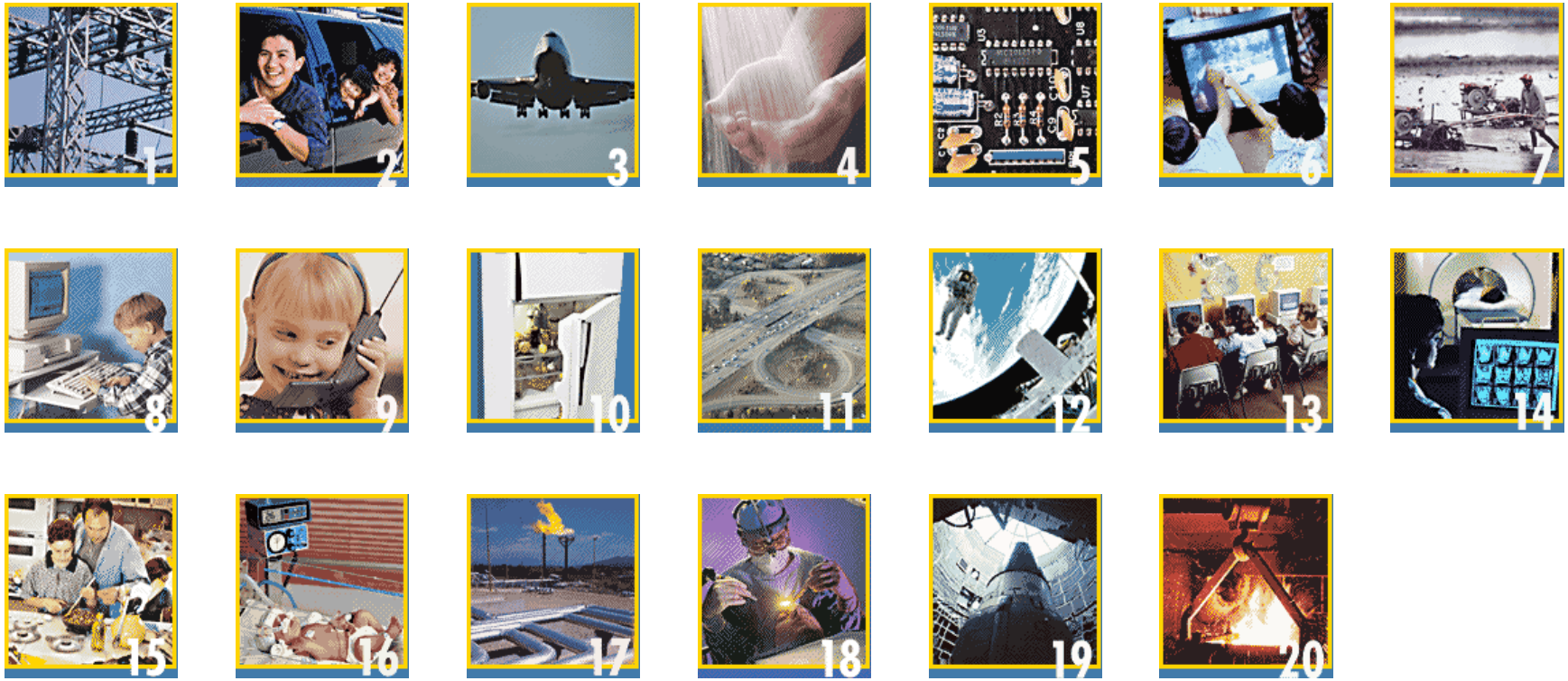
Signal Processing for Computational Imaging

Minh N. Do

Department of Electrical and Computer Engineering

University of Illinois at Urbana-Champaign

20 Greatest Engineering Achievements of the 20th Century



Selected by the U.S. National Academy of Engineering

www.greatachievements.org

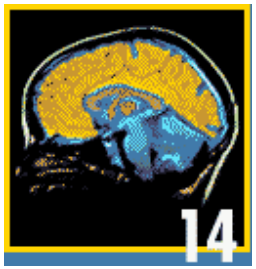
20 Greatest Engineering Achievements of the 20th Century

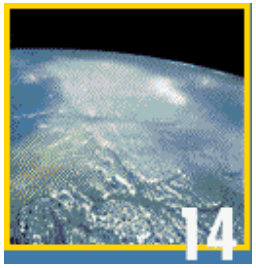
1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. **Imaging**
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Imaging

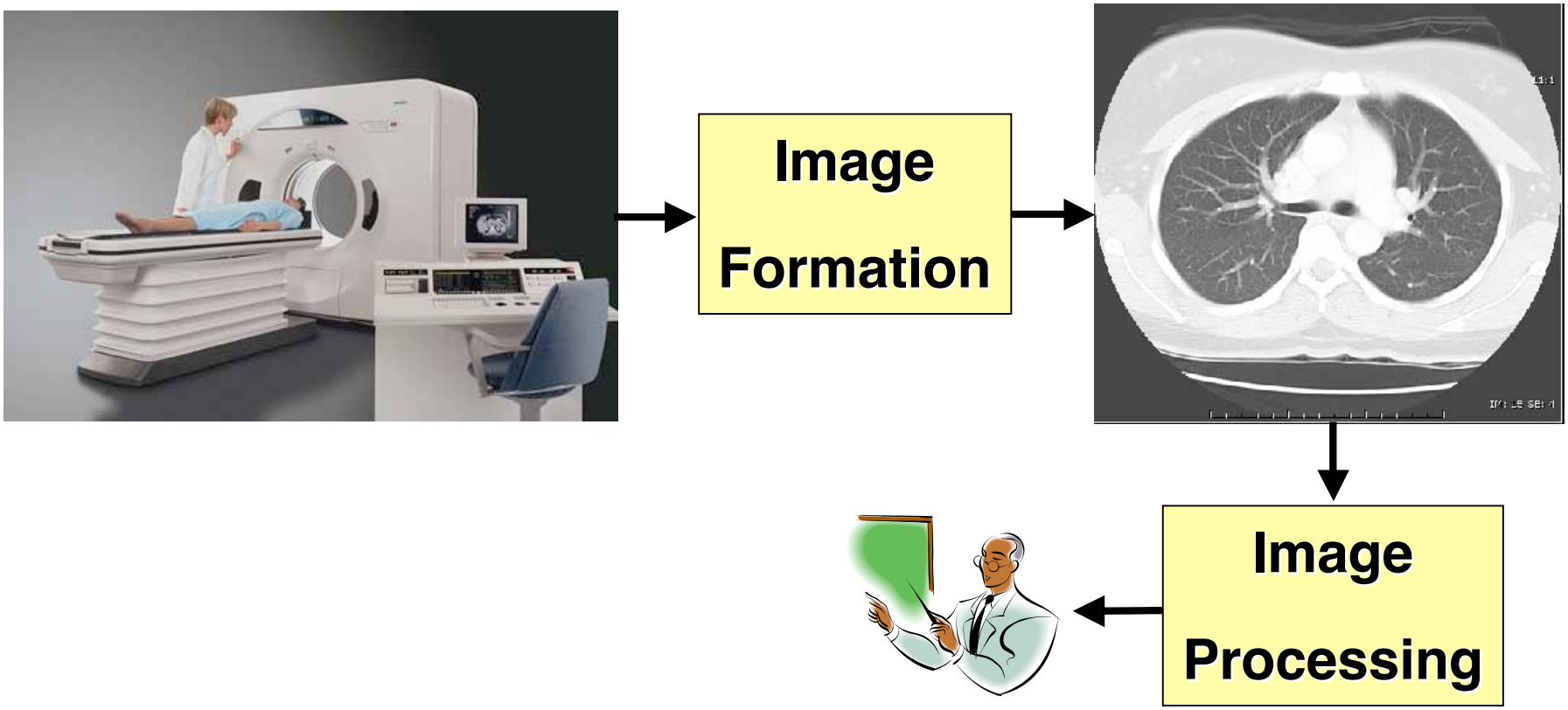
- **In 1900…**
  - Only simple microscopes, telescopes, and black and white photographs.

- **In 2000…**
  - Color photographs, movies, and television
  - New sensors that greatly expand our “vision”
    - see tiny atomic particles to vast galaxies
    - see inside the human body
    - track weather patterns, …
  - The entire microelectronics revolution is based upon imaging



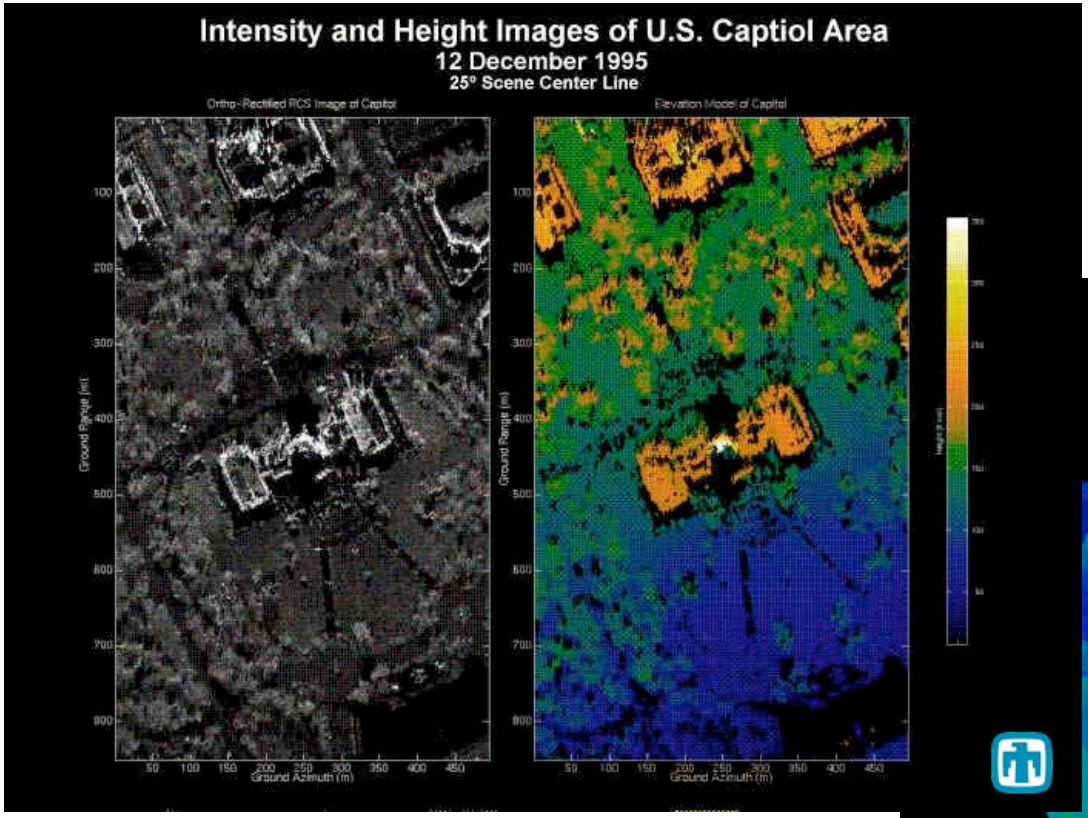


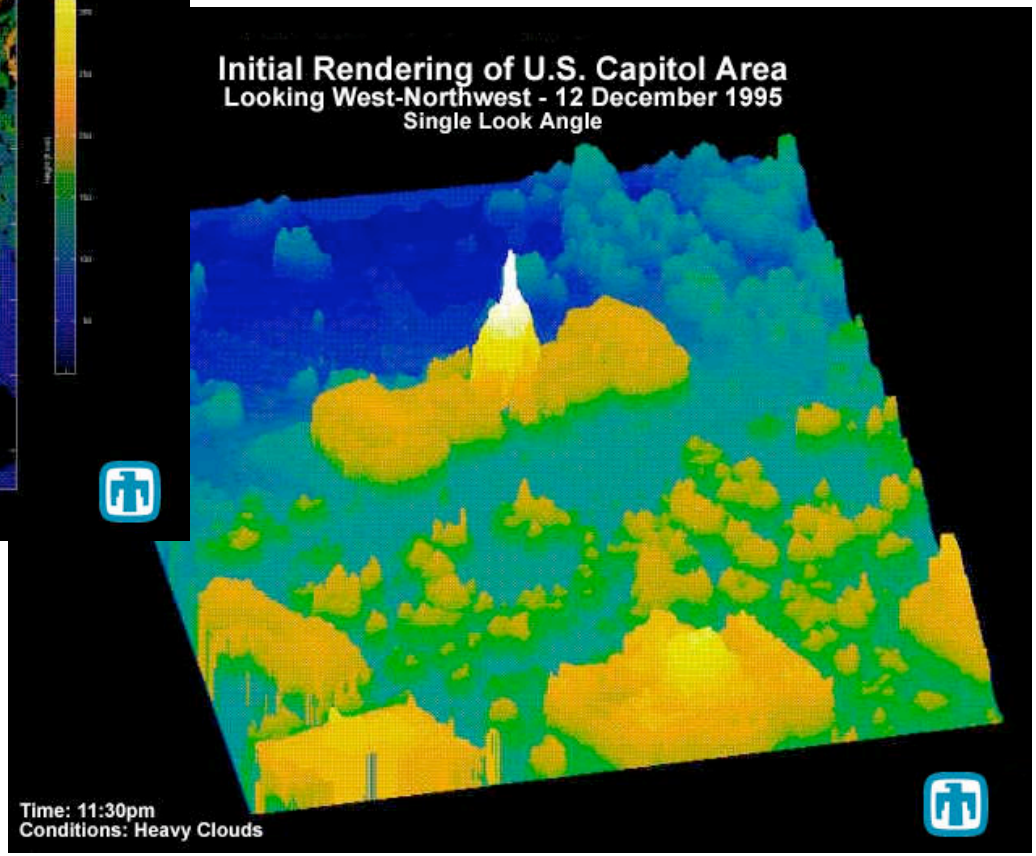
Imaging = Image Formation + Processing



- Examples: optical imaging, radar imaging, computer tomography (CT), magnetic resonance imaging (MRI).

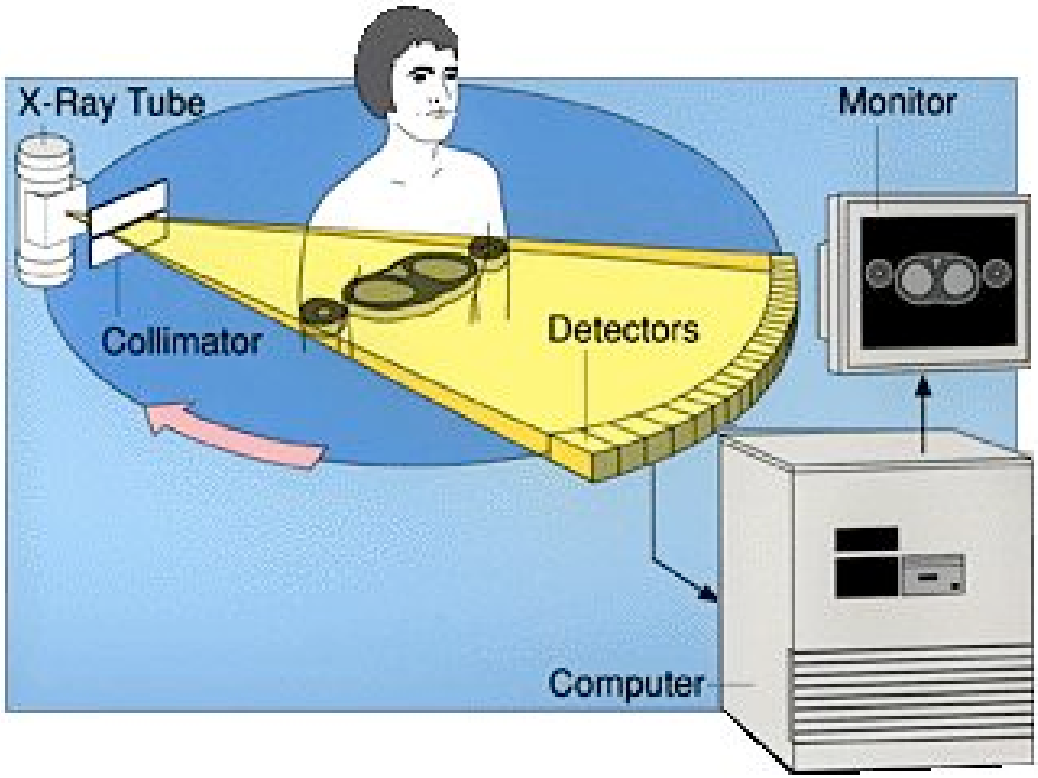
Synthetic Aperture Radar (SAR)

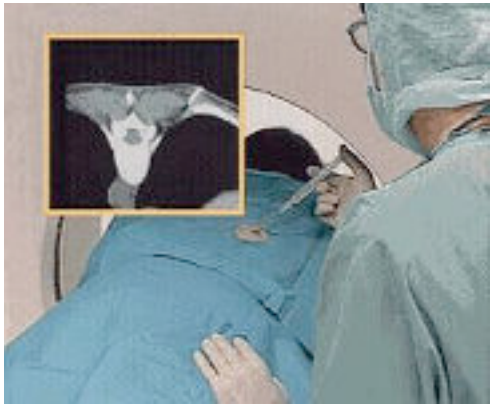




www.sandia.gov/RADAR

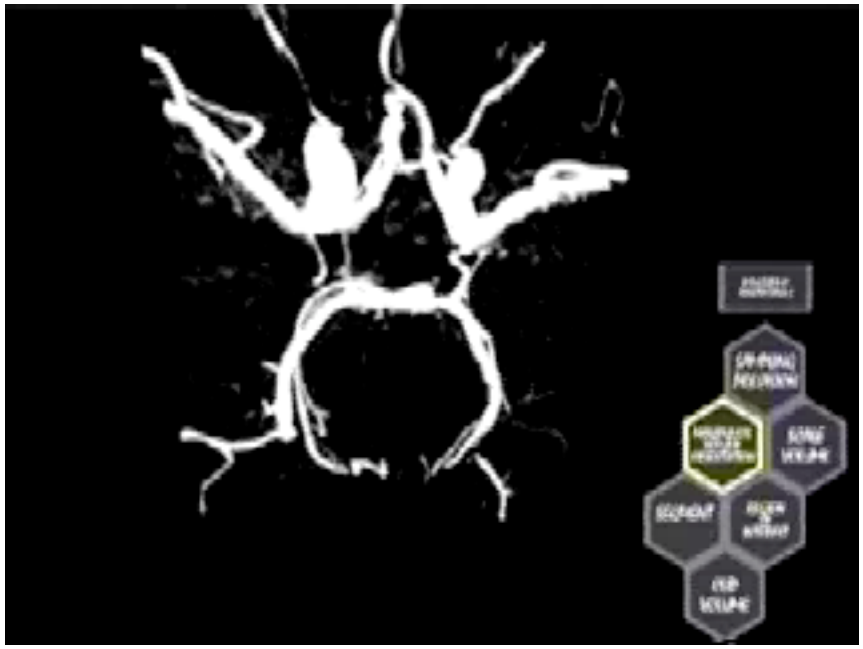
Computer Tomography (CT)

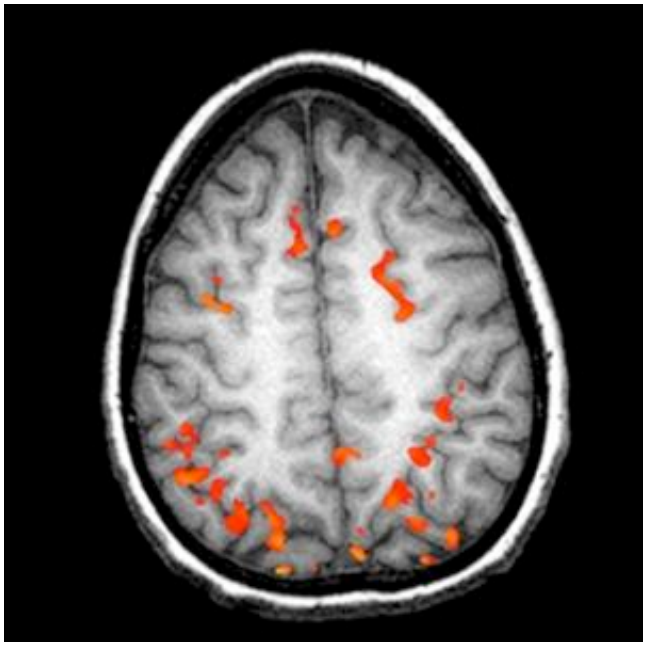




www.imaginis.com/ct-scan

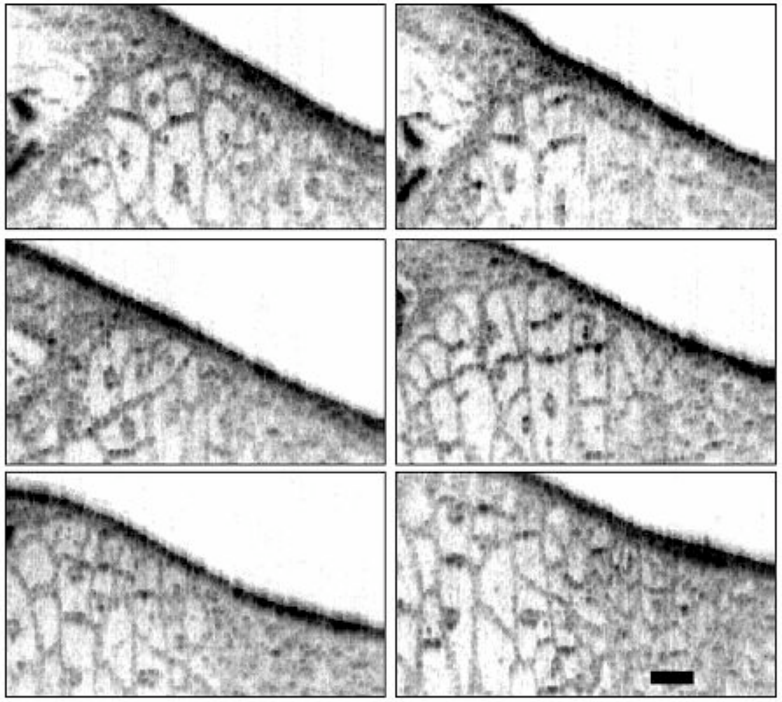
Magnetic Resonance Imaging (MRI)

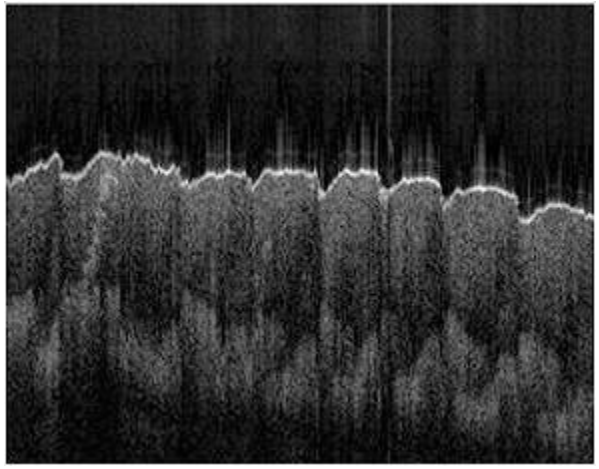


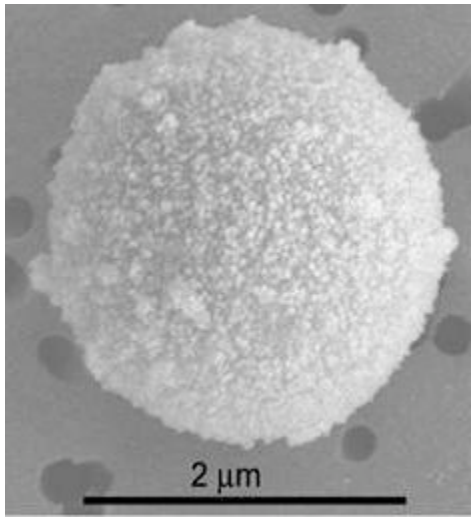


www.uic.edu/com/mrc/

Optical Coherence Tomography (OCT)







bil.nb.uiuc.edu

Imaging = Image Formation + Processing

Image Formation

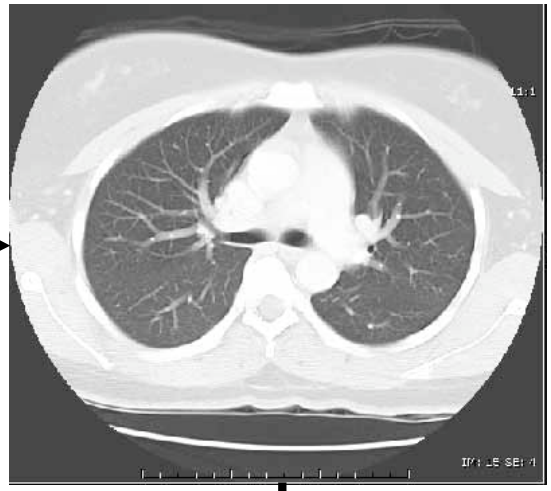
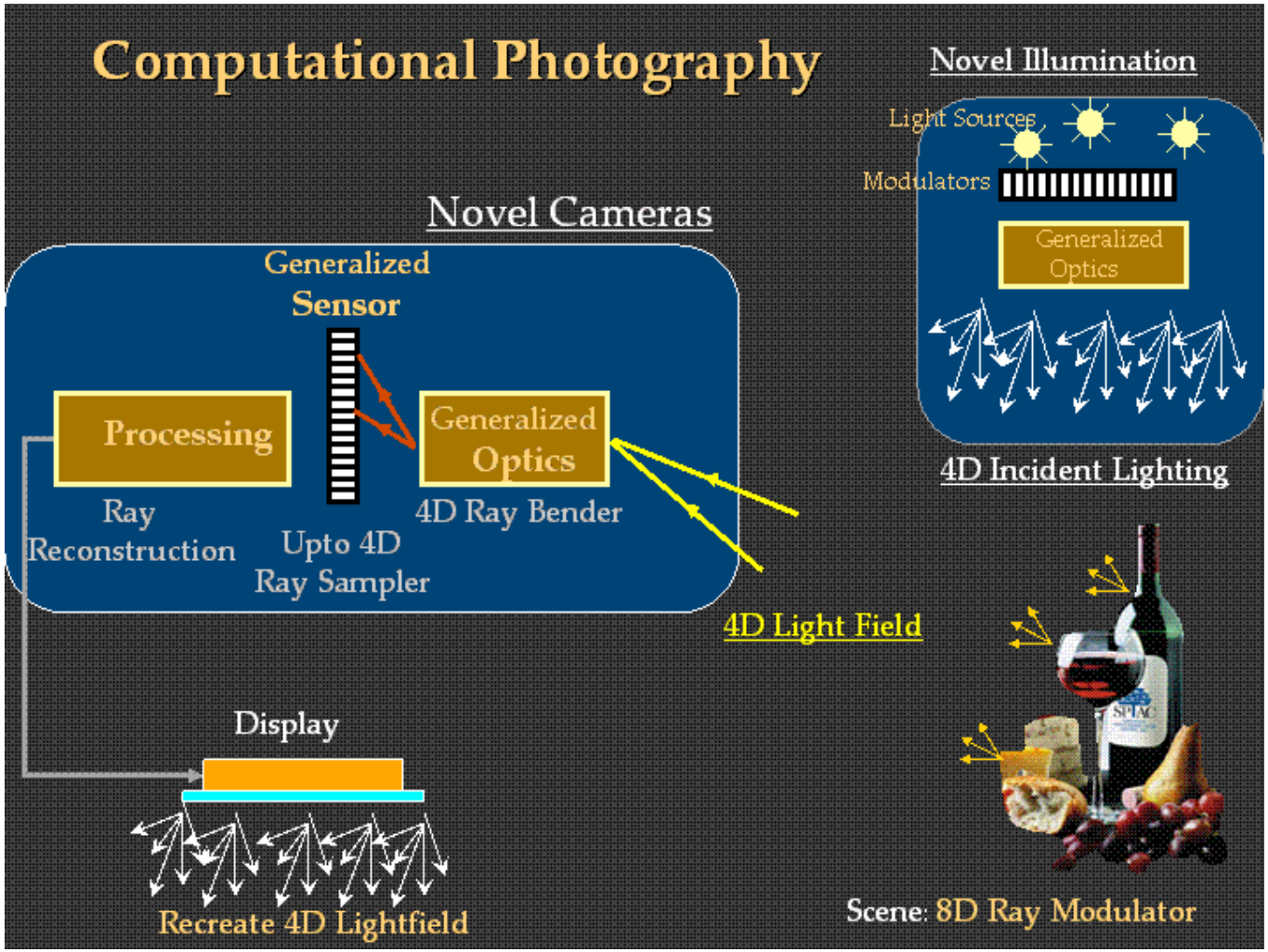


Image Processing

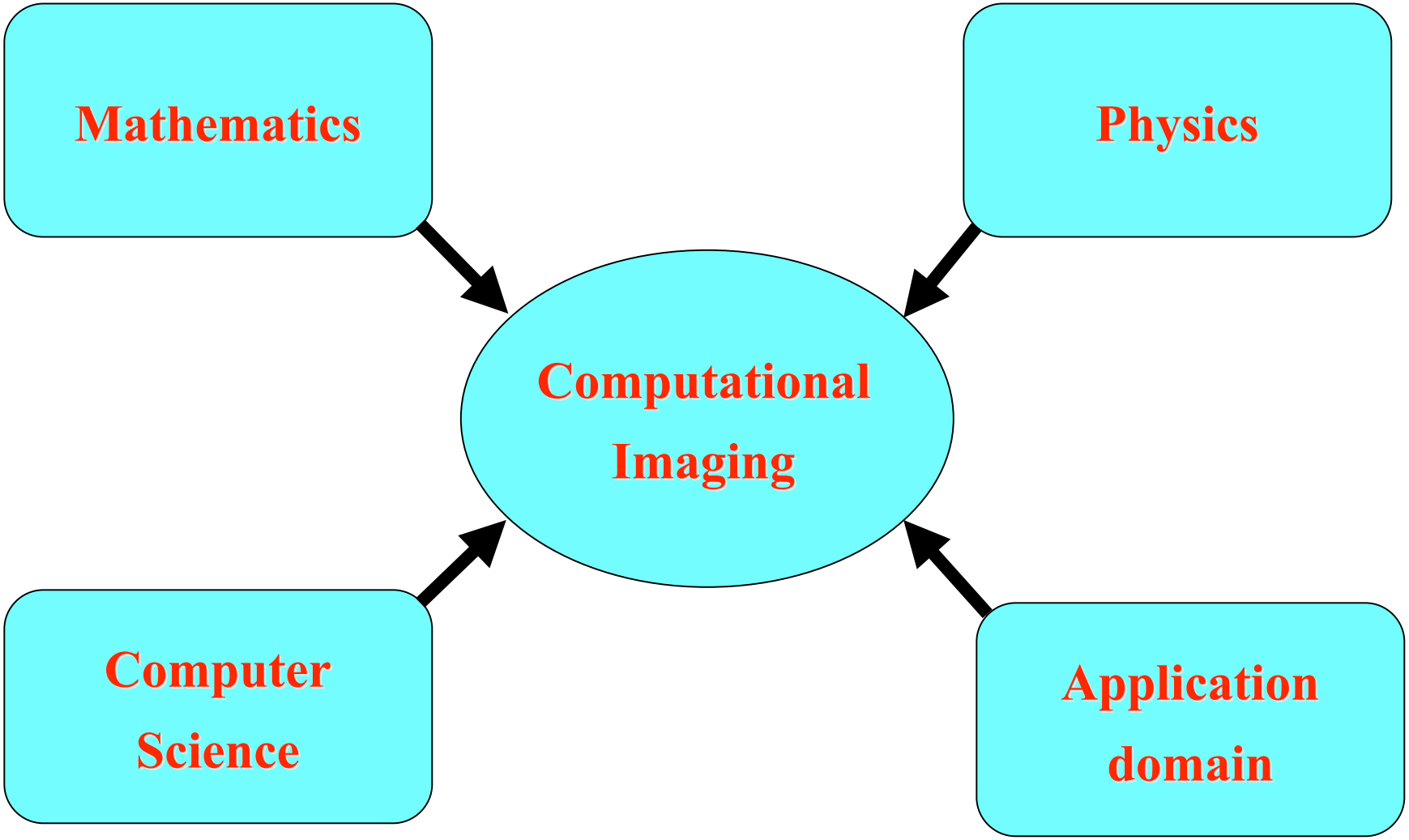
Tradition scope of signal processing

Computational Photography



www.merl.com/people/raskar/photo/

Imaging is a Multidisciplinary Field And Signal Processing is the Glue



An Application Domain: Health Care

- In 2005, the U.S. spent 16% of its GDP on health care.
  It is projected that this will reach 20% by 2015.
  - Starbucks: healthcare cost exceeds coffee.
  - General Motor: healthcare cost exceeds steel.

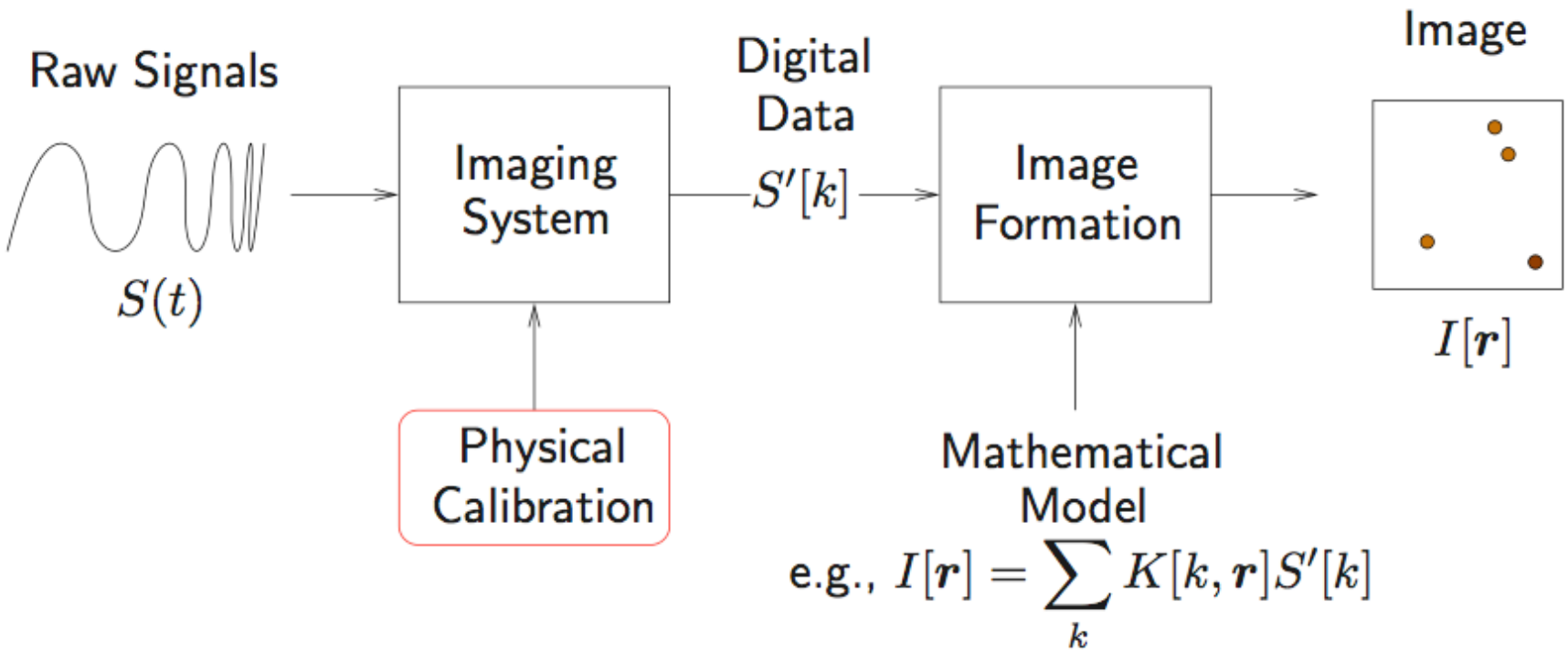
- A quarter of total Medicare budget is spent in the last year of life; 40% of it is on the last 30 days.

  Goal: Individualized treatments based on better medical imaging

- In developing countries: desire to have low-cost and effective population screening.

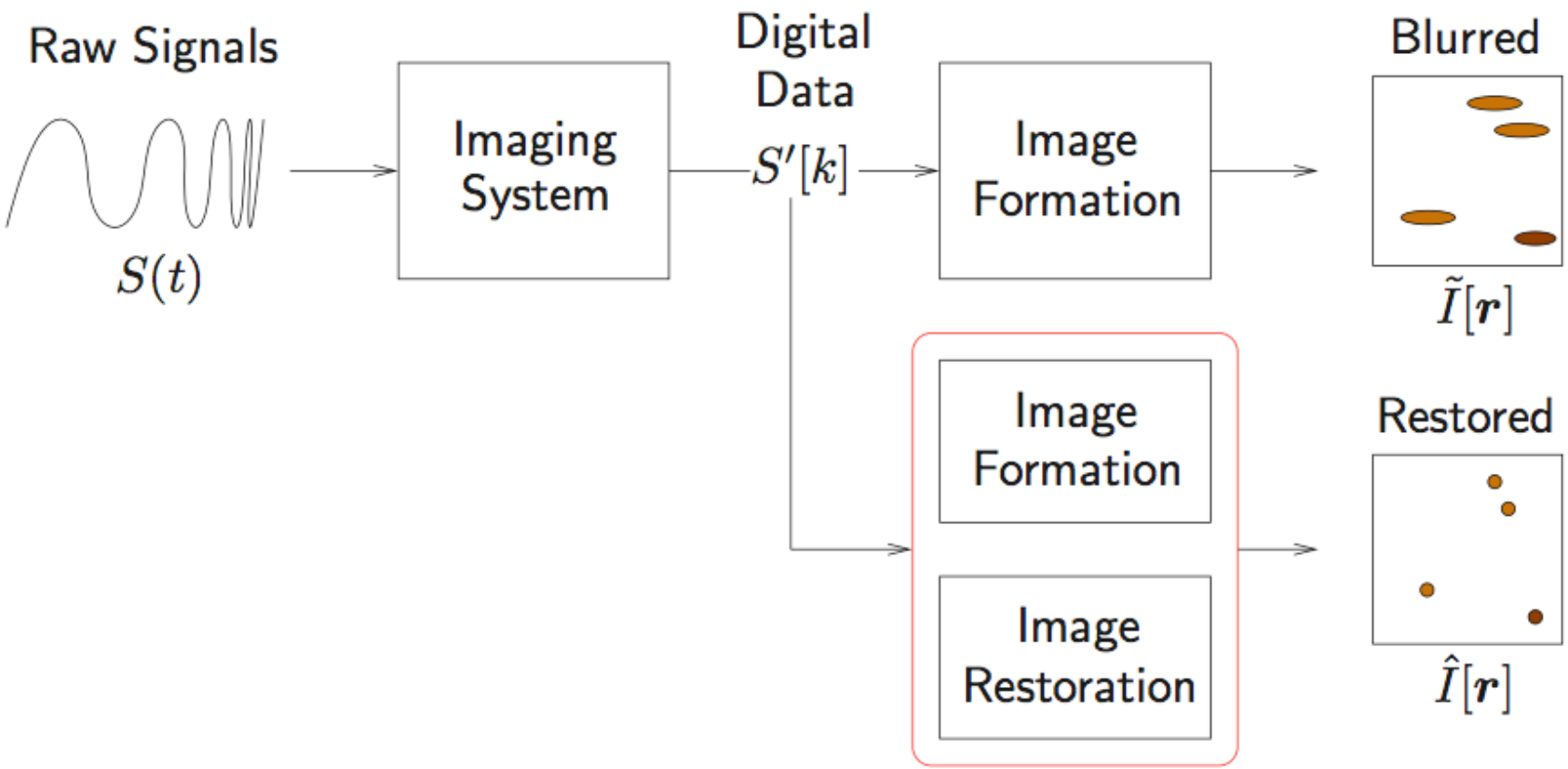
Hardware Approach to Imaging System Calibration

- Require expensive hardware modification and calibration



Computational Approach to Calibration

- Apply signal processing methods to form useful imagery from imperfect signal measurements.
- Use computational power to overcome physical limitations.



MRI with Field Inhomogeneity

- Field inhomogeneity is a key factor affecting MRI image reconstruction

$$s(\mathbf{k}) = \int f(\mathbf{r}) e^{-i\omega(\mathbf{r})t} e^{-i2\pi(\mathbf{k}(t)\cdot\mathbf{r})} d\mathbf{r}.$$

data

image

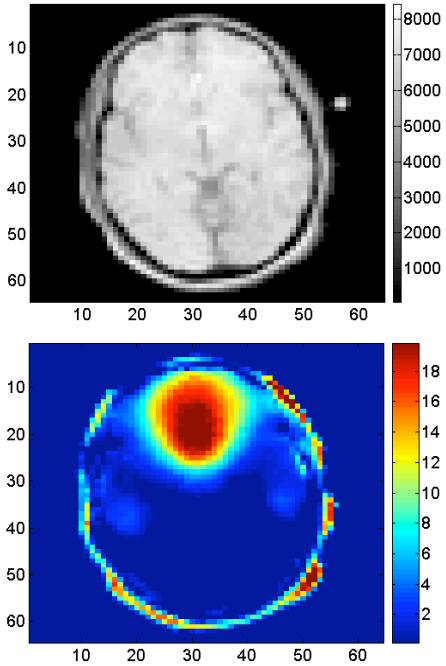
field map

$$s[m] = \sum_{n=0}^{N-1} a_n e^{i\phi_n m},$$

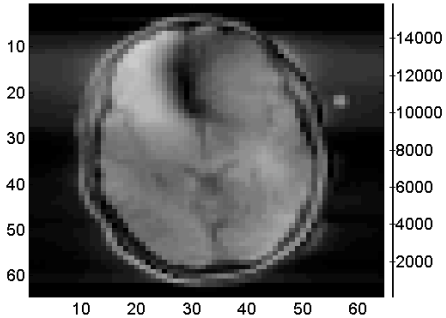
Harmonic Retrieval !

Joint Estimation in MRI using Harmonic Retrieval Methods

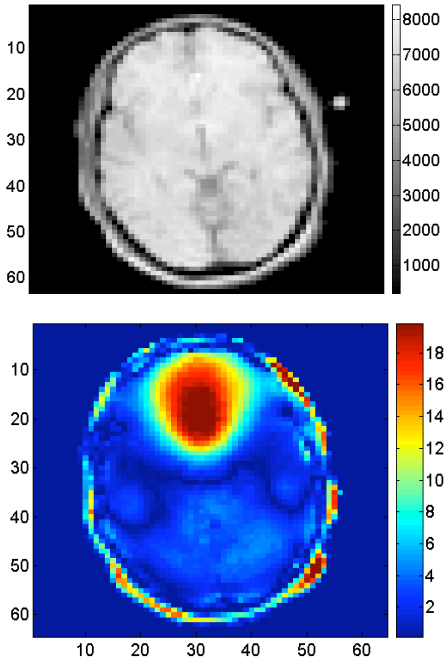
Original image and field map



Standard reconstruction

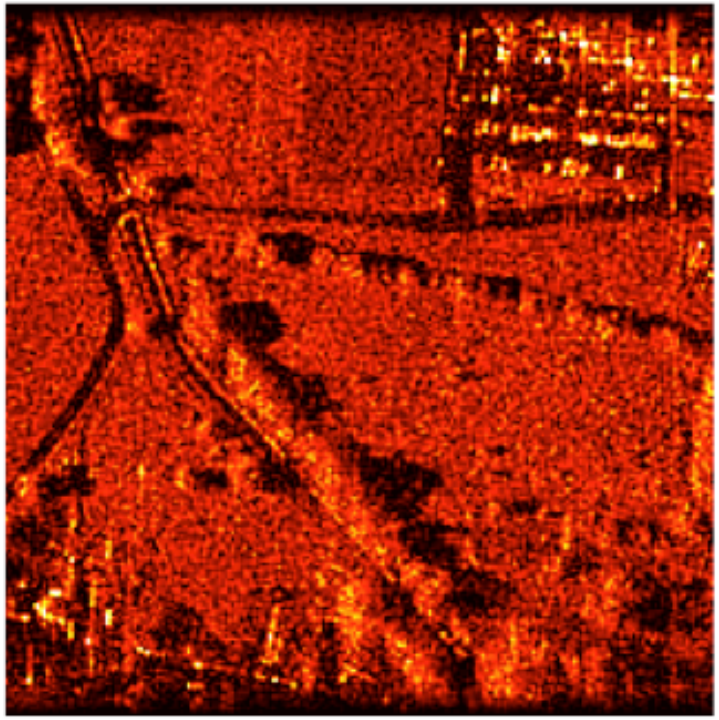


Our reconstruction

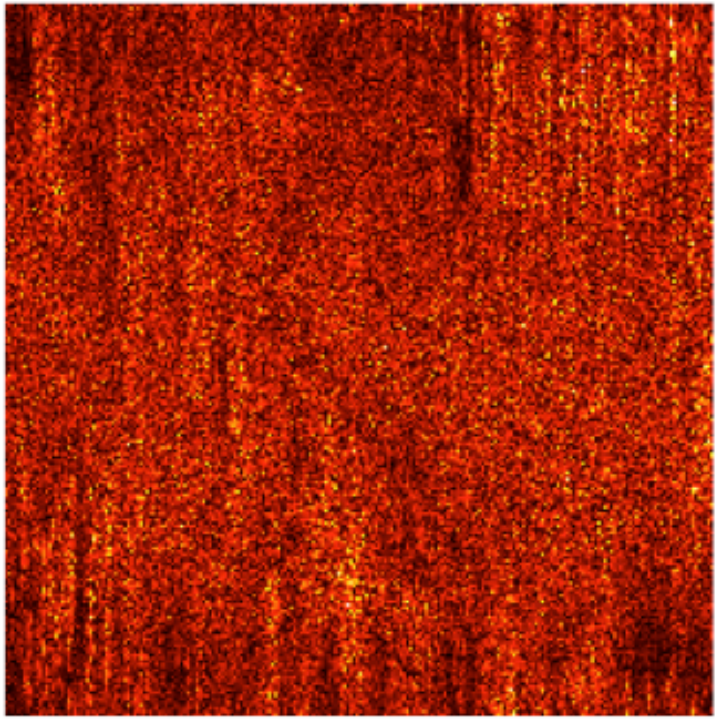


H. Nguyen et al., 2007

Autofocus Problem in Synthetic Aperture Radar (SAR)



Perfectly-focused image*

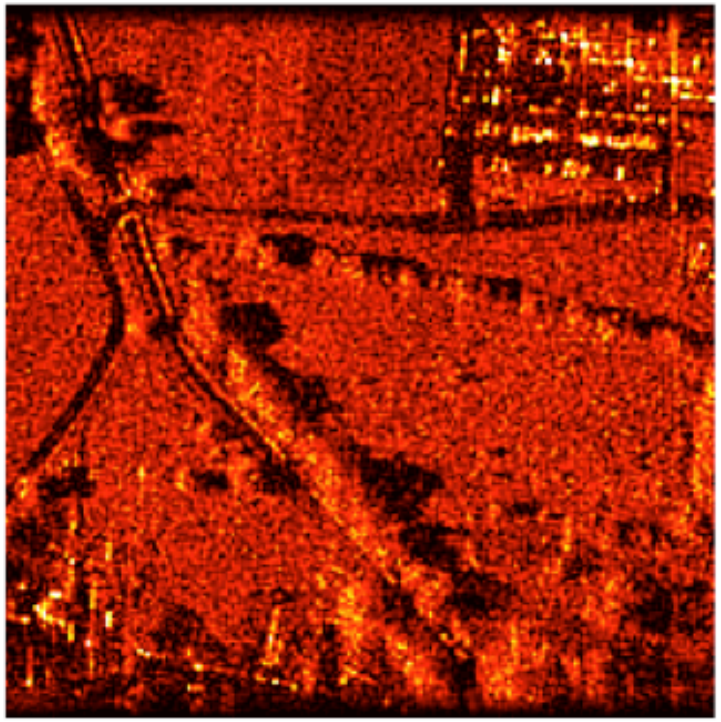


Defocused image (quadratic error)

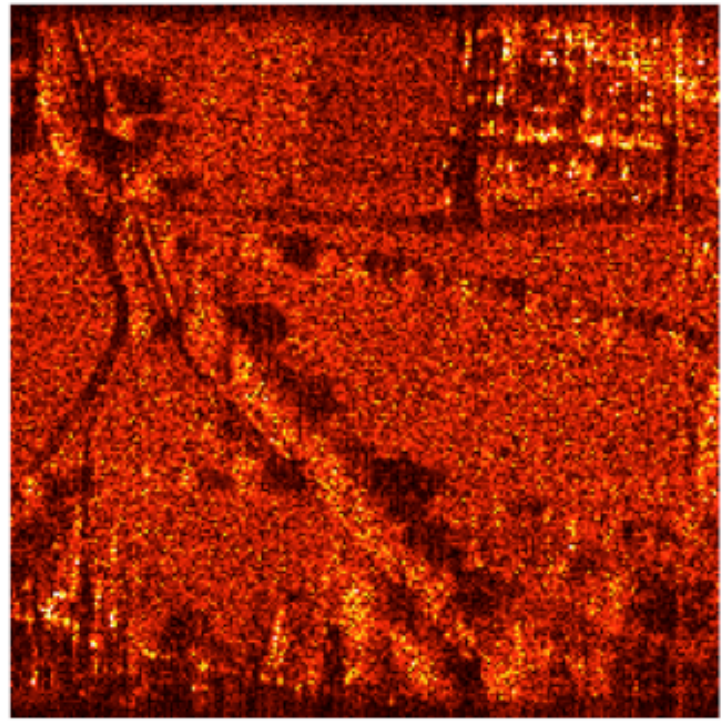
$$g[m,n] = DFT_k^{-1}\{G[k,n]\}$$

$$\tilde{G}[k,n] = G[k,n]\ e^{j\phi_e[k]}$$

MCA: MultiChanel Autofocus



MCA ($\mathrm{SNR}_{out} = \mathbf{25.9}$ dB, 0.58 s)

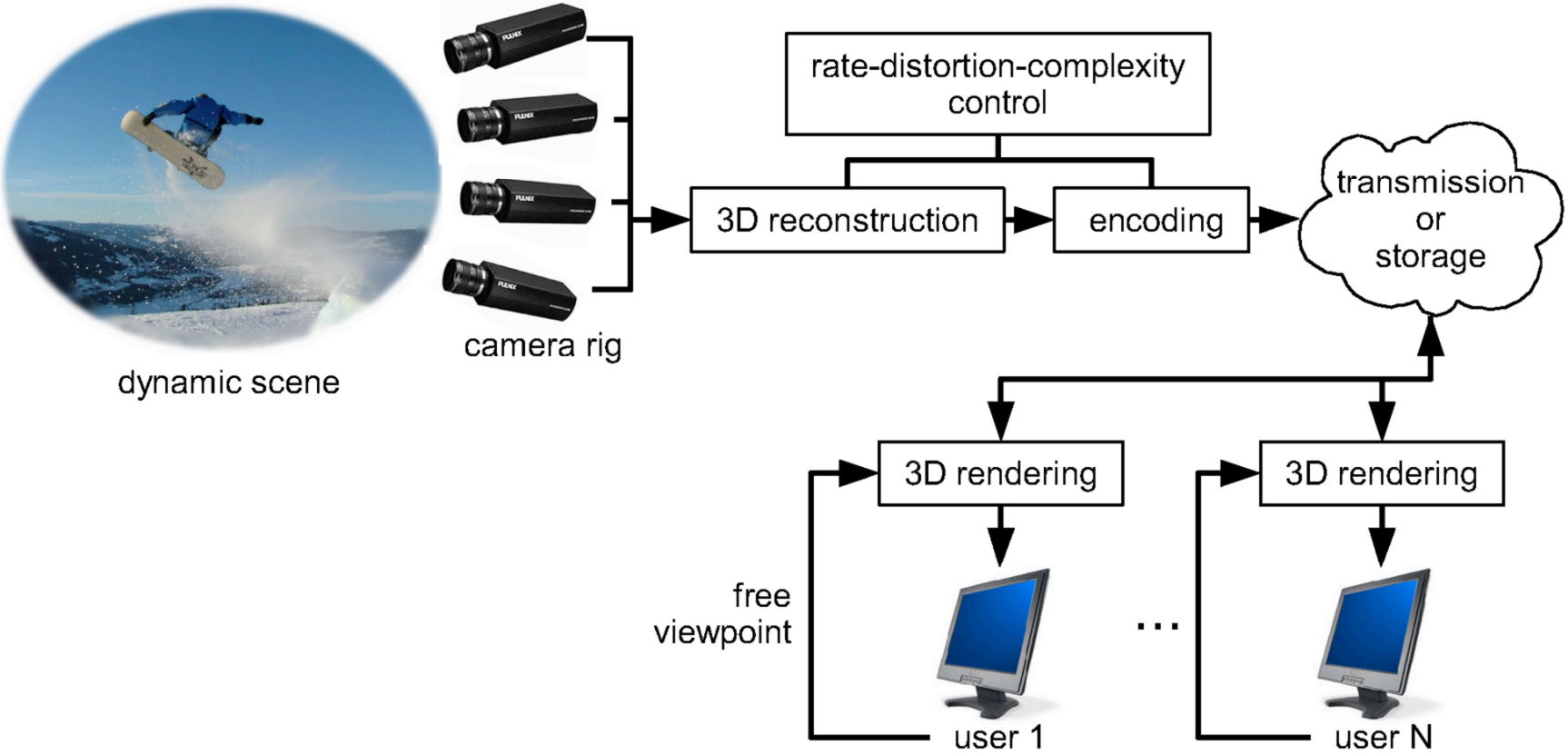


PGA ($\mathrm{SNR}_{out} = \mathbf{2.17}$ dB, 4.03 s)

$$\hat{\boldsymbol{g}}(\boldsymbol{f}) = \sum_{k=0}^{M-1} f_k \, \boldsymbol{\varphi}^{[k]}(\tilde{\boldsymbol{g}}), \quad \text{where} \quad \boldsymbol{\varphi}^{[k]}(\tilde{\boldsymbol{g}}) = \boldsymbol{C}\{\boldsymbol{e}_k\}\tilde{\boldsymbol{g}}$$

R. Morrison et al., 2007

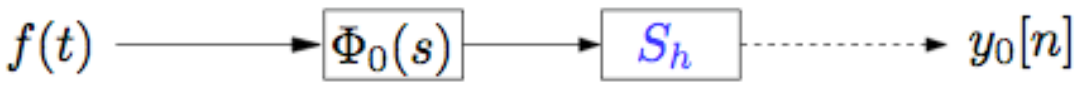
Beyond Television… Remote Reality



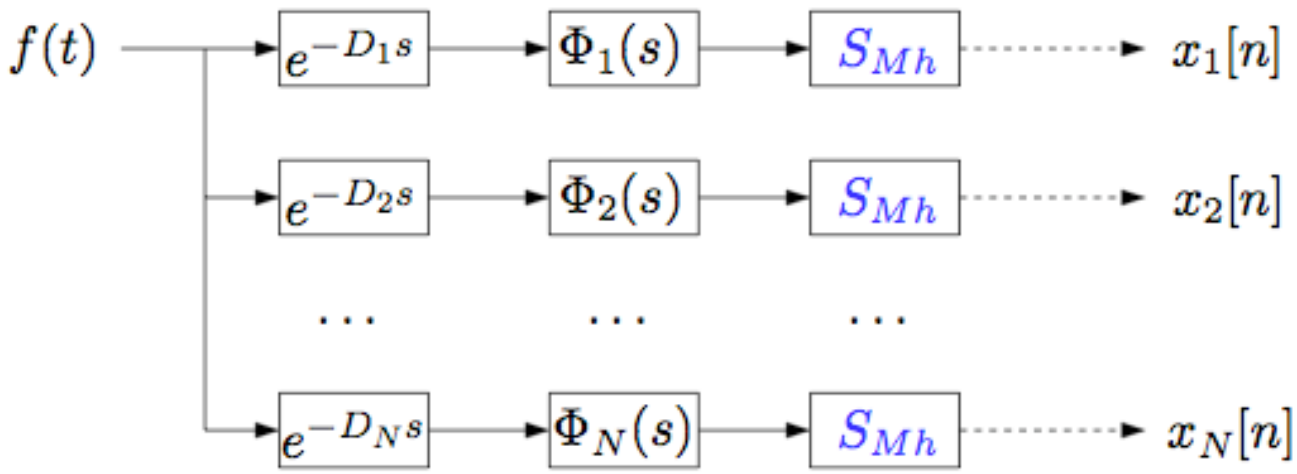
M. Maitre et al., 2007

Multi-Channel Sampling

- We want to approximate the high-resolution signal $y_0[n]$:



- ... from low-resolution signals $\{x_i[n]\}_{i=1}^{N}$:

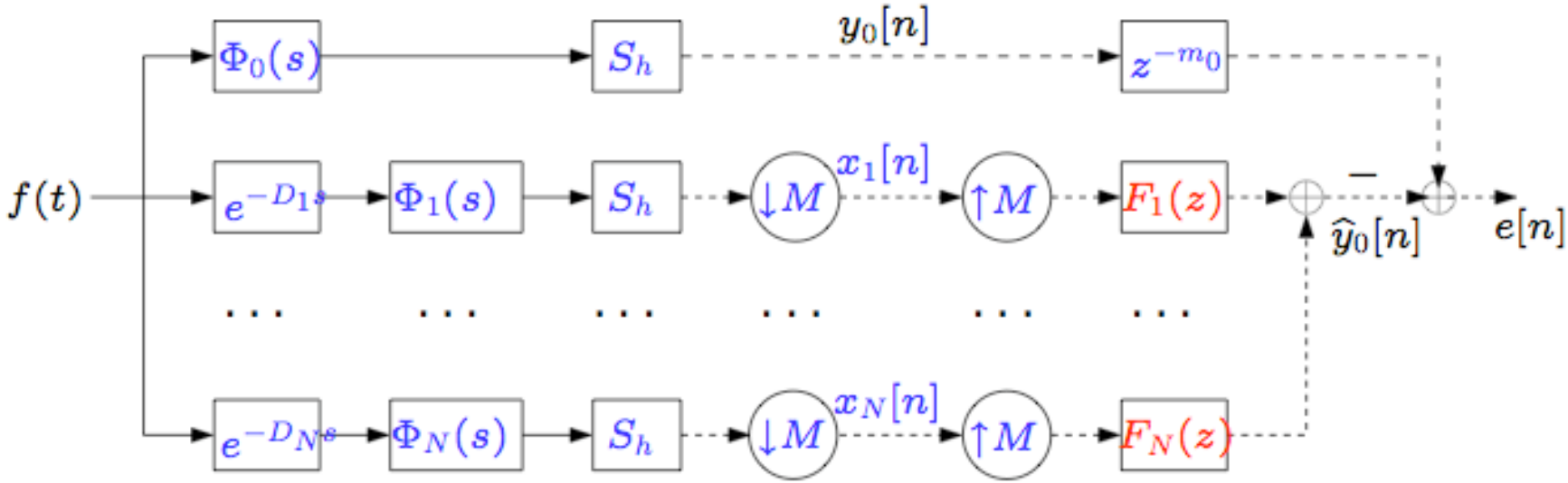


- Challenges:
  - No assumptions on input signals.
  - Presence of fractional delays.

Minimax Design of Hybrid Filter Banks

We want to design filters $\{F_i(z)\}_{i=1}^{N}$ to minimize the $\mathcal{H}_\infty$ norm of the continuous-input discrete-output induced error system $\mathcal{K}$:

$$\|\mathcal{K}\|_\infty = \sup \frac{\|e\|_{l_2}}{\|f\|_{L_2}} \quad \begin{array}{ll} \longleftarrow & \text{discrete} - \text{domain} \\ \longleftarrow & \text{continuous} - \text{domain} \end{array}$$



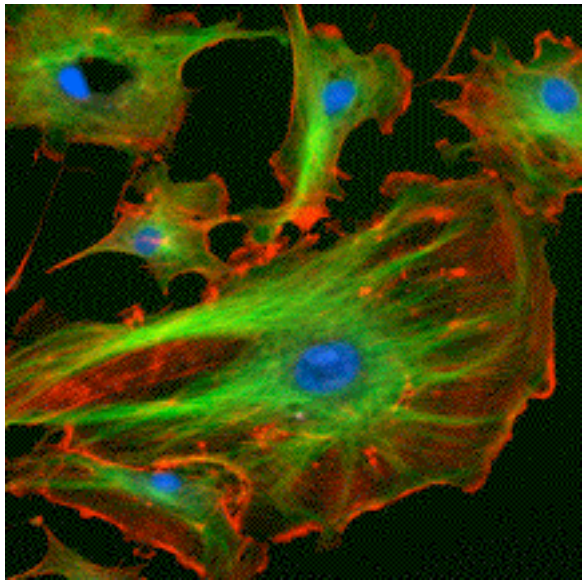
H. Nguyen and MD, 2007

Image Processing:
The Key is Efficient Image Representation

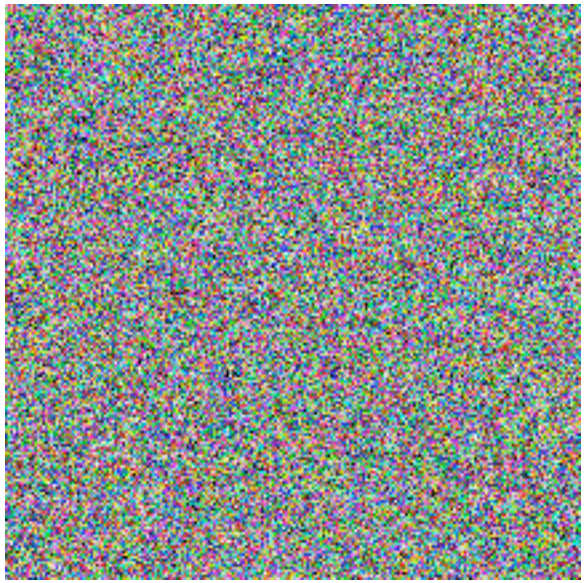
- **Goal:** Parsimonious view of pictorial information

A natural image

A biological image



A random image



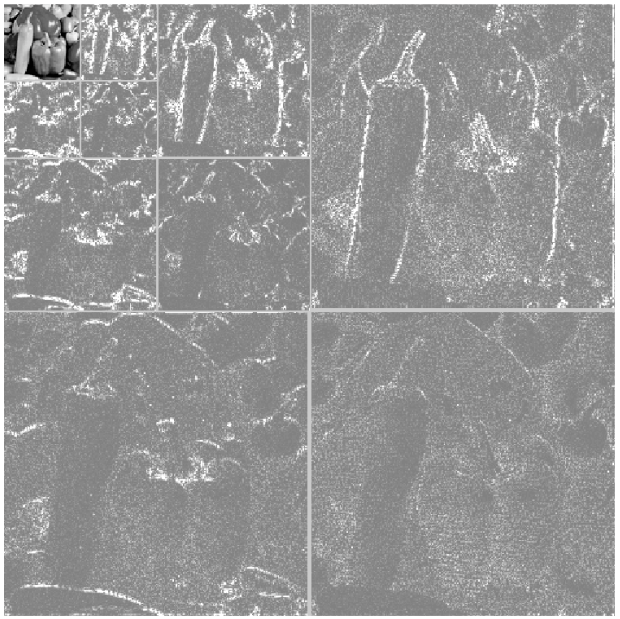
Natural images "live" in a very tiny bit

of the space of all possible "images"

Image Representation via Transforms

Original domain: pixels

Wavelet domain: coefficients



Example of Impact on Applications

Are We There?

"…the 20 bits per second which, the psychologists assure us, that the human eye is capable of taking in…"

D. Gabor, 1959

One image $\xrightarrow{\text{Human eye } (\approx 5 \text{ sec.})}$ 100 bits

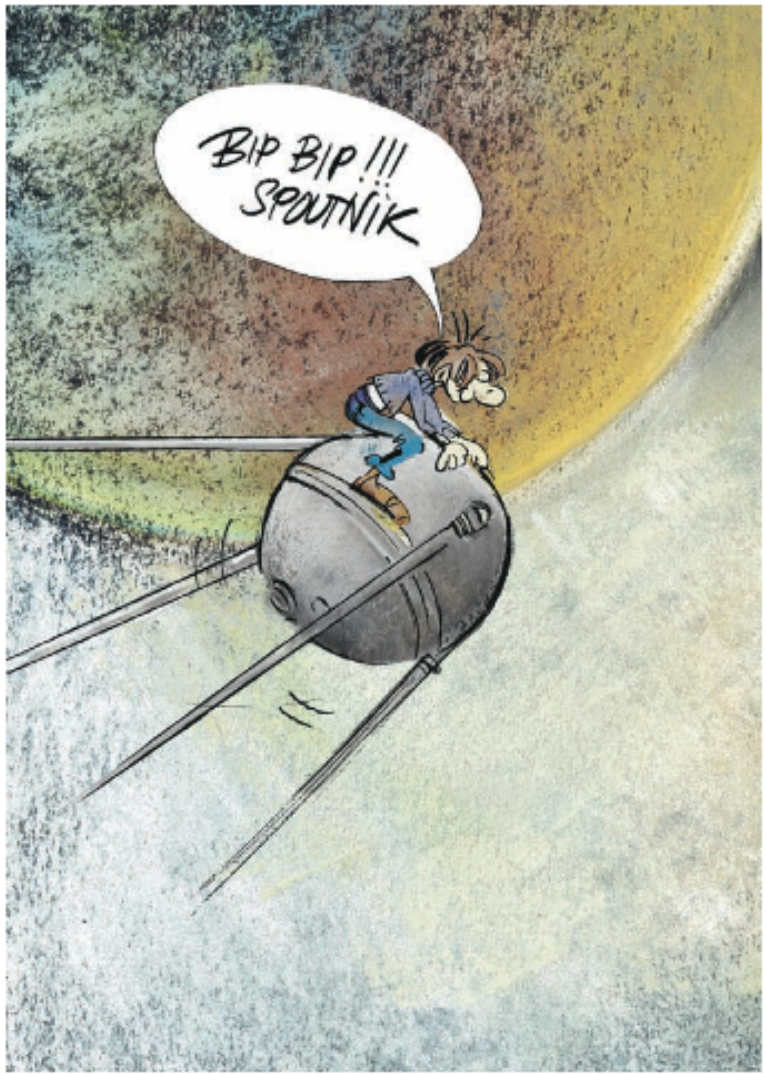
One image $\xrightarrow{\text{JPEG-2000 (wavelets)}}$ 1'000'000 bits

What Have We Learnt from Sputnik?

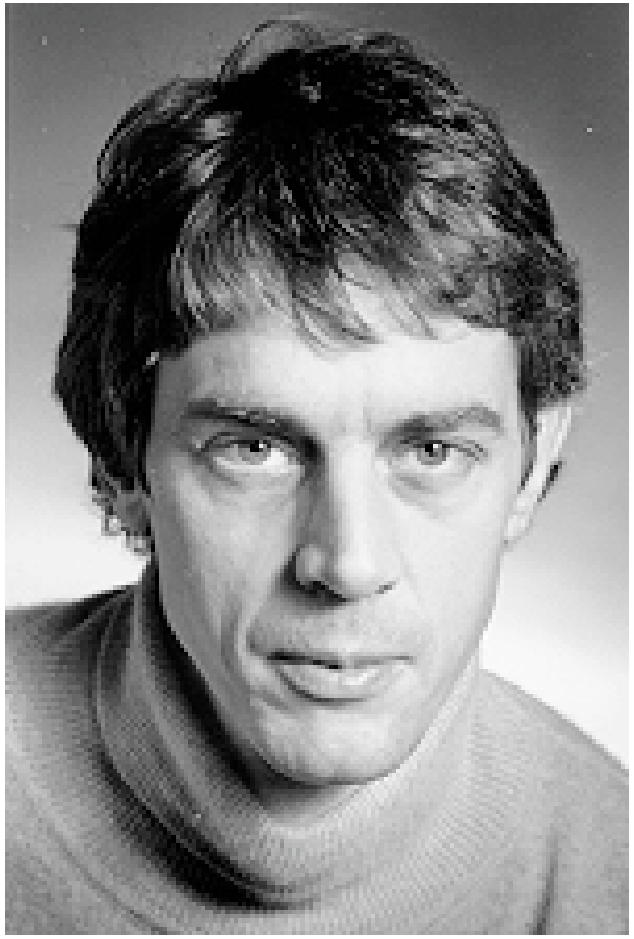
"The lesson of the past 50 years, however, is that the more humanity discovers about space, the rarer and more precious life on Earth seems."

***Economists**, 27 Sep 2007*

End of Part 1



Part 2



Martin Number

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Happy Birthday Martin!