The Physics of Space-Based Gravitational Wave Interferometers

PREFACE

The first direct observation of a gravitational wave (GW) signal, announced by the **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory (**LIGO**) project on February 11, 2016, represents one of the most important achievements in experimental physics today and a milestone in fundamental physics. This historic moment also parallels the early astronomical observations made by Galileo Galilei in the year 1610 as it marks the beginning of GW Astronomy. Very much like Galileo then, we have just started to explore the observational capabilities of this new field, which promises to unveil secrets of the Universe inaccessible by any other means.

Together with the **L**aser **I**nterferometer **S**pace **A**ntenna (**LISA**), a joint ESA-NASA project for flying a space-based GW interferometer operating in the mHz GW frequency band, additional mission concepts have been proposed in the open literature and some are now undergoing their development cycles. As this new class of interferometers is expected to fly in the 2030 decade, the need exists for educating new generations of GW astronomers and experimental physicists interested to work in this field.

It is within this spirit I have decided to give a series of lectures on space-based GW interferometry as a course in the graduate program of the National Institute for Space Research (INPE) in Sao Jose' dos Campos, Sao Paulo (Brazil). The course is organized in twenty-four 2.0-hours-long lectures, and it is aimed at graduate students in physics, applied physics, and engineering, and also at interested postdoctoral fellows and faculty. It is my hope each lecture will be highly interactive….there are no senseless question as it is only by asking questions that we may better understand a subject!

This course will rely on a set of papers and review articles as guiding elements. Although it **does not require** any homework or final test to be passed by the enrolled students, it **does require** each student to give a seminar on a topic of his/her choice that is directly related to what discussed during the lectures.

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Course Synopsis

This course is a set of lectures on gravitational waves and their detection by space-based interferometry. The main concepts underlining the physics of these instruments will be presented by discussing idealized as well as realistic interferometer configurations. The topics addressed provide the foundations needed for analyzing and investigating current and future space-based interferometer designs.

Content:

- Introduction to the course

- Gravitational Waves (GWs)
    - GWs: Properties and Description
    - GWs: Generation and the Quadrupole formalism
    - GWs: Detection techniques

- Data Analysis Considerations
    - Probability distributions; Gaussian vs non-Gaussian noise
        - Spectral densities, correlation functions, Wiener-Khintchine theorem
        - Linear signal processing
        - Wiener filter for optimal signal processing
        - Illustrations via the noise spectra of existing LIGO-VIRGO data.
    - Signal processing
        - Hypothesis testing
        - Noise performance validation techniques
        - Signal-to-noise Ratio
        - Sensitivity of a GW detector

- One-arm Detectors: Interplanetary spacecraft Doppler tracking and pulsar timing
    - Derivation of the "one-way" Doppler response to a GW signal
    - Noise sources
    - Fundamental noise limitation to the sensitivity of one-arm detectors

- What is an interferometer?
    - Examples of ground-based interferometers (LIGO, VIRGO, KAGRA);
    - What is the response of an equal-arm interferometer to a GW signal?
    - A one-arm interferometer (i.e. a "one-arm bandit"): can it detect GWs?

- Space-based Interferometers – Idealized Configuration
    - Statement of the problem
    - Static configuration: Derivation of the first-generation Time-Delay Interferometric (TDI) combinations
    - The space of all the TDI measurements generated by a three-arm constellation
    - GW signal transfer functions into the TDI combinations
    - Noise transfer functions into the TDI combinations
    - Clock synchronization, timing, arm-lengths, sampling interpolation,…...: accuracy requirements

- Space-based Interferometers – Realistic Configuration
    - Arm lengths and inter-spacecraft velocities change in time!
    - 2nd generation TDI
    - Onboard Clocks vs. Optical Frequency Combs architectures
    - Data processing requirements on the heterodyne measurements

- Gravitational Reference Sensors
    - What is a drag-free satellite?
    - Acceleration noise sources on a spacecraft @ 1AU
    - Existing drag-free designs
    - The LISA Pathfinder experiment.