Single-Photon Techniques for the Detection of Periodic Optical Signals

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Publications

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

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

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Extraterrestrial laser pulses

- transmitted signal (periodic) + noise

\[ s(t) \]

\[ \tau \approx \text{ns} \]
\[ T \approx 100 \, \mu\text{s} \quad (f \approx 10 \, \text{kHz}) \]

- receiving setup

- available information, "events"

\[ t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5 \quad t_6 \quad t_7 \quad t_8 \quad t_9 \]
\[ t_i \quad \ldots \text{times of arrival} \quad t_N \]

red ... laser events
blue ... noise events
detector dead time \( > \tau \)
Extraterrestrial laser pulses: histogram of time differences

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

Example: 1 received „pulse“ photon per period \( T = 100 \mu s \), 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:**
- $D_T = 10\, \text{m}$
- $1.8 \cdot 10^{23} \, \text{ph/pulse} @ 850\, \text{nm}$ \hspace{1cm} ($E_T = 4.2 \cdot 10^4\, \text{J}$)
- $f = 10\, \text{kHz}$

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

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500 ly
Pulsar Signal

input power

![Diagram showing pulsar signal with symbols and time intervals](image)

Crab pulsar
\[ \tau \approx 3 \text{ ms} \]
\[ T \approx 33 \text{ ms} \ (f = 30 \text{ Hz}) \]

pulsar events
(detector dead time \(<\!\!<\!\!\tau\)>)

pulsar +noise events

\[ t_1 \ t_2 \ t_4 \quad t_i - t_j = t_{ij} \quad t_3 \]
Simulation of pulsar events

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

\[ T = 33.7 \text{ ms} \]
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 $\eta_\nu$.

flux density $F_\nu$ of Crab pulsar (measurements ○, interpolation —).

![Graph showing spectral region and flux density measurements for Crab pulsar, with frequency $\nu$ in units of $10^{14}$ Hz and wavelength in micrometers.]
Simulation of noise events

- sky background rate $n_{SB}$
- nebular background rate $n_{NB}$
- detector dark count rate $n_D$

Total noise rate $n_n = n_{SB} + n_{NB} + n_D$

- night sky magnitude
- field of view fov
- spectral band
- e.g. Crab nebula
- e.g. 50 s$^{-1}$
Example 1

- Crab pulsar ($V = 16.6$ mag, $T \approx 33$ ms)
- Telescope diameter $D_R = 0.8$ m (VLT ... Vienna little telescope)
- $\Delta \lambda = 650$ nm
- Transmission = 0.45
- $\Rightarrow$ pulsar events/period $n_P = 40$
- $fov = 1$ arcsec
- $\Rightarrow$ 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 $n_P = 3.6$
- $f_{ov} = 0.6$ 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 ($= T/50$)

**detail of histogram:**

- envelope of one period $T$ after superimposing the first 240 consecutive blocks of length $T$
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 $n_P = 0.59$
- $f_{\text{ov}} = 0.1$ 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 ($= T/20$)

**Detail of histogram:**

![Histogram detail](image)
signal-to-noise ratio:

\[ SN_{Hist} = \frac{H_p}{\sigma_{Hn}} = \frac{H_p}{(\overline{H_n})^{1/2}} \]

\( \sigma_{Hn} \) ... standard deviation of \( H_n \)

<table>
<thead>
<tr>
<th>example 1</th>
<th>example 2</th>
<th>example 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( SN_{Hist} )</td>
<td>33</td>
<td>8.1</td>
</tr>
</tbody>
</table>
Required pulsar events $n_p$/period vs. measurement time $M$

\[ \frac{n_p y}{\sqrt{SN_{Hist}}} \]

\[ n_n = 2000 \text{ s}^{-1} \quad \geq 1.3 \text{ mag} \]

\[ 820 \text{ s}^{-1} \quad 300 \text{ s}^{-1} \]

\[ 100 \text{ s}^{-1} \]

\[ M = P \cdot T \quad [\text{s}] \]

$n_p$ ... 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