Dynamic Instabilities in Staged Combustion

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Motivation & Objectives

- Motivation
  - The power industry is being forced toward tighter control of boilers to meet new governmental and economic requirements
  - Driving Forces
    - Government regulations forcing lower emissions
    - Economic pressures (deregulation) forcing improved boiler efficiencies
- Objectives
  - Develop dynamic burners that exceed the performance of current static burner designs.
  - Develop dynamic control strategies based on manipulation of short-time-scale nonlinear instabilities that exceed the performance of current techniques.

Power industry environment

- Combustion viewed as a “static” or non-dynamic process
- Burners viewed as “static” mechanical devices (I.e., burners should contain no moving parts)
- Trying to meet new requirements with static hardware modifications
- Current state-of-the-art control based on long-tie-scale (time-averaged) techniques
- Very conservative industry
- Reluctant to adopt new ideas bearing financial risk

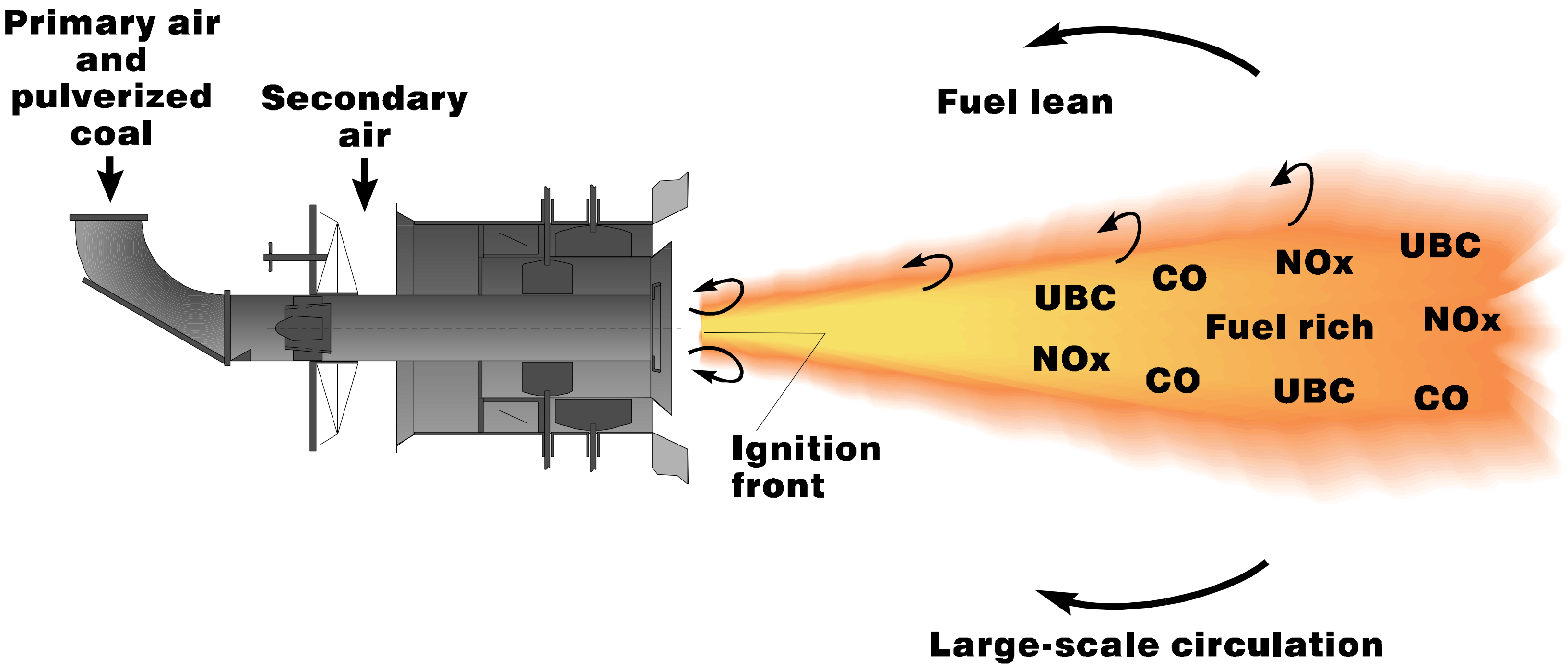
Practical application issues

- Utility/industrial boilers usually contain multiple burners (60-80 burners maximum)
- Burners fire into a common combustion chamber
- Burners fire from opposite walls or corners
- Groups of burners fed by a common fuel supply
- Limited existing data on individual burners
- Limited access for additional data collection
- Minimal means of individual burner control

Flame Physics

- Burner composed of concentric jets
    - Fuel rich core jet (all fuel introduced through core jet)
    - Multiple, fuel-free annular outer jets
- All jets can have tangential momentum in addition to axial momentum
- Performance dominated by the stability/instability of the highly nonlinear fuel ignition process (flame front)
- Flame front stability/instability involves spatio-temporal dynamics
    - Turbulent mixing of jets
    - Heat release patterns near the burner exit plane
    - Large-scale recirculation of combustion products
    - Perturbations of auxiliary equipment (i.e. feeders, pulverizers, fans)

Pulverized coal burner



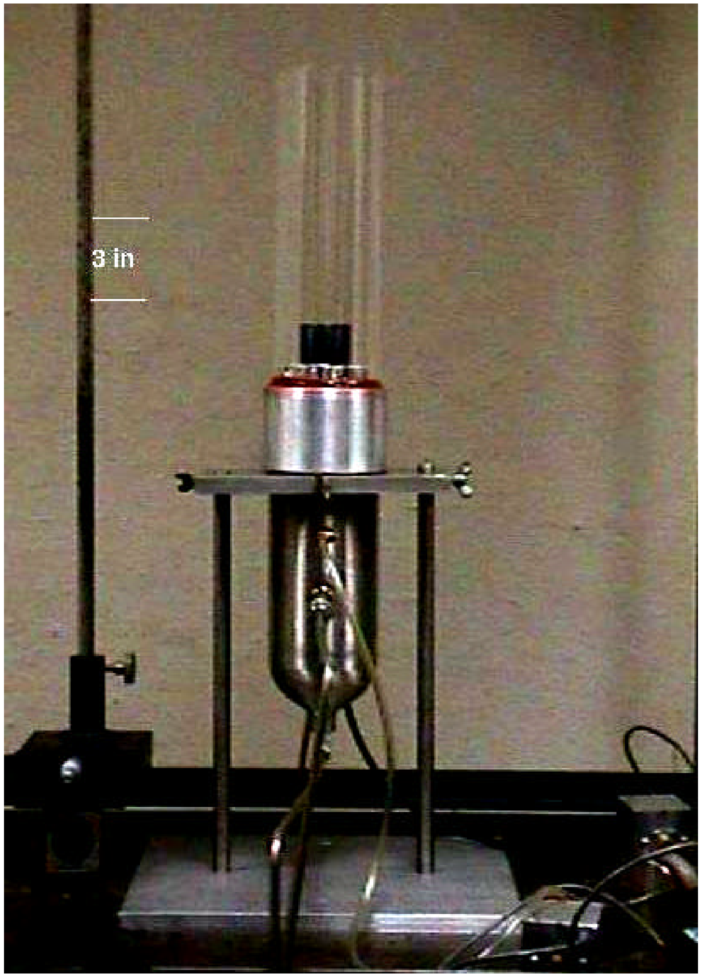
General approach

- Recognize that a flame is a spatio-temporal, nonlinear, dynamical entity
- Collect data from flames of different scales (laboratory-scale up to 30 Wt)
- Apply the latest nonlinear techniques for spatio-temporal control developed by the nonlinear dynamics community
- Link our basic understanding of chaos and nonlinear dynamics to our in-depth knowledge of flame physics
- Develop new diagnostic techniques and control strategies for boiler flames

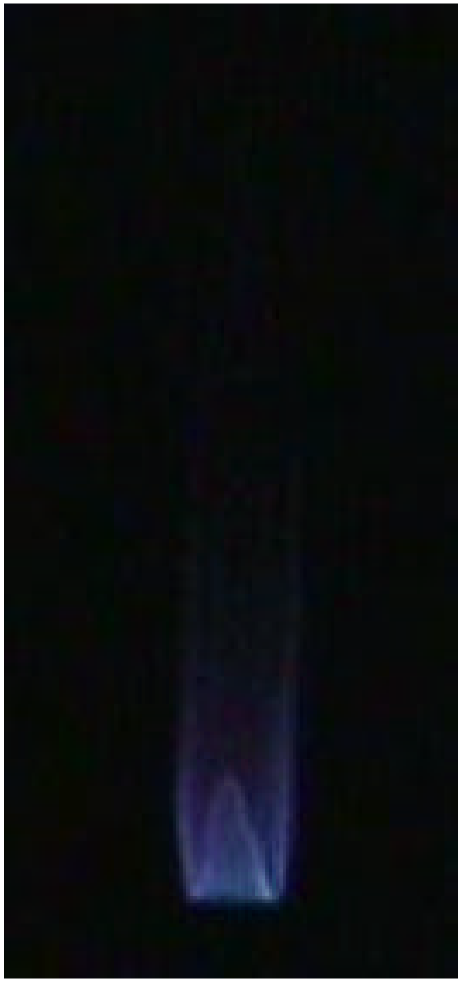
Flame Experiments

- Full-size (30 MWt) burner capable of coal, oil, gas firing
  - Pressure, optical, acoustic time series signals
  - TEAC digital data acquisition (48 kHz max, 16 channels max)
  - Std. burner DAS for nominal operating/performance parameters including flows, temperatures, exit CO, NOx (15 sec. Samples)
  - Std. Burner adjustments including fuel and air feed rate, primary/secondary air split, swirl in primary and secondary zones.
- Laboratory (6 kWt) gas-fired burner (methane, propane)
  - Pressure, optical, acoustic time series signals
  - PC, oscilloscope DAS (100 kHz max, 8 channels max)
  - Nominal flue gas analysis (HC, O_2)
  - Wide range of staging adjustment
  - Capability for transient driving of key parameters

We use a staged laboratory burner to study instabilities and flicker under controlled, low-noise conditions



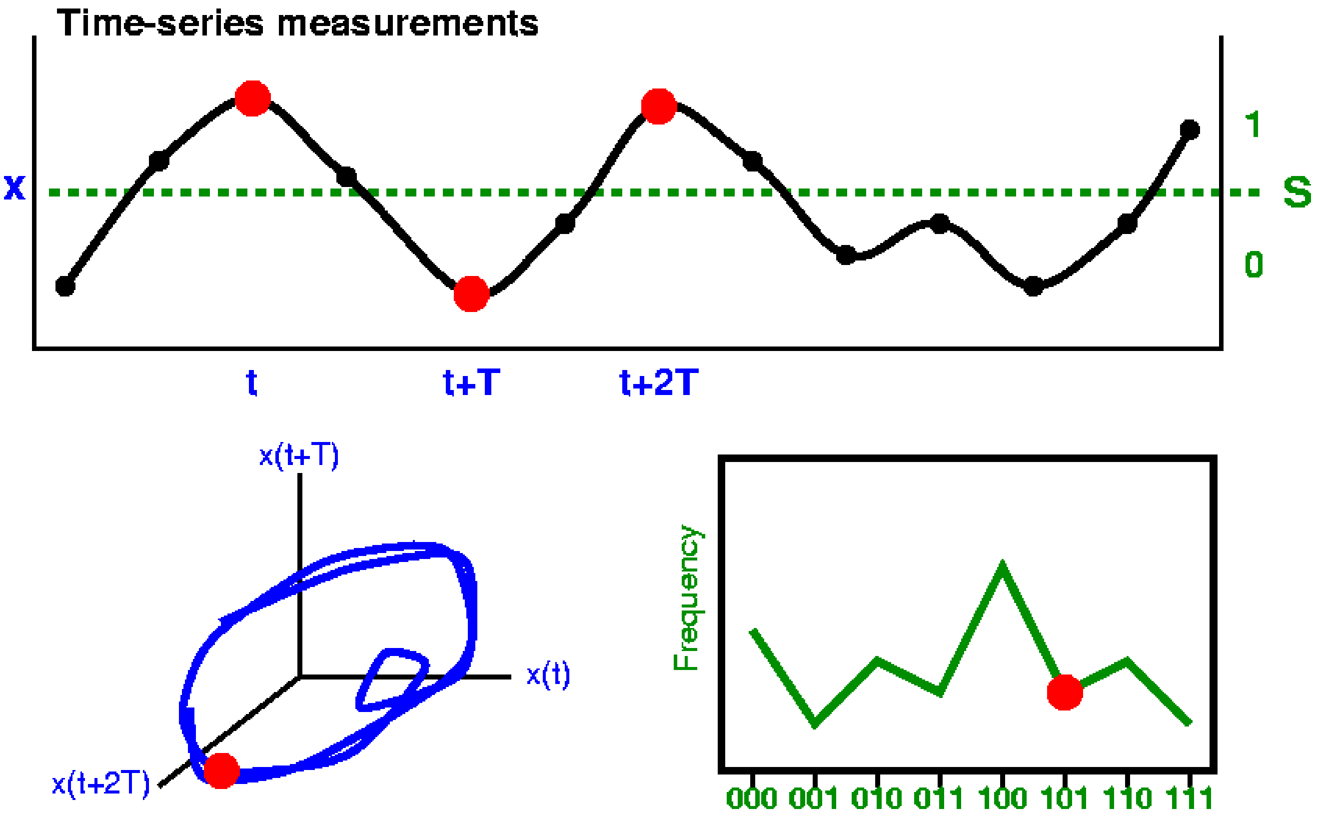
General Configuration



68% Primary Air

48% Primary Air

Symbolization has similarities to time-delay embedding



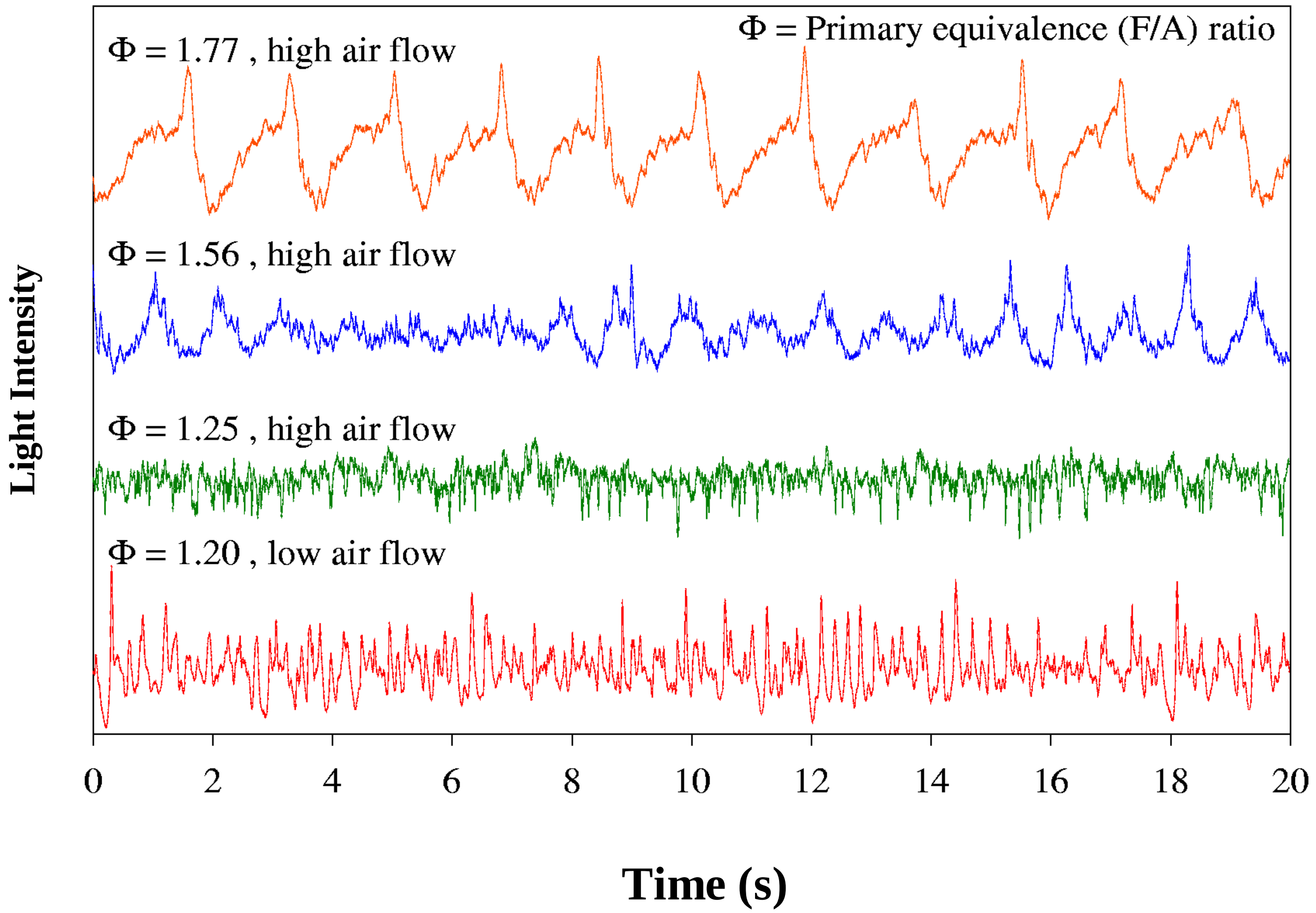
Time-delay embedding

Characterize geometry

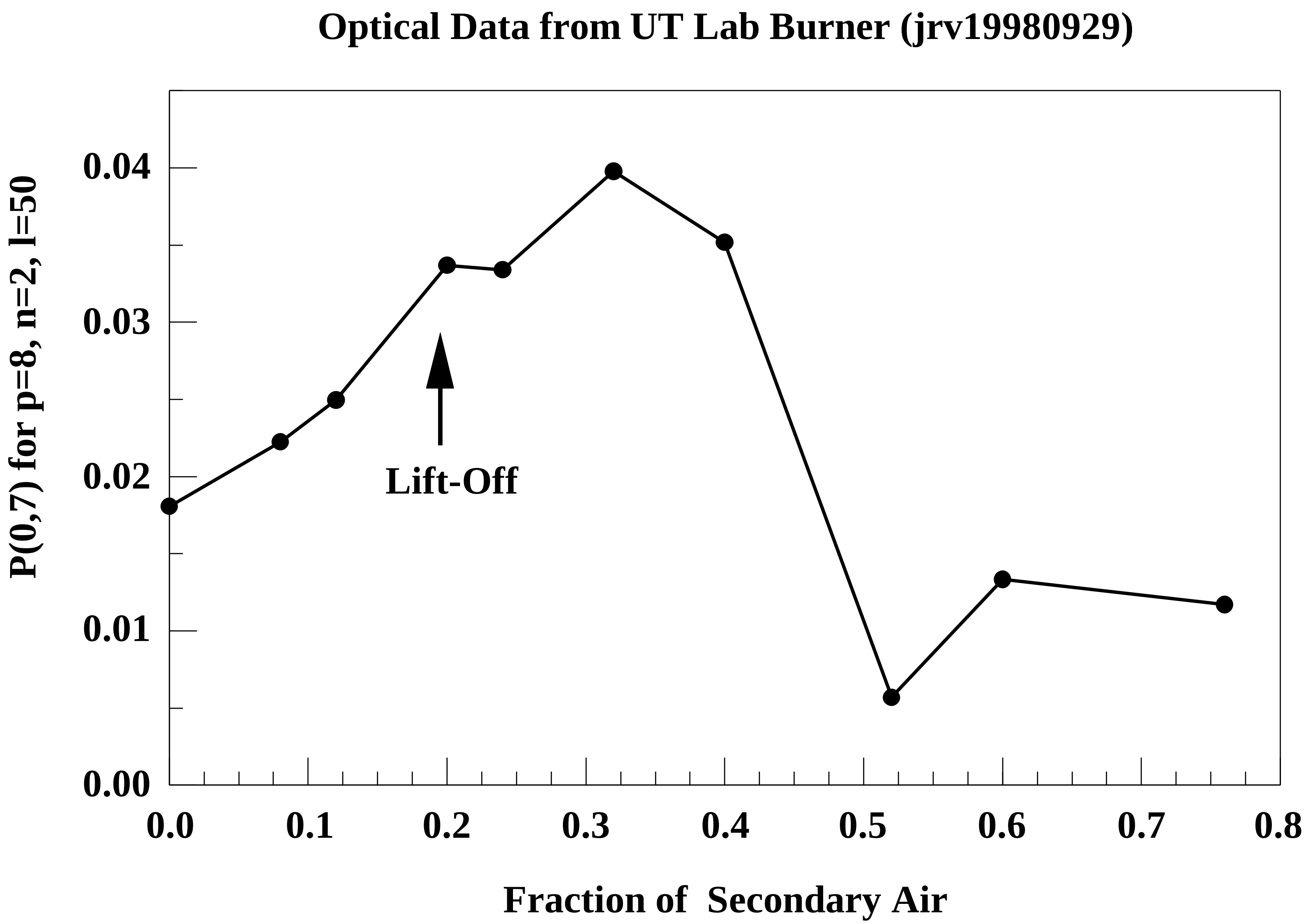
Symbol-sequence analysis

Characterize information

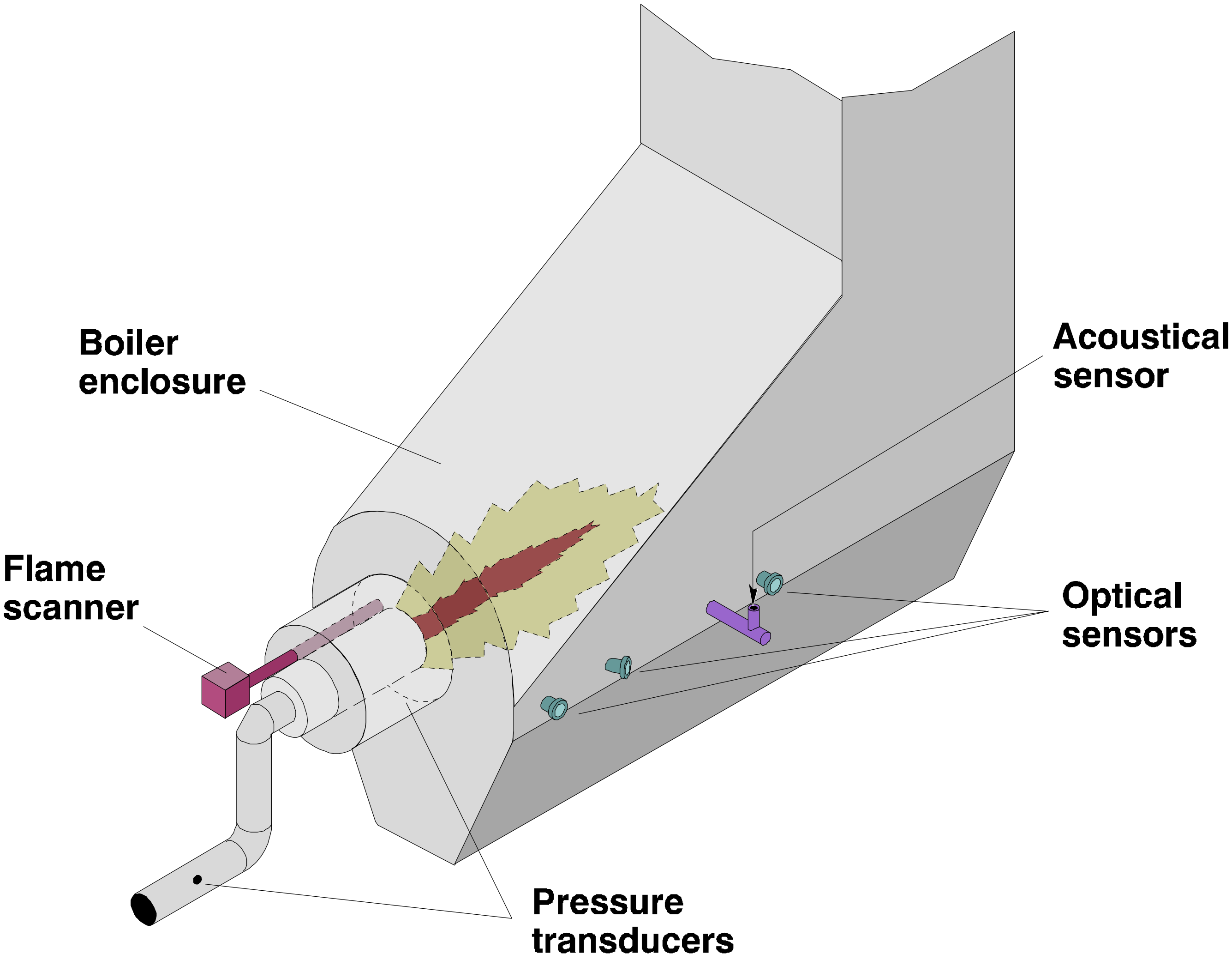
Like the CEDF, lab burner instabilities appear as changes in the optical “spike” patterns



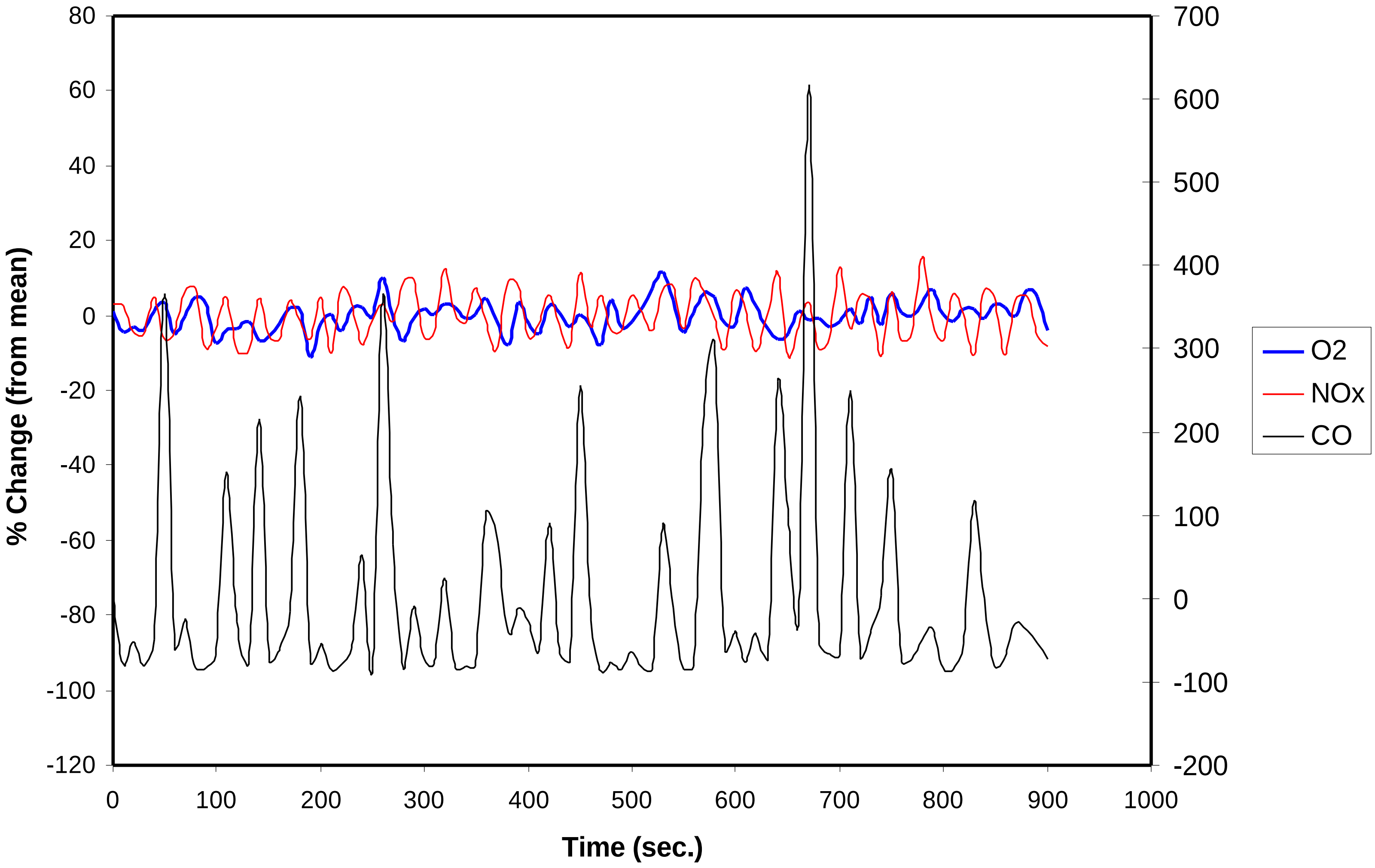
The lab burner’s trend in symbol patterns with liftoff appear similar to those in the CEDF



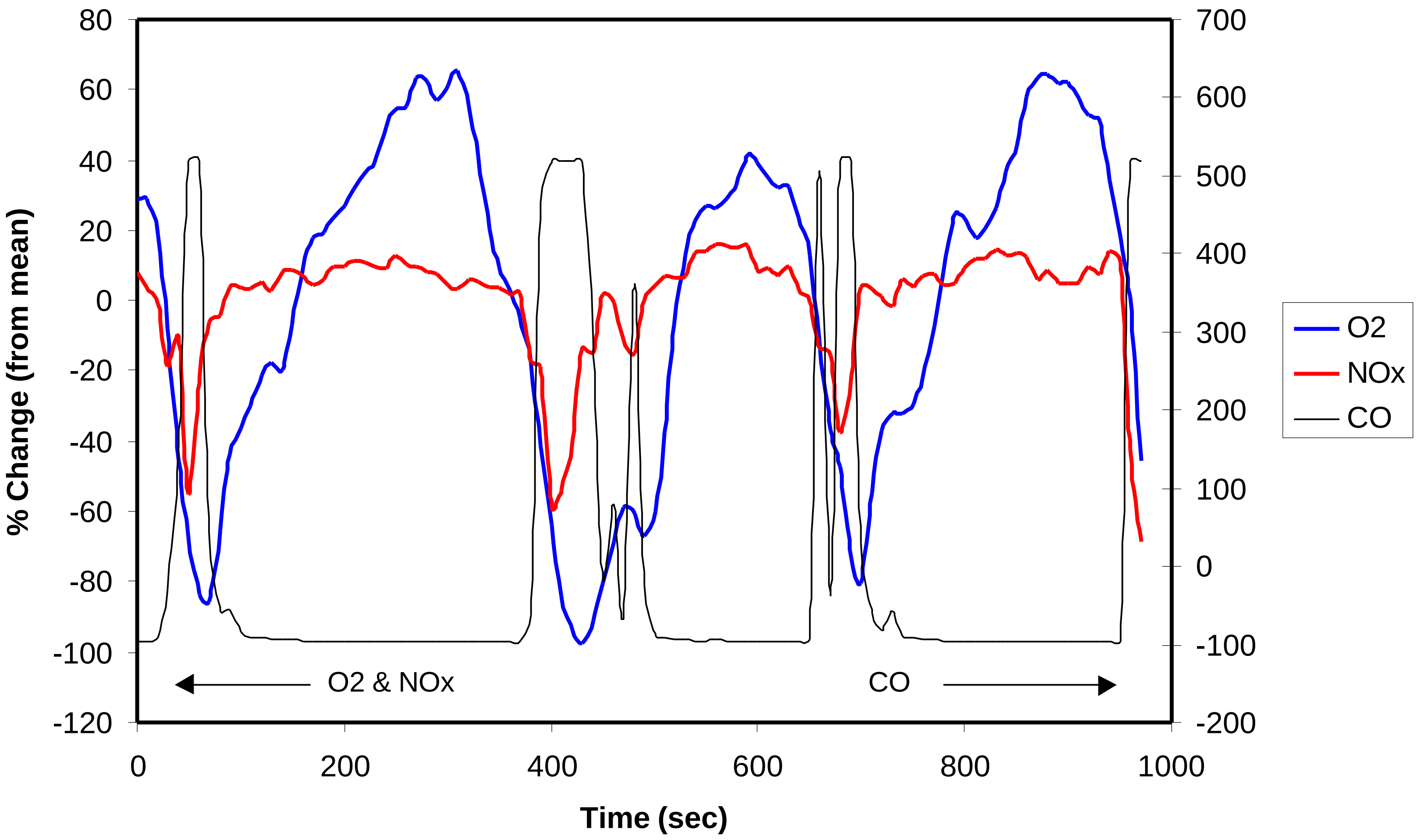
CEDF Instrumentation



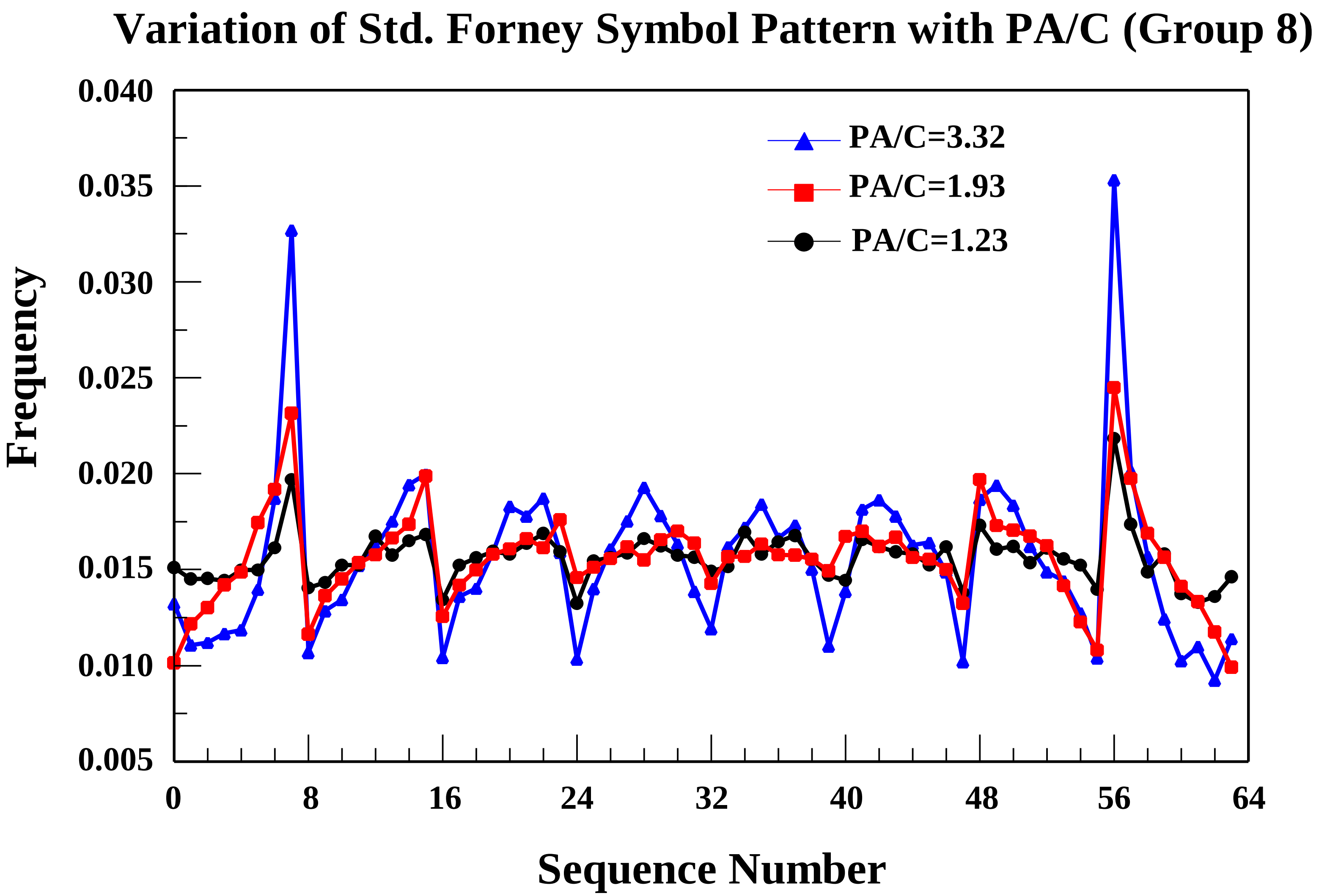
Baseline Performance Data



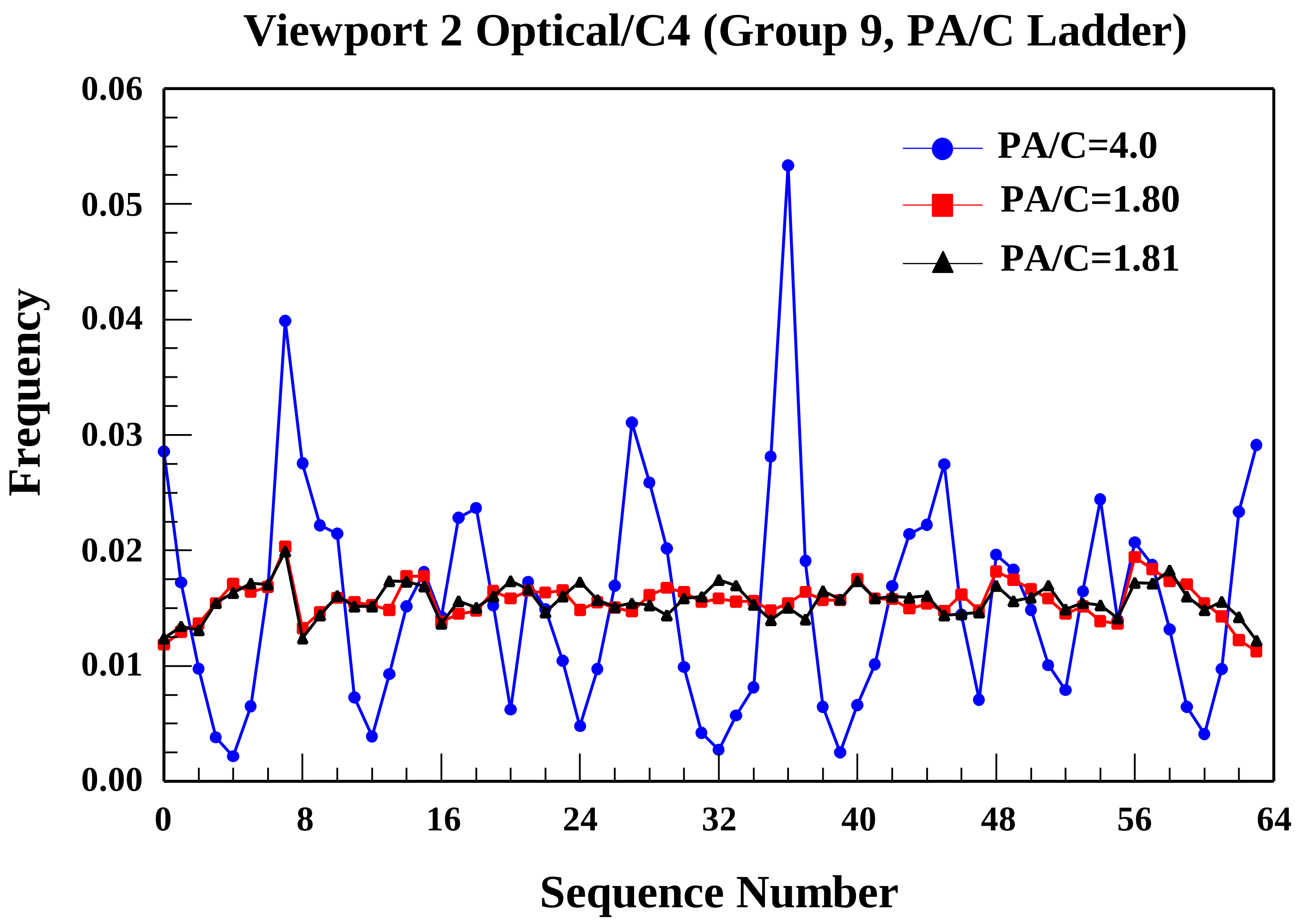
Conveying Limit Performance Data



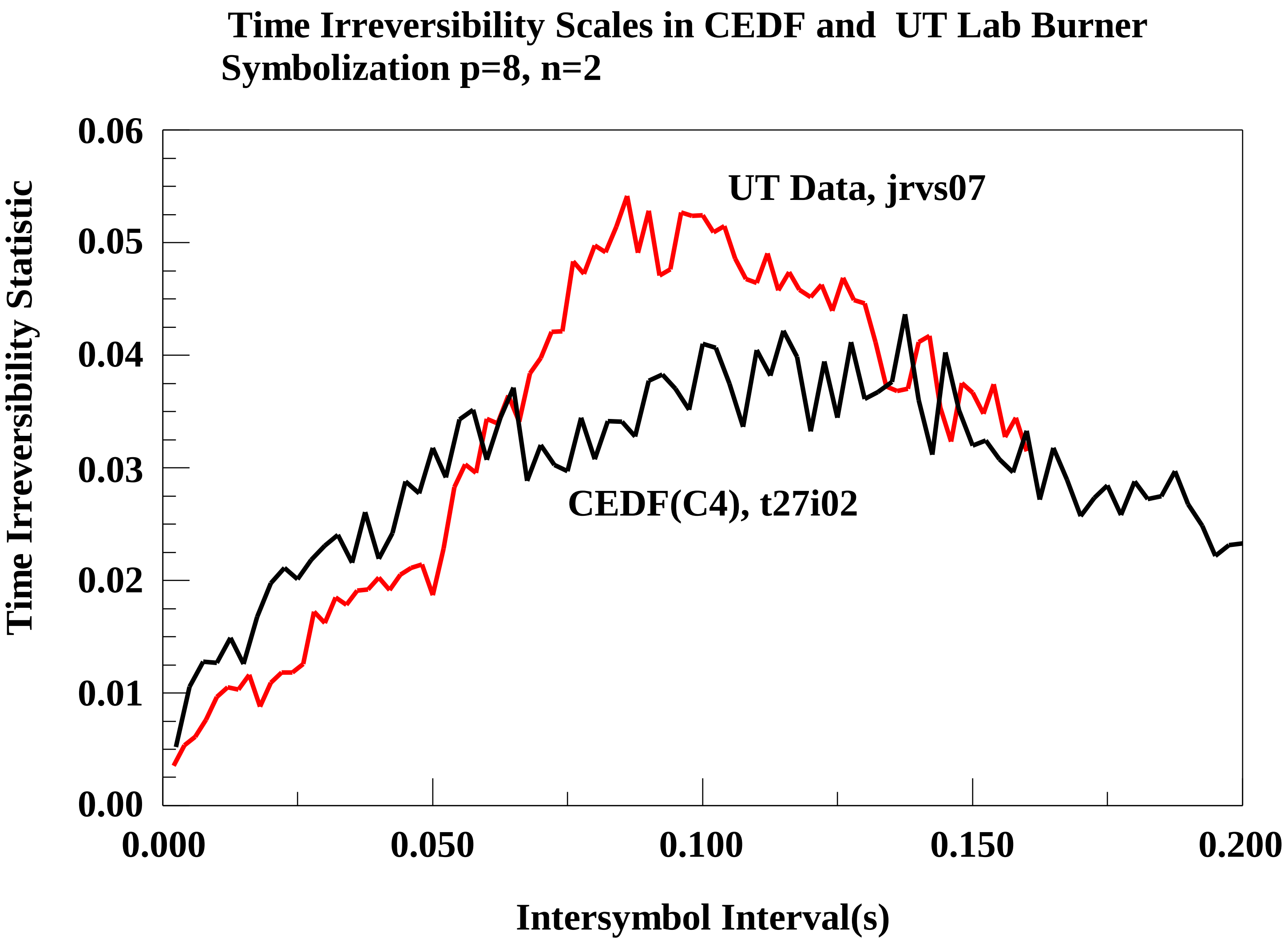
Symbol sequence histograms for the std Forney (C7) clearly reveal transitions in primary air/coal ratio



Symbol sequence patterns are very sensitive to lift-off



The nonlinear time scales in the lab burner and unfiltered CEDF optical measurements appear similar



Key Findings

- Dynamic patterns in standard flame scanner signals can provide important diagnostic information about flame state
- Practical diagnostics for burner management should utilize known operating limits as benchmarks for correlations
- Continuous monitoring is important because “spontaneous” shifts in flame pattern can occur
- Association of low-dimensional dynamics with operating limits may be a generally useful feature of complex systems
- In-depth small-scale burner studies could lead to very general correlations for NOx
- The optimal burner state appears to be high-dimensional and nearly Gaussian
- Symbolization is likely to be useful for diagnosing many other types of complex systems