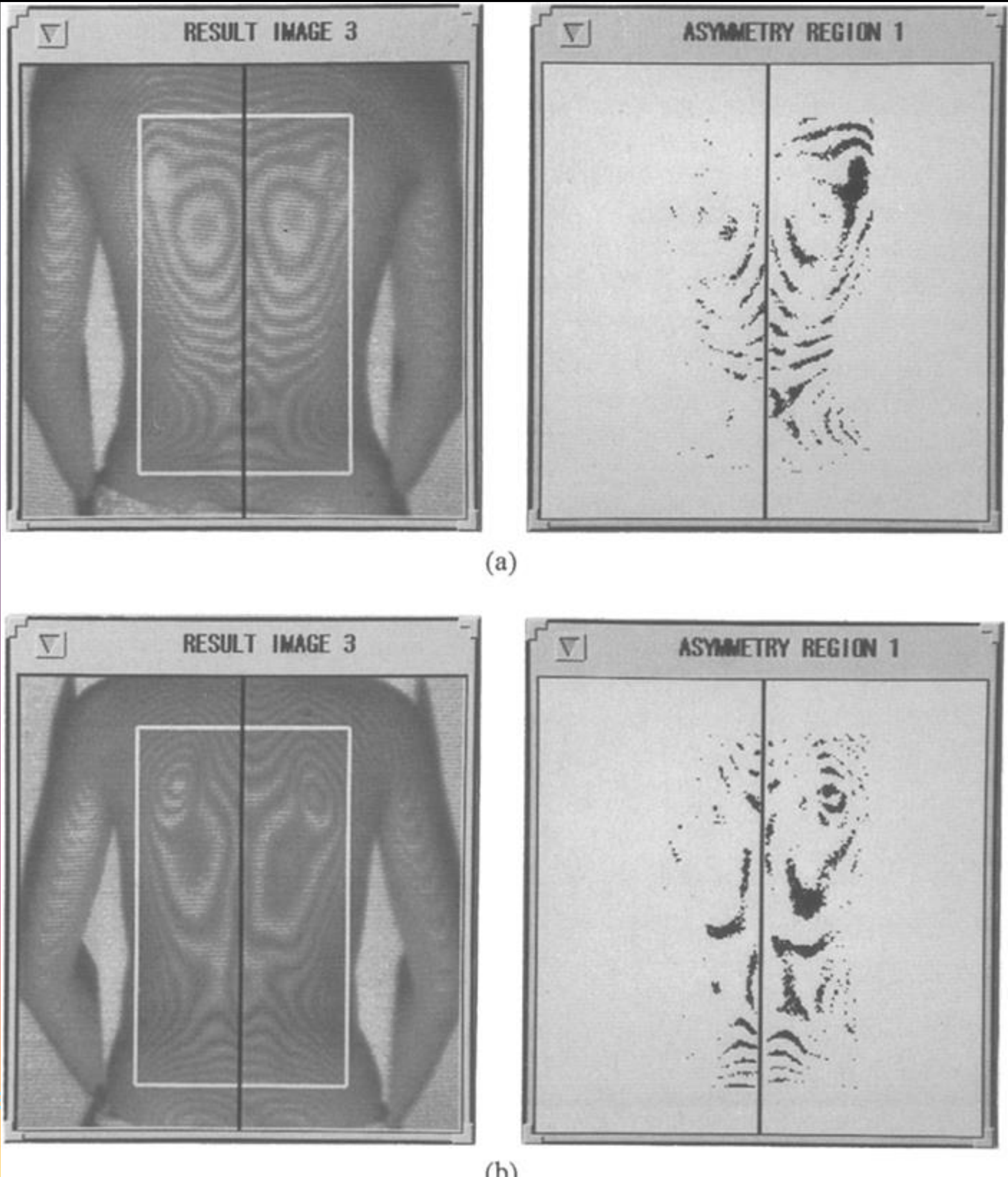
Moiré – Metrology







Moiré - Metrology



http://www.springerlink.com/conte

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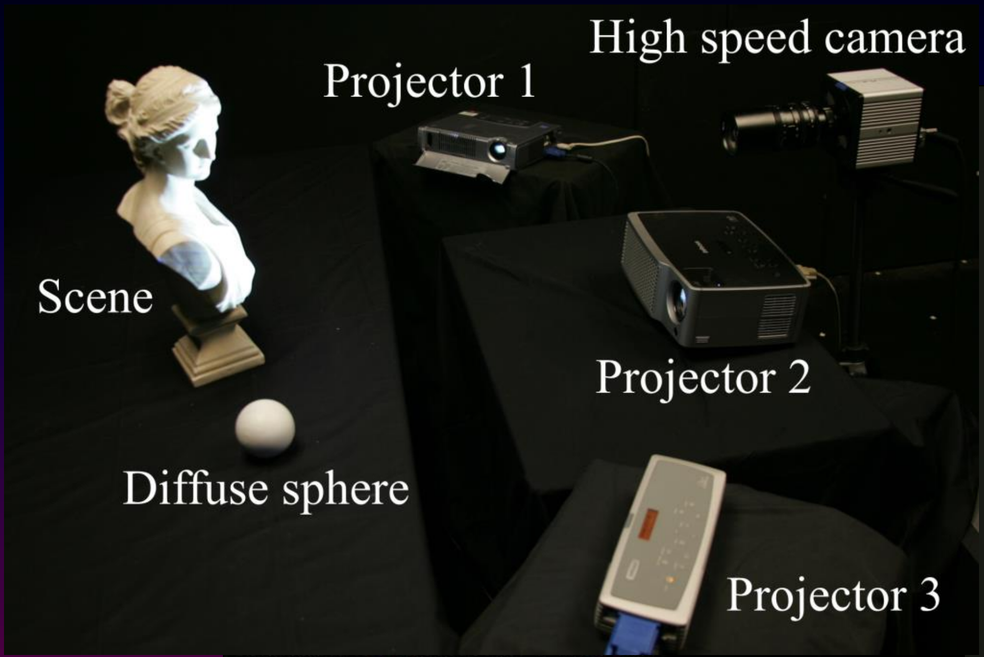
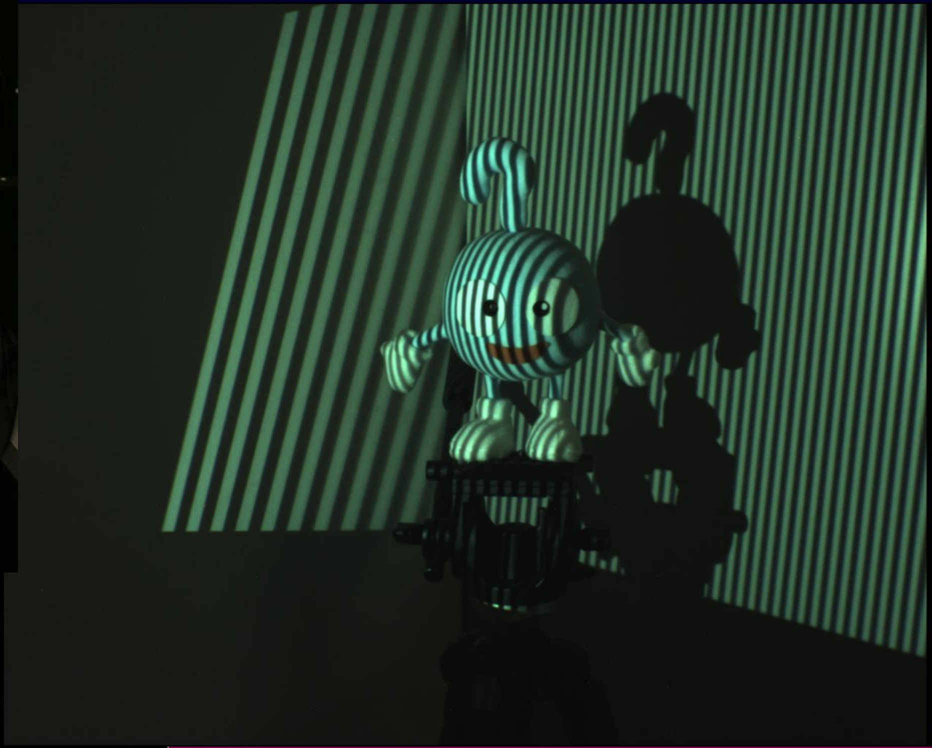
Metrology: structured light



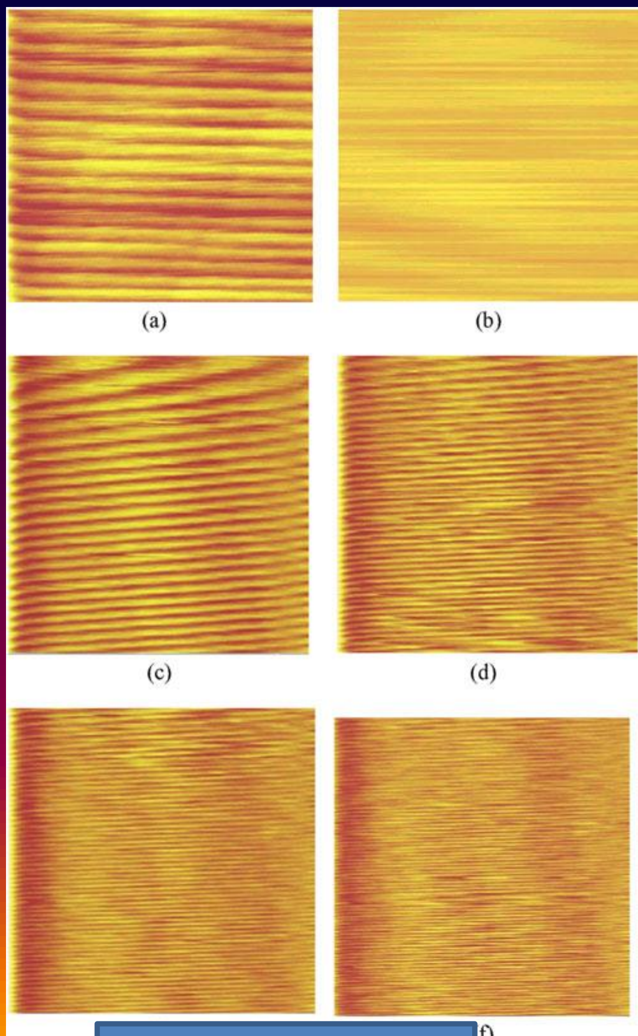


Materials – surfaces – STM – Pyrolitic Graphite

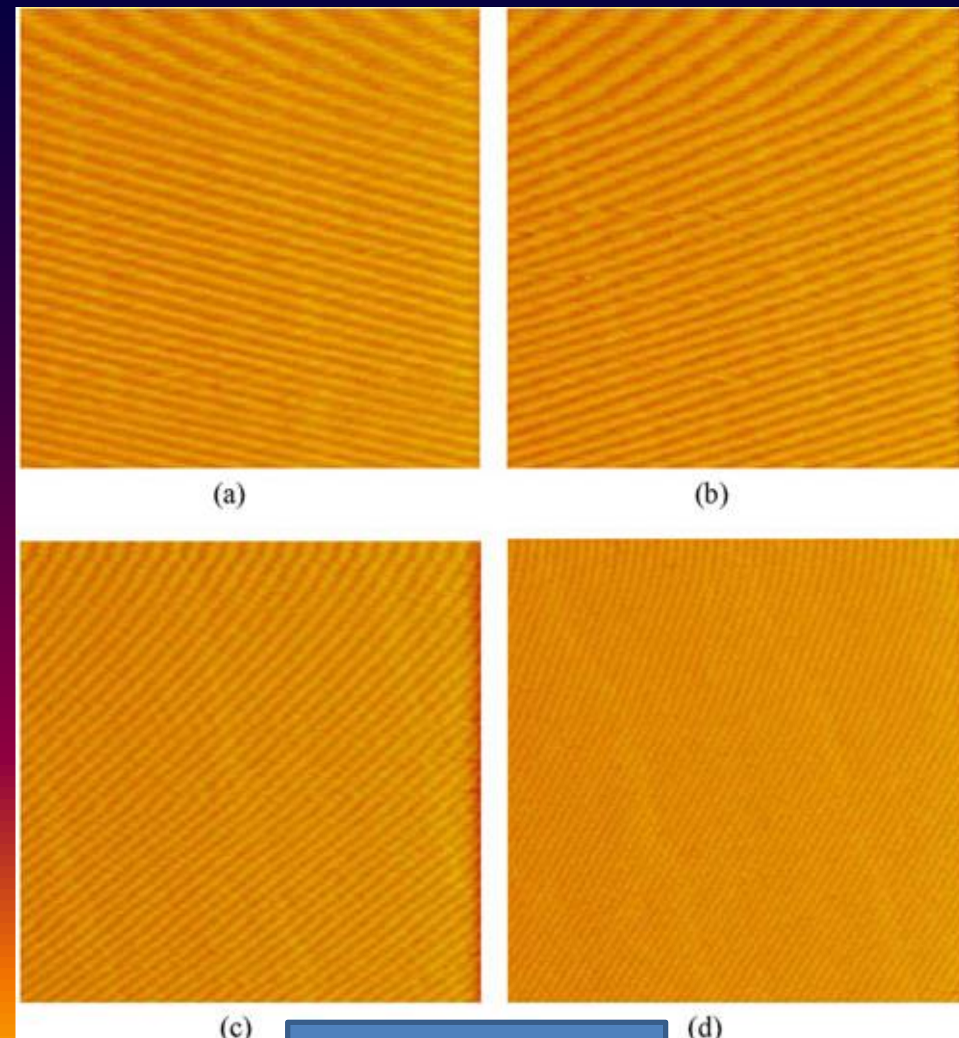
http://iopscience.iop.org/0957-4484/15/8/022/pdf/nano4_8_022.pdf

Moiré : “interferência” entre a rede atómica e o padrão de varrimento do STM

“Amplifica” as irregularidade da rede comensuráveis com a periodicidade do varrimento



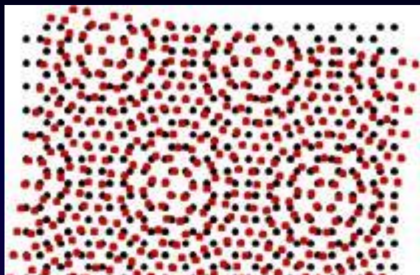
Translations



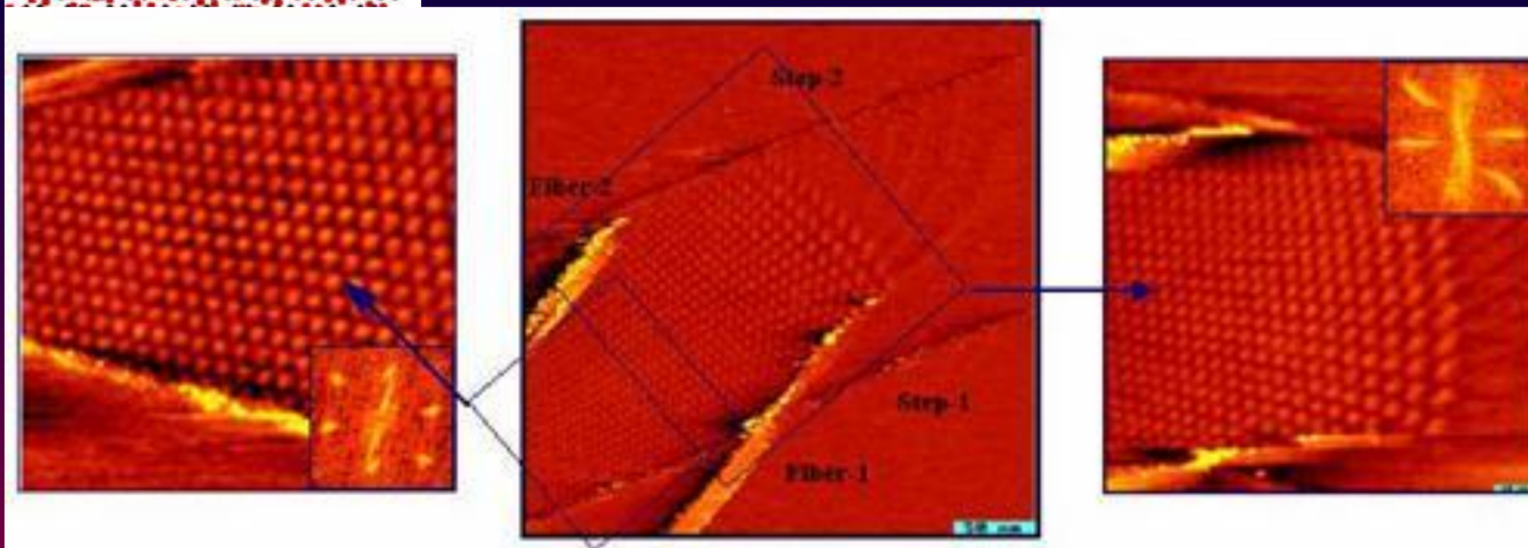
Rotations

Materials – surfaces – STM – Pyrolitic Graphite

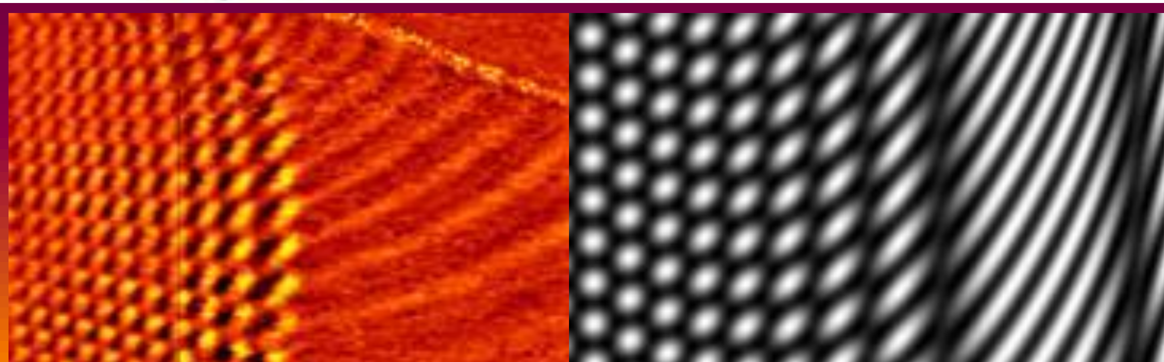
http://www.iitk.ac.in/infocell/iitk/newhtml/storyoftheweek39.htm



Padrão gerado por Moiré entre duas redes hexagonais, ligeiramente rodadas: a superficial e outra sub-superficial – período 10-100x superior que a constante de rede



Duas fibras num terraço. Detalhes de duas zonas, com periodicidades variáveis



Observação STM (esquerda), modelo (direita)

As fibras induzem uma pequena rotação de 2.3º no terraço, mas não nas proximidades das fibras

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Conclusions

Physics deals with art of measurement

Measuring means selecting sensors and the sampling strategy

When periodic or completely unknown patterns are at stake … be careful and try to consider all cases.

Artifacts stemming from measurement processes are needed for industry, commerce and services

Instabilities have many applications

Instabilities give rise to optical measurement methods

At 1D, engineers call the differences f_1-f_2 as 'demodulation' and have lots of ways to manipulate them (remember AM e FM modulation in radio…)

Whenever there is a display, a screen, a digital projector, a scanner, a copier, on the imaging chain … be **CAREFUL**!

When the object can be anticipated, artefacts are easy to cope with, and the measurement strategy can be fine-tuned

If the objects are unknown... Well, nature is often simetric, repetitive... Be careful... Remember the planet Mars in 1976...

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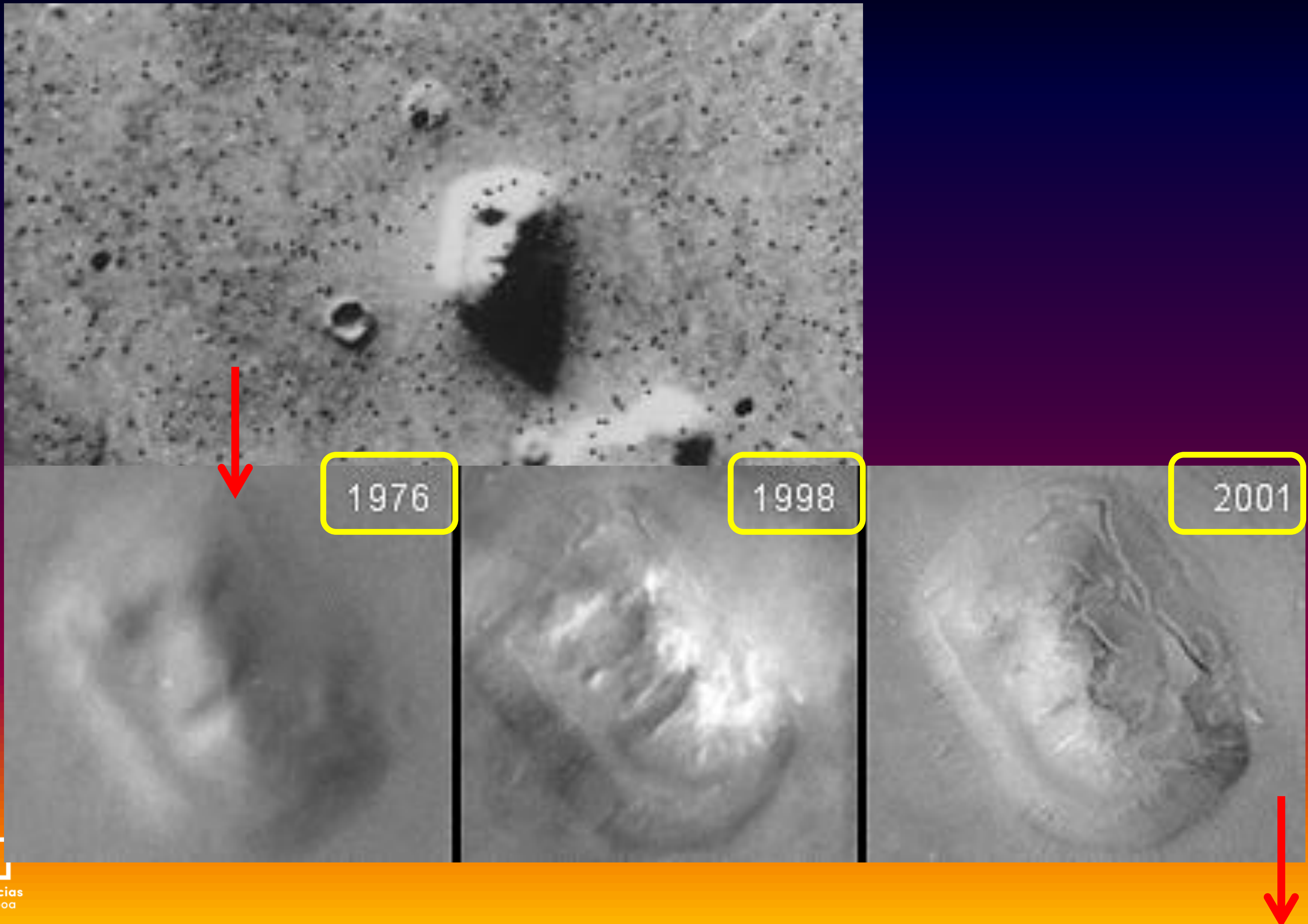
Face on Mars (1976 → 2001)



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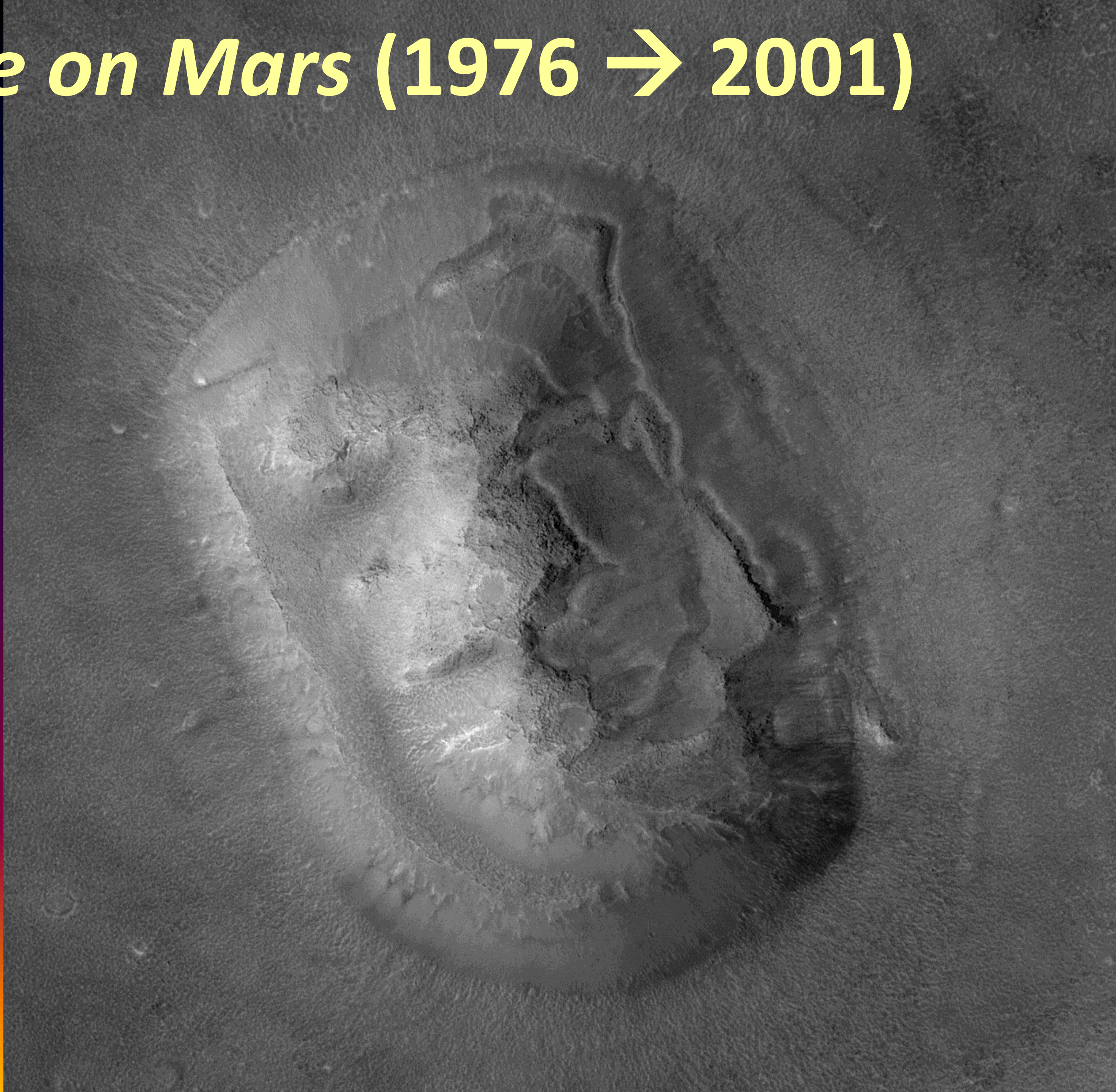
Face on Mars (1976 → 2001)



The END

Thank you

Ciências ULisboa

Bibliography

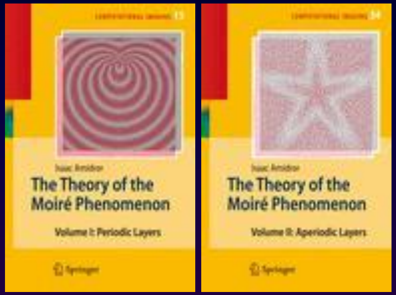
The theory of the Moiré phenomenon:

Periodic (I) and Aperiodic (II) layers

Isaac Amidror

Springer, 2009

http://diwww.epfl.ch/w3lsp/books//moire



Optical Document Security (2nd ed.)

Rudolf L. van Renesse (Ed.)

Artech House, 1998

Hidden and scrambled images – a review

Rudolf L. van Renesse

SPIE Vol. 4677, pp. 333-348 (2002)

Ciências ULisboa

Sampling: Moirés & aliasing

- Os problemas de amostragem podem decorrer de:
  - Funções de banda não limitada
    - É o caso, sempre, de funções periódicas...
  - Frequência de amostragem mal escolhida
  - Filtragem passa-baixo do espectro do sinal amostrado incorrecta.
- Estes problemas existem na conversão ADC de
  - Imagens "tramadas" *(halftone screen)* em relação com a
  - Passo de amostragem do sensor (resolução)
- São tipicamente referidos como *aliasing*
- Neste contexto, o aliasing pode ser visto como o caso particular em que
  - $r_1(x,y)$ representa a reflectância da imagem inicial
  - $r_2(x,y)$ representa o pente 2D que descreve o dispositivo de amostragem
- Da convolução entre os espectros decorre a existência de múltiplas réplicas de $R_1(u,v)$, cada uma das quais centrada em cada um dos impulsos de $R_2(u,v)$.
- Se a frequência de amostragem $f < 2f_{max}$, existe sobreposição entre réplicas de $R_1(u,v)$ → altas frequências das réplicas sobrepõem-se (aditivamente) à réplica central de $R_1(u,v)$, aumentando a energia das **baixas frequências** ou criando **artefactos de baixa frequência** não existentes em $r_1(x,y)$.
- A filtragem passa-baixo não permite a reprodução fiel do sinal

Sampling: Moirés & aliasing

- If $R_1(u,v)$ descreases fast (although not being band-limited) aliasing imposes slight degradations: loss of high frequency details, degradation of contours, ...

- If the signal is periodic or if it contains periodic patterns, its spectrum $R_1(u,v)$ and its replications after convolution, may contain intense pulses, some of them, eventually, within the visibility circle, and generating artifacts which do not exist in the original signal.

- Classical sampling theory addresses
  - Continuous spectra and band-limited images
- Na approach based on Moiré enables sampling of
  - Periodic signals
- ...and frequencies smaller than Nyquist can be used provided unwelcome frequencies are outside the visibility circle.
  - Although spectral superposition forbids the reconstruction of $r_1(x,y)$, this does not necessarily creates artifacts (moiré)

- Anti-aliasing: removal, by low-pass filtering, of high-frequency details, impossible to resolve by the sampling system.

http://www.imageprocessingbasics.com/image-sampling-and-aliasing/ →

http://www.imageprocessingbasics.com/image-sampling-and-aliasing/

- Image processing Basics ([Image processing Basics](http://www.imageprocessingbasics.com/image-sampling-and-aliasing/))

[Spatial resolution](#)
Explains the Rayleigh spatial resolution limit.

[Sampling and aliasing](#)
See how different sampling resolutions can cause aliasing, and how to do anti-aliasing.

[Pixel re-quantization](#)
Explore in real time the effects of changing the number of pixel quantization levels.

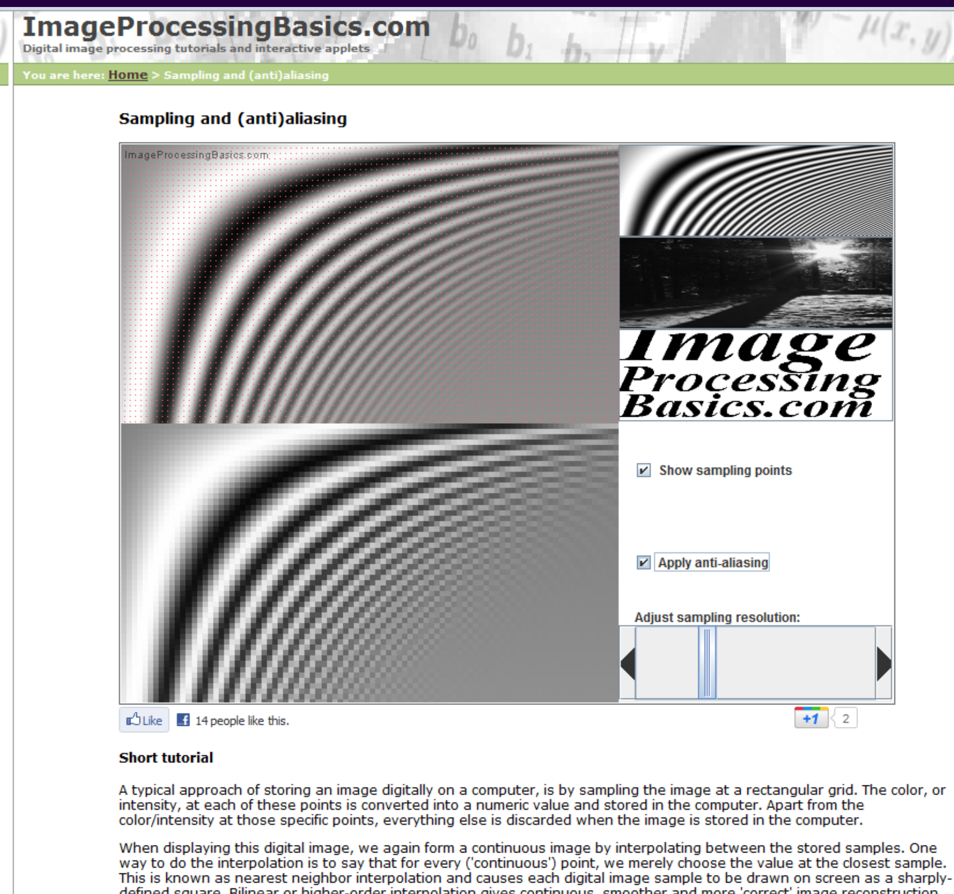
[Geometric transforms](#)
See the effects of varying the parameters in the affine geometric transform.

[Graylevel transforms](#)
Interactively explore the effect of changing the parameters in graylevel transform functions.

[Histogram equalization](#)
Perform histogram equalization or do some histogram specification interactively.

[Local graylevel mapping](#)
Perform local graylevel mapping, both equalization and linear graylevel transforms.

[Convolution-based filters](#)
Edit convolution kernels, and immediately see the resulting images and the kernels' frequency responses.

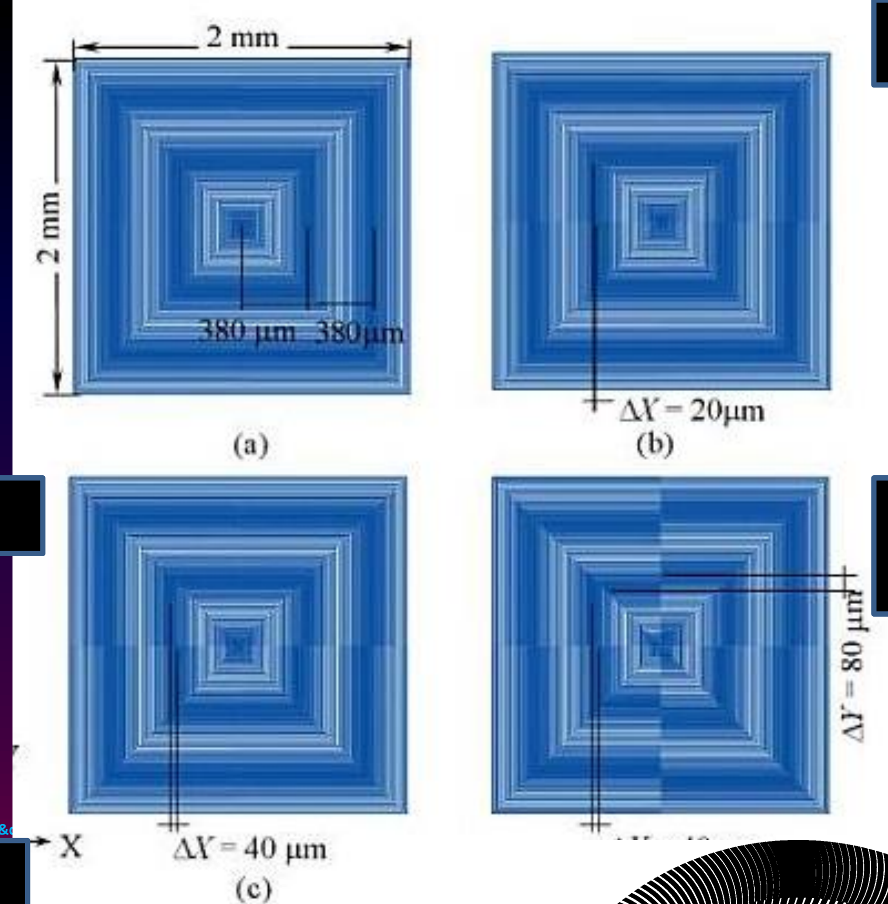


Alignements

Masks in integrated circuits

Offset printing plates

http://books.google.pt/books?id=n-xkaj7SWD0C&pg=PA539&dq=alignment+moir%C3%A9&hl=pt-PT&ei=W9PLTrakNoGL8gO9oLnKDw&sa=X&oi=book_result&ct=result&resnum=1&ved=0CC4Q6AEwAA#v=onepage&q
%20moir%C3%A9&f=false

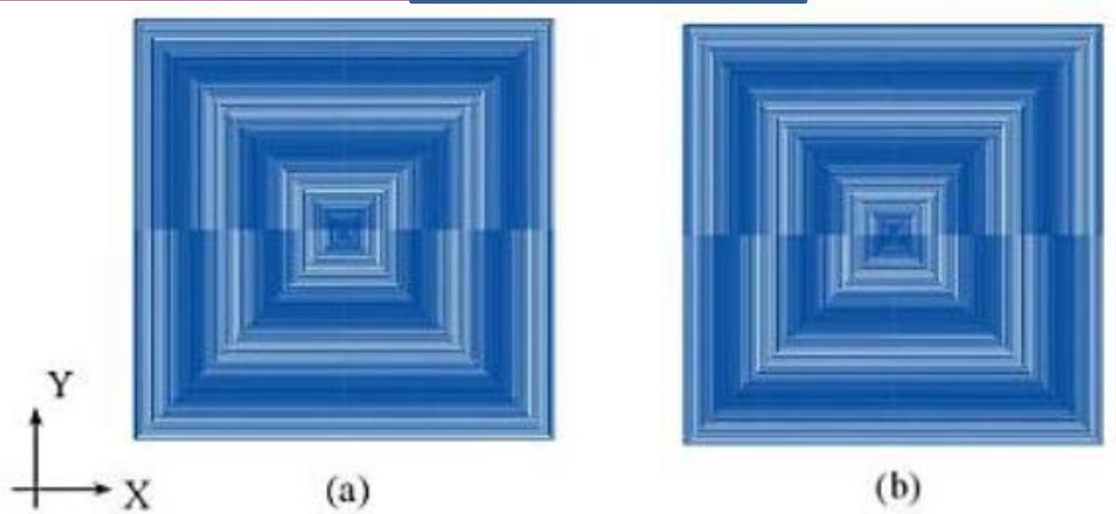


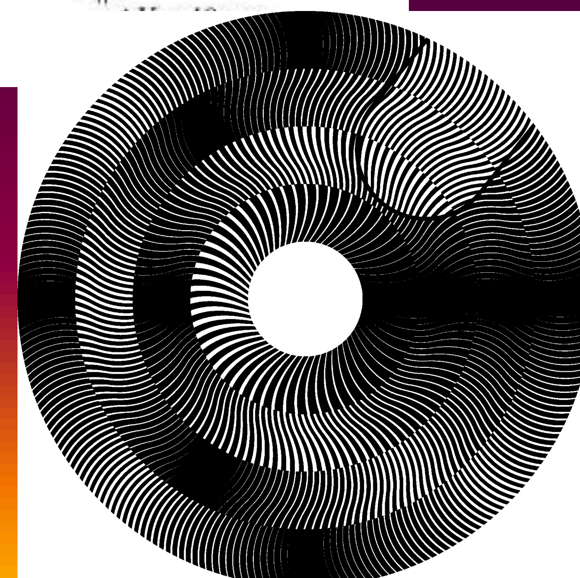
0.5 µm

1 µm

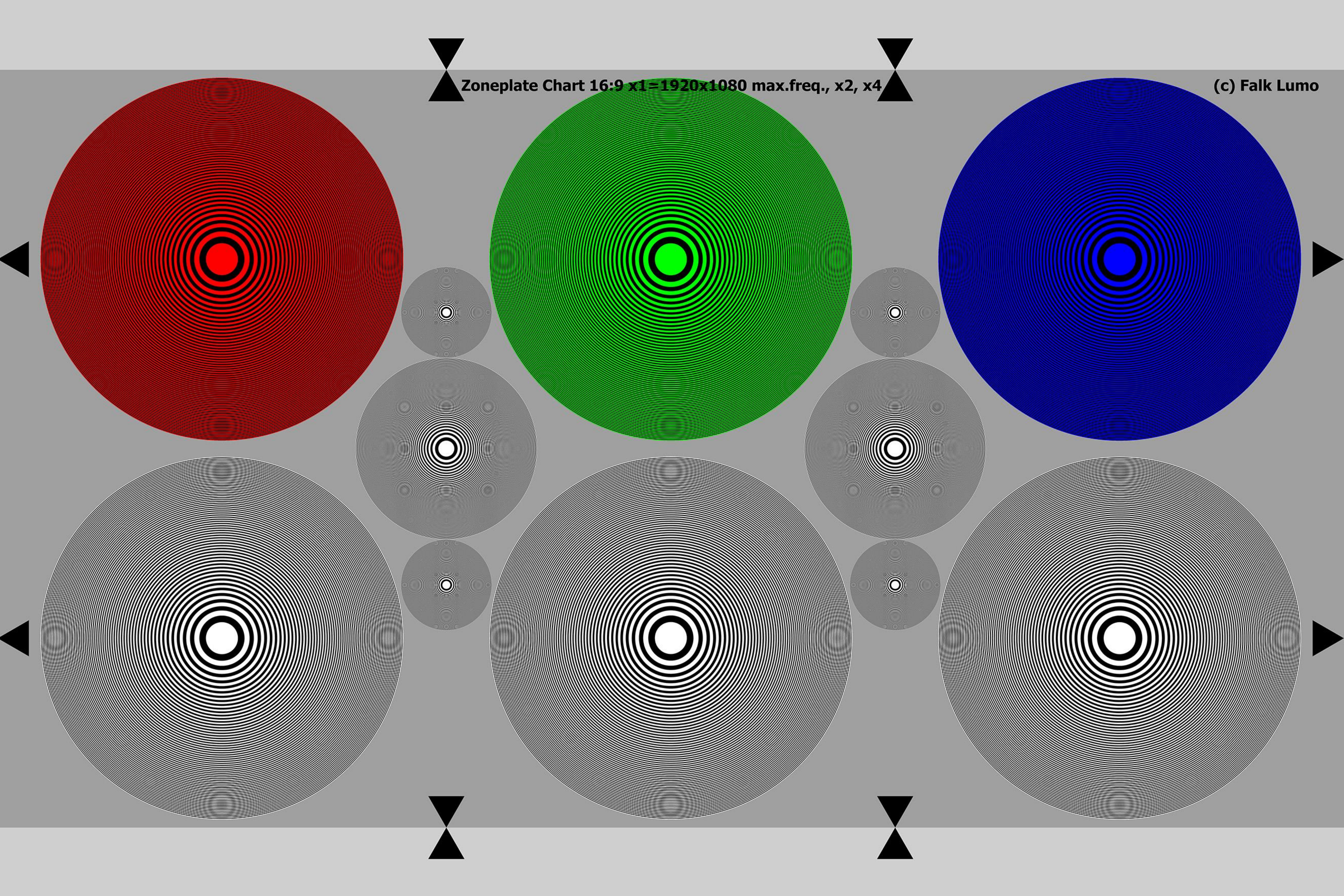
Δx=1 µm
Δy=2 µm

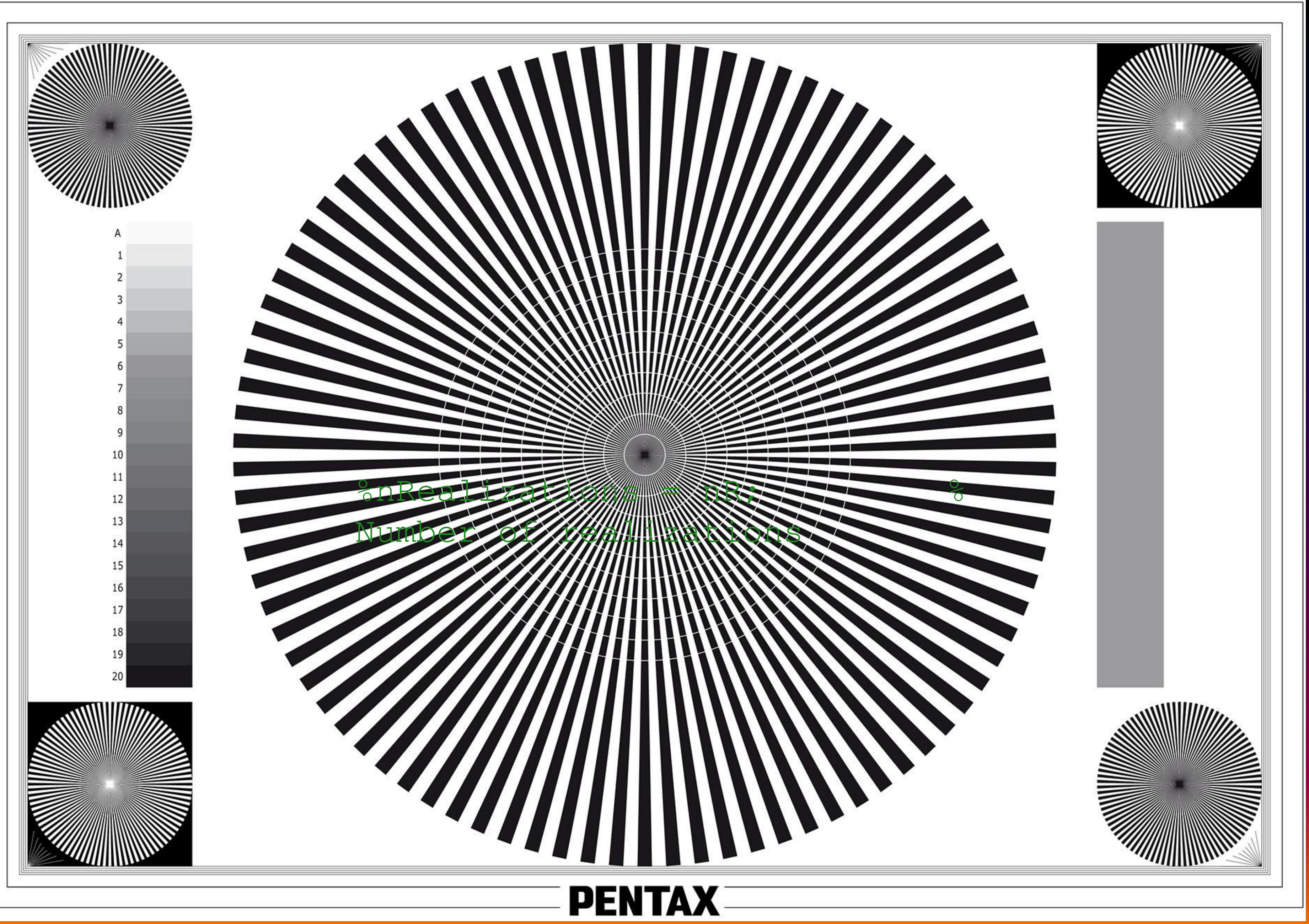
Δx = +/- 2µm





Test targets or holograms?





%nRealizations = nR; %

Number of realizations