Two-photon interferometry simulations

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Abstract

Two-photon interferometry is an innovative quantum astrometry technique based on quantum mechanics that gives more precise measurements compared with classical one-photon interferometry. Two photons from independent light sources are interfered using a beam splitter and thus become quantum entangled. In theory, measurements in the number of photons in different channels of the telescopes give information about the relative separation between the two light sources. The two-photon interferometry has many potential applications such as direct imaging of black hole accretion discs, mapping microlensing events, directly resolving the star-planet binary systems, etc. My project involves studying the response of the photon coincidence rate due to Earth's rotation for arbitrary telescope placements and source positions in the sky by developing a simulator. I worked with the bright star catalog to select out target pairs of stars based on their properties such as position and brightness. The selected star pairs then become the input data for the simulator to analyze. Lastly, the simulator is used to generate simulated data which can be used for estimating the precision between the theoretical results and the real data in the future.

Introduction

Classical interferometry has been very successful at taking measurements of astronomical objects, but the cost of building optical path to correlate signals between telescopes is significant. Due to the rise of quantum mechanics, astronomers are seeking methods of producing more precise measurements of the sky with less cost by using quantum mechanics. Two-photon interferometry is one of the ideas that use the idea of quantum entanglement between two light sources to do precise dynamic astrometry without constructing an optical path for interferometers.

$$\langle N(xy)\rangle = \frac{k(S_1+S_2)^2}{8}\left[1 \pm V_{2PS}\cos\left(\frac{2\pi}{\lambda}\vec{B}\cdot(\hat{s_1}-\hat{s_2}) + \frac{2\pi\Delta L}{\lambda}\right)\right]$$

Equation [1]: It describes the expected coincidence count for different channel combinations: + for {xy} = channel *cg* and *dh*, - for {xy} = channel *ch* and *dg,* where k is a constant term determined by the properties of the telescope, *S1* and *S2* are the flux density of the two sources, V_{2PS} is the two-point visibility which depends on source flux density, ΔL is the instrumental path length difference, B is the baseline vector of the two telescopes, *s_1* and *s_2* are the source unit vector pointing to the telescope, and λ is the observation wavelength.

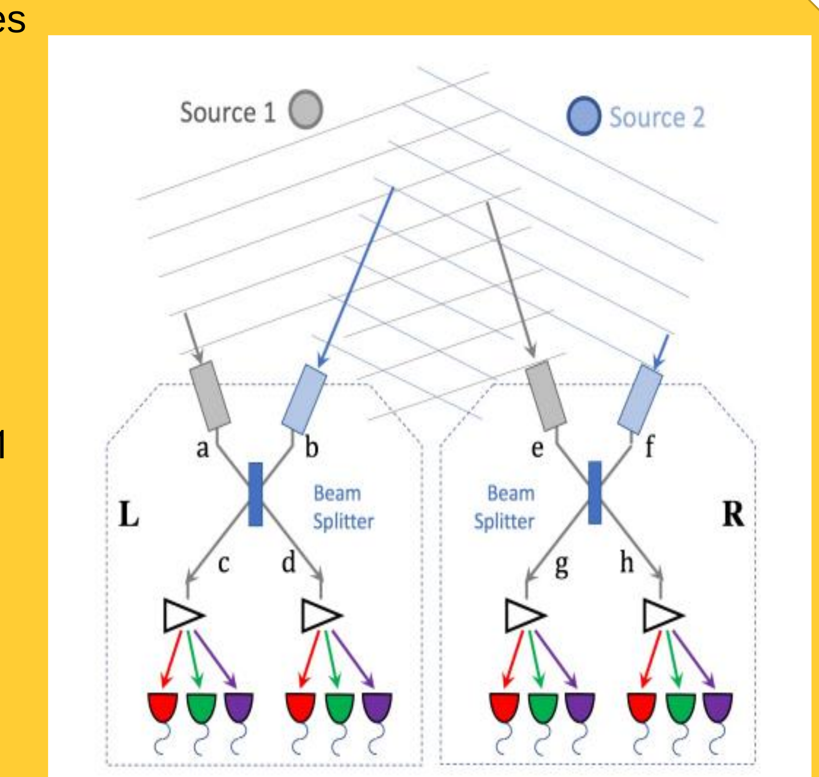

Figure [1]: This figure shows the general setup for the two telescopes and two sources in the sky. Since photons appear to travel in plane waves if the sources are far away, the arrival time for photons from a source is different for telescope L and R due to the path difference. Therefore, the path difference of photons traveling to the two telescope leads to phase shift of δ1 for source 1 and δ2 for source 2. The probability of observing the photon at different channels is related to the difference of the phase shift, or δ1−δ2, which depends on the relative position of two sources in the sky.

Results/Discussions:

- The telescopes are placed in the east-west direction, so that they are parallel to the plane
- of Equator. There are 18 star pairs if ignore the 4th condition.
- We understand how oscillation frequency of Equation [1] varies with time, which has a sinusoidal shape as it reaches maximum oscillation frequency and zero-frequency as Earth rotates.
- Also understand the relationship of maximum oscillation frequency vs. angular separation of the two sources in right ascension and declination.

Scatter plot showing the maximum oscillation frequency of 18 pairs of stars vs. separation in right ascension and declination:

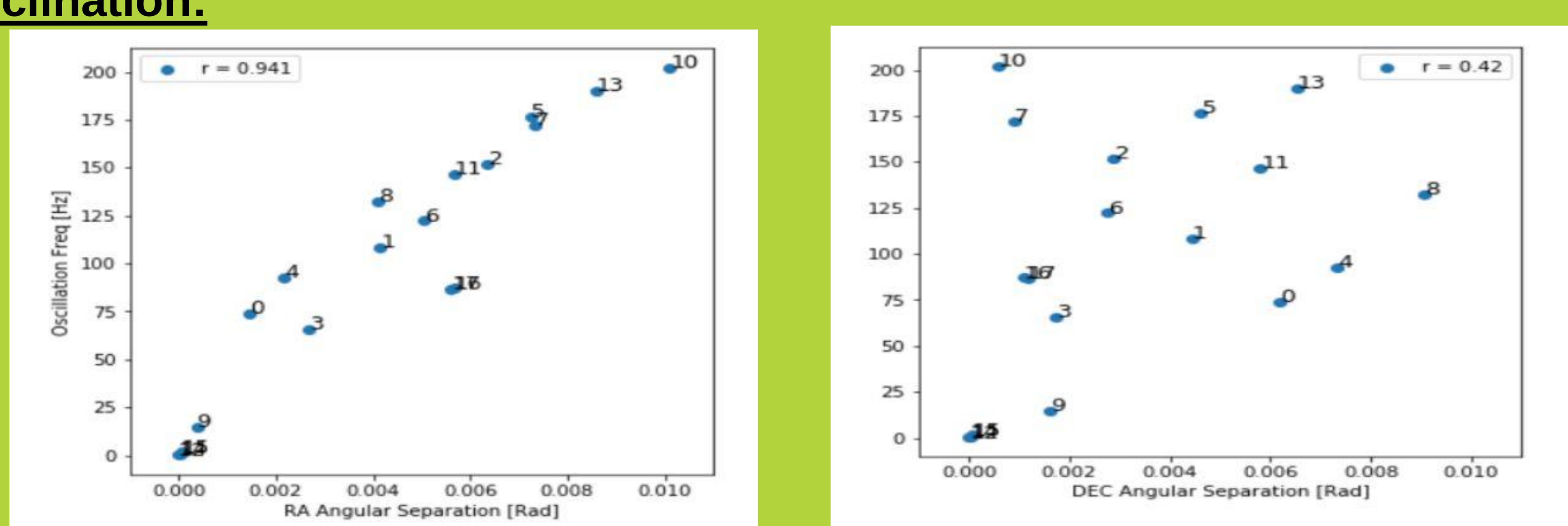

Figure [2]: **Left**: the maximum oscillation frequency of the coincidence rate vs. the angular separation in right ascension with Pearson's R coefficient of 0.941. **Right**: the maximum oscillation frequency of the coincidence rate vs. the angular separation in declination with Pearson's R coefficient of 0.42. The number next to the dot represents the pair #. The strong correlation between the angular separation in right ascension and the small effect with separation in declination with telescope separated in the east-west are predicted by theory, and the simulator did reflect that. Although I expected a much more linear relationship between oscillation frequency and separation in right ascension, which can be looked at in the future

Simulated data vs. Theoretical result.

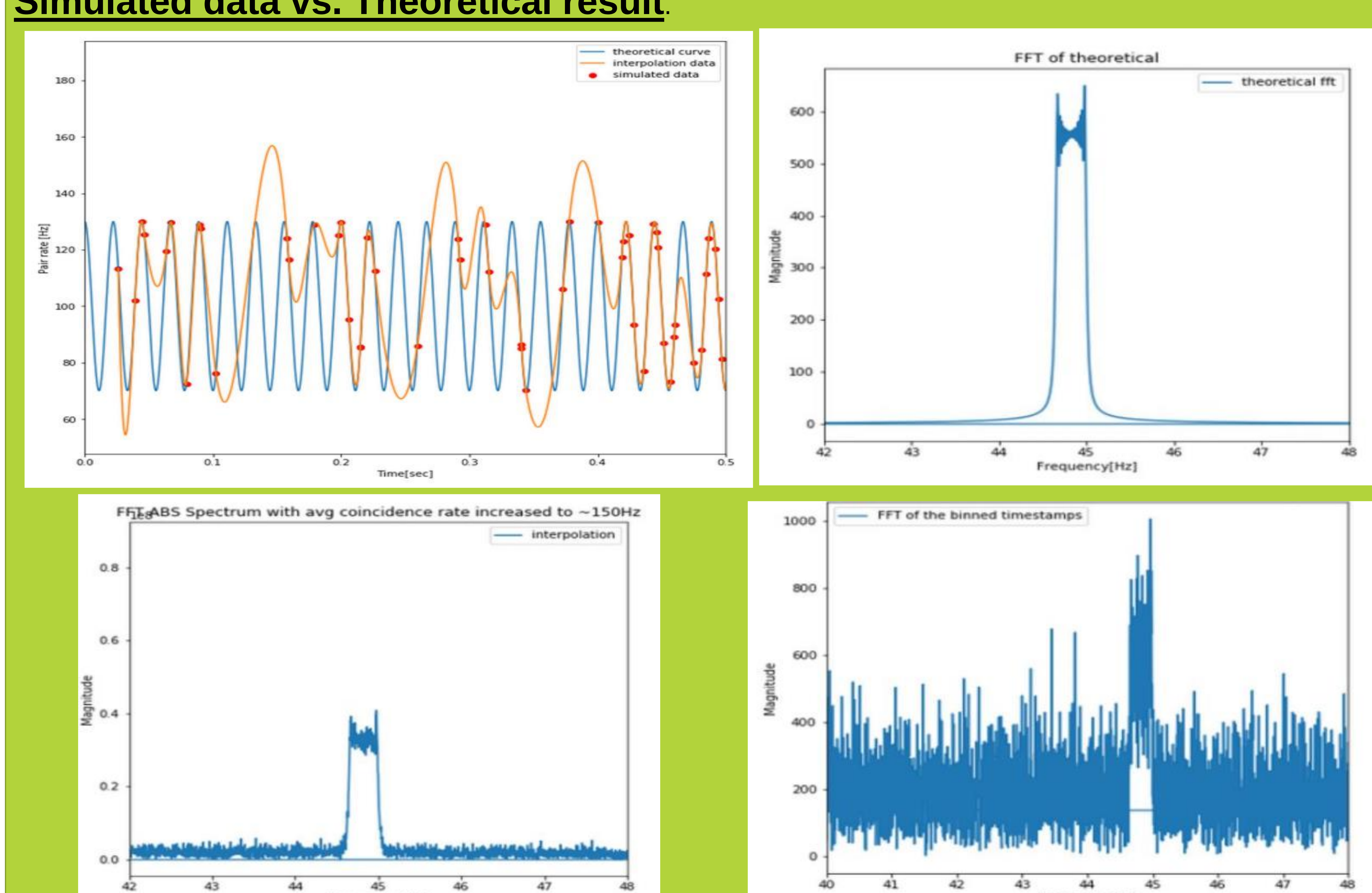

Figure [3]: **Top left**: It displays the coincidence pair rate as a function of time for three types of data. The blue curve shows the theoretical coincidence pair rate for a specific pair of stars observed by two telescopes separated in the East-west sense on Earth. The red dots represent the simulated data points generated using statistics, while the orange curve connecting the red dots are the interpolated data points using cubic interpolation. **Top right**: It shows the theoretical Fourier power spectrum of the blue curve, since it spans over a range of frequencies, we know the oscillation frequency of the blue curve changes over time. **Bottom left**: It shows the FFT of the interpolated data, we observe the same peak, but a lot less precise and noisy background. **Bottom right**: It shows the FFT of just the red data points, we see that even though we can still recover the same FFT, but it is a lot less precise compared with interpolated data.

Future Work: Next step is to construct a maximum likelihood estimation on the simulated data to deduce parameters like oscillation frequency and visibility and compare them with the theoretical data to estimate the precision.

Methods

Simulator:

The main functionality of this simulator is to produce Equation [1] by generating an appropriate environment (Figure [1]) and supplying it with positions of the two telescopes on Earth and stars position in right ascension and declination.

Bright Star Catalogue Processor (Input data for simulator):

- The bright star catalogue, or BSC, is a star catalogue that lists around 9000 stars of stellar magnitude 6.5 or brighter.
- This catalogue must be processed by applying several constraints so that it will eventually return pairs of stars along with their information of declination, right ascension and flux density.
- Constraints include:
  1. Stars whose relative declination between the telescope declination needs to be within30 Degrees.
  2. The spectral flux density of stars should have at least 50 [Jy].
  3. The angular separation distance between the two stars in a pair must be less than 0.01 rad.
  4. Stars should be 180 Degrees (12 Hours) to 225 Degrees (15 Hours) behind the sun so that they can be seen in the night sky.

Simulated Data:

- Goal is to create simulated data that would represent the distribution of number of coincidence in the real observation.
- Poisson process is used to simulate the number of coincidence counts for each oscillation cycle,
- Inverse the cumulative probability function, or CDF, (Equation [4]) to determine the corresponding phase and timestamp of that coincidence count

Equation [4]: $CDF(\phi) = \frac{\phi \pm V\sin(\phi) + \pi}{2\pi} \qquad \phi \in [-\pi, \pi]$

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