Steps towards intensity interferometry in space

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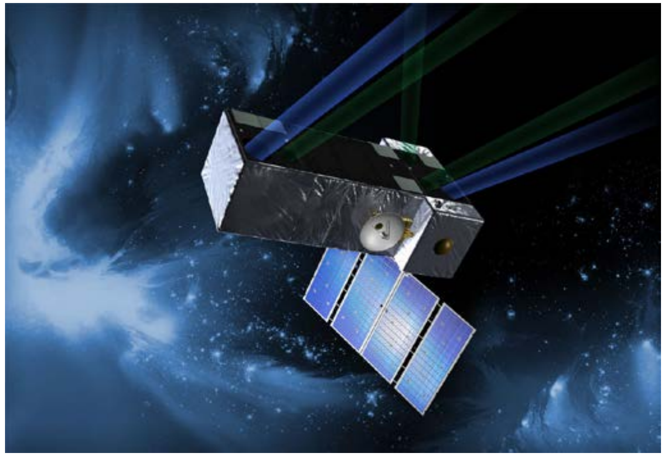
Space interferometry

Many efforts, over 40 years, to send an interferometer to space

Advantages: freedom from turbulence, from opaque atmosphere

The most advanced: SIM (space interferometry mission)

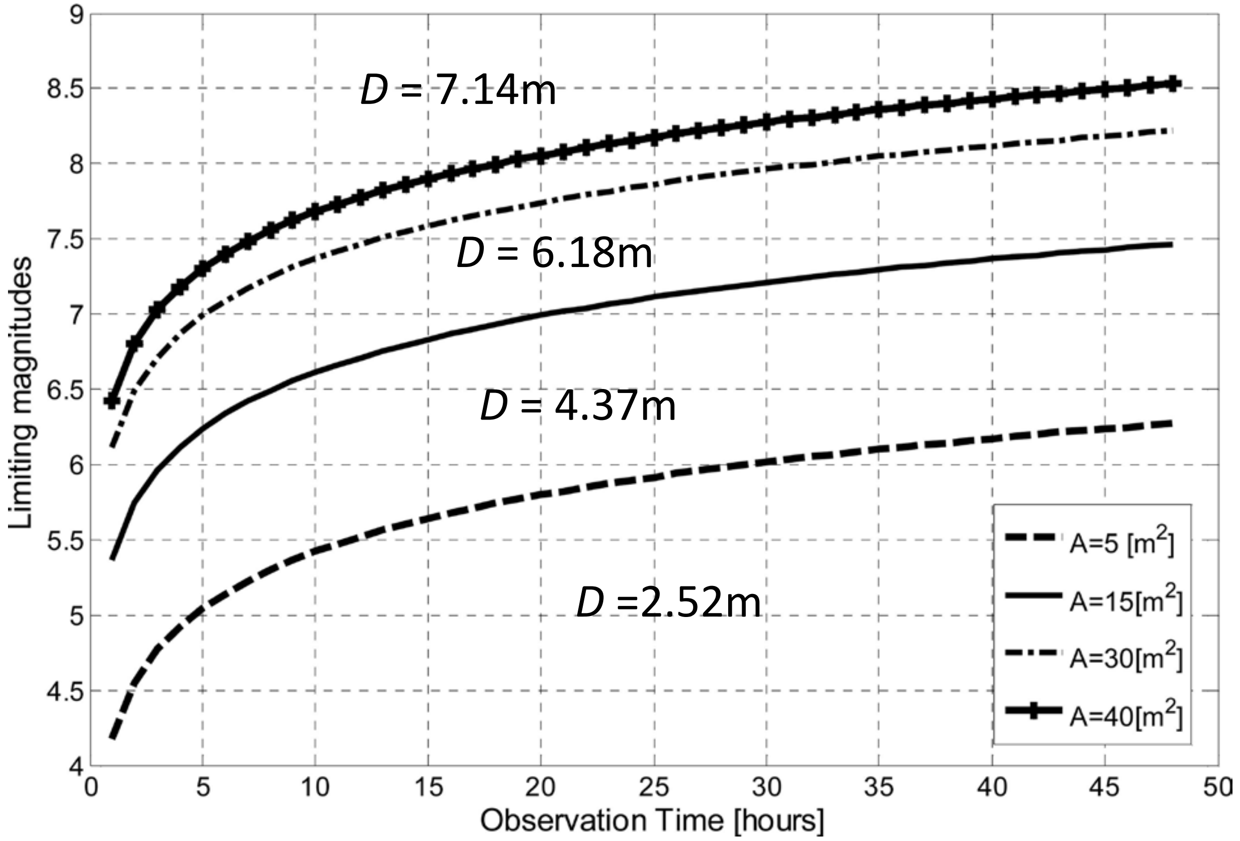
Cancelled in 2010: requirements were too exacting, price too high



A much easier alternative: intensity interferometry

Space intensity interferometry

Proposal by Klein, Guelman and Lipson, 2007



Typical (u, v) diagram for a pair of satellites in two almost identical elliptical orbits with the same sense of satellite rotation and different source directions.

Achievable magnitude as a function of observation time and aperture area (λ = 1µm). Better SNR and resolutions are expected in the ultra-violet.

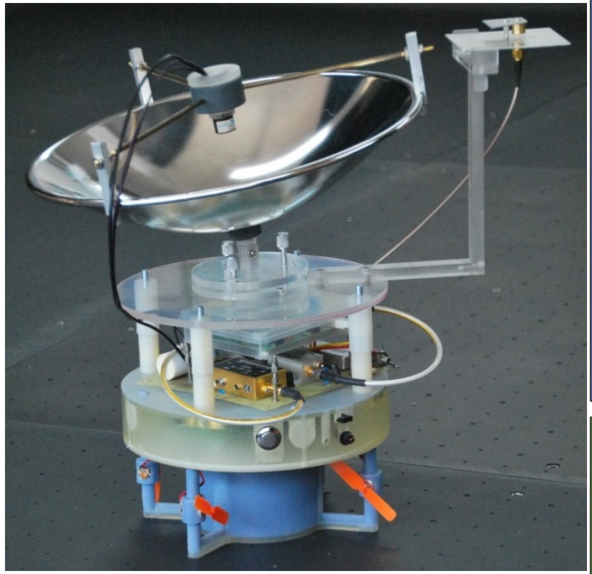
Comparison of interferometry methods

	Amplitude interferometry (ground)	Intensity interferometry (space)
base-lines	short, fixed	unlimited, flexible
wavelength range	mid-visible to infra-red	far ultra-violet to visible
quality of optics	100 nm	3 mm
accuracy of delay lines	100 nm	3 mm, software corrigible
magnitude limit	~8	~8
integration time	minutes	hours
spectral resolution	fine	coarse (fine in single-dish mode)
technical bottleneck	mechanical stability	satellite communications

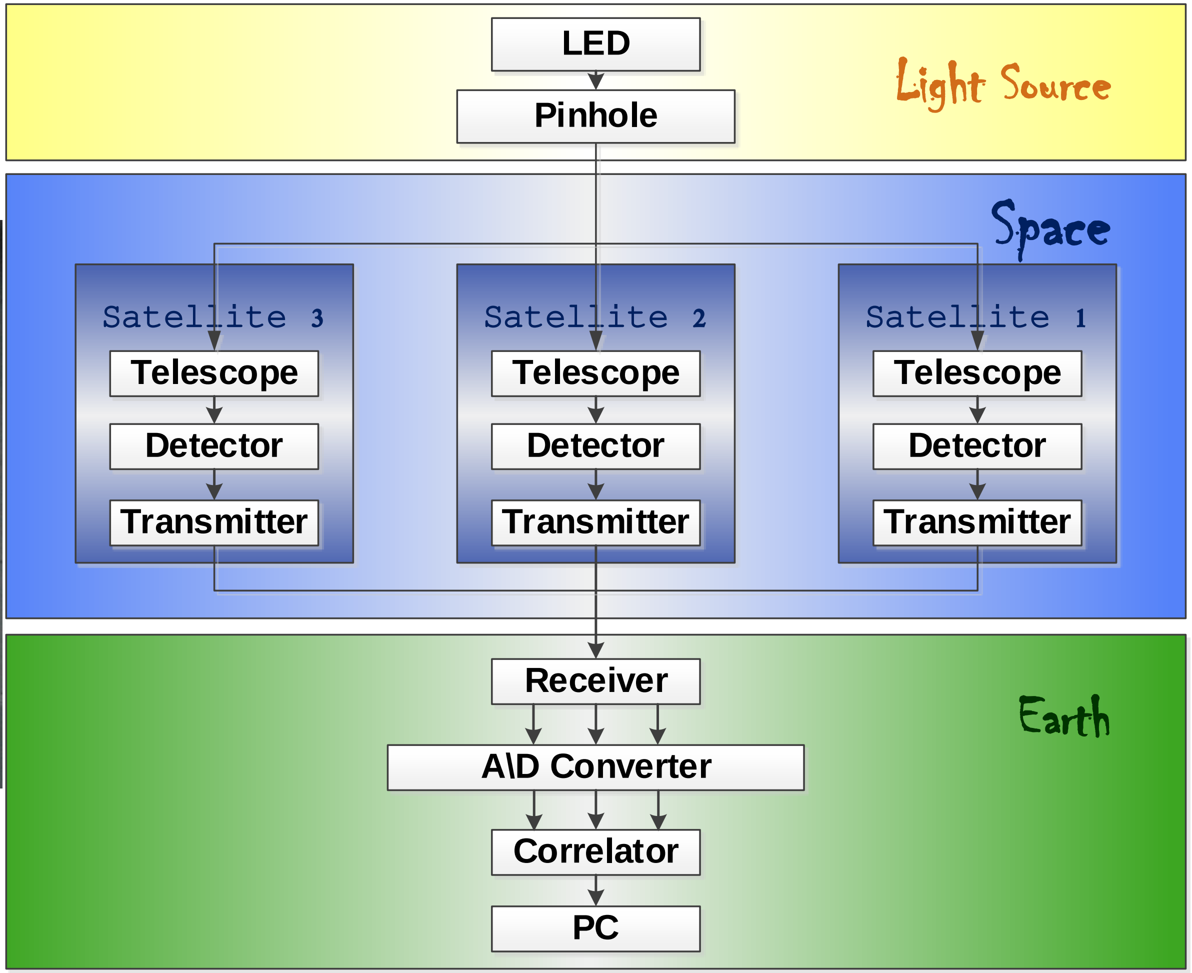
Previous work

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

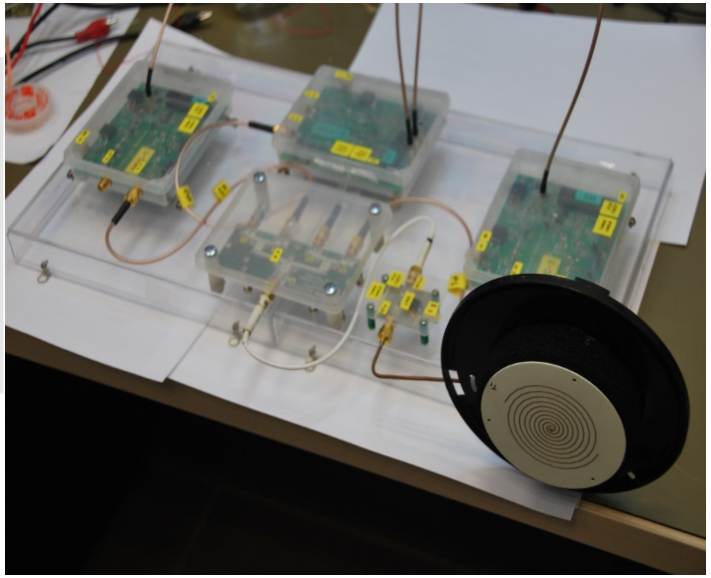
Space interferometry in the lab



Photomultiplie
Light collector
Tilt mechanism
Preamplifier + transmitter
Rotation propellers



Receivers
0.95 GHz bandwidth
@ 3.1, 4.2 & 5.9 GHz



Processing (I)

Analogue-to-digital converters

Up to 5 giga-samples per second (GSPS)

Virtex-6 FPGA

Delay

Correlation

Integration

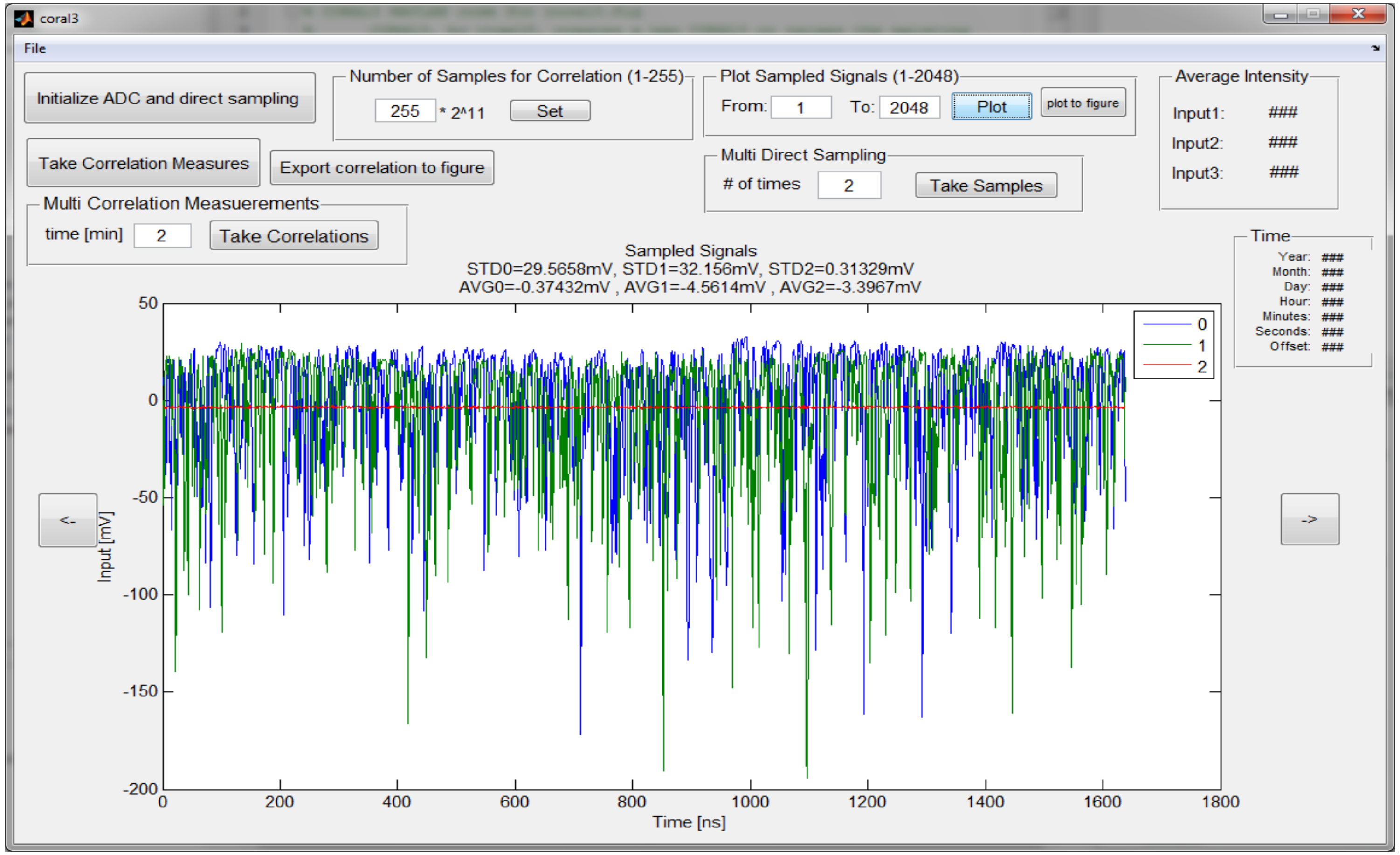
Transfer to host PC

Processing (II)

Alternative method:

Grab data with fast scope

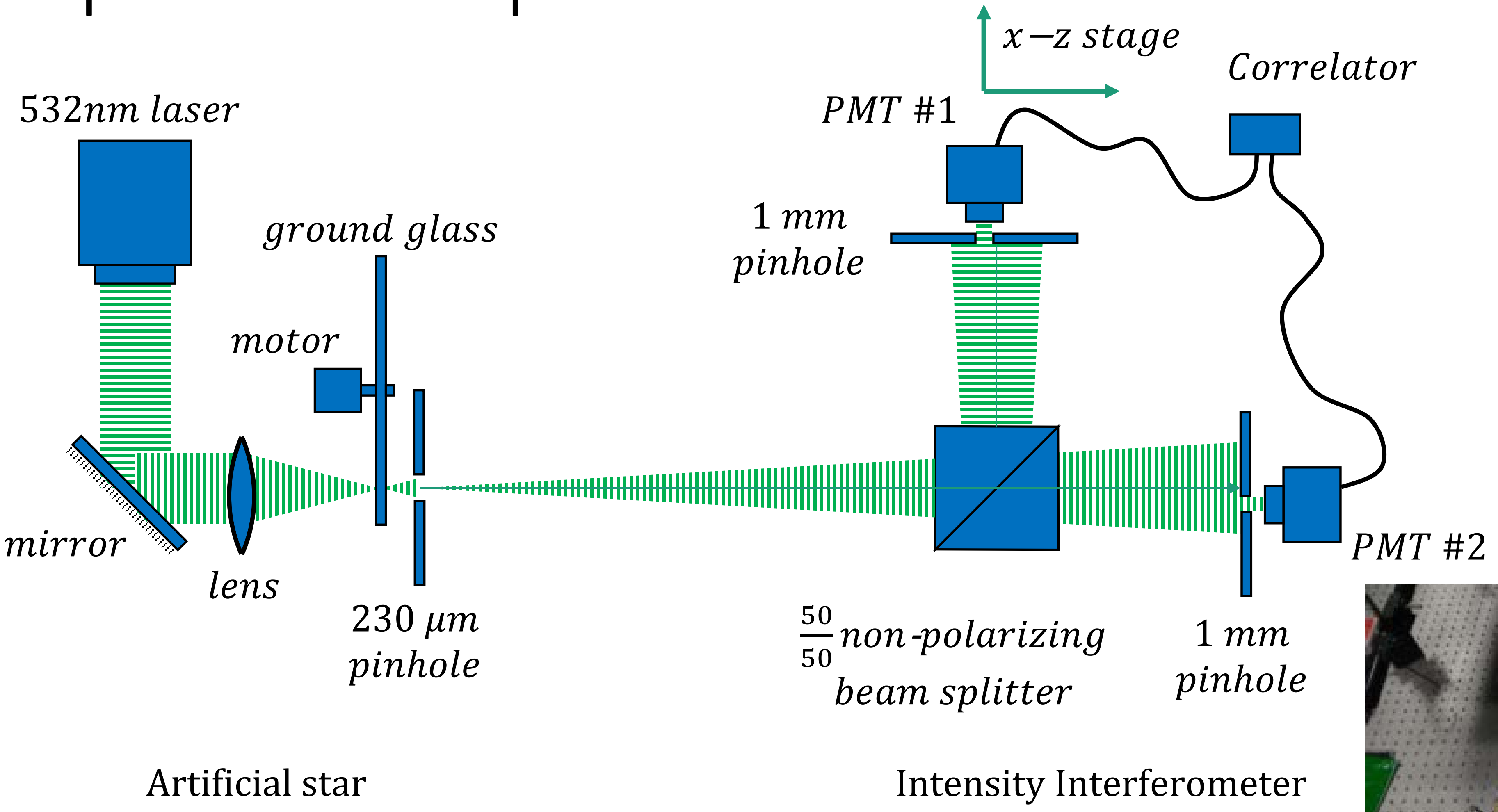
Analyse in PC

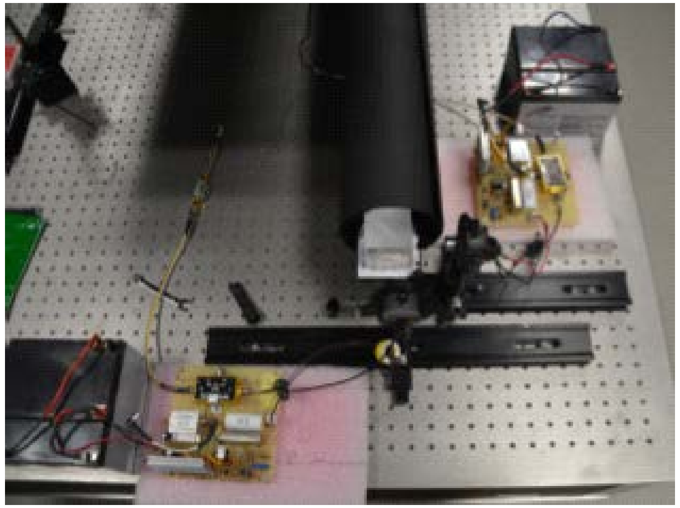


Three channels (red – inactive)

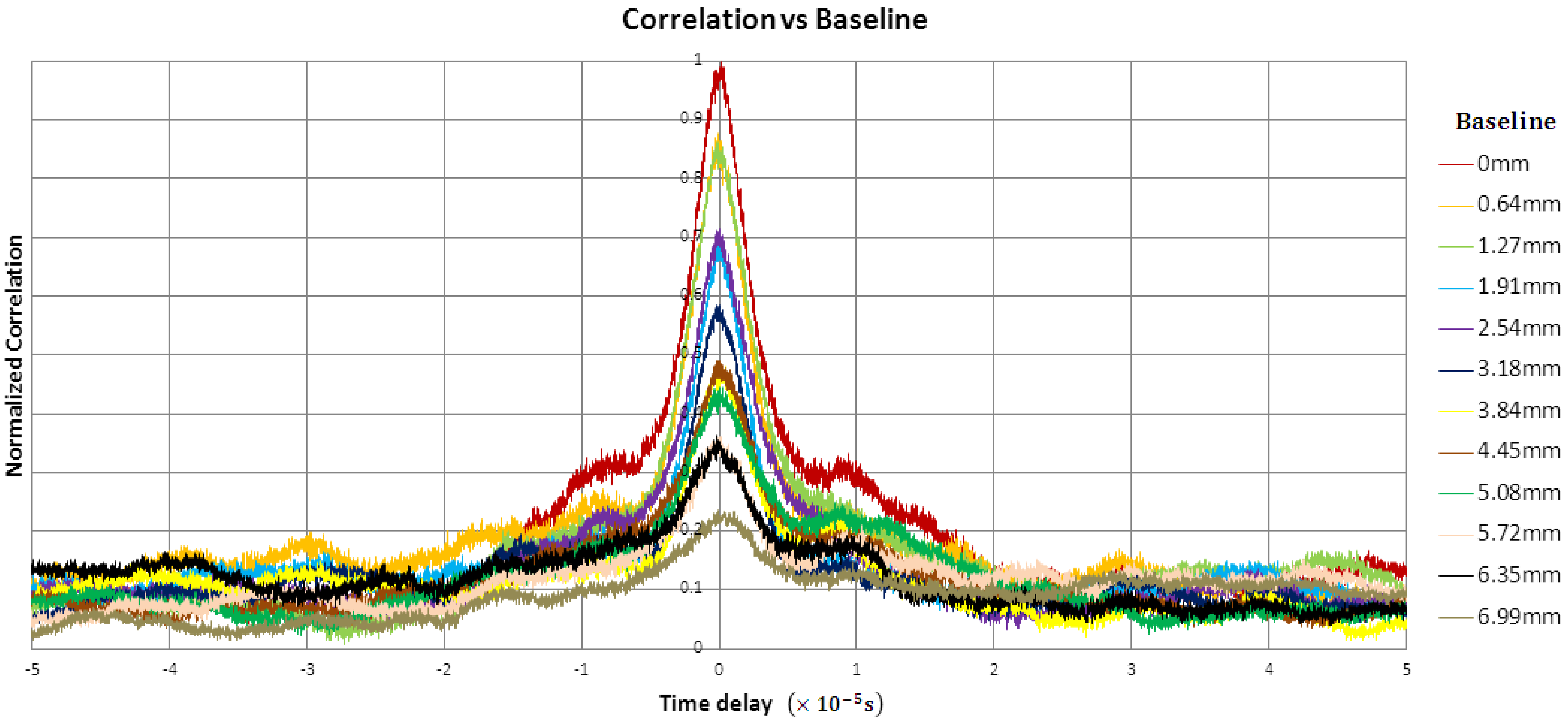
LED: 415 nm.
Power: 2.8 W.
Pin-hole: 15 μm.
H = 78 cm.
D = 0 cm.

Optical set-up

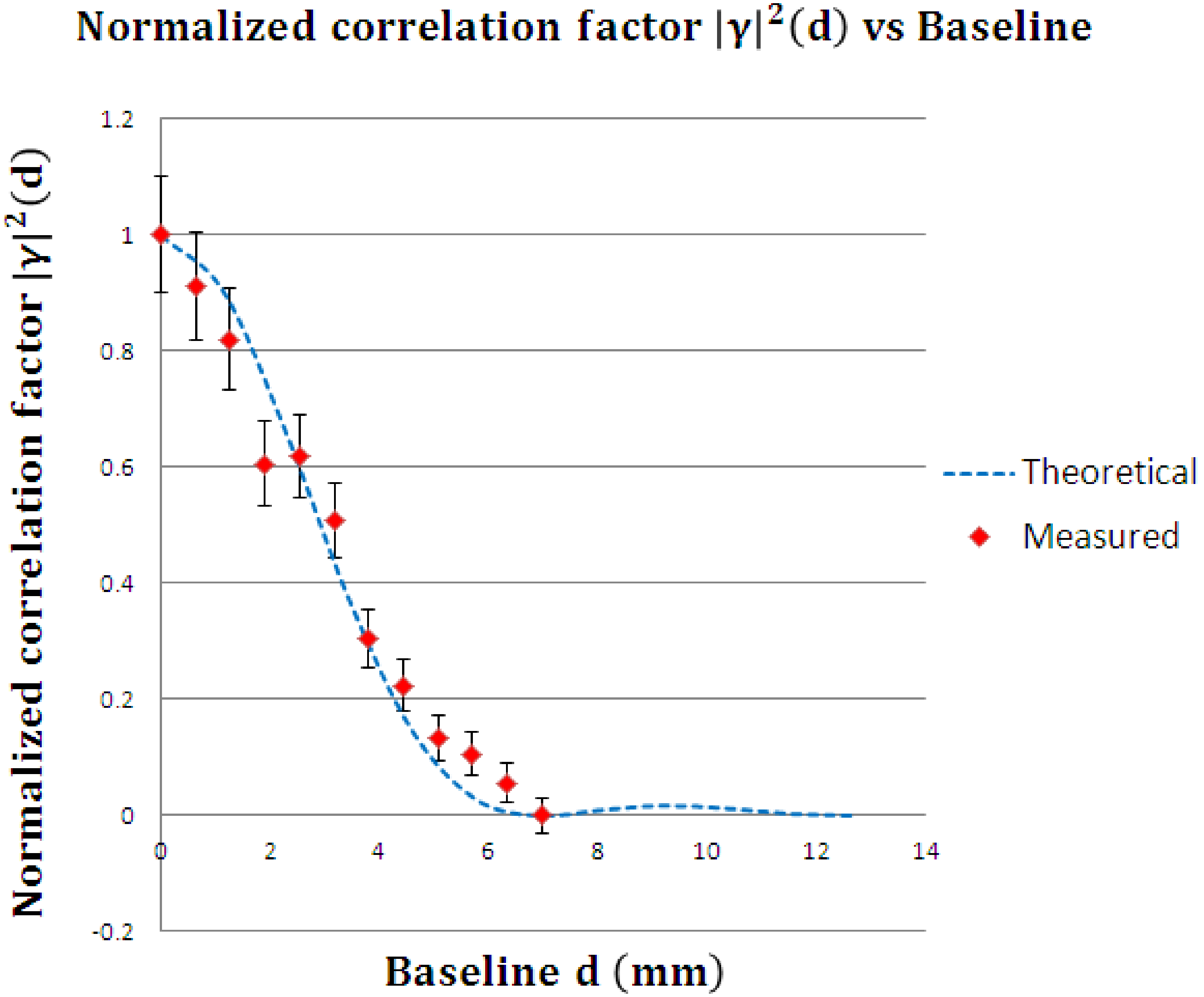




raw correlation



Dependence on base-line



The communications bottleneck

Growing baselines, on the ground and in space

Coaxial transmission difficult or impossible

Fibre optics for stellar intensity transmission not likely

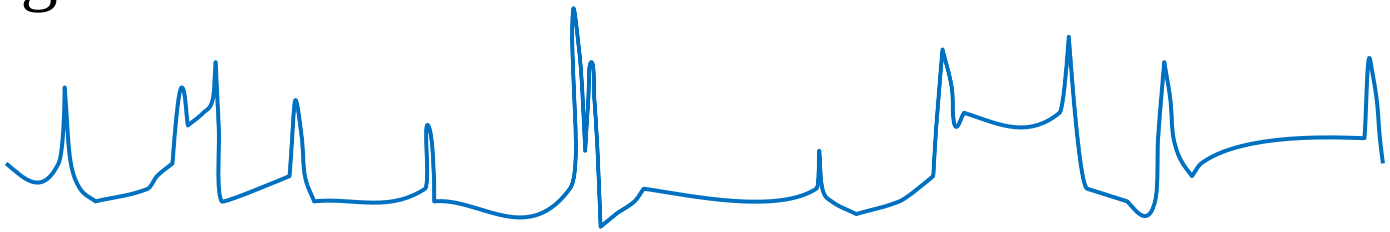
- Limited space-bandwidth product:
  - low input efficiency (extended PSF)
  - allowed dispersion < 3 mm
- Delay still has to be performed electronically or mechanically

Can we compress the detected currents?

We first check the method of Compressed Sensing

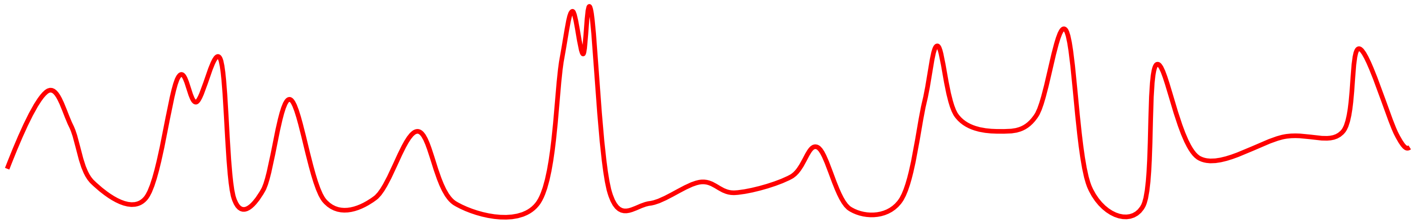
Reducing the sampling frequency

Original time trace



Requires dense sampling

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



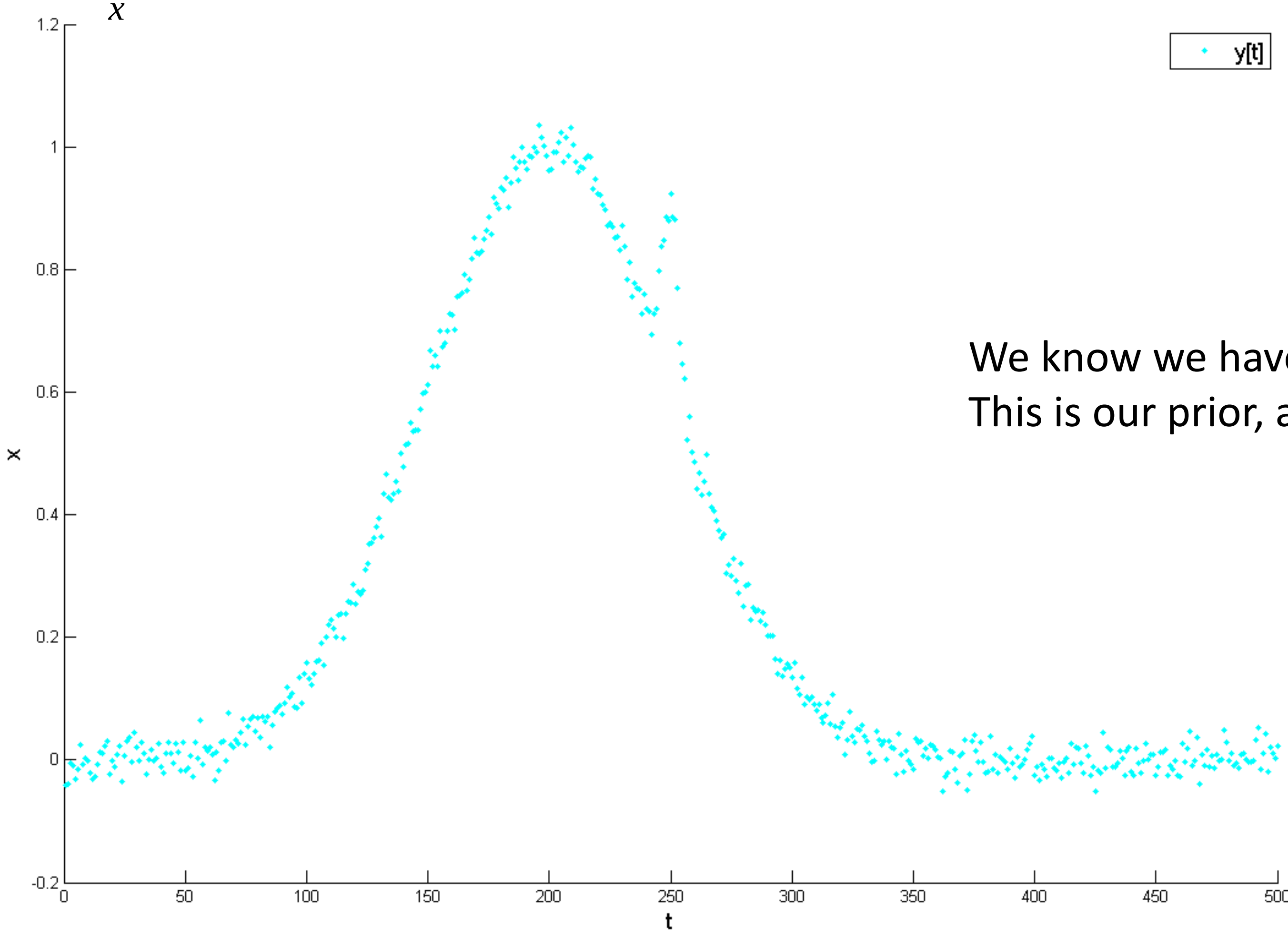
Allows sparser sampling

Compressed sensing

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

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

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



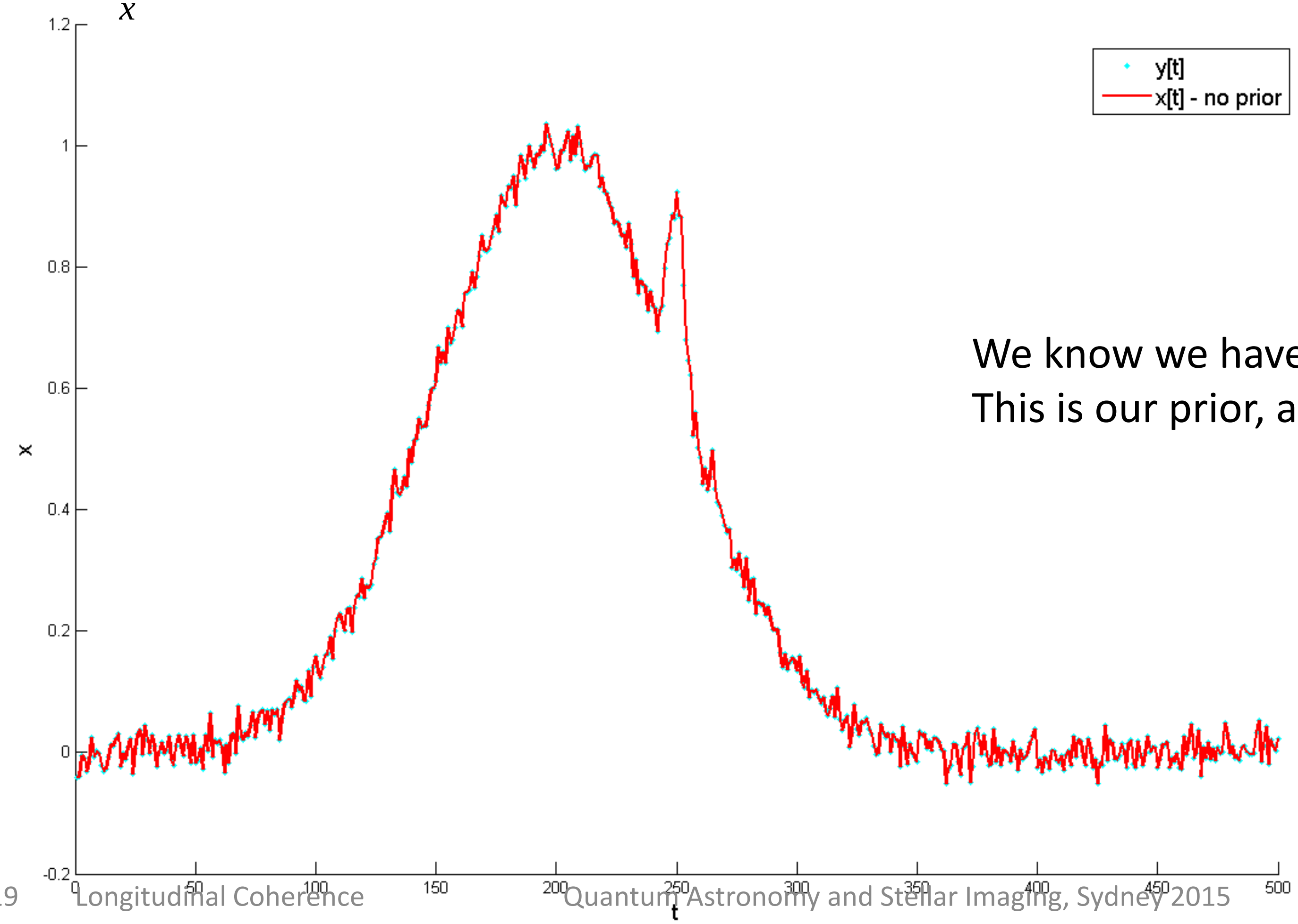
We know we have two gaussians, of unknown parameters.
This is our prior, and we now need to find their parameters.

Compressed sensing

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

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

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



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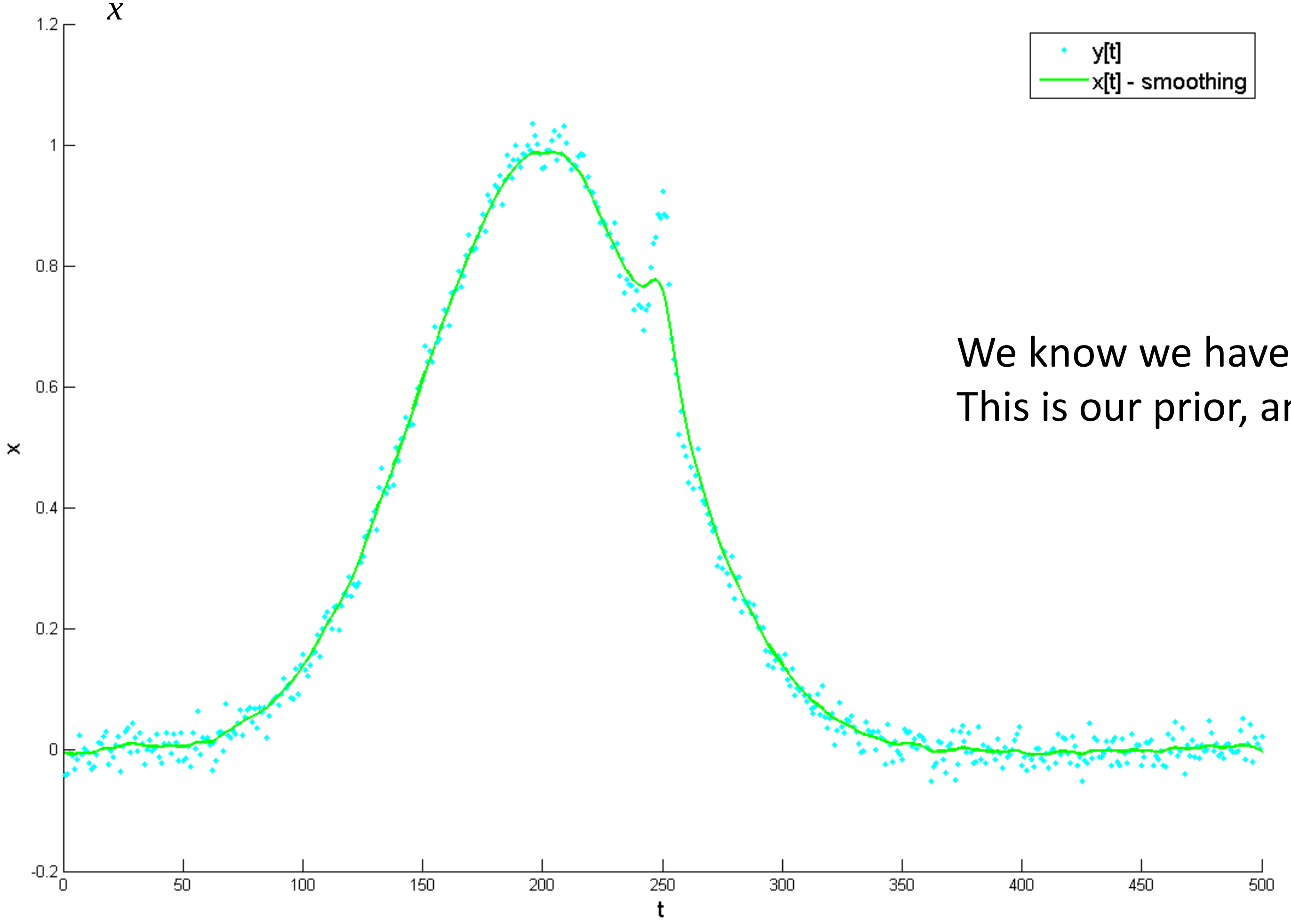
Compressed sensing

$$f(\vec{x}) = \|\vec{x}-\vec{y}\|^2 + G(\vec{x}) \qquad G(\vec{x}) = \lambda\|L\vec{x}\|^2$$

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



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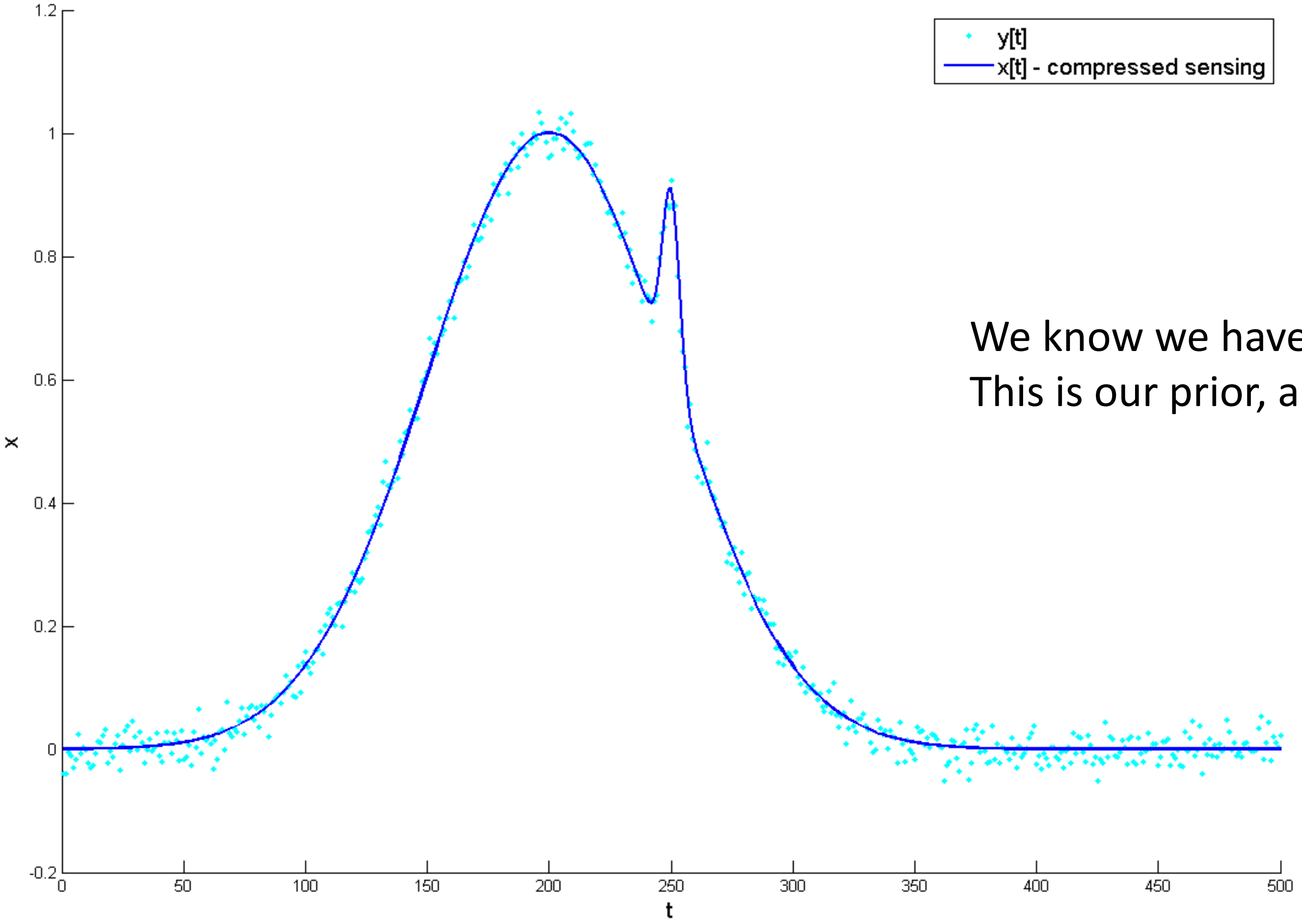
$$G(\vec{x}) = \lambda \|\alpha\|_0^0$$

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



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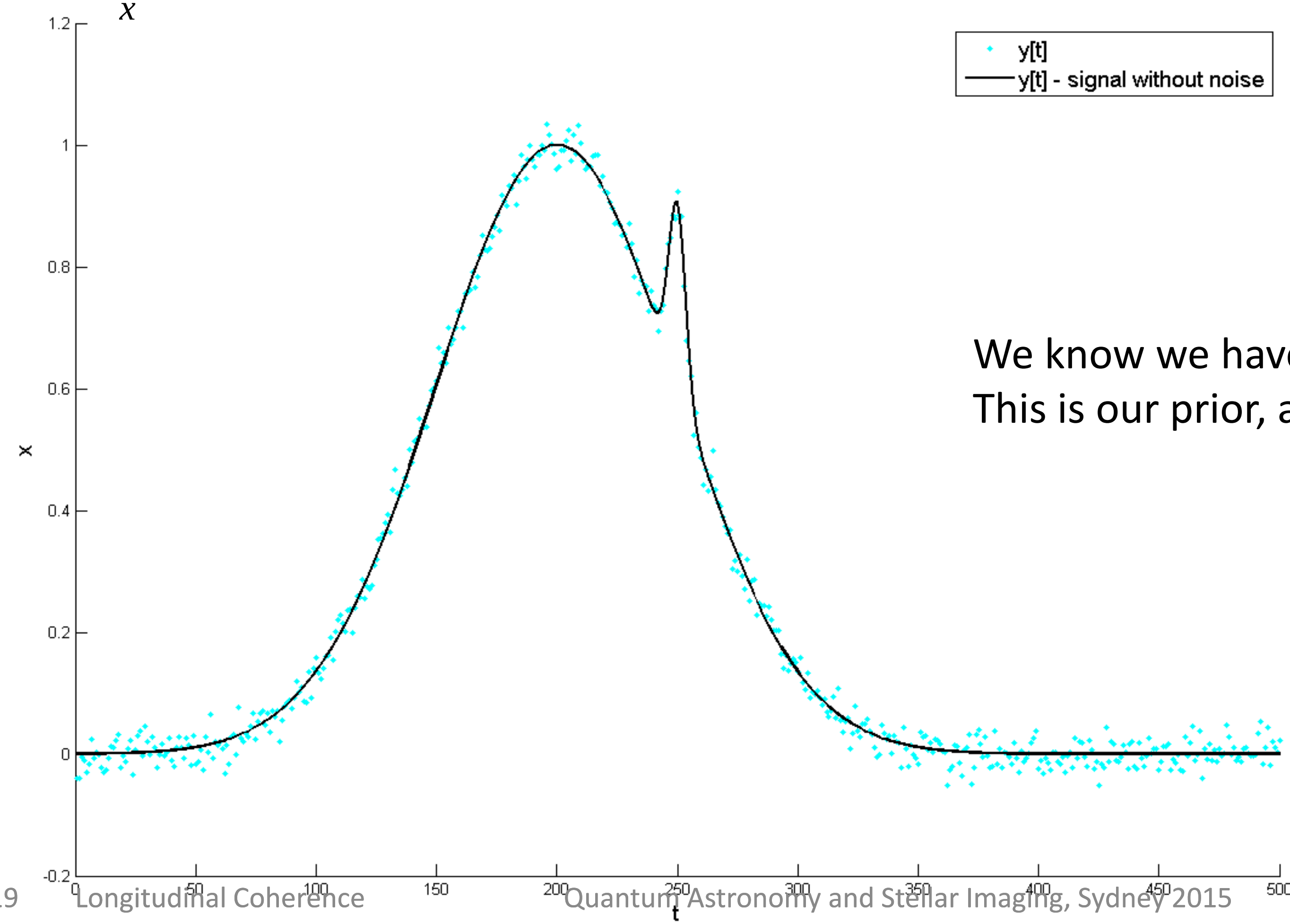

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Compressed sensing

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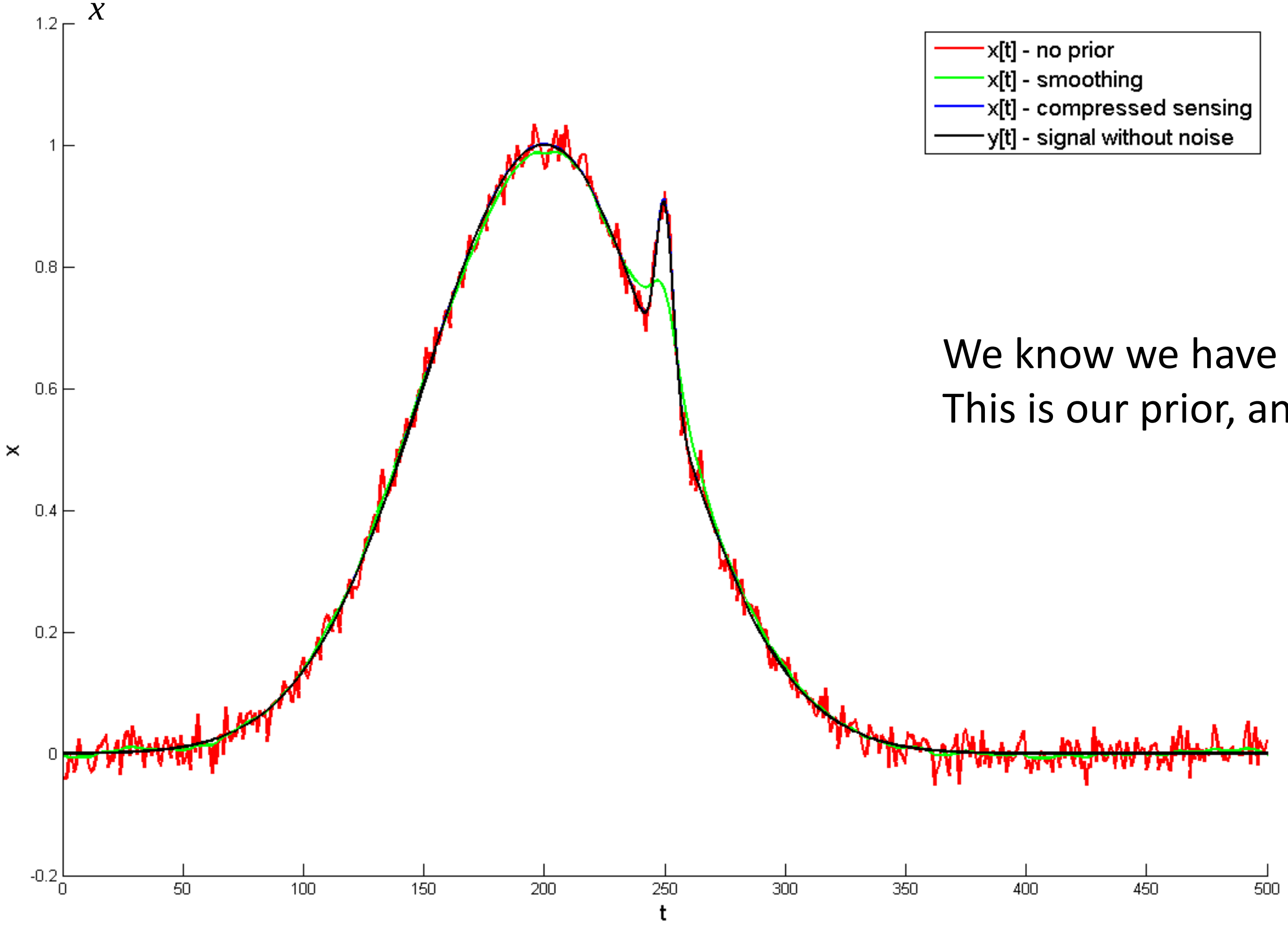
$$G\left(\vec{x}\right)=\lambda\left\|\alpha\right\|_{0}^{0}$$

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



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Compressed sensing

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

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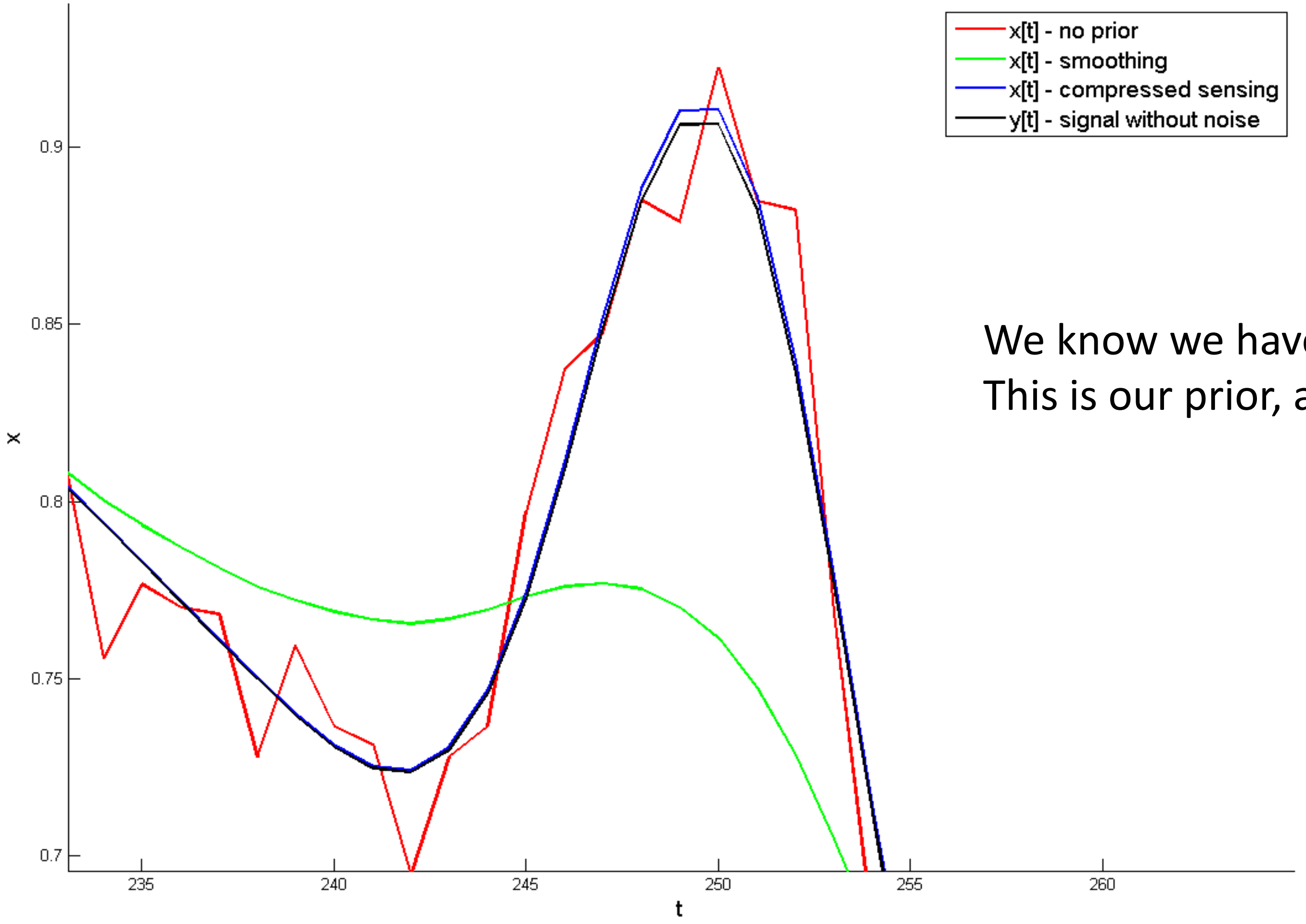
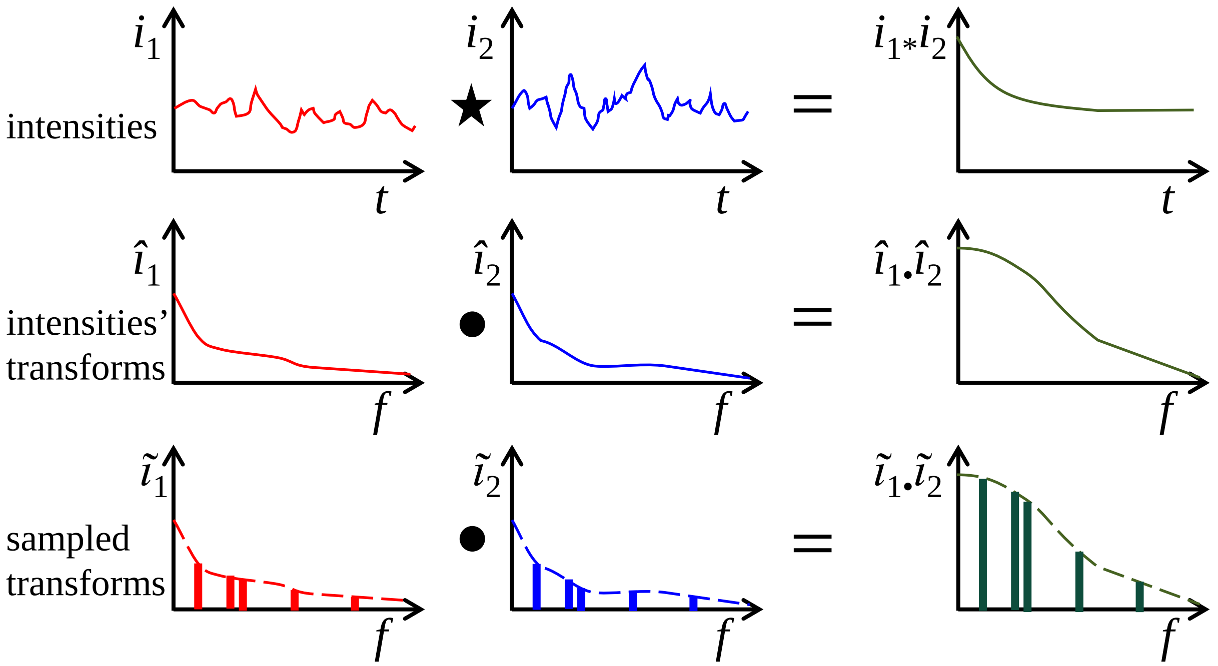


We know we have two gaussians, of unknown parameters.
This is our prior, and we now need to find their parameters.

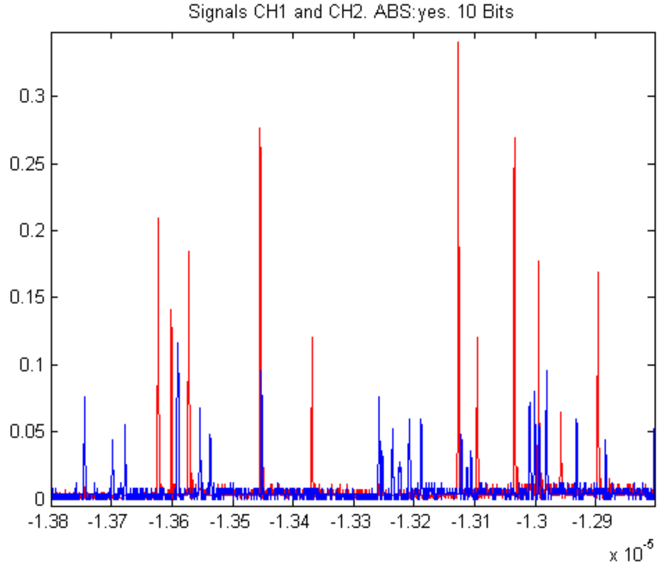
The case for Fourier compression

- Correlation can be performed by Fourier multiplication
- One of the compression methods uses only some Fourier components
- We have to use the same Fourier components on both channels
- After multiplication of same components, many other are still missing
- The missing components are provided by prior knowledge:
  - All pulses are positive and have the same shape
  - Two pulses cannot be nearer than the detector dead time
  - At low count rate, the chances for >1photon/pulse are negligible
  - Delay between two intensities is approximately known

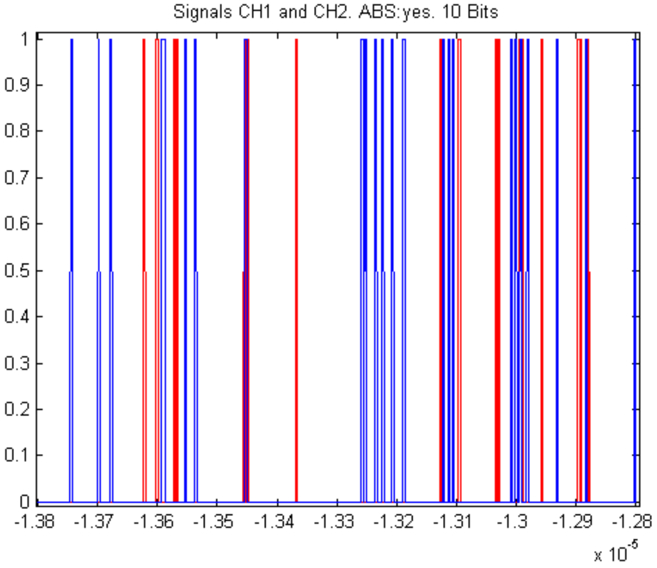


Photon clipping

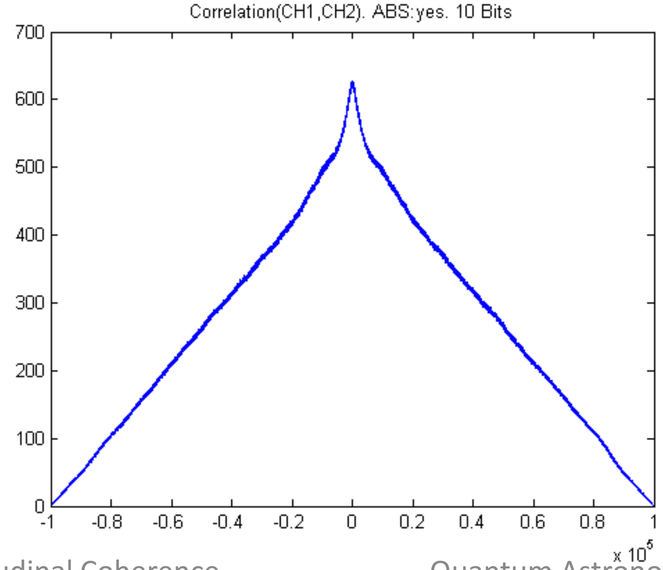
Raw signals
Two channels



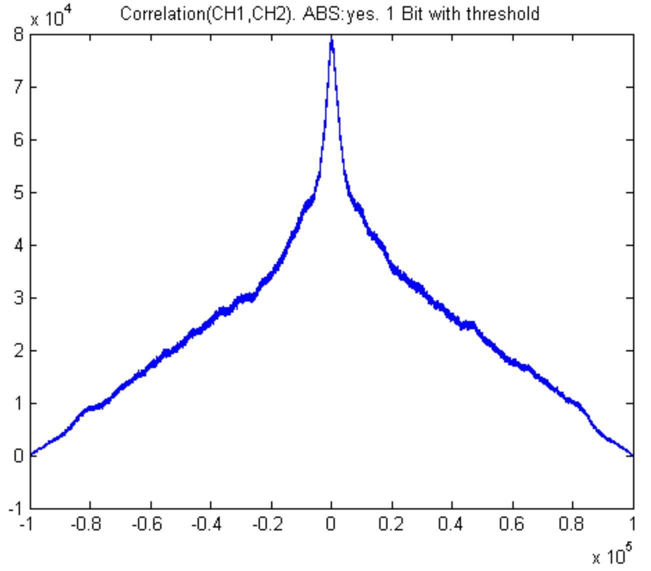
Clipped signals
Two channels



Correlation of
full signal



Correlation of
cropped signal



Increasing the signal

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

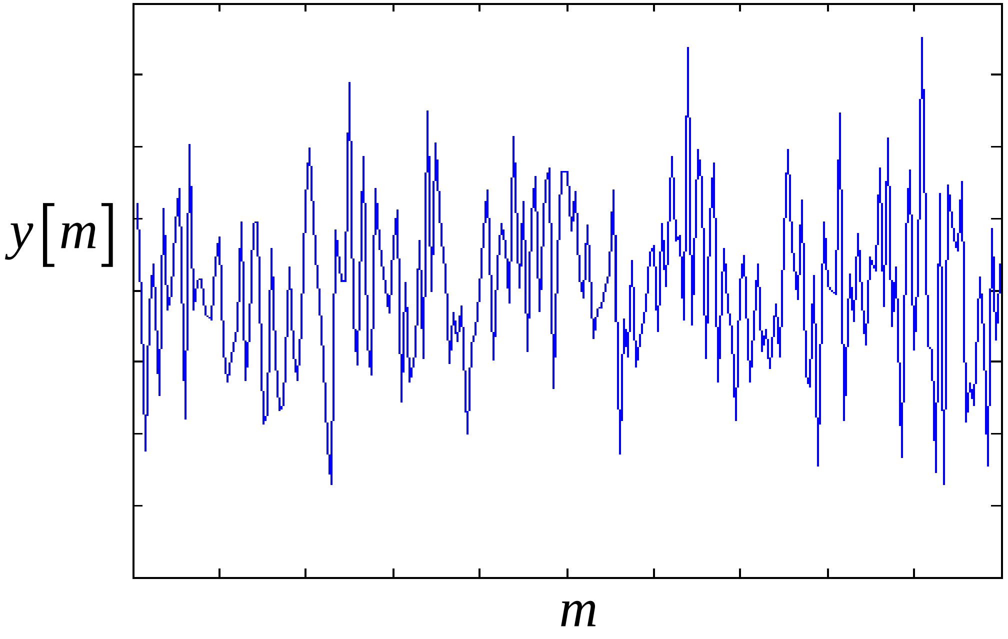
correlation of two inputs

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

$$x[m]\equiv Normal(0,1)$$

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

modelled as δ correlation and gaussian noise



$$N=10^{12}$$

Increasing the signal

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

correlation of two inputs

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

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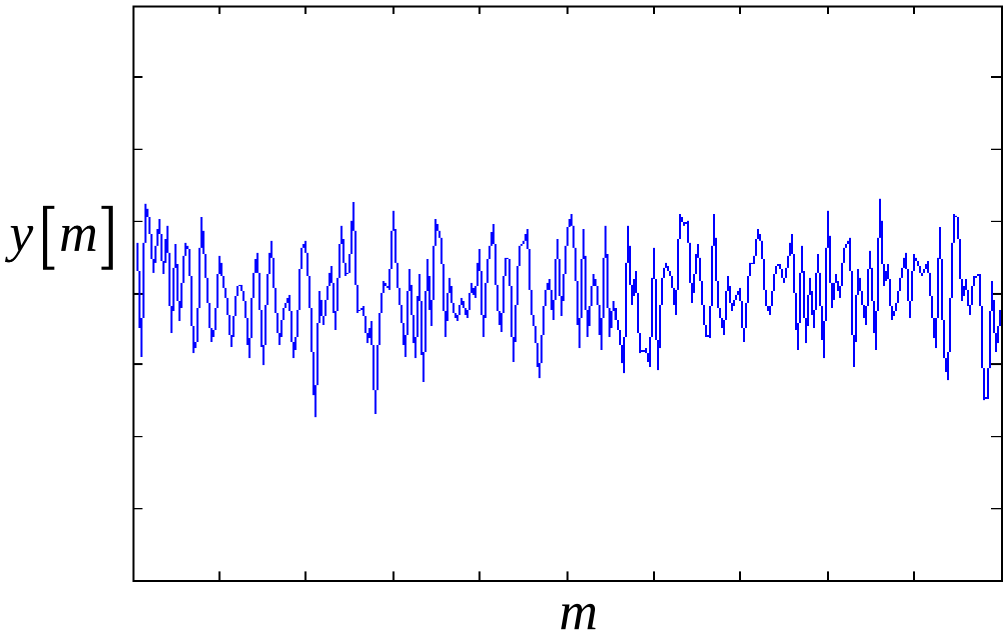


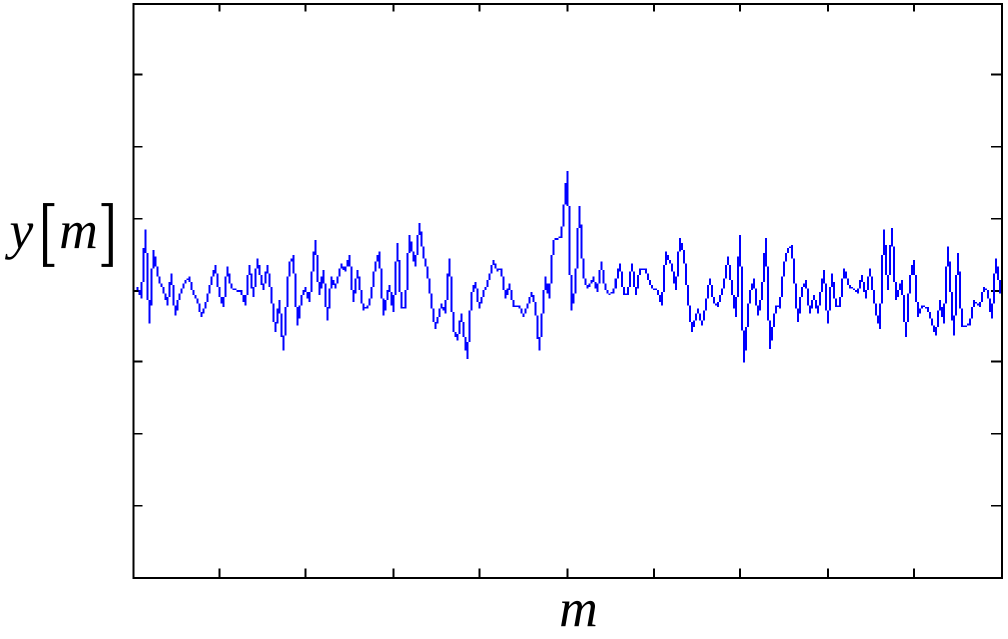
$$N=3\cdot 10^{12}$$

Increasing the signal

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

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

$$\alpha=\frac{\tau_c}{T}\bar{n}^2\left|\gamma_d\right|^2 \quad , \quad \beta=\frac{\bar{n}}{\sqrt{N}}$$ modelled as δ correlation and gaussian noise



$N=10^{13}$

Increasing the signal

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

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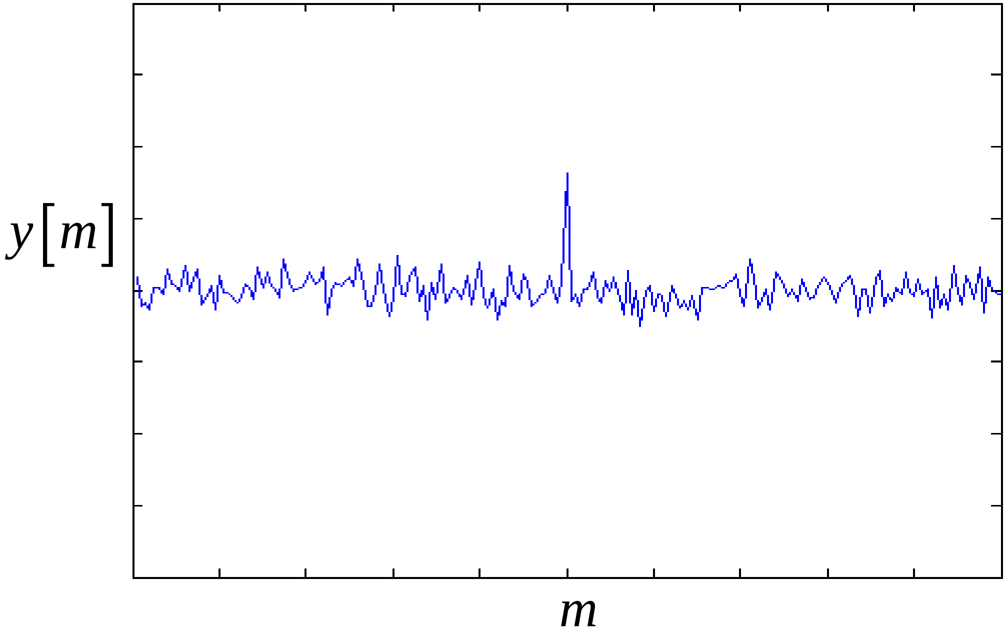

$$N=3\cdot 10^{13}$$

Increasing the signal

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

correlation of two inputs

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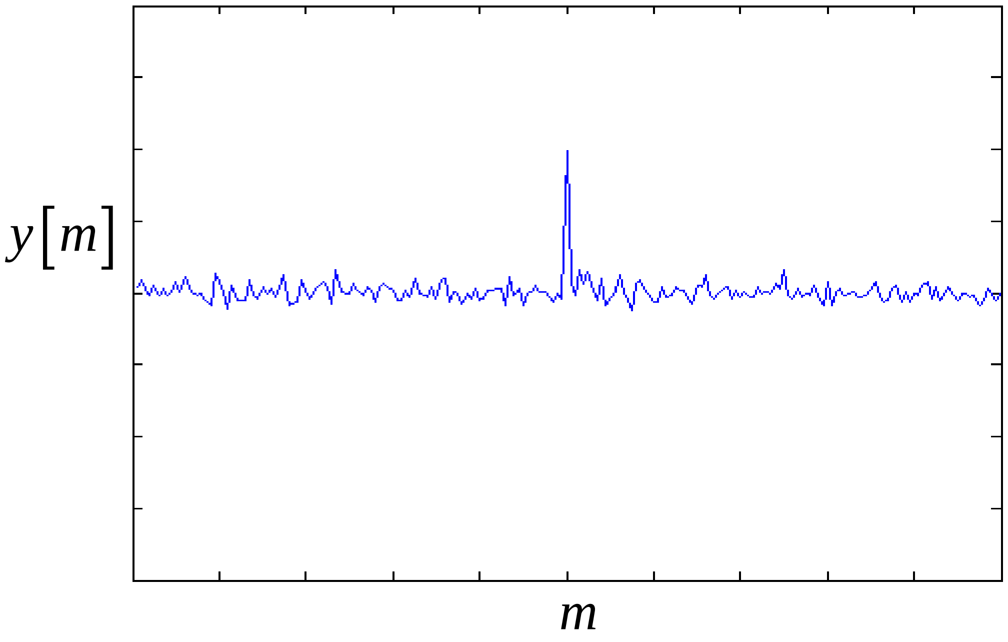
modelled as δ correlation and gaussian noise



$$N=10^{14}$$

Increasing the signal

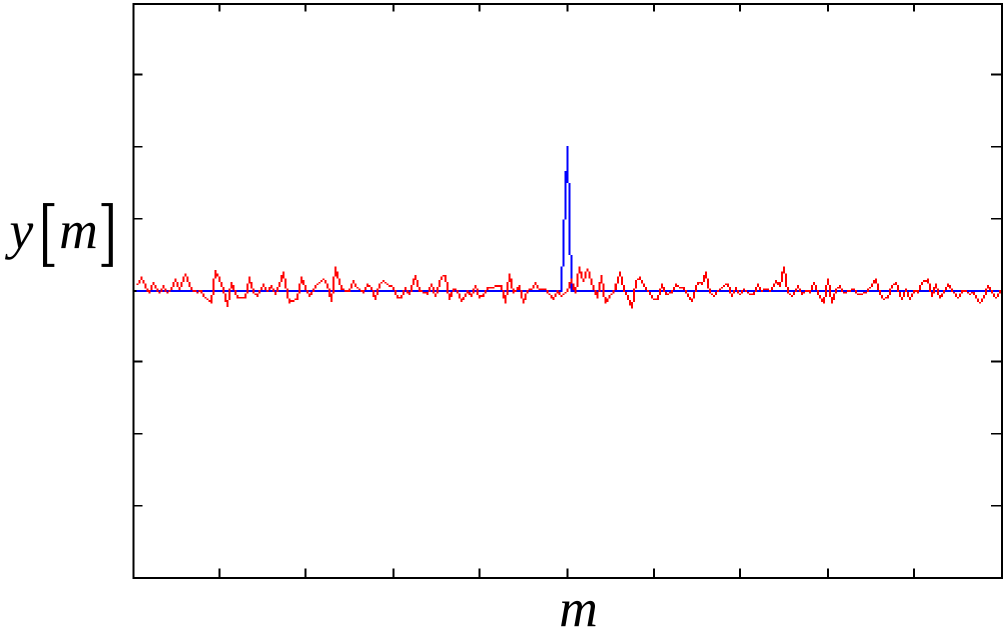
$$y[m]=\frac{1}{N}\sum_{l=1}^{N}\left(n_1[l]-\bar{n}\right)\left(n_2[l+m]-\bar{n}\right)$$

correlation of two inputs

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

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

modelled as δ correlation and gaussian noise

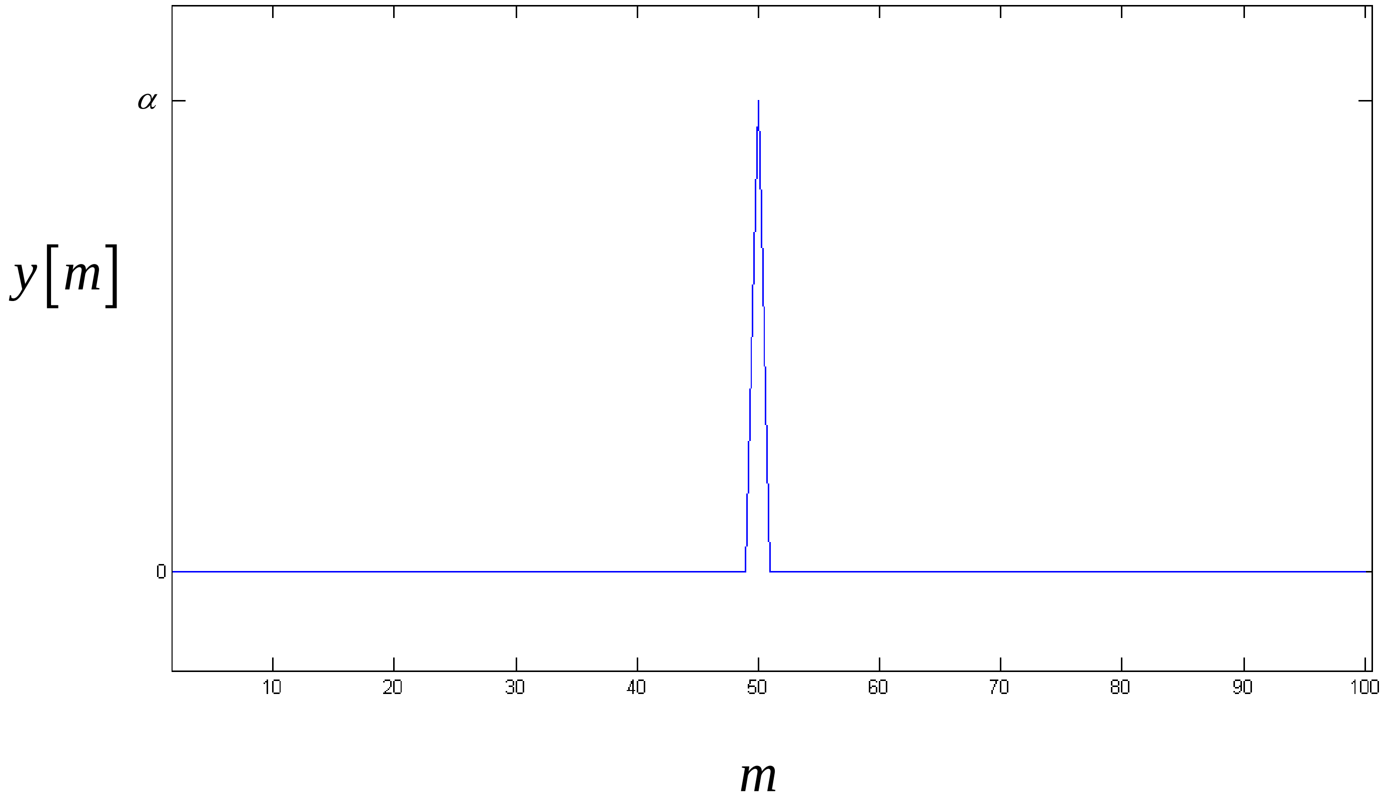


$$N=10^{14}$$

Simple case: no noise

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

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

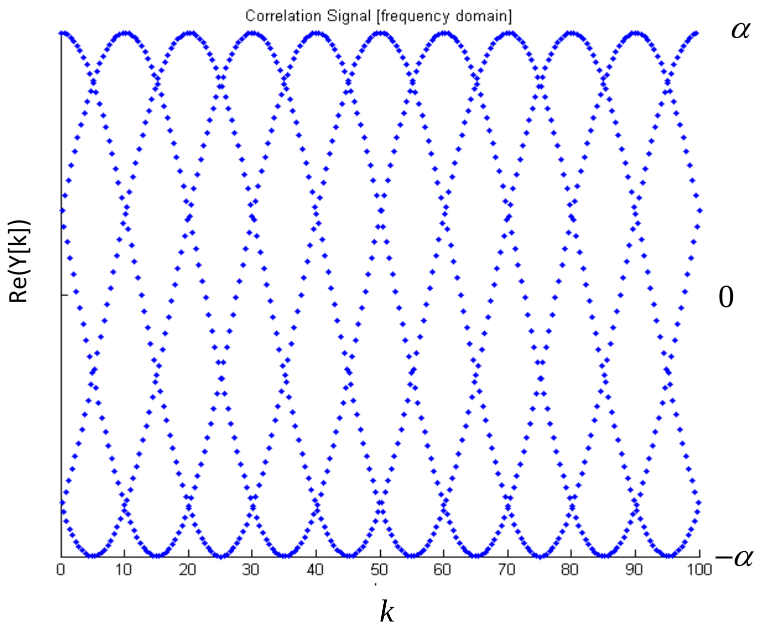


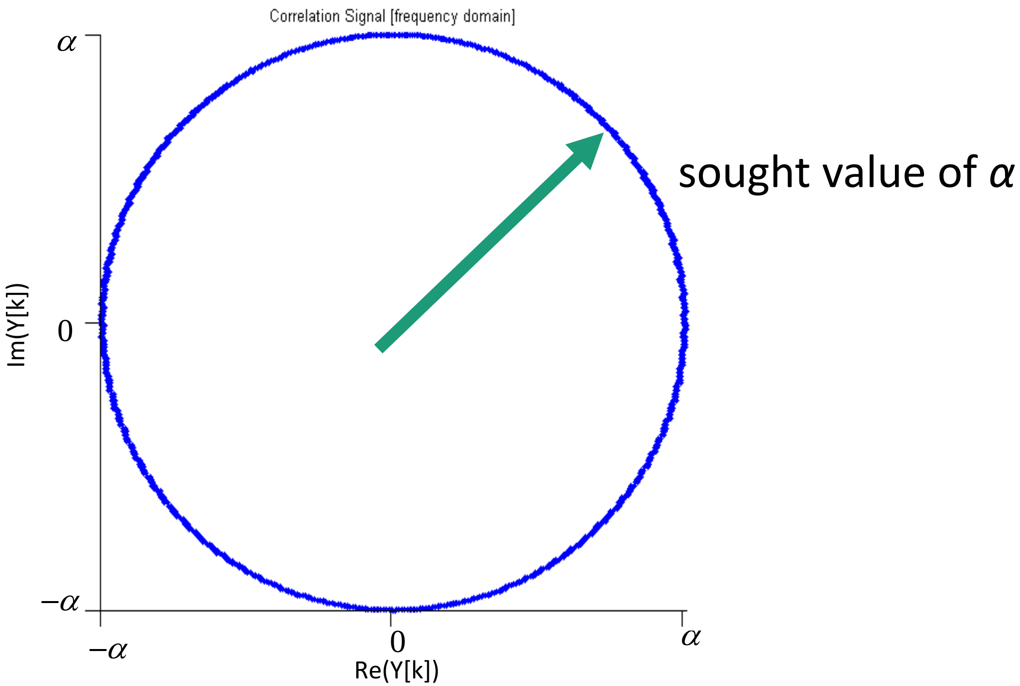
Simple case: no noise, Fourier domain

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

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

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

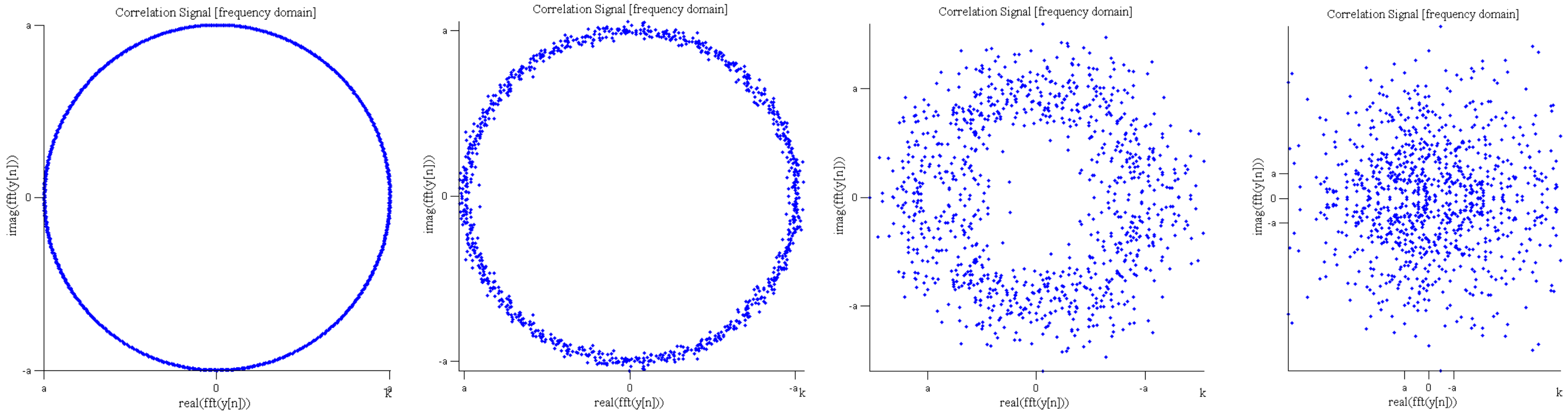




Simple case: with noise, Fourier domain

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

$\beta = 0$ $\beta = 0.001\alpha$ $\beta = 0.01\alpha$ $\beta = 0.1\alpha$



Correlation (circle radius) buried in Poisson noise

Dropping frequencies drops points, not noise

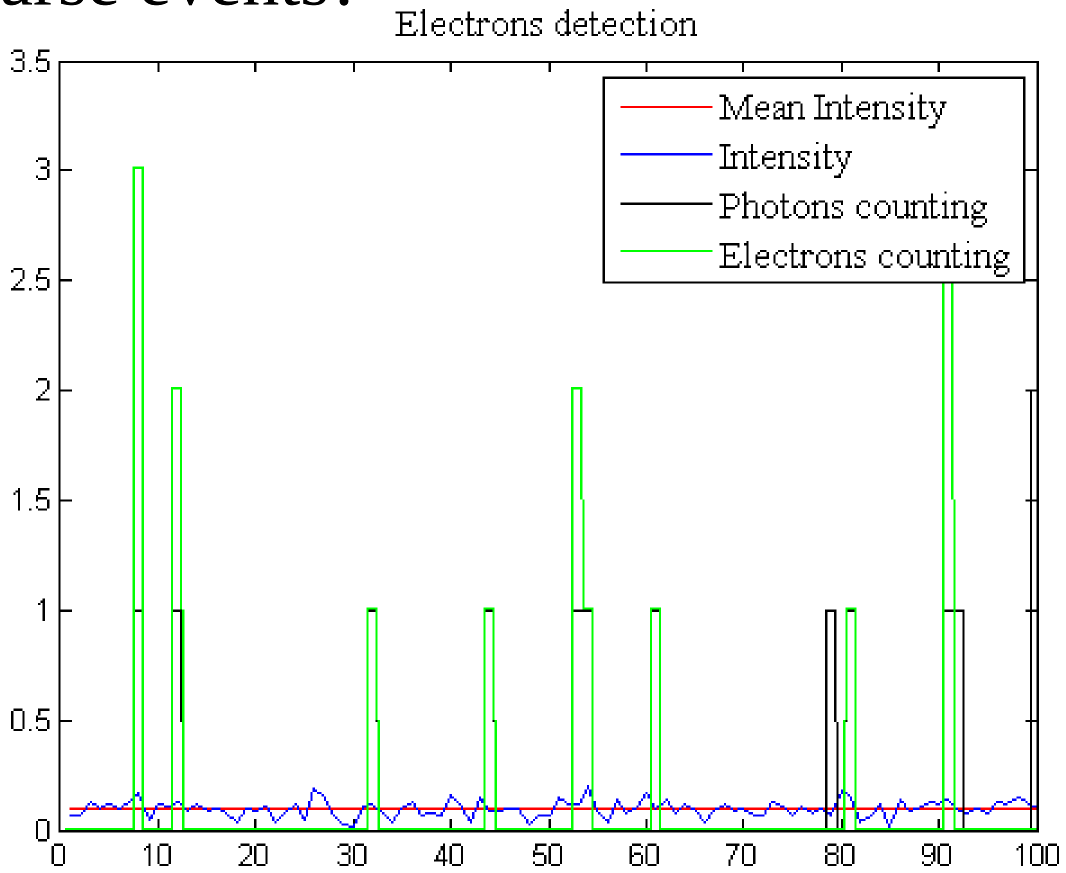
Other compression methods

Compressed sensing is partially useful, only if delay is known exactly

Can we use the fact that we have sparse events?

$$\bar{n} << 1$$

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



Compression efficiency

Various compression schemes, here showing run-length

No gain for brighter objects, $m < 8$

Fine for transmitting colour band channels

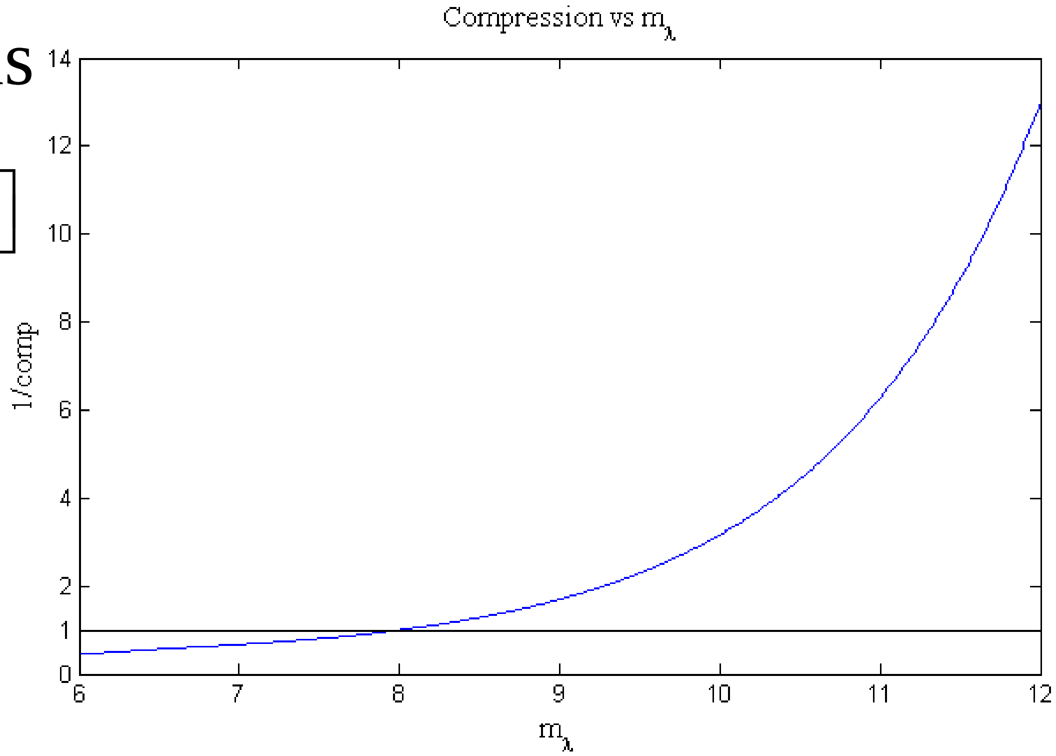
$$comp(\bar{n}) = \frac{\langle b \rangle}{\langle k \rangle} = \frac{2\left[\bar{n} - \log_2(\bar{n})\right]}{1/\bar{n}} = 2\left[\bar{n}^2 - \bar{n}\log_2(\bar{n})\right]$$

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

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

$$\eta \cong 0.9$$

$$A \cong 30m^2$$



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

Thank you!

Additional slides

Set-up parameters

- Distance between the "star" and the beam splitter: $L \sim 1$ m
- Laser wavelength: $\lambda = 532$ nm
- Pinhole diameter: d_{PH}=230 μm
- Speckle size in the PMT plane: $d_{sp} = \frac{L\lambda}{d_{PH}} \cong 2.3$ mm
- PMT collection area is $\sim 1 \times 1$ cm^2.
- To reduce the PMT collection area below a single speckle size, two pinholes (of $\sim$1mm diameter) are placed in front of each PMT.
- The "star" pinhole is placed as close as possible to the ground glass.
- PMT resolution time: 0.8 ns
- Coherence time of the artificial star: ~10 μs
- Integration time (for 100 patches): $100 \cdot 400$ μs $= 40$ ms
- The speckle size is determined by a size of the focused laser spot on the ground glass and can be controlled by moving the lens.