Quantum Annealing for Gamma-Ray Source Detection and Localization with AGILE Data

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ABSTRACT

Maximum Likelihood Estimation (MLE) is the standard method to detect and localize gamma-ray sources, estimating their flux, position and significance together with the background from photon count maps. Since this estimation is an optimization over the emission model parameters, it is a natural candidate for quantum annealing, which encodes an optimization task in the ground state of an Ising Hamiltonian. We reformulate the standard likelihood analysis of AGILE-GRID data as a Quadratic Unconstrained Binary Optimization (QUBO) problem, approximating the Poisson likelihood with a least-squares cost and expanding all parameters in binary form, including the source position, which is chosen among a grid of candidate nodes. We solve this task with Simulated Quantum Annealing (SQA) and benchmark it on 200 simulated observations at high Galactic latitude against AGILEpy, the official AGILE analysis library. Both approaches recover the source flux with comparable systematic errors (9.8% classical, 8.0% QUBO), with mean isotropic-background residuals of −0.13 and +0.02, respectively. The QUBO selects the correct position among 81 candidate nodes on a 0.5° grid in 92% of the maps. These results show that quantum annealing reaches an accuracy close to that of the classical pipeline.

1. Introduction

The standard approach to detecting and localizing sources in gamma-ray count maps relies on maximizing the Poisson likelihood of the observed photons [1]. We analyze the observations from the AGILE satellite, a mission of the Italian Space Agency [2]. Extracting sources from these data via maximum-likelihood is a complex multi-parameter optimization task, fitting several source and background parameters, making it a natural candidate for quantum computing [3], using the quantum annealing paradigm [4]. These techniques are increasingly being explored for data-analysis problems in astrophysics and cosmology [5]. We reformulated the classical maximum-likelihood analysis as a Quadratic Unconstrained Binary Optimization (QUBO) problem. This is a methodological proof of concept, our goal is to show that a widely used classical astrophysical algorithm can be translated into a quantum framework without loss of scientific accuracy.

2. Optimization Model

We validate the method on 200 AGILE-GRID observations simulated with the AGILE Science Tools and AGILEpy, at high Galactic latitude. A quantum annealer minimizes a quadratic form in binary variables, so we must change our function to a least-squares cost:

$$\chi^2 = \|Rx - d\|^2 = x^T W x - 2V^T x + d \cdot d,$$

where d is the flattened observed count map, x represents the model parameters, and the columns of R are the templates of the emission components, from which follow $W = R^T R$ and $V = R^T d$.

Each parameter is written as a fixed-point binary expansion, using 8 qubits for the background and 10 qubits for the source flux.

To perform localization, the continuous coordinates are replaced by a regular grid of M candidate positions.

The predicted counts in pixel *(i,j)* are modelled as:

$$\theta_{ij} = g_b B_{ij} + \sum_{m=1}^{M} z_m \, c_a^{(m)} S_{ij}^{(m)},$$

where B_{ij} is the template of the isotropic background with its parameter g_b and each candidate position m carries a unit-flux template $S_{ij}^{(m)}$, its flux amplitude $c_a^{(m)}$, and a binary indicator z_m.

The QUBO is solved with the SQA sampler of OpenJij, a classical path-integral Monte Carlo emulation of quantum annealing. The classical benchmark is the official AGILEpy pipeline.

3. Results and Future Work

Both pipelines recover the source flux across the full range, with a mean bias of +9.8% for AGILEpy and +8.0% for the QUBO. The isotropic normalization is recovered without significant bias, with mean raw residuals of -0.13 (classical) and +0.02 (QUBO), as shown in Figure 1.

The overestimate of the flux is larger for faint sources, however the estimates between the two approaches are in good agreement (Figure 2). For localization, AGILEpy recovers the source position within one pixel (0.5°) in 98% of the maps, while the QUBO finds it in 92% of the cases.

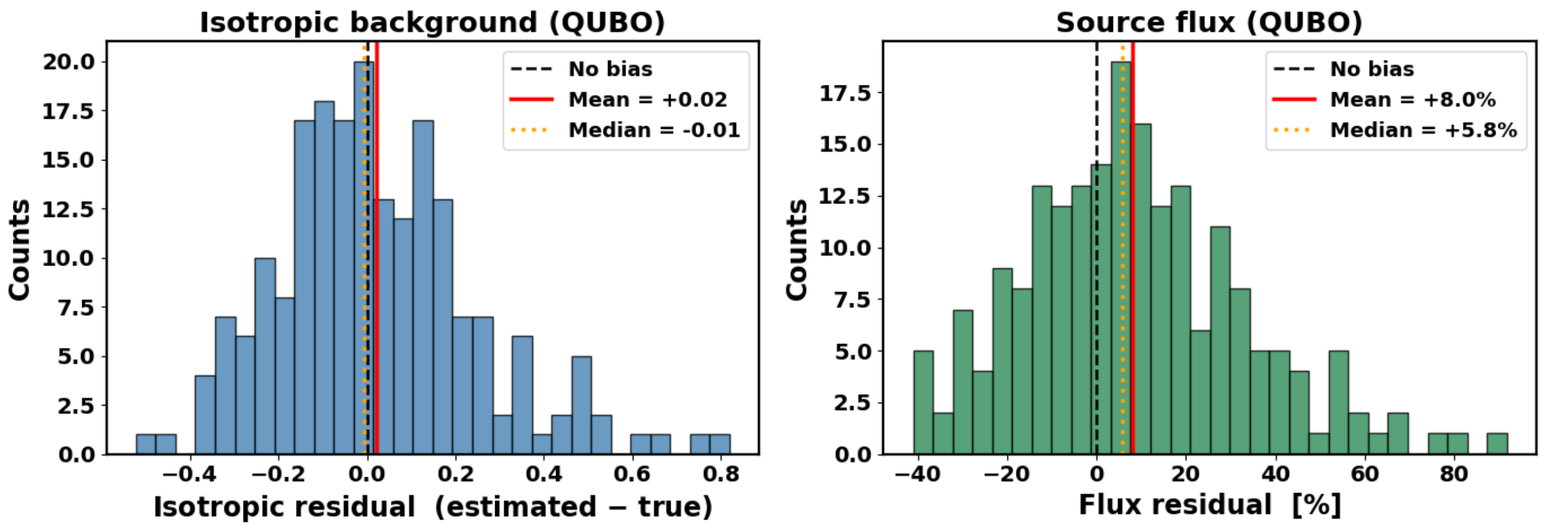


Figure 1: Distribution of the QUBO residuals for the isotropic background (left) and the source flux (right), with mean and median.

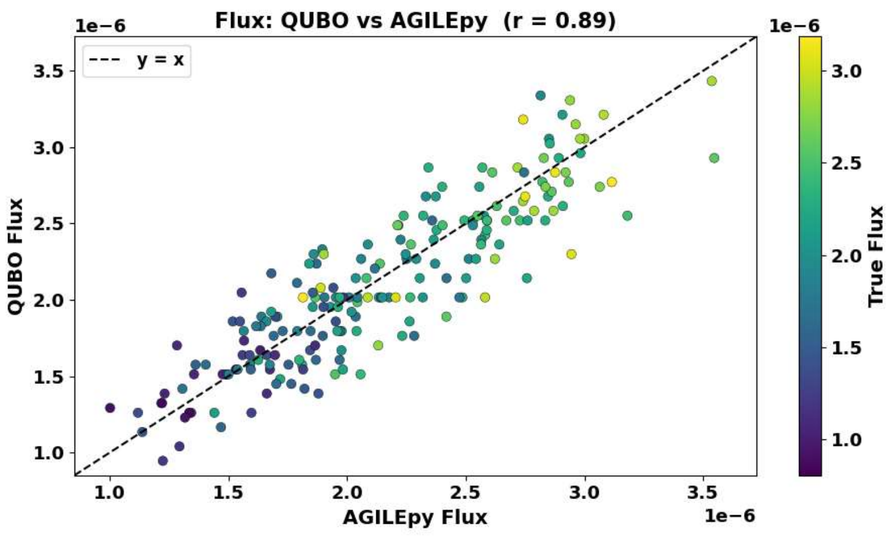


Figure 2: QUBO vs. AGILEpy source flux, colour-coded by the true flux. The estimates of the two pipelines show a high correlation.

A natural next step is to run this problem on real D-Wave hardware and study how noise affects the optimization process. This work can also be extended to handle multiple close sources and to reach lower Galactic latitudes, by introducing an additional template and parameter.

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