GW Data Analysis: China School 2019

Syllabus

This syllabus contains a list of major topics to be covered during the school along with a list of reference material. The aim of the school is to provide hands-on training in some of the main methods used in gravitational wave data analysis for ground and spaced-based detectors. A side-effect will be training in good coding and the use of collaborative tools for code development. The course is divided into 6 main topics, starting from an introductory level and ending at an advanced level.

Reading

- *Textbook*: Swarm intelligence methods for statistical regression, Soumya D. Mohanty, CRC press/Chapman & Hall (2018).
    - We will mainly use Appendix A and C, and Chapters 1, 4, and 5
    - If you are new to probability theory, it is highly recommended that you read Appendix A before Topic 3 starts
    - Reading Chapter 1 will help in understanding Topic 4 although not everything is covered in this chapter
    - Chapter 4 and 5 are essential for Topics 5 and 6
- *Supplementary textbook*:
    - Signal Processing for communications, Prandoni and Vetterli, Chapters 1 through 5.
    - It is not essential to have this book but reading the chapters listed above will help understand the material in Topic 1 better.
- Additional material to be provided during the course

Course Plan

Lecture session	Lab session (Tentative; List of exercises likely to be adjusted and tuned during the course)
Introduction (1 lecture) *Overview of Gravitational Wave Astronomy, its current status and future prospects*	

1. The importance of data analysis in GW astronomy
2. Gravitational wave theory for data analysts
3. Types of astrophysical sources of GWs
    a. Binary inspiral
	1. Meet and greet
	2. Logistics
	    a. Matlab
	    b. Textbook
	    c. GitHub
	3. Daily schedule

<table>
<tr><td>b. Burst signals
c. Continuous wave and stochastic signals
4. Gravitational wave detectors
a. Ground-based
b. Space-based
c. Pulsar timing array</td><td></td></tr>
<tr><td colspan="2">Topic 1: Basic signal processing (2 lectures)
Signal processing concepts essential for understanding GW data analysis
Recommended reading: Supplementary textbook, Chapters 1 through 5</td></tr>
<tr><td>1. Signal: Analog and digital
2. Fourier transform
3. Filtering
a. Convolution
b. Windowing
c. Linear time invariant systems
d. Transfer function and impulse response
e. Applications
4. Sampling theorem
a. Nyquist frequency
b. Aliasing
c. Anti-aliasing
5. Discrete Fourier Transform
a. Fast Fourier Transform
6. Digital filtering
a. FIR and IIR filters
b. Filter design
7. Geometrical picture
a. Vector space of signals
b. Basis transformation
c. Wavelet basis: Discrete Wavelet Transform
8. Time-frequency analysis</td><td>1. Generate
I. Sinusoidal signals
II. Sine-Gaussian signals
III. Linear and quadratic chirps
IV. Frequency modulated carriers
V. Amplitude modulated carriers
VI. AM-FM modulation
VII. Synthesize audio signals in Matlab
2. FFT:
I. Effect of window choices (Boxcar vs. Hamming) on FFT
II. Effect of aliasing
3. Basic lowpass, bandpass, and highpass filtering
4. Spectrograms</td></tr>
<tr><td colspan="2">Topic 2: Gravitational Wave Strain Signal (1 lecture)
From gravitational wave to the signal recorded by GW detectors</td></tr>
<tr><td>1. From GW to Strain (long-wavelength approximation)
a. Static detector
b. Antenna pattern functions
c. Network of static interferometric detectors
d. Moving and rigidly rotating detector</td><td>1. Antenna pattern functions in the detector frame for a 90 degree arm static interferometer
2. Strain signal for a circular non-evolving binary in static interferometer
3. LISA orbit (rigid approximation)
4. LISA strain response (Michelson)</td></tr>
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<tr><td>2. From strain to detector response</td><td>5. LISA strain response with Doppler shift</td></tr>
<tr><td colspan="2" align="center">Topic 3: Noise (1 lecture)
Basic concepts in the mathematical theory of noise
Recommended reading: Appendix A of Textbook</td></tr>
<tr><td>1. Random variables
2. Probability theory
    a. Single random variable
    b. Multiple random variables
3. Mathematical description of noise
    a. Wide-sense stationarity
    b. Gaussian noise
    c. Power spectral density
        i. White noise
        ii. Colored noise
4. Wiener-Khinchin theorem
    a. Coloring
    b. Whitening
5. Noise in GW detectors
    a. Sensitivity curves
    b. Technical noise
        i. Line noise
        ii. Glitches
        iii. Non-stationarity</td><td>1. Generate noisy data containing signals from Topic 1 lab
2. Use filtering to generate colored Gaussian noise
3. Output of simple pendulum transfer function to WGN input
4. Generate colored noise with LIGO design sensitivity
5. Whiten noise floor of LIGO data
6. Notch filtering of line noise from whitened LIGO data</td></tr>
<tr><td colspan="2" align="center">Topic 4: Detection and estimation of signals in noise (Chapter 1 of textbook)
(2 lectures)
Fundamental concepts behind the techniques used for extracting GW signals from noisy detector data</td></tr>
<tr><td>1. Estimation
    a. Maximum Likelihood Estimation (MLE)
    b. MLE for Gaussian noise: Least-squares
    c. Cramer-Rao lower bound on estimation error
2. Detection
    a. Binary hypotheses
    b. False alarm and false dismissal
    c. Neyman-Pearson criterion and likelihood ratio test (LRT)
    d. Signal-to-noise ratio (SNR)
    e. Composite hypotheses
    f. Generalized Likelihood Ratio Test (GLRT)</td><td>1. Implement LRT for dc signal in WGN
    a. Obtain distribution of LR under null and alternative hypotheses
2. Implement LRT for sinusoid with known parameters
3. Implement GLRT for sinusoid with unknown frequency, amplitude, and phase
4. Compares LRT and GLRT for same SNR and False alarm probability
5. Quadratic chirp in WGN
    a. Normalize signal amplitude for a specified SNR
    b. Make cross-sectional plots of fitness function</td></tr>
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<td>3. GLRT for Gaussian noise
a. Likelihood ratio test for sinusoid
b. GLRT for sinusoid of unknown amplitude, phase, and time of arrival
c. Matched filtering: GLRT for unknown time of arrival
4. Intrinsic and extrinsic parameters
5. The optimization challenge in GW data analysis
6. Beyond MLE and GLRT
a. Time-frequency analysis
b. Regularization
7. Issues in the analysis of real data</td>
<td>6. Quadratic chirp in simulated LIGO noise
a. Inject with specified SNR in colored noise
b. Implement LRT
7. LRT for LISA White Dwarf Binary in WGN</td>
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<tr>
<td colspan="2">Topic 5: Particle Swarm Optimization (Chapter 4 & 5)
(1 lecture)
A highly effective technique for optimization over intrinsic parameters in GW data analysis problems
Required reading: Chapter 4 and 5 of textbook</td>
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<td>1. Gbest PSO
2. Lbest PSO</td>
<td rowspan="3">1. GLRT using PSO for quadratic chirp in WGN
2. GLRT using PSO for quadratic chirp in simulated LIGO noise
3. GLRT using PSO for white dwarf binary signal in WGN</td>
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<tr>
<td>Topic 6: Advanced topics in applications of PSO to GW data analysis problems
(1 lecture)</td>
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<td>1. Binary inspiral detection and estimation in network data
2. Tuning strategy</td>
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