Characterizing optical complexity with tools of nonlinear time-series analysis

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Dynamical optical complexity

- **Optical spikes**
  Semiconductor laser with optical feedback

- **Extreme pulses**
  Semiconductor laser with injection

- **Polarization switching**
  VCSELs

- **Optical turbulence**
  Fibre laser
Optical systems allow recording long time-series under controlled conditions.

With this “optical big data” we can
  • test novel analysis tools (prediction, control).
  • capture relevant features in the data (classification, model verification, parameter estimation).
Semiconductor lasers

- Edge-emitting lasers (EELs)
- Vertical-cavity (VCSELs)

Fibre laser

L=1-10μm, single longitudinal mode

L=1 km, millions of longitudinal modes
Method of time-series analysis: ordinal patterns

- **X**: \(\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}\)

Brandt & Pompe, PRL 88, 174102 (2002)

The OP probabilities allow to identify frequent patterns in the *ordering* of the data points.

- **Advantage**: the probabilities uncover temporal correlations.
- **Drawback**: we lose information about the actual values.
How to select D?
depends on:
- The length of the data.
- The length of correlations in the data.
First example: optical spikes in EELs with optical feedback

\[ X = \{ \Delta T_i, \Delta T_{i+1}, \Delta T_{i+2}, \ldots \} \]

Time intervals between spikes

Empirical data

Error bars computed with a binomial test, gray region is consistent with \( p_i = 1/6 \ \forall \ i \).

Example 2: early warning of an abrupt transition

VCSEL polarization-resolved intensity when a control parameter varies (pump current)

Entropy computed from transition probabilities (‘012’→ ‘012’, etc.) in a sliding window of 500 data points.

Three early-warning indicators

**PS data**

- $s_p / \log D_l$
- $s_n / \log D_l$
- $a_c$

**NO PS data**

- $s_p / \log D_l$
- $s_n / \log D_l$
- $a_c$
Example 3: laminar–turbulence regime transition in a fiber laser

A. Aragoneses et al, arxiv.org/abs/1505.07365
Example 4: extreme pulses in an injected semiconductor laser

- Optical rogue waves

C. Bonatto et al, PRL 107, 053901 (2011)
What is a Rogue Wave?

A “monster wave”, a “freak wave”, an ultra-high wave. Can develop suddenly even in calm and apparently safe seas.

Adapted from F. Dias (Dublin, Ireland)
RWs appear suddenly and vanish without a trace

A challenge for boats and also, for the oil and gas industry, for the design of safe off-shore platforms.

Source: National Geographic
Since 2003 wave profiles were measured with 4 lasers mounted on a bridge at the oil production site Ekofisk in the North Sea.

A RW was detected 9/11/2007 during a storm.
Optical RWs: first observation

Injected semiconductor lasers provide a controllable setup for the study of RWs

- RW definition: pulse above a threshold \((\langle H \rangle + 4-8 \sigma)\)
RWs can be **deterministic**, generated by a crisis-like process.

RWs can be **predicted** with a certain anticipation time.

RWs can be **controlled** via noise and/or modulation.

Governing equations

- Complex field, $E$
- Carrier density, $N$

\[
\begin{align*}
\frac{dE}{dt} &= \frac{1}{2\tau_p} (1 + i\alpha)(N - 1)E + i\Delta\omega + \sqrt{P_{\text{inj}}} + \sqrt{2\beta_{\text{sp}}/\tau_N} \xi(t) \\
\frac{dN}{dt} &= \frac{1}{\tau_N} \left( \mu - N - N|E|^2 \right)
\end{align*}
\]

Solitary laser parameters: $\alpha, \tau_p, \tau_N, \mu$

$\mu$: normalized pump current parameter

Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

optical injection
$\eta$: injection strength
$\Delta\omega = \omega_s - \omega_m$: detuning
spontaneous emission noise
Threshold: $\langle H \rangle + 8\sigma$
RWs can be suppressed by periodic modulation

\[ \mu = \mu_0 + \mu_{\text{mod}} \sin(2\pi f_{\text{mod}} t) \]

White = No RWs

S. Perrone, J. Zamora Munt, R. Vilaseca and C. Masoller, PRA 89, 033804 (2014)
RWs can be induced by the combined influence of noise and modulation

\[ \beta_{sp} = 0 \quad \text{and} \quad \beta_{sp} = 0.01 \]

White = No RWs

“safe” parameter region is robust to noise
Take home message:
When observing complex output signals, nonlinear analysis tools might capture hidden features in the data.

Present work:
- characterizing the performance of these analysis tools for anticipating i) extreme pulses (identifying precursors) and ii) abrupt transitions (false positives and false negatives).
- applying nonlinear tools to 2D optical biomedical images (H2020 BE-OPTICAL).

Extreme Events in Complex Optical Systems
www.eecos.org
VCSEL polarization-switching data:
• Y. Hong (Bangor University, UK)
• S. Barland (INLN, Nice, France)

Fibre laser data:
• Prof. Turitsyn’group (Aston University, UK)
THANK YOU FOR YOUR ATTENTION!

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