Long-baseline intensity interferometry: data transmission and correlation

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Workshop on Hanbury Brown & Twiss interferometry
Nice, 13 May 2014

Participants

- Graduate (MSc) students
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- Faculty
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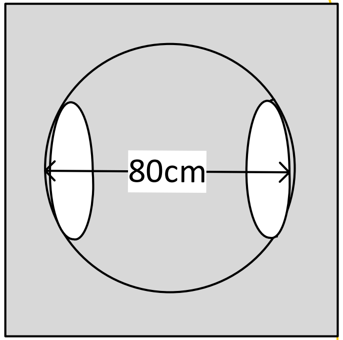
  - Pini Gurfil
- Technical support
  - Dr Dan Spektor
  - Hovik Agalarian
  - Communications lab, EE dept.
  - Distributed Space Systems Lab

Contents

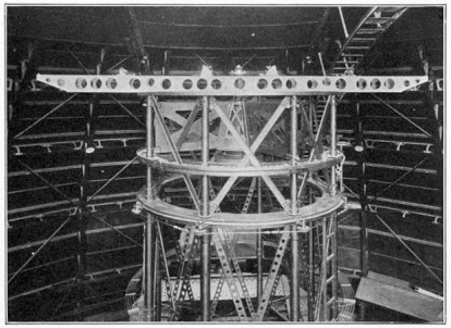
- Why intensity interferometry
- Why revival
- New possibilities
- Previous experiments
- Correlation at a distance
- Transmitting the intensities
- Future directions
- Summary

Amplitude interferometry pioneers

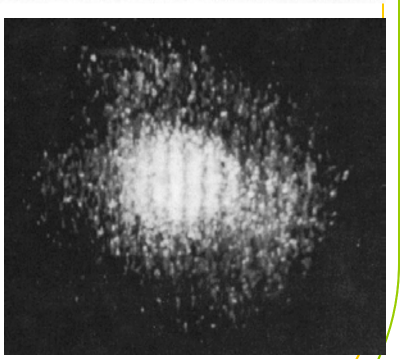
- Stephan, inside the aperture, 1870
  - 0.8 m



- Michelson, outside the aperture, 1920
  - 6 m



- (HBT, 1965-72)



- Labeyrie, outside the telescope, 1975
  - 13 m

Why intensity interferometry

- Science developments
  - Quantum physics
  - Astrophysical knowledge
- Technology developments
  - Fast detectors
  - Radio technology
    - Light collectors
    - Fast electronics
    - Correlators
    - Coaxes
  - Human intervention not necessary (cf. Michelson's eye)

Why revival

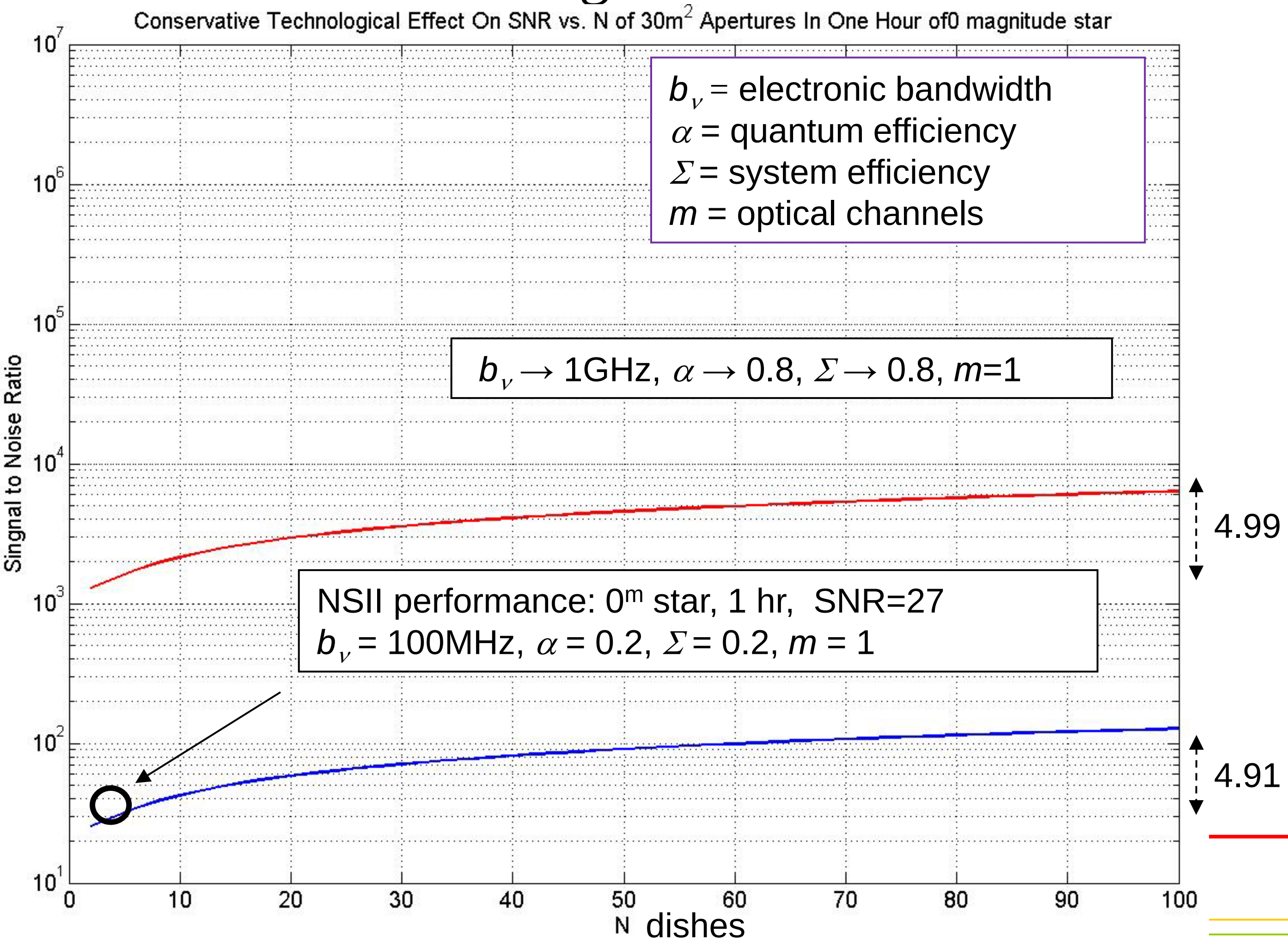
- Science developments
  - Astrophysical knowledge
  - Photonics
  - Other fields of physics: particles, biophysics
- Technology developments
  - Detectors: faster and redder
  - Electronics: faster and digital
  - Optics: fibres
  - Space

New possibilities

- Science developments
  - Astrophysical knowledge
  - photonics
- Technology developments
  - Detectors: faster and redder
  - Electronics: faster and digital
  - Optics: fibres
  - Space
- New opportunities
  - Ĉerenkov arrays
  - Antarctica

Previous experiments (Technion) I

- Theoretical studies
  - Ofir and Ribak: higher-order correlations



Conservative Technological Effect On SNR vs. N of 30m^2 Apertures In One Hour of0 magnitude star

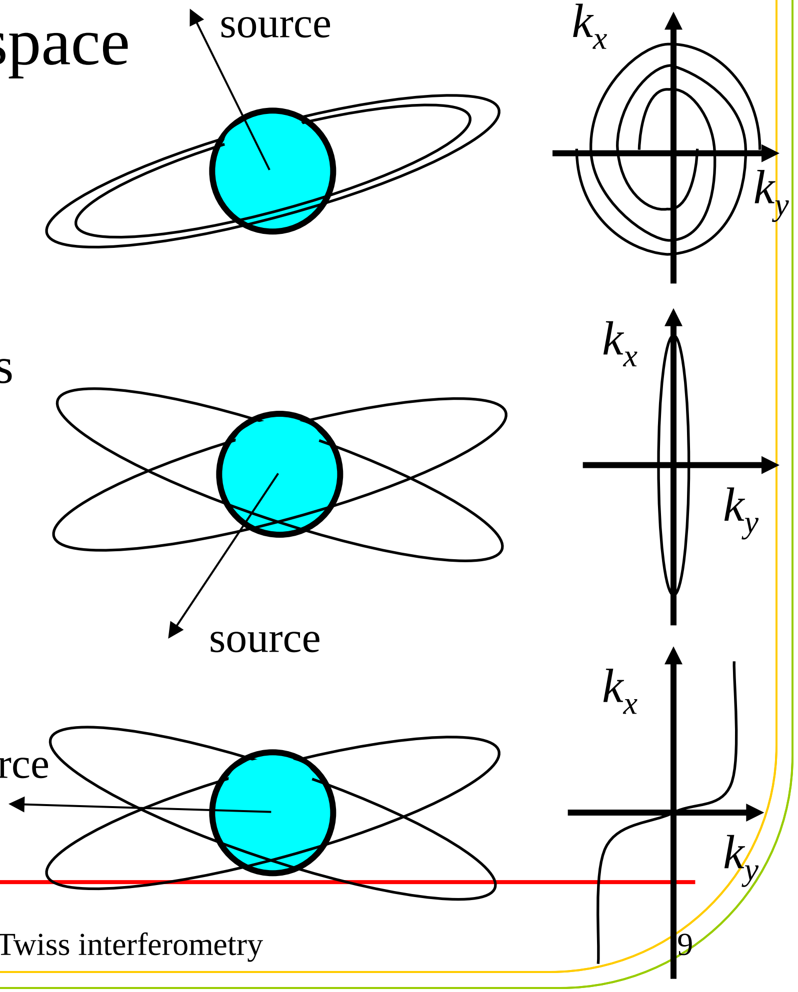
b_ν = electronic bandwidth
α = quantum efficiency
Σ = system efficiency
m = optical channels

$b_\nu \to$ 1GHz, $\alpha \to 0.8$, $\Sigma \to 0.8$, m=1

NSII performance: 0^m star, 1 hr, SNR=27
b_ν = 100MHz, $\alpha = 0.2$, $\Sigma = 0.2$, $m = 1$

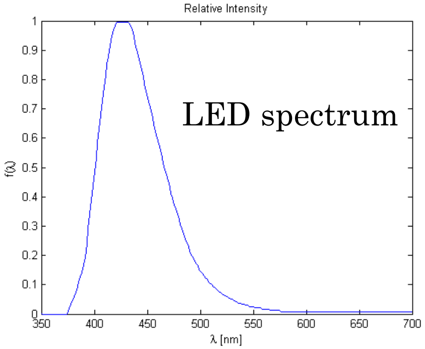
Previous experiments (Technion) II

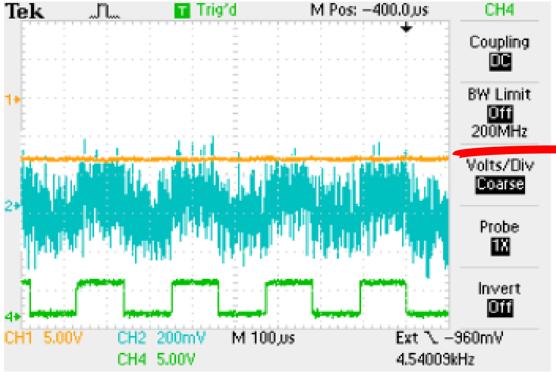
- Theoretical studies
  - Ofir and Ribak: higher-order correlations
  - Klein, Guellman, Lipson: space
    - All wavelengths possible
    - Formation flight
      - Satellites orbits
      - Keeping constant baselines
      - Optimal fuel consumption
      - Control laws



Previous experiments (Technion) III

- Theoretical studies
  - Ofir and Ribak: higher-order correlations
  - Klein, Guellman, Lipson: space intensity interferometry
- Laboratory studies
  - Spektor, Lipson, Ribak
    - Blue LEDs metres from Fresnel lenses
    - Fast photomultipliers, lock-in amp.
    - 2000’s correlation electronics: AD8302





Tek Trig’d M Pos: −400.0µs CH4

Coupling DC

BW Limit Off 200MHz

Volts/Div Coarse

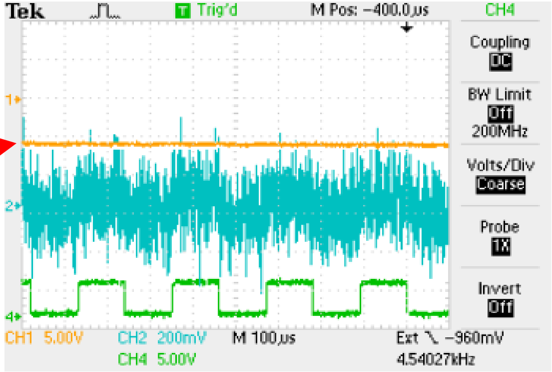
Probe 1X

Invert Off

CH1 5.00V CH2 200mV M 100µs Ext −960mV

CH4 5.00V 4.54009kHz

no signal



Tek Trig’d M Pos: −400.0µs CH4

Coupling DC

BW Limit Off 200MHz

Volts/Div Coarse

Probe 1X

Invert Off

CH1 5.00V CH2 200mV M 100µs Ext −960mV

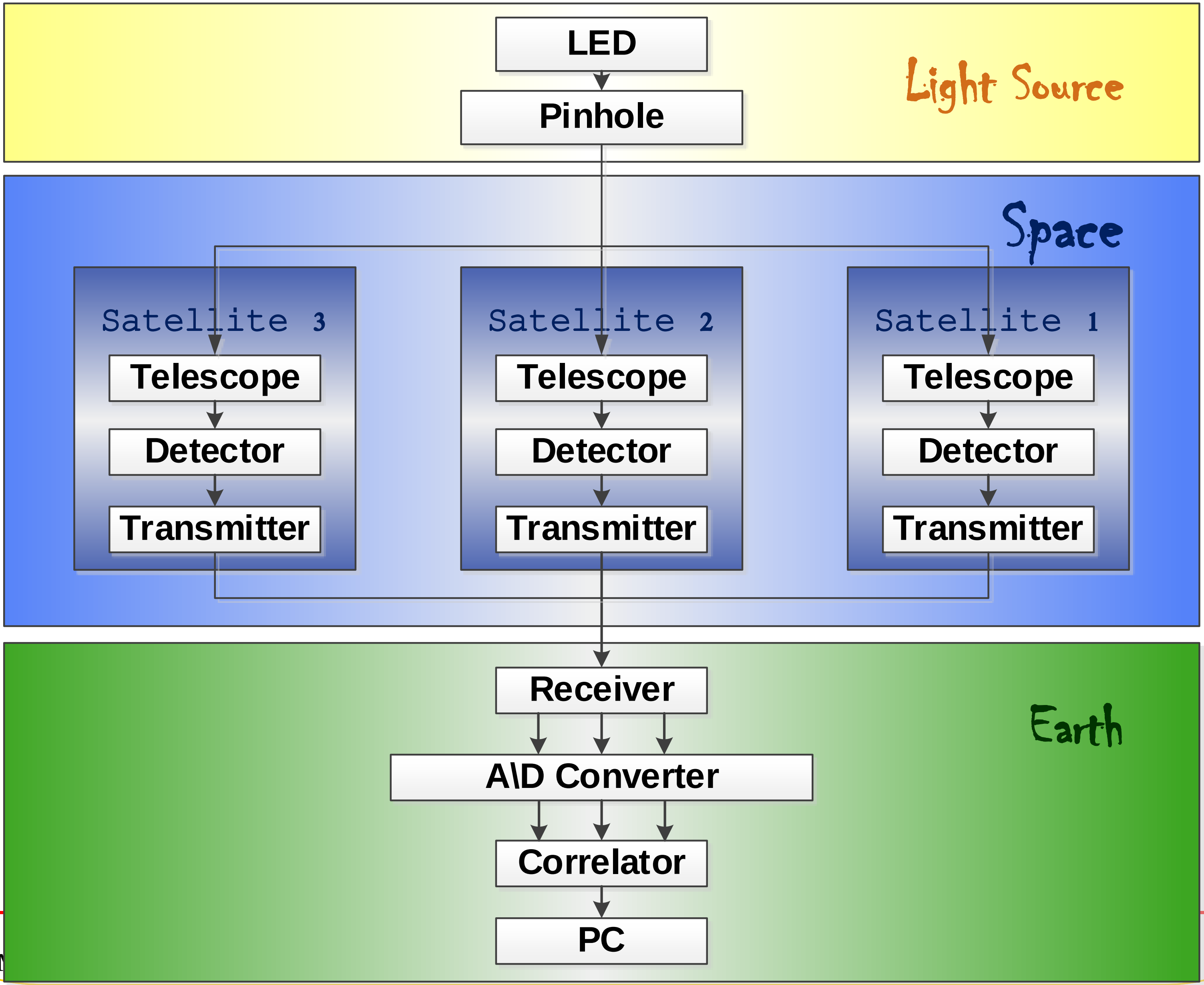
CH4 5.00V 4.54027kHz

with signal

Correlation at a distance

- Asher Space Research Institute
  - Physics and Aeronautics
- Distributed Space Systems Laboratory
  - ERC support
  - Air table, vehicle location
  - Dark room

Scheme



Light Source

LED

Pinhole

Space

Satellite 3

Telescope

Detector

Transmitter

Satellite 2

Telescope

Detector

Transmitter

Satellite 1

Telescope

Detector

Transmitter

Earth

Receiver

A\D Converter

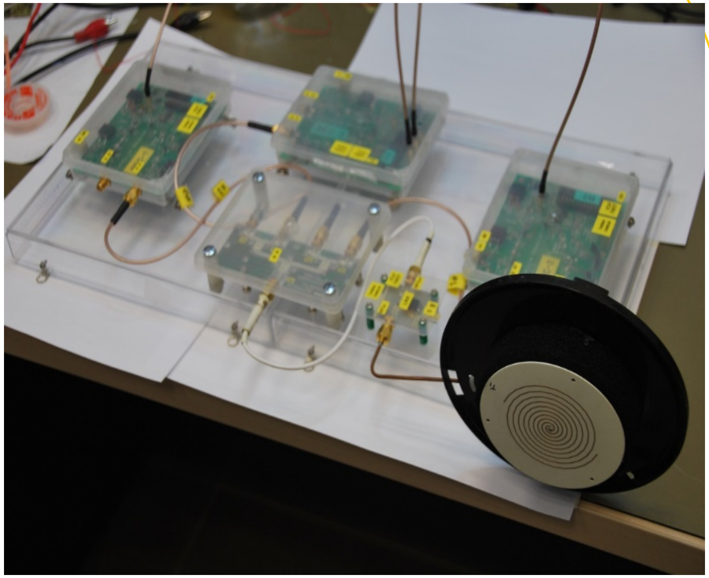
Correlator

PC

Components I

Three
receivers

0.95 GHz bandwidth
@ 3.1, 4.2 & 5.9 GHz



Common
antenna

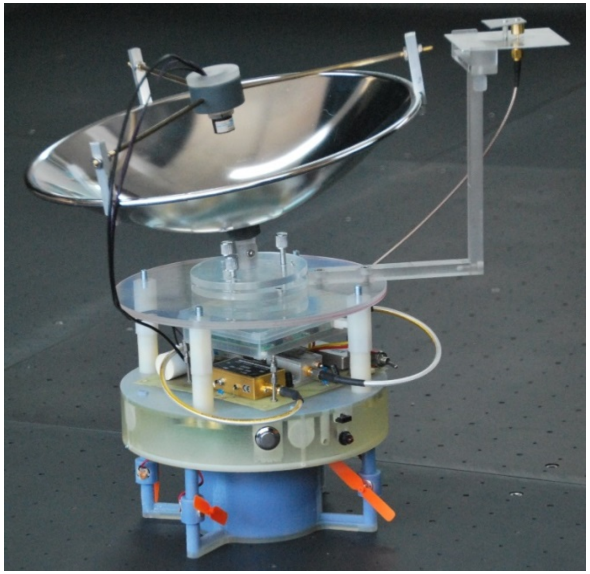
Photomultiplier

Light collector

Tilt mechanism

Preamplifier
+ transmitter

Rotation propellers

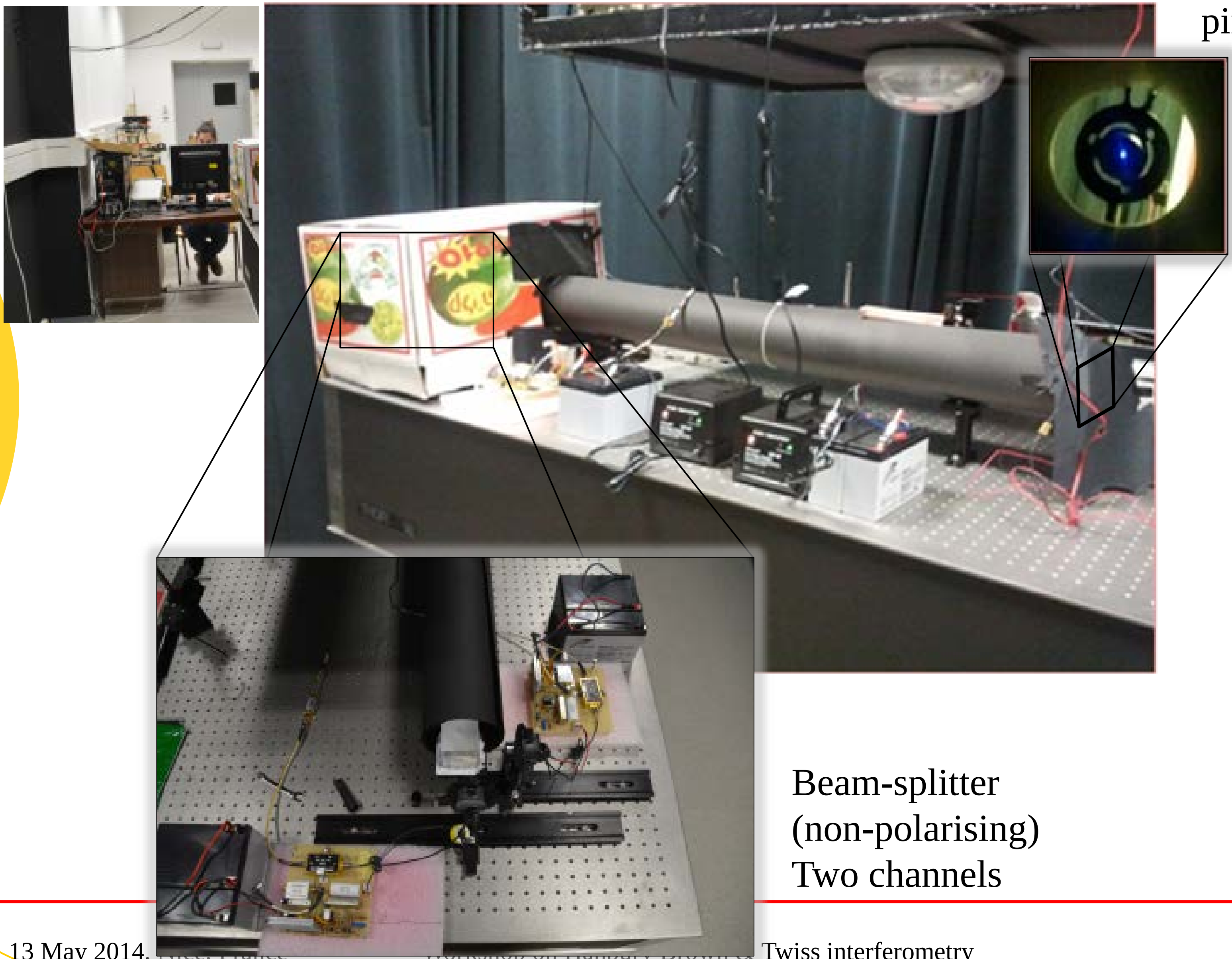


Antenna

Components II

- Analogue-to-digital converters
  - Up to 5 giga-samples per second (GSPS)
- Virtex-6 FPGA
  - Delay
  - Correlation
  - Integration
  - Transfer to host PC

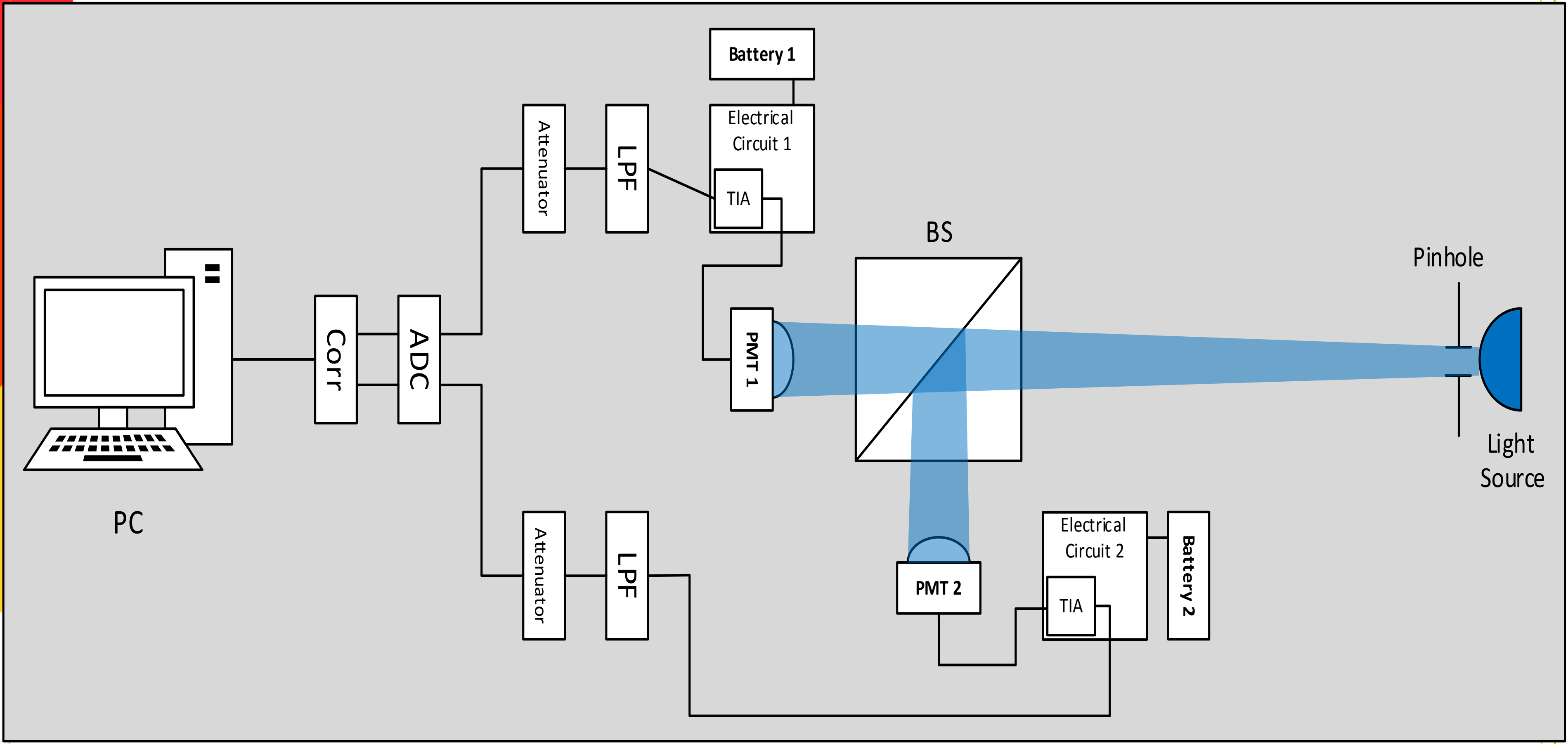
Dark-room experiment



Blue LED +
pin-hole

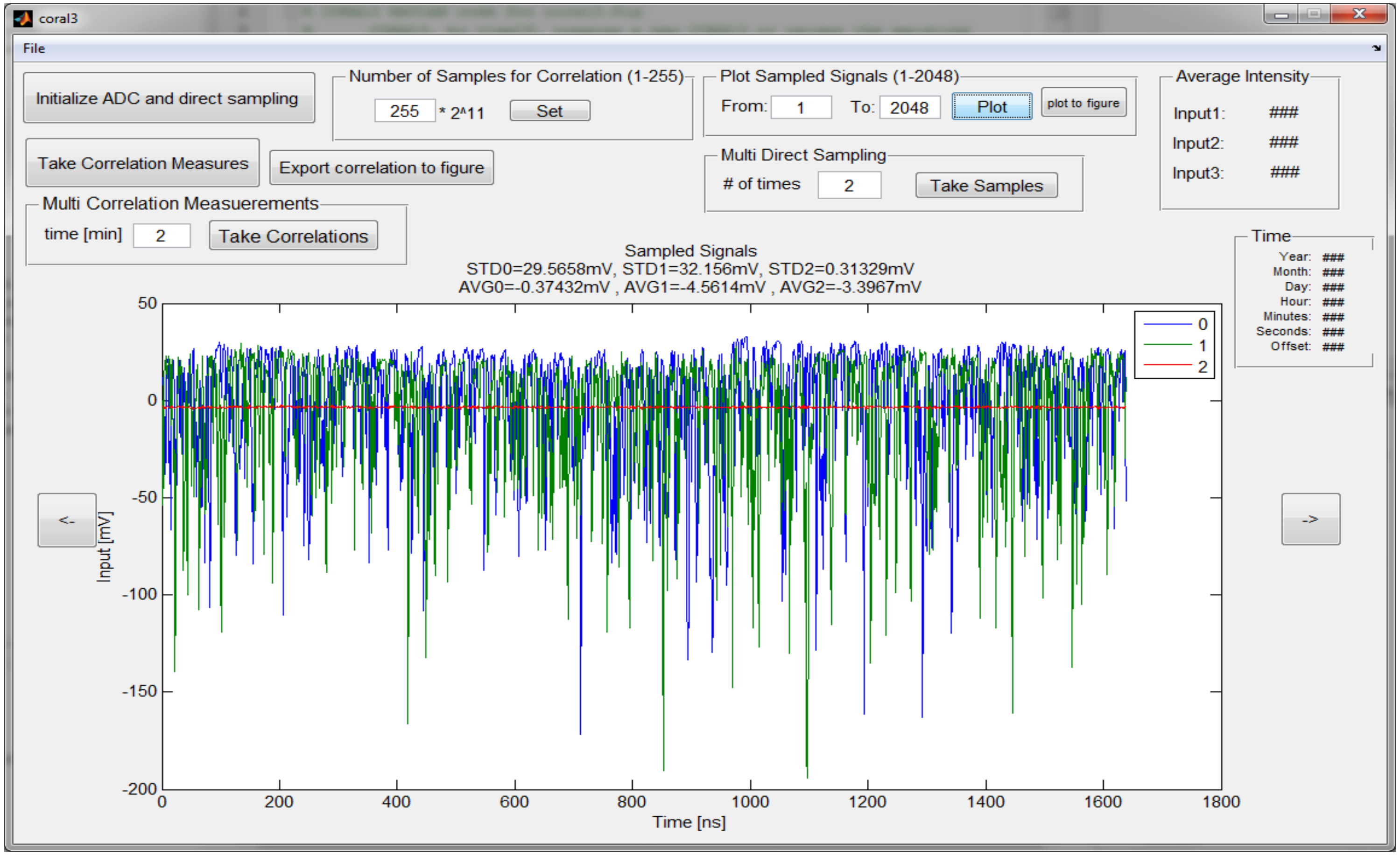
Beam-splitter
(non-polarising)
Two channels

Dark-room set-up



- Some experiments: switch A/D and correlator by fast scope and memory

Typical input



Number of Samples for Correlation (1-255): 255 * 2^11

Plot Sampled Signals (1-2048)
From: 1 To: 2048

Multi Direct Sampling
# of times 2

Multi Correlation Measurements
time [min] 2

Average Intensity
Input1: ###
Input2: ###
Input3: ###

Time
Year: ###
Month: ###
Day: ###
Hour: ###
Minutes: ###
Seconds: ###
Offset: ###

Sampled Signals
STD0=29.5658mV, STD1=32.156mV, STD2=0.31329mV
AVG0=-0.37432mV , AVG1=-4.5614mV , AVG2=-3.3967mV

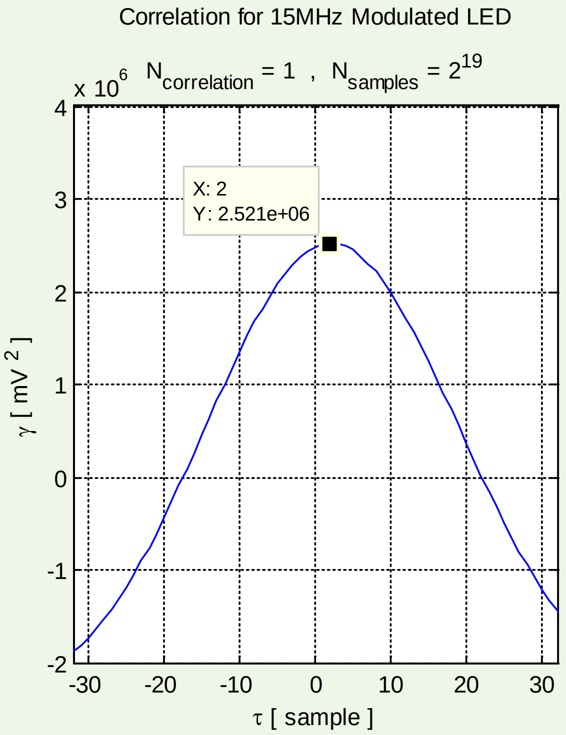
- Three channels (red – inactive)
- LED: 415 nm. Power: 2.8 W. Pin-hole: 15 µm. H = 78 cm. D = 0 cm.

Electronic delay

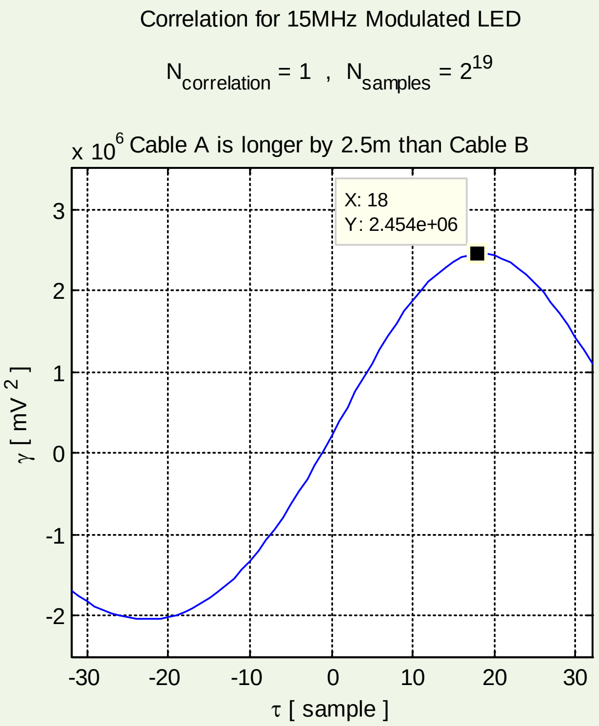
Correlation of 15MHz modulated LED

15 MHz Modulated Blue LED , Duty Cycle = 20% , $h = 78\ cm$, d=0

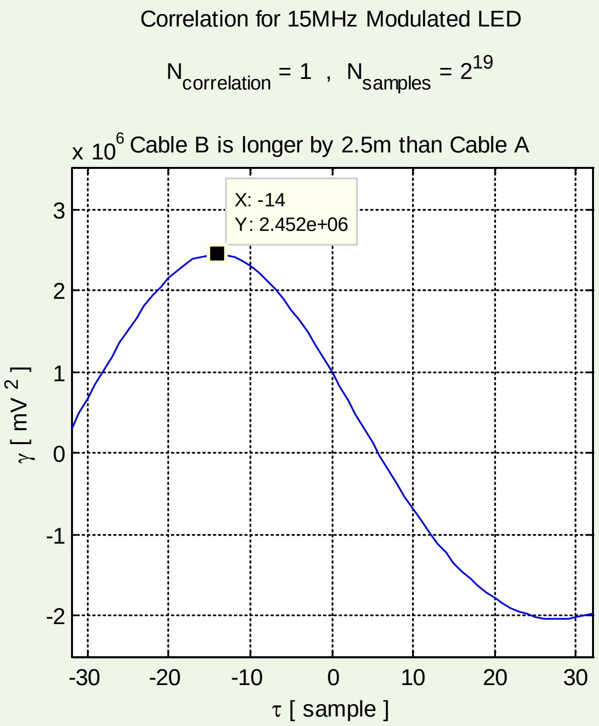
Cables – Same length



Cable A is longer by 2.5m



Cable B is longer by 2.5m

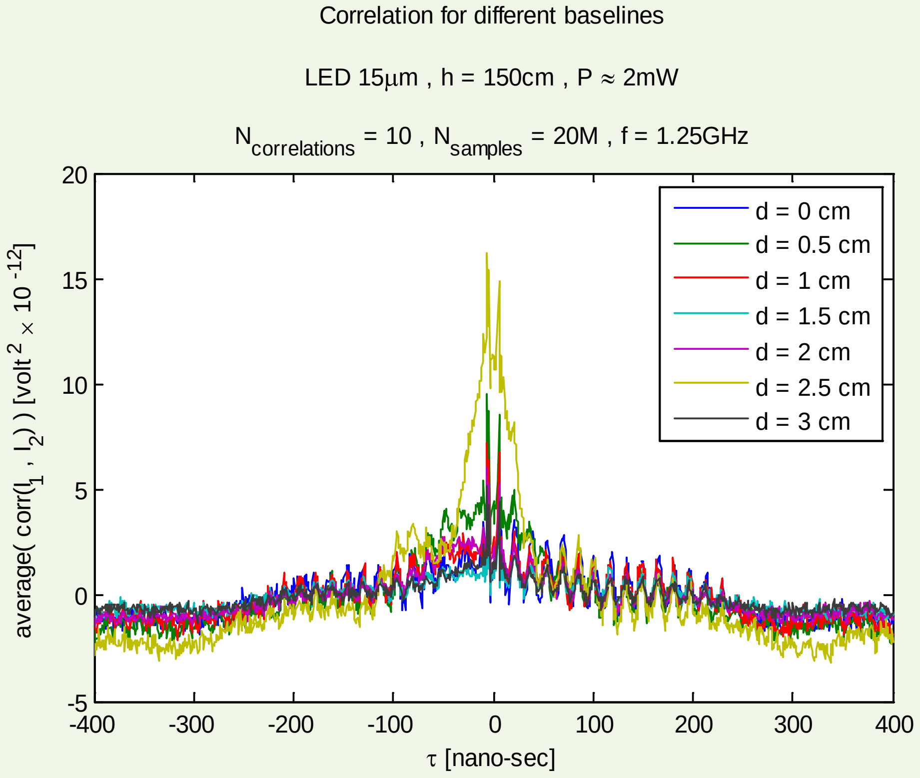


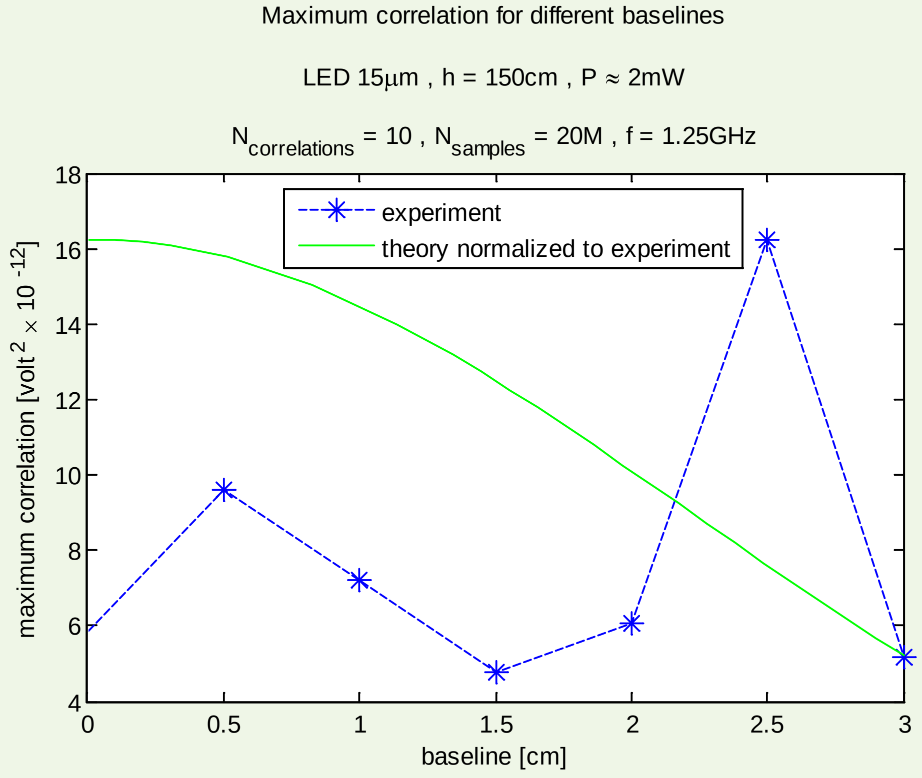
Electronic delay

Correlation of low power LED for different baselines

Blue LED ,$\lambda = 465nm$, $a = 15\mu m$, $P \approx 2mW$,
$h = 150cm$, *f=1.25 GHz* ,Cables – same length

Correlations for different baselines	**Maximum Correlation for different baselines**





Digital band-width

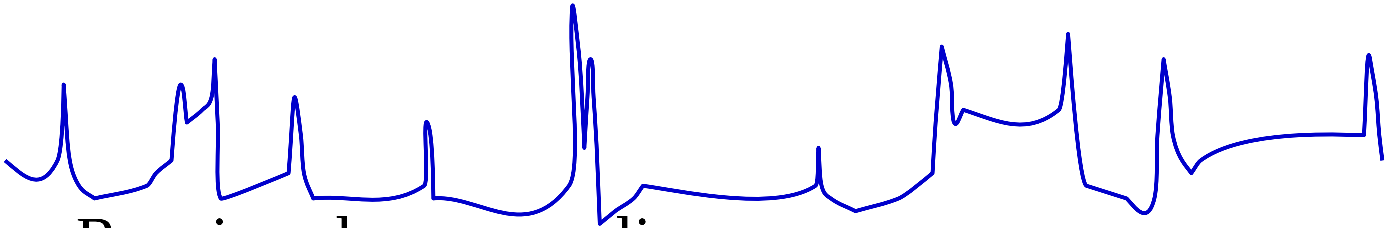
- Short integration times
- Effective continuous sample rates
- Our setup: 3×500,000 samples / 0.8 s = 1.875 Msamples / s
- HBT: 24 MHz × 2 = 48 Msamples / s
- HBT integration time: 1.5 h
- For the same number of samples we need to integrate for 38 h
- Solution: clip measurements, use 1 bit correlation (not 10 bit)
- Also: remove all mobile phone signals (use μ-metal shield)

Transmitting the intensities

- Growing baselines, on the ground and in space
- Coaxial transmission difficult or impossible
- Fibre optics for stellar light transmission not likely
  - Limited space-bandwidth product: low efficiency
  - Delay still has to be performed electronically or mechanically
- Can we compress the detected currents?
- We first check the method of Compressed Sensing

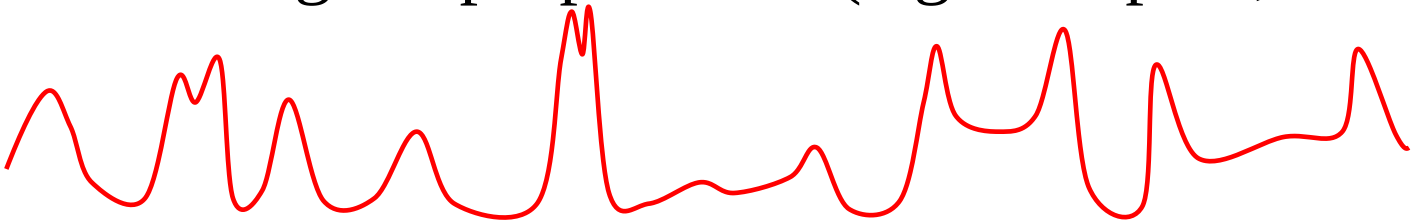
Compressed sensing principle

- Original time trace



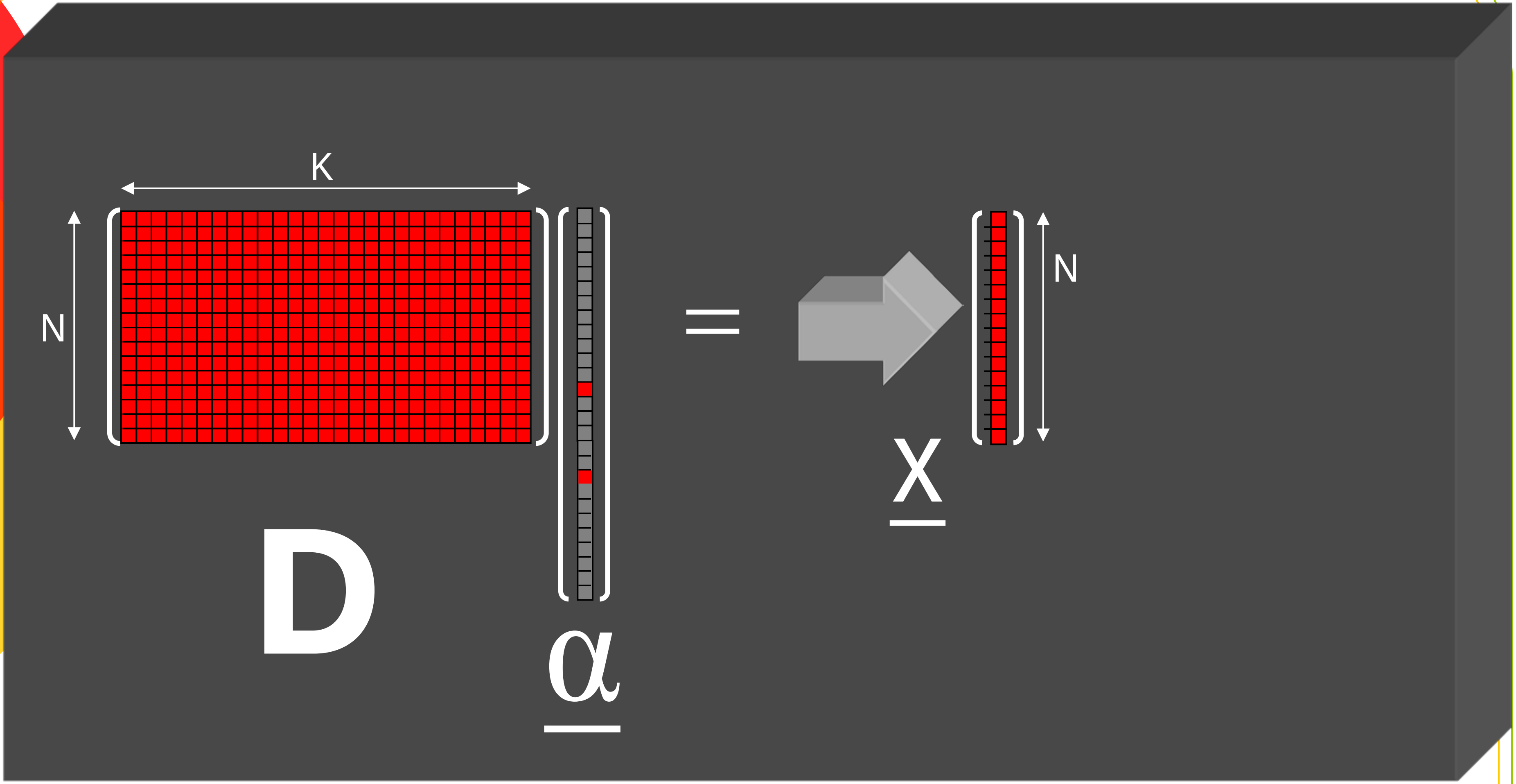
  - Requires dense sampling

- After using the proper filter (e.g. low-pass, wavelets)



  - Allows sparser sampling

Compressed sensing: matrix notation



Sparse and Redundant Representation Modeling of Signals –
Theory and Applications
By Michael Elad

Compressed sensing

$$f\left(\vec{x}\right)=\left\|\vec{x}-\vec{y}\right\|^2+G\left(\vec{x}\right)$$

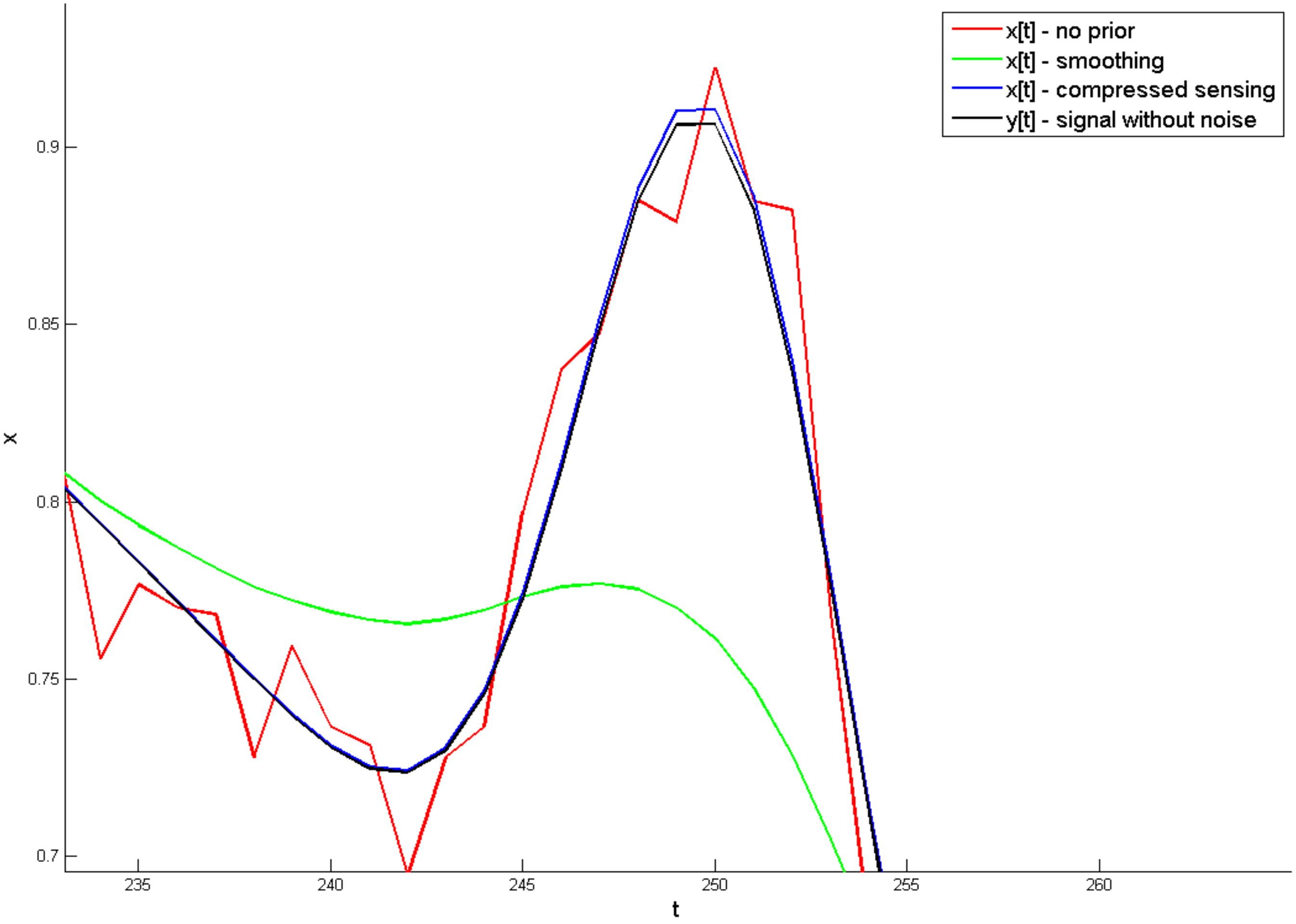
$$\arg\min_{\hat{\vec{x}}}\left\{f\left(\vec{x}\right)\right\}$$

$$G\left(\vec{x}\right)=0$$

$$G\left(\vec{x}\right)=\lambda\left\|L\vec{x}\right\|^2$$

$$G\left(\vec{x}\right)=\left\|\alpha\right\|_0^0$$

$$for\quad x=D\alpha$$

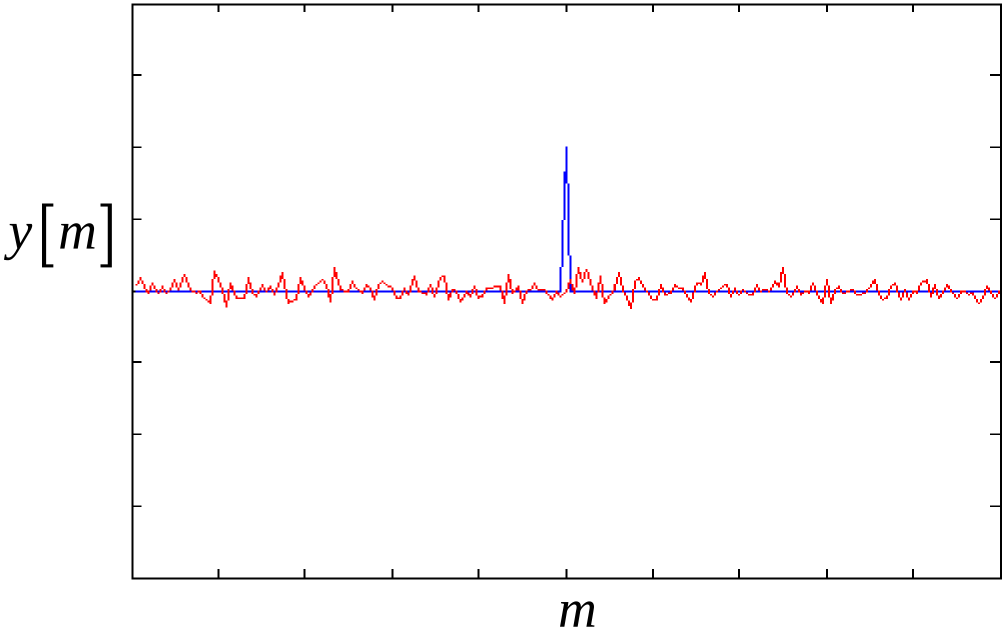


The correlation properties

$$y[m] = \frac{1}{N}\sum_{l=1}^{N}\left(n_1[l]-\bar{n}\right)\left(n_2[l+m]-\bar{n}\right)$$

$$y[m] = \alpha\delta\left[m-m_0\right] + \beta x[m] \qquad x[m] \equiv Normal\left(0,1\right)$$

$$\alpha = \frac{\tau_c}{T}\bar{n}^2\left|\gamma_d\right|^2 \quad , \qquad \beta = \frac{\bar{n}}{\sqrt{N}}$$

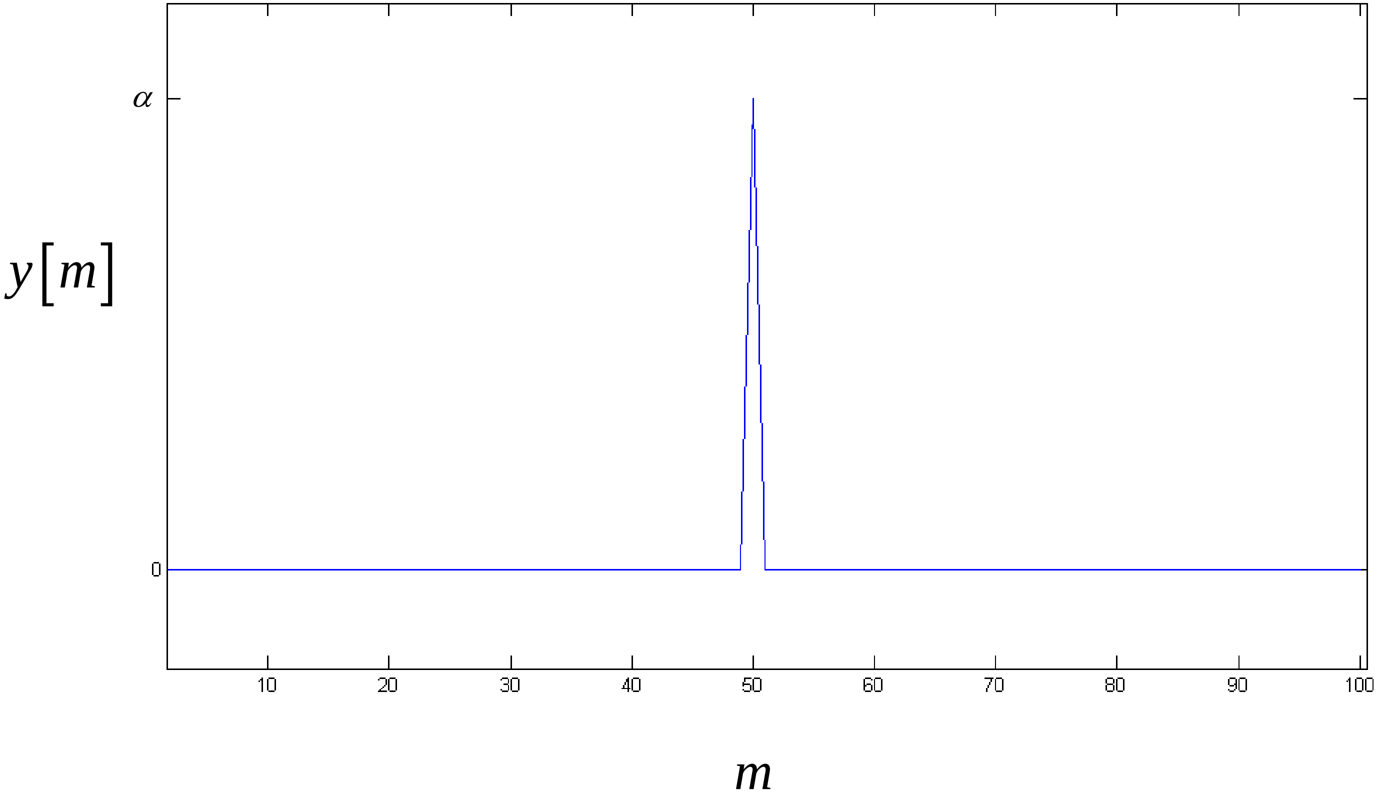


$N = 10^{12}$
$N = 10^{14}$
$N = 3\cdot 10^{12}$
$N = 3\cdot 10^{13}$

Taking a simple case

$$y[m] = \alpha\delta[m - m_0] + \beta x[m] \qquad \beta \to 0$$

$$Y[k] = \mathbb{F}\{y[m]\}_{[k]} = \mathbb{F}\{\alpha\delta[m - m_0]\}_{[k]} = \alpha e^{i2\pi k m_0 / N}$$

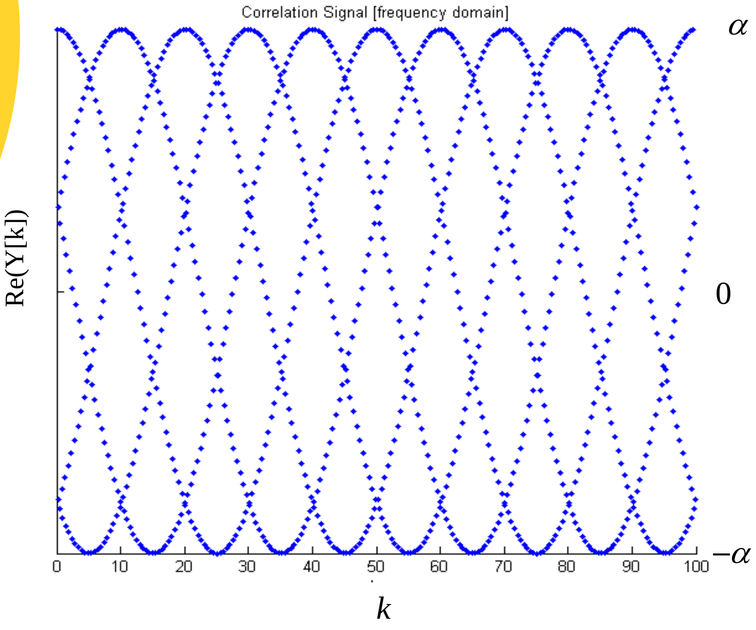


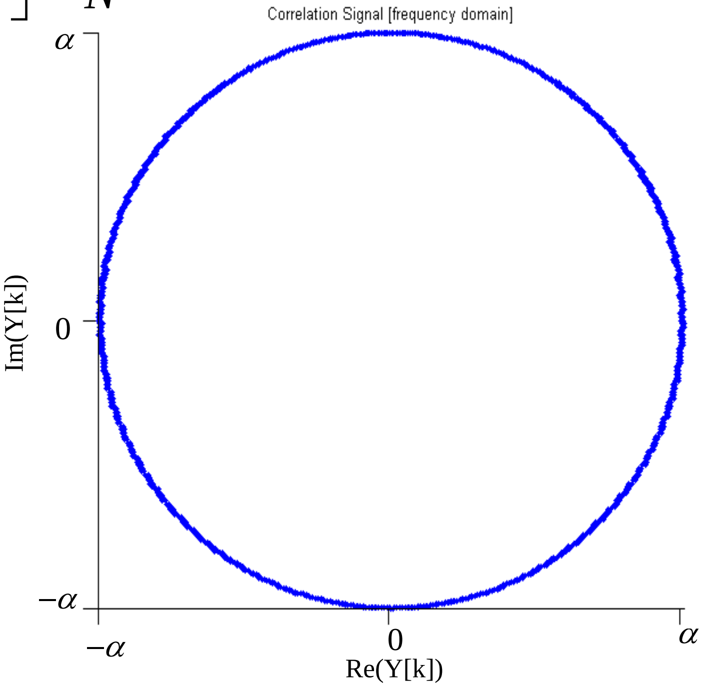
A simple case: Fourier domain

$$y[m] = \alpha\delta[m - m_0] + \beta x[m] \qquad \beta \to 0$$

$$Y[k] = \mathbb{F}\{y[m]\}_{[k]} = \mathbb{F}\{\alpha\delta[m - m_0]\}_{[k]} = \alpha e^{i2\pi k m_0/N}$$

$$Y[k] = \mathbb{F}\left[\frac{1}{N}\sum_{l=1}^{N}(n_1[l+m] - \bar{n})(n_2[l] - \bar{n})\right] = \frac{1}{N}(\hat{n}_1[k] - \bar{n})(\hat{n}_2[-k] - \bar{n})$$

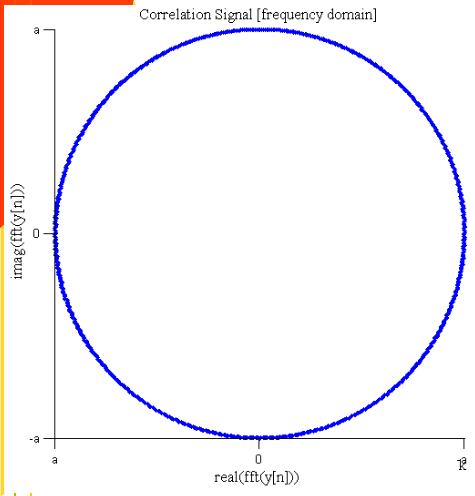




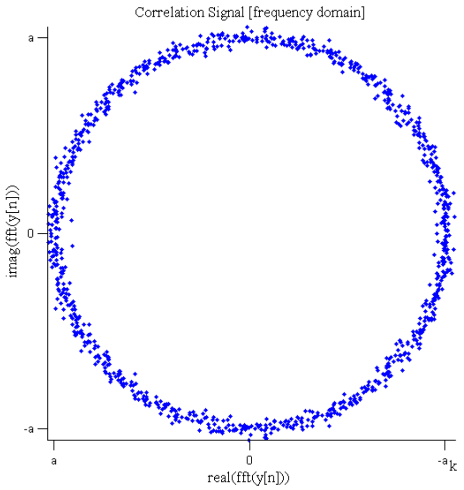
Poisson noise in Fourier domain

$$f[k] \equiv \beta \sum_{m=1}^{N} x[m] e^{i2\pi\kappa(k)m/N} = \beta \sqrt{\frac{N}{2}} \left(x_1[k] + i x_2[k] \right)$$

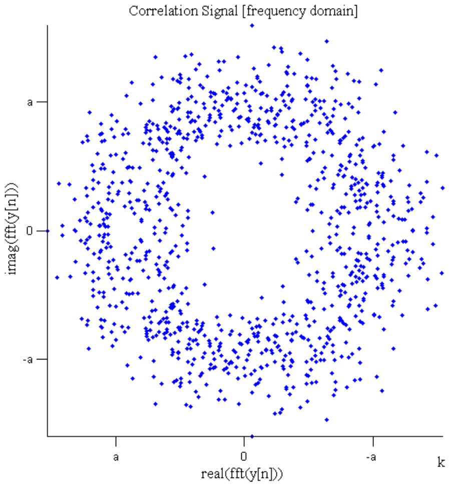
$\beta = 0$



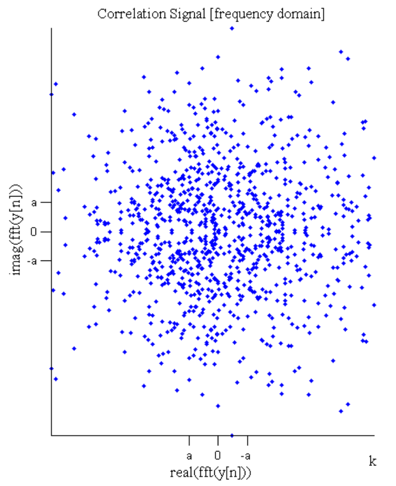
$\beta = 0.001\alpha$



$\beta = 0.01\alpha$



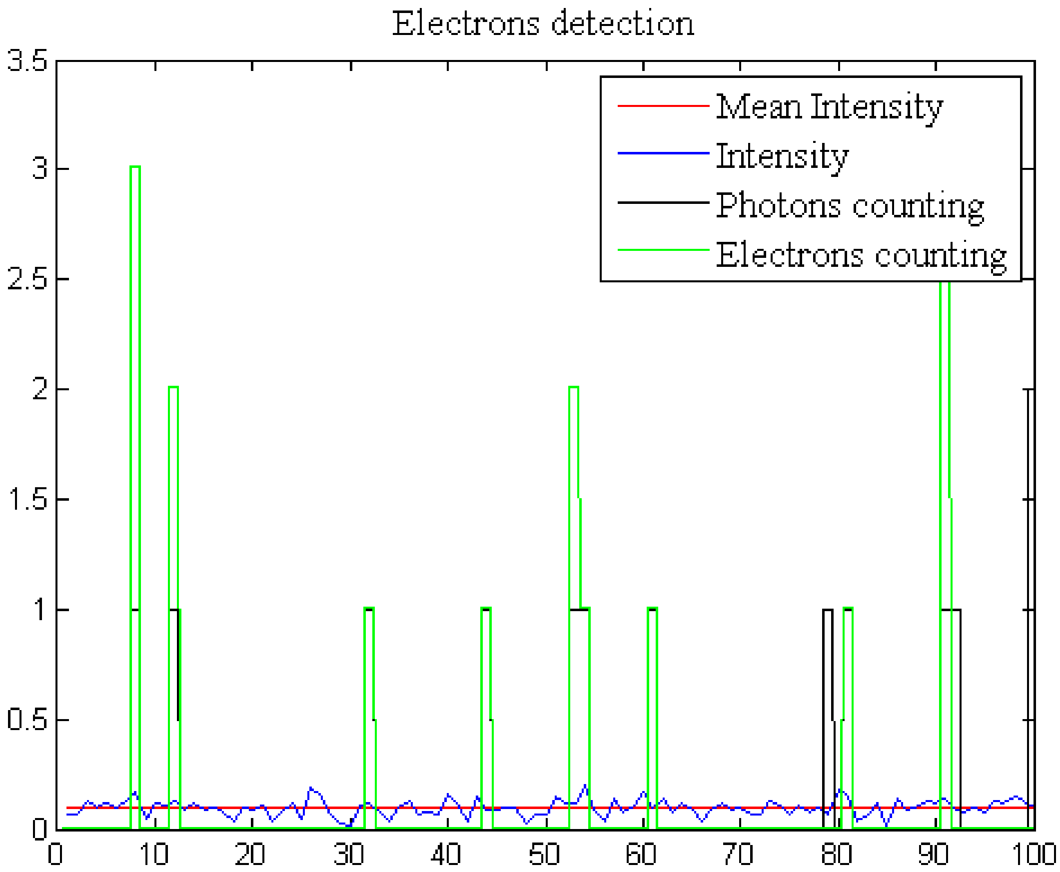
$\beta = 0.1\alpha$



- Correlation (circle radius) buried in Poisson noise
- Dropping frequencies drops points, not noise

Other compression methods

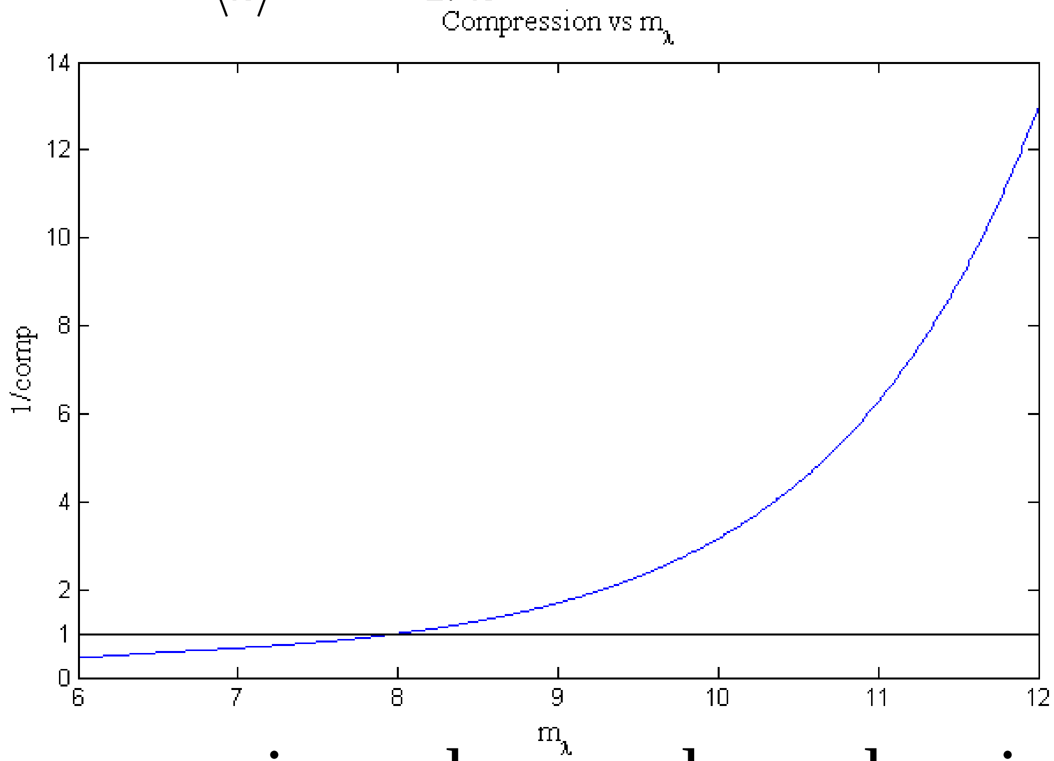
$$\bar{n} \ll 1 \qquad \frac{p\{y=2, x=2, n(t)\}}{p\{y=1, x=2, n(t)\}} = n(t)\,2e^{-1} \ll 1$$



- Sparse photons, sparse photoelectrons

Compression efficiency

$$comp\left(\bar{n}\right)=\frac{\langle b\rangle}{\langle k\rangle}=\frac{2\left[\bar{n}-\log_2\left(\bar{n}\right)\right]}{1/\bar{n}}=2\left[\bar{n}^2-\bar{n}\log_2\left(\bar{n}\right)\right]$$



$$\delta\omega \cong 10^{14}$$

$$T \cong 10^{-9}$$

$$\eta \cong 0.9$$

$$A \cong 30m^2$$

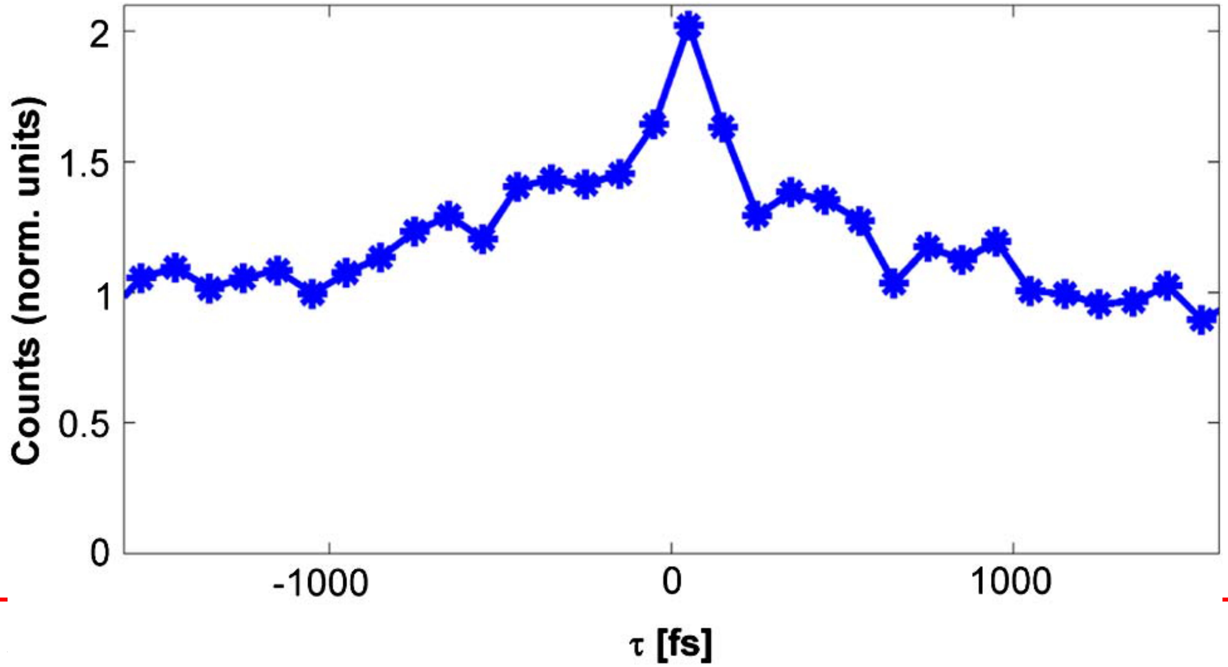
- Various compression schemes, here showing run-length
- No gain for brighter objects, $m < 8$

Future directions

- System improvement steps
    - Rewrite correlator to 1 bit to improve flow
    - Add third channel, test closure
    - Test on moving platforms
    - Test other compression options

Research directions

- Use electronic analog correlation (still faster)
- Use photonic correlation (e.g. HBT in OCT)
  - Nonlinear optics
  - Requires very narrow beams, optical delay lines



Summary

- We built a lab system to test space HBT
  - Integration and testing proceeding
- Checked the options of compressing data
  - Compressed sensing depends on reduced band-width
  - Requires widest band possible
  - Other compression methods useful at low flux