Single-Photon Techniques for the Detection of Periodic Optical Signals

Presentation at
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Walter Leeb

institute of telecommunications

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

Publications

Single-Photon Technique for the Detection of **Periodic Extraterrestrial Laser Pulses**

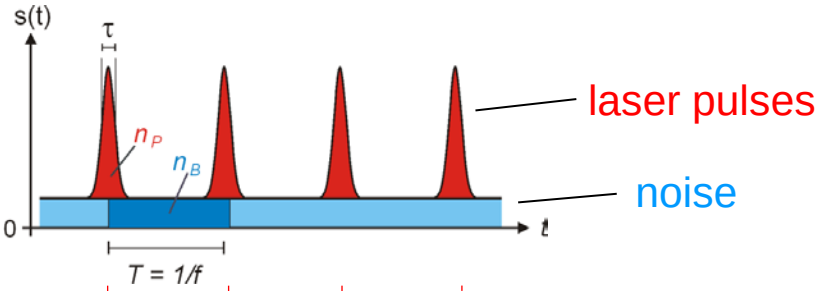
W. R. Leeb, A. Poppe, E. Hammel, J. Alves, M. Brunner, S. Meingast
Astrobiology 13, 6, 521 – 535 (2013)

Simulated Low-Intensity Optical **Pulsar Observation** with Single-Photon Detector

W. R. Leeb, J. Alves, S. Meingast, M. Brunner
Submitted to A&A, Nov. 2014

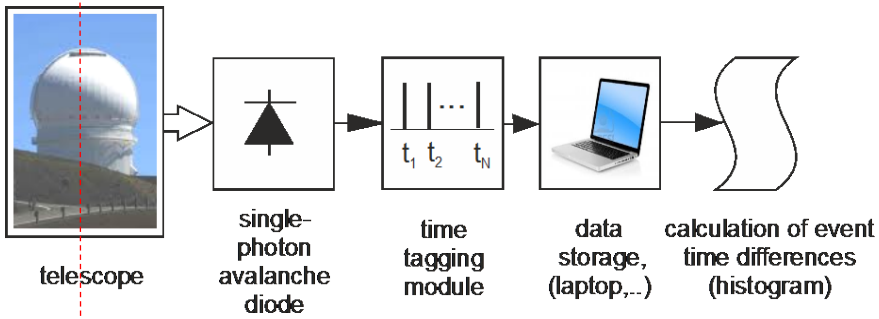
Extraterrestrial laser pulses

- transmitted signal (periodic) + noise

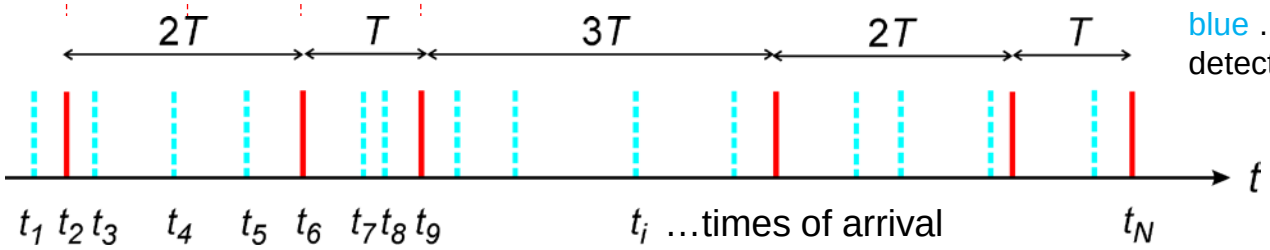


typical:
$\tau \approx$ ns
T ≈ 100 µs (f ≈ 10 kHz)

- receiving setup



- available information, „events“

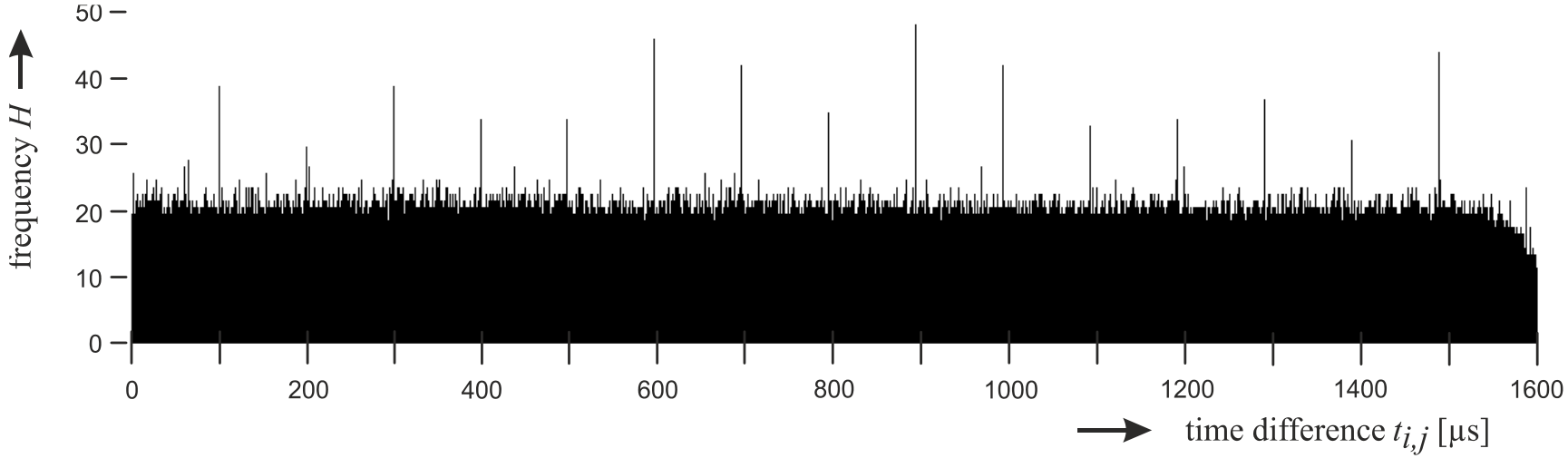


red … laser events
blue … noise events
detector dead time > τ

Extraterrestrial laser pulses: histogram of time differences

- calculate (all) time differences $t_{i,j} = t_i - t_j$ (j = 1,2,…N-1, i = j+1, j+2, … N)
- generate a histogram showing the number of occurences (= frequency *H*) of time differences $t_{i,j}$ within bins of prescribed bin width *bw*

Example: **1** received „pulse“ photon per period *T* = 100 µs,
187 noise photons per period *T*,
measurement time = 24 ms (240 periods),
histogram with *bw* = 1 ns (shown for $t_{i,j} \leq 16\ T$ (total length = 250 *T*))



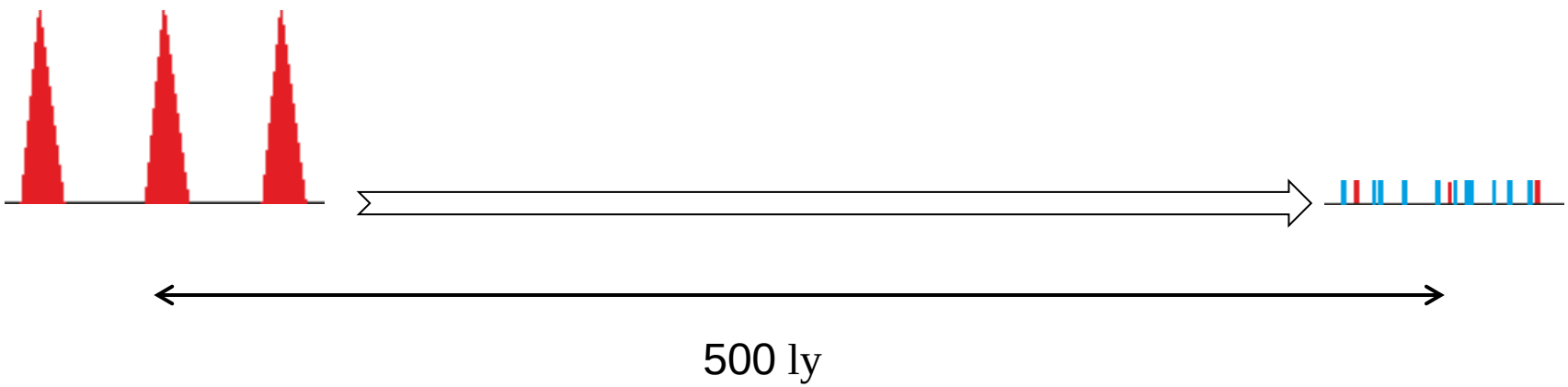
the envelope of the (full) histogram is the
autocorrelation function of the received optical signal

Scenario

background: G2V-star

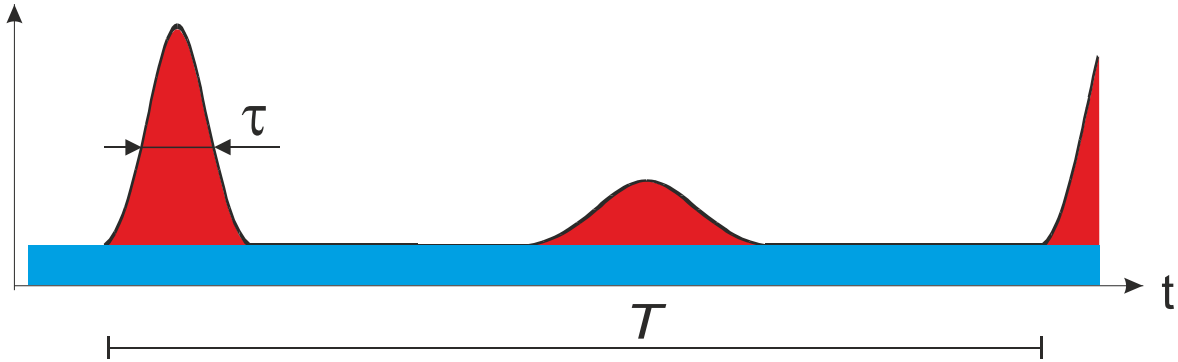
laser transmitter on exoplanet:
D_T = 10 m
$1.8 \cdot 10^{23}$ ph/pulse @ 850 nm ($E_T = 4.2 \cdot 10^4$ J)
f = 10 kHz

receiver on Earth:
D_R = 1.7 m
1 ph/pulse (average)
$\Delta\lambda$ = 290 nm
measurement time = 24 ms



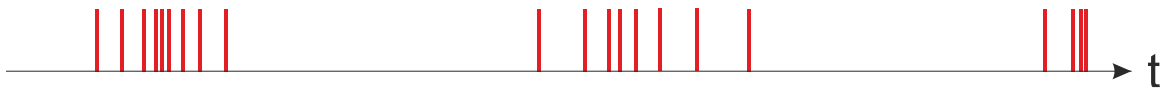
Pulsar Signal

input power

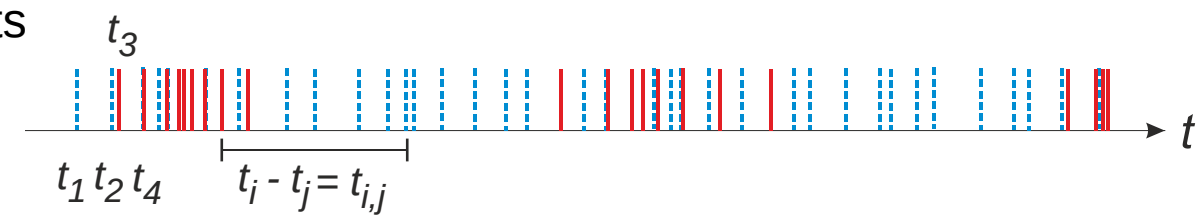


Crab pulsar
$\tau \approx$ **3 ms**
T ≈ 33 ms (f = 30 Hz)

pulsar events
(detector dead time << τ)

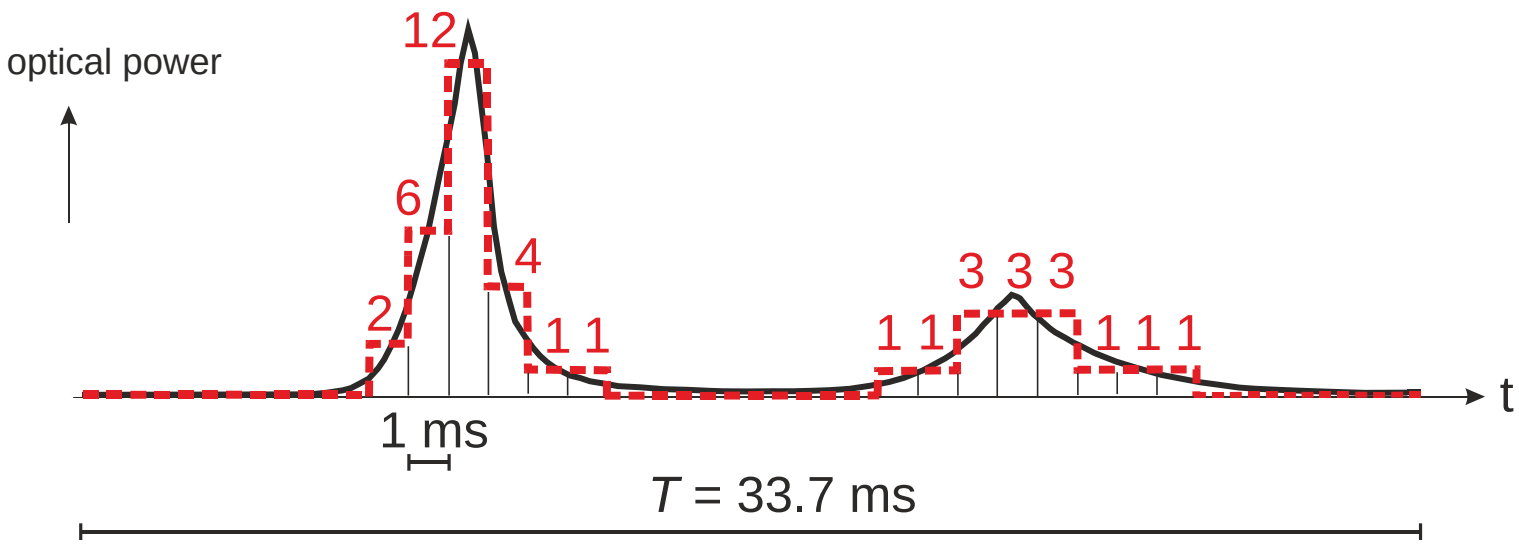


pulsar
+noise
events



Simulation of pulsar events

- Crab-like light curve (visible, near infared)
- digitized into 1 ms-wide steps
- red numbers: relative number of events at random instants of time within step



Number of pulsar events n_p

n_p … pulsar events/period T

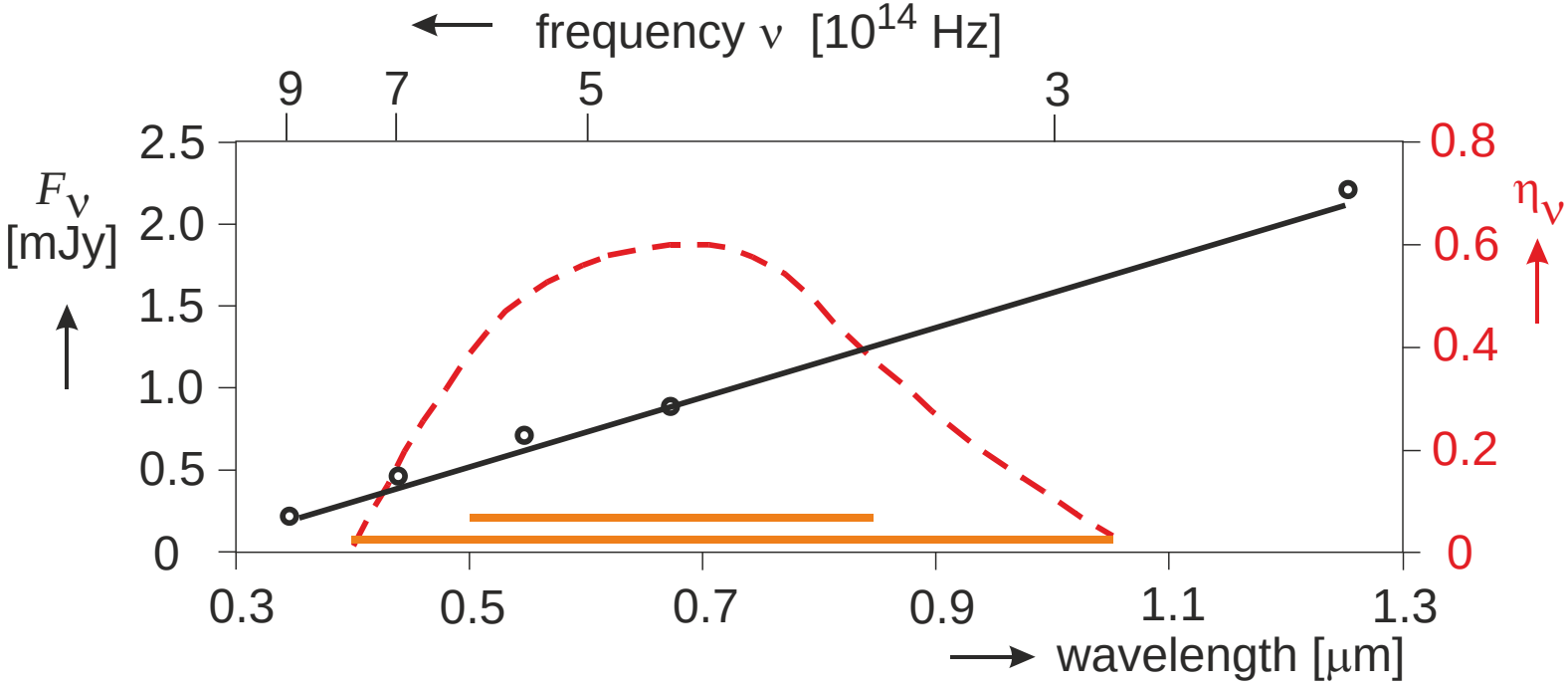
depends on

- pulsar flux density
- pulsar period T
- telescope diameter D_R
- losses in atmosphere and instrument
- quantum efficiency of detector
- used detector bandwidth $\Delta\lambda$

Spectral region, pulsar flux density

detector quantum efficiency η_ν

flux density F_ν of Crab pulsar (measurements o, interpolation —)



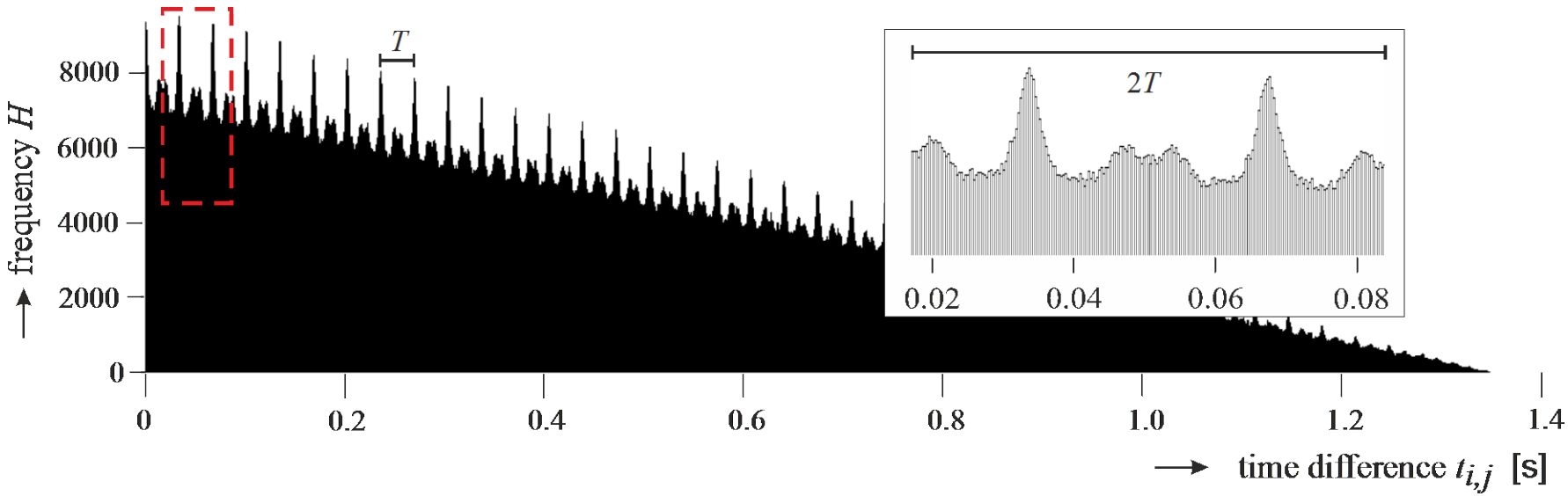
Simulation of noise events

- sky background rate n_{SB} ⇨
  - night sky magnitude
  - field of view fov
  - spectral band
- nebular background rate n_{NB}
  - e.g. Crab nebula
- detector dark count rate n_D
  - e.g. 50 s^{-1}

total noise rate $\boldsymbol{n_n} = n_{SB} + n_{NB} + n_D$

Example 1

- Crab pulsar (V = 16.6 mag, $T \approx 33$ ms)
- telescope diameter D_R = 0.8 m (vlt … Vienna litte telescope)
- $\Delta\lambda$ = 650 nm
- transmission = 0.45
- $\Rightarrow$ pulsar events/period n_P = 40
- *fov* = 1 arsec
- $\Rightarrow$ noise event rate n_n = 3120 s^{-1} (Vienna)
- measurement time M = 1.35 s (P = 40 periods)
- bin width *bw* = 0.3 ms

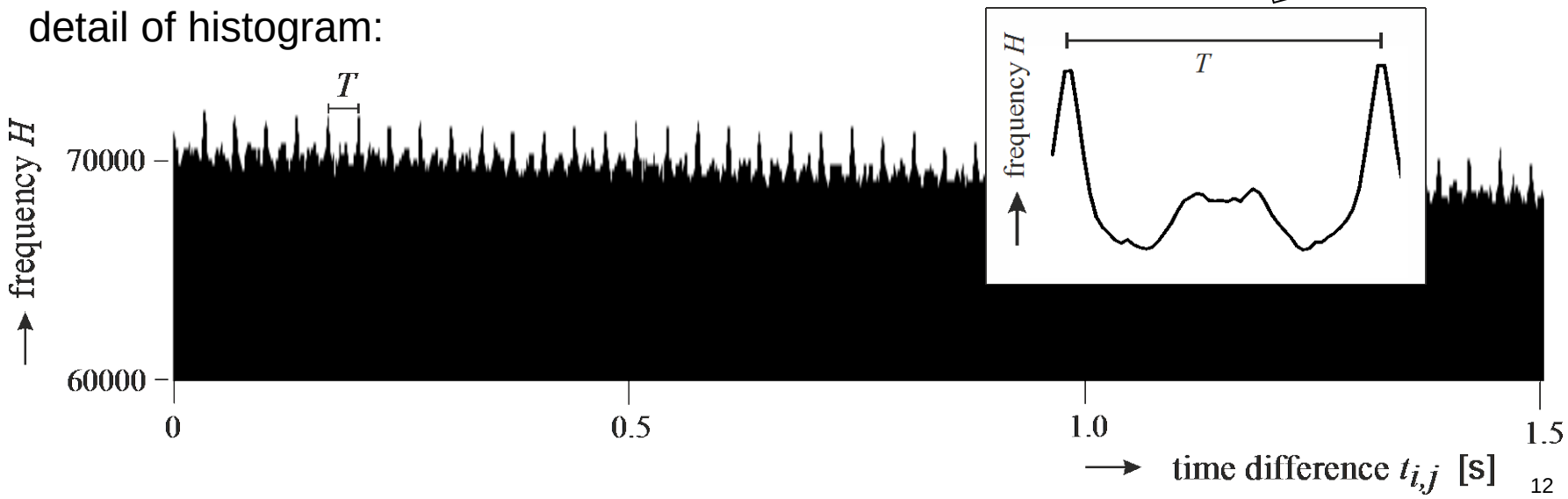


Example 2

- **Crab-like** pulsar (**V = 24.6 mag,** $T \approx 33$ ms)
- telescope diameter D_R = 8.2 m (VLT, Paranal)
- $\Delta\lambda$ = 350 nm
- transmission = 0.9
- $\Rightarrow$ pulsar events/period n_P = 3.6
- *fov* = 0.6 arsec
- $\Rightarrow$ noise event rate n_n = 1210 s^{-1} („old“ pulsar, n_{NB} = 0)
- measurement time M = 61 s (P = 1800 periods)
- bin width *bw* = 0.76 ms (= T/50)

envelope of one period T after superimposing the first 240 consecutive blocks of length T

detail of histogram:

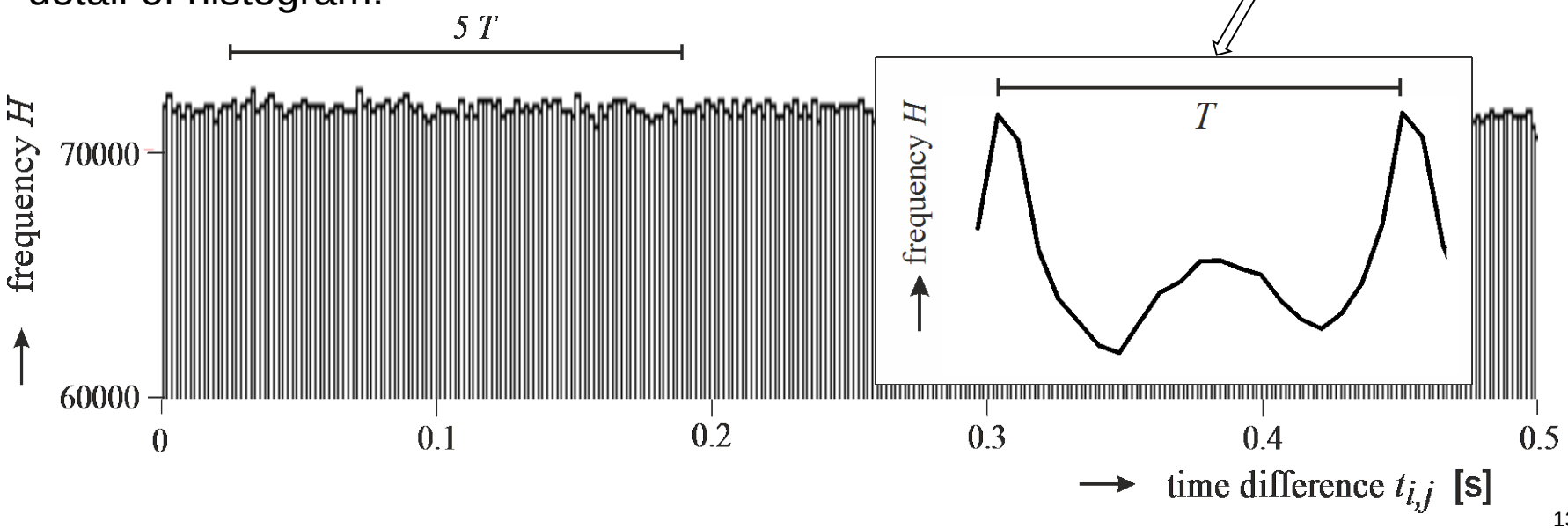


Example 3

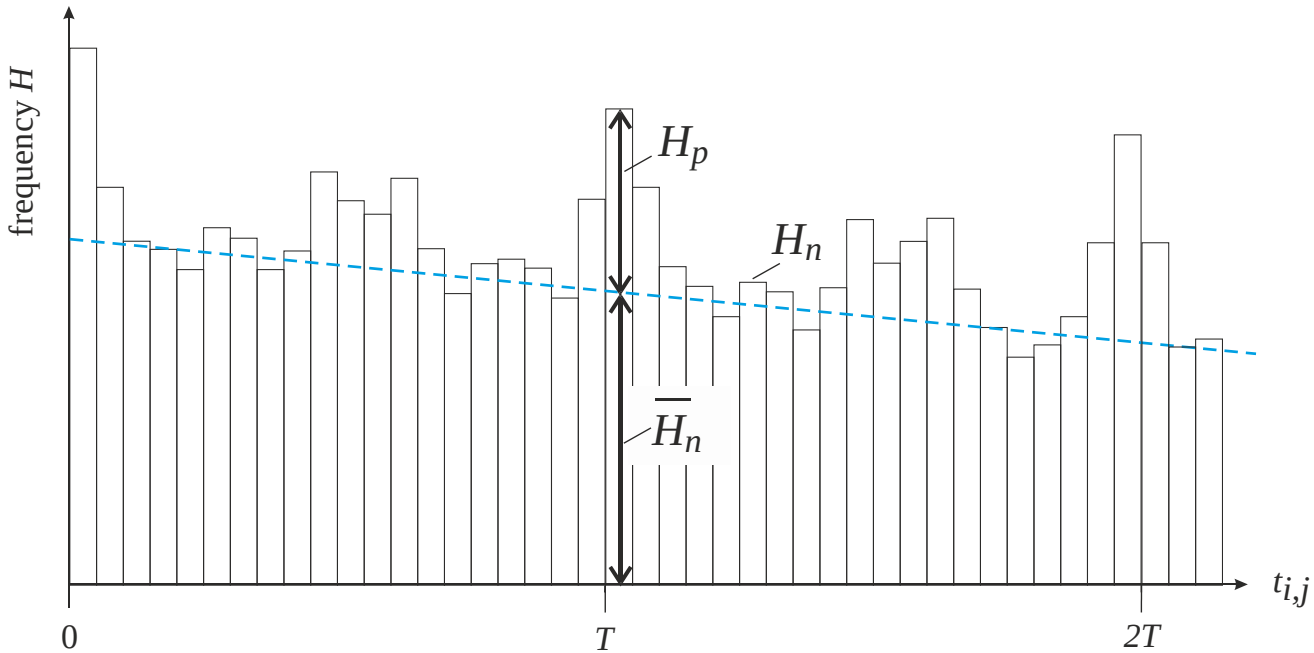
- **Crab-like** pulsar (**V = 30 mag,** $T \approx 33$ ms)
- telescope diameter D_R = 40 m (ELT)
- $\Delta\lambda$ = 350 nm
- transmission = 0.9
- $\Rightarrow$ pulsar events/period n_P = 0.59
- *fov* = 0.1 arsec
- $\Rightarrow$ noise event rate n_n = 820 s^{-1} („old“ pulsar, n_{NB} = 0)
- measurement time M = 61 s (P = 1800 periods)
- bin width b*w* = 1.685 ms (= T/20)

envelope of one period T after superimposing the first 700 consecutive blocks of lengths T

detail of histogram:



Signal-to-noise ratio

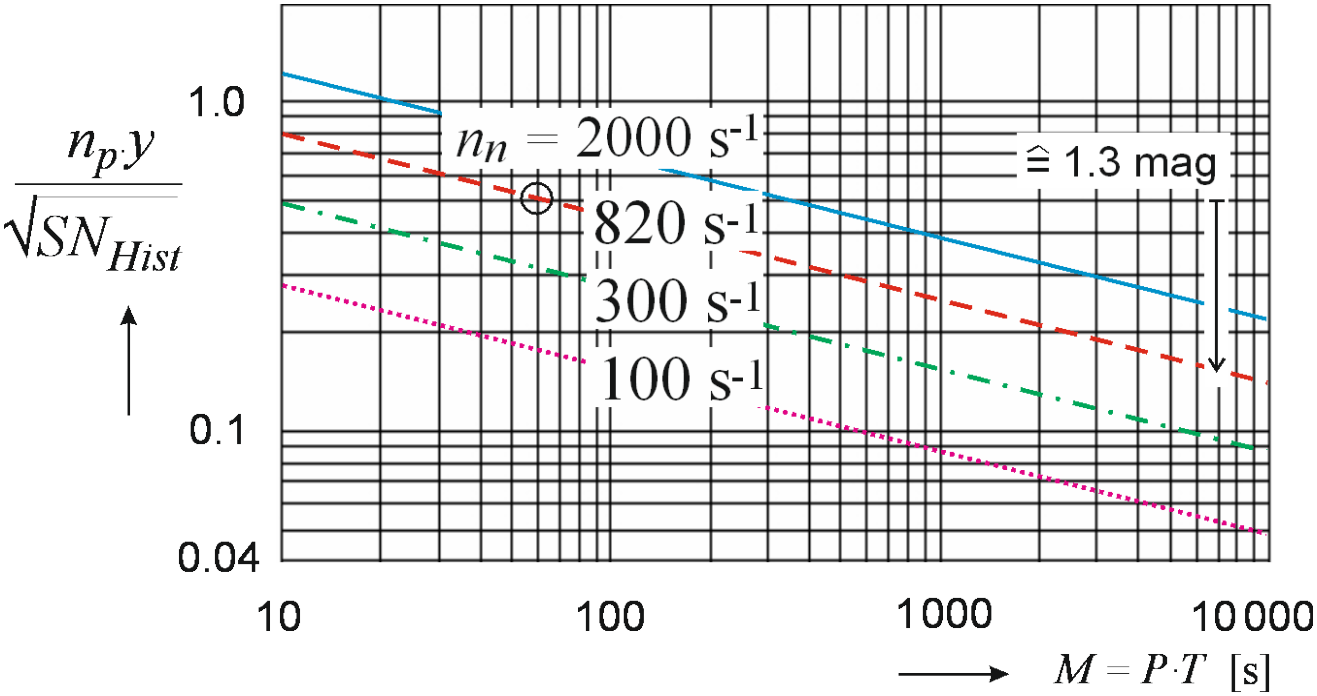


signal-to-noise ratio: $$SN_{Hist} = H_p / \sigma_{Hn} = H_p / (\overline{H_n})^{1/2}$$

σ_{Hn} ... standard deviation of H_n

	example 1	example 2	example 3
SN_{Hist}	33	8.1	0.55

Required pulsar events n_p/period vs. measurement time M



$n_p \propto M^{-1/4}$

n_p ...pulsar events/period
y ... fraction of n_p leading to histogram peak (= 0.65 for Crab pulsar)
SN_{Hist} ... signal-to-noise ratio in histogram
M ... measurement time
T ... pulsar period
P ... number of periods recorded
n_n ... rate of noise events
O … example 3

BUT: after superimposing histogram blocks of length T:

$n_p \propto M^{-1/2}$

Comparison to „classic“ techniques

- first step
  - **NOT** binning of times of arrival (TOA, t_i) into time slots followed by manipulating the number of TOAs − of either consecutive slots or of slot time differences)

  - **BUT** establishing a histogram of differences of times of arrival (t_i - t_j)

- *all available* information (i.e. all t_i) is used

- we do not obtain the pulsar‘s light curve but its autocorrelation function