Real-Time Health Analytics for TURBO Telescope's Image Processing Pipeline

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The Total-Coverage Ultra-Fast Response to Binary-Mergers Observatory (TURBO) is a collaborative astrophysics initiative led by the University of Minnesota, in partnership with the University of New Mexico and the University of Crete. TURBO is designed to capture the earliest light from cataclysmic events within approximately two seconds of receiving alerts from gravitational wave detectors. This rapid response capability enables the study of phenomena critical to understanding the synthesis of heavy elements and the expansion rate of the universe. For other phenomena such as supernovae, early emission is often delayed relative to the explosion, and TURBO's high-cadence imaging is well suited to capturing this early light. A key component of TURBO's real-time capabilities is its automated image processing pipeline, which performs raw image calibration, astrometric alignment, image differencing, candidate source identification, and machine learning-based classification. This system enables fast and robust identification of transient sources, streamlining data flow from telescope to classification in under a minute. I built a web tool called the Image Health Website (IHW) to better analyze errors in this pipeline.

I. INTRODUCTION

Binary neutron star (BNS) mergers represent one of the most energetic and complex phenomena in modern astrophysics. These events are characterized by the coalescence of two neutron stars, compact remnants of massive stellar evolution, producing gravitational waves, electromagnetic radiation across the spectrum, and ejecting neutron-rich matter that powers rapid neutron-capture (r-process) nucleosynthesis [10]. The landmark detection of GW170817 and its electromagnetic counterparts ushered in the era of multi-messenger astronomy [6], providing unprecedented insights into the properties of dense nuclear matter, the equation of state (EOS) at supra-nuclear densities, and the astrophysical sites of heavy element formation [3, 9]. This paper provides scientific background on: BNS inspiral, merger dynamics, post-merger evolution, observational signatures and reviews the creation and maintenance of the Image Health Website (IHW), a real-time analysis tool for the image processing pipeline.

Astrophysical transients (brief, energetic events such as supernovae and compact object mergers) offer invaluable insights into the fundamental processes shaping our universe. Observing these phenomena in real time is crucial for understanding the mechanisms of element formation, the behavior of extreme matter, and the dynamics of cosmic expansion [1]. Traditional telescopic systems, however, often lack the speed and flexibility required to capture the initial moments of these fleeting events.

TURBO addresses this limitation with a distributed, high-cadence observational system designed for latency well under one minute. TURBO's two principal science goals are: (1) to respond to gravitational wave triggers within ~ 2 seconds, early enough to observe optical counterparts brighten during inspiral, and (2) to perform continuous, high-cadence (< 2 min) monitoring of nearby galaxies (< 72 Mpc) to detect shock breakout from core-collapse and thermonuclear supernovae. The observatory will also respond to neutrino and gamma-ray burst (GRB) triggers [8].

To achieve this, TURBO deploys 12 Celestron RASA 0.28 m optical tube assemblies at each of two sites: Magdalena Ridge Observatory (New Mexico) and Skinakas Observatory (Crete). Each telescope is paired with a ZWO ASI 6200MM camera housing the back-illuminated Sony IMX455 sensor. The array of 12 telescopes per site achieves an instantaneous field of view of 88.8 square degrees, allowing TURBO to rapidly tile and survey large localization regions, critical for LIGO-Virgo-KAGRA detection follow-up in Observing Run 5 and beyond [12].

TURBO's mechanical infrastructure includes six Planewave L-350 direct-drive mounts at each site to provide sub-2-second slew times. Custom steel-frame clamshell enclosures ensure structural resilience against high winds, wide sky access ($> 75\%$), and electromagnetic shielding.

The image processing pipeline developed by the TURBO team enables end-to-end data processing in under one minute. Using a combination of Python-based modules, the Saccadic Fast Fourier Transform (SFFT) subtraction algorithm [2], and GPU acceleration on RTX 4090 hardware, the system performs real-time image calibration, subtraction, transient candidate extraction, and photometric calibration.

These technological and logistical innovations collectively position TURBO as a pioneering facility in rapid-response astronomy, uniquely suited to the demands of future multi-messenger astrophysics.

II. SCIENTIFIC BACKGROUND

A. Neutron Star Structure and Equation of State

Neutron stars possess densities exceeding nuclear saturation ($\approx 2.8 \times 10^{14}\,\mathrm{g\,cm^{-3}}$) and exhibit strong gravitational and magnetic fields. Their internal composition, ranging from a crust of nuclei and free neutrons to a core potentially containing hyperons, deconfined quarks, or exotic condensates, is governed by the poorly constrained equation of state (EOS) of dense matter. Observations of neutron stars with masses up to $\approx 2\,M_\odot$ and radii between 11–14 km provide macroscopic constraints [1]. Tidal deformability measurements from GW170817 further narrow viable EOS models [3]. As gravitational wave observatories enhance sensitivity, high-cadence electromagnetic facilities such as TURBO offer complementary constraints by capturing transient light curves associated with merger aftermaths, which are sensitive to remnant structure and composition.

B. Inspiral Dynamics and Tidal Effects

During the late inspiral phase, tidal interactions between neutron stars induce deformations that enhance gravitational wave emission and accelerate orbital decay. The dimensionless tidal deformability parameter, Λ, encapsulates the EOS-dependent tidal response and is imprinted on the phase evolution of the GW signal. For a $1.4\,M_\odot$ neutron star, multi-messenger constraints from GW170817 suggest $\Lambda \sim 300$–800 [4]. Numerical relativity simulations indicate that stiffer EOSs prolong the inspiral and shift post-merger oscillation frequencies [5]. These details, embedded in the high-frequency GW signal, also influence ejecta mass and velocity—parameters directly observable via optical counterparts. TURBO's rapid response and deep imaging will enable early characterization of such signatures, linking EM light curves to underlying tidal physics.

C. Gravitational Wave Emission

The GW signature of a BNS merger features a "chirp", an increasing frequency and amplitude culminating in merger. Ground-based detectors such as LIGO, Virgo, and KAGRA are sensitive to inspiral signals up to a few kHz, but the post-merger remnant emits higher-frequency signals ($\gtrsim 2\,\mathrm{kHz}$), which are challenging to detect with current sensitivity [6]. The nature of this remnant—whether a prompt collapse or a hypermassive neutron star—significantly affects both the GW signal and the associated electromagnetic emission. TURBO is designed to capture this emission within seconds, bridging the gap between GW detection and optical follow-up, especially in cases where post-merger GWs are sub-threshold.

D. Merger and Post-Merger Hydrodynamics

Merger hydrodynamics produce extreme conditions, with temperatures exceeding $10^{11}\,\mathrm{K}$ and strong shocks, that influence ejecta composition and geometry. The formation of a hypermassive neutron star can delay collapse, drive neutrino winds, and amplify magnetic fields ($\sim 10^{15}\,\mathrm{G}$), all contributing to the observed kilonova light curve [7]. Simulations reveal that these features correlate with viewing angle and merger asymmetry. The high cadence and wide field of view of TURBO will enable time-resolved observations of these rapidly evolving transients, supporting detailed modeling of post-merger energy release mechanisms.

E. Electromagnetic Counterparts

The electromagnetic signature of BNS mergers spans from gamma-rays to radio. The short gamma-ray burst GRB 170817A, detected 1.7 s after GW170817, linked BNS mergers to GRBs [8]. Its subsequent kilonova (AT 2017gfo) evolved from blue to red in days, shaped by the radioactive decay of freshly synthesized r-process elements [9]. Early blue emission arises from lanthanide-poor ejecta, while later red emission traces lanthanide-rich material. These phases depend on ejecta velocity, mass, and composition—all observable in optical bands. With its ability to observe transients within seconds of GW triggers, TURBO is uniquely positioned to resolve these early color transitions and probe the angular structure of merger outflows.

F. R-Process Nucleosynthesis and Chemical Evolution

Binary neutron star mergers are a leading site for the r-process, responsible for synthesizing elements beyond iron via rapid neutron capture. Ejecta masses from simulations range from 10^{-3} to $10^{-2}\,M_{\odot}$, with low electron fractions ($Y_e \lesssim 0.2$) favoring production of heavy elements like gold and platinum [10]. The radioactive decay of these elements powers kilonova emission. By capturing light curves from the earliest post-merger moments, TURBO can help determine the mass, velocity, and composition of the ejecta, anchoring nucleosynthetic yield models and contributing to galactic chemical evolution studies.

G. Numerical Relativity and Analytical Models

Theoretical modeling of BNS mergers employs general relativistic magnetohydrodynamic (GRMHD) simulations, integrating microphysical EOSs, neutrino transport, and magnetic field amplification. Simulations performed with codes such as SpEC and Whisky have revealed relationships between merger parameters and observable signatures in both GW and EM channels [11]. Analytical frameworks, like effective one body (EOB) models with tidal corrections, are vital for GW parameter estimation. Complementary electromagnetic models are essential for interpreting observed light curves, and TURBO's data will provide a key testing ground for such models in upcoming observing runs.

H. Multi-Messenger Parameter Inference

While the promise of multi-messenger astrophysics is profound, it is worth noting that to date, only one event—GW170817—has been definitively observed with both gravitational wave and electromagnetic counterparts. Bayesian inference frameworks that combine

GW data with EM light curves can constrain mass ratio, tidal deformability, viewing angle, and neutron star radius. For GW170817, these combined analyses limited the radius of a 1.4 $M_\odot$ neutron star to 11.3–13.5 km (90% credible) [12]. As next-generation observatories reduce GW localization uncertainty, rapid-response systems such as TURBO will play an increasingly central role in localizing events and extracting physical parameters through photometric evolution.

III. IMAGE HEALTH WEBSITE (IHW)

To support real-time monitoring and diagnostics of the TURBO pipeline, I developed a custom analytics dashboard, the Image Health Website (IHW). This web-based interface enables users to query, visualize, and interact with metadata from pipeline runs in near real time. It is designed to streamline troubleshooting, performance analysis, and failure diagnostics for thousands of processed astronomical images per day.

The IHW is built using the Next.js framework with TypeScript, selected for its tight integration of frontend and backend logic, high performance, and support for modern web development features critical to an interactive analytics interface. Several core features of Next.js were leveraged in the development of IHW.

Server-side rendering (SSR) is utilized to ensure fast load times and high perceived responsiveness. Unlike client-side rendering (CSR), which delays content until JavaScript is fully executed in the browser, SSR allows the server to pre-render each page with populated data. Because the PostgreSQL database is hosted on the same physical machine as the application server, SSR ensures that both network latency and time-to-first-byte (TTFB) are minimized, improving the first contentful paint (FCP) and overall user experience.

Automatic code splitting ensures that only the JavaScript relevant to the current route is downloaded, significantly reducing the initial bundle size. Given the complexity of the IHW, which includes histograms, data tables, and dynamic controls, this optimization is essential to maintain fluid performance and avoid bottlenecks due to unused code paths being loaded.

API routes within the Next.js project are used to define custom backend endpoints for database access. This architecture simplifies both development and deployment, as it avoids the need to maintain a separate backend framework or server. Each API route handles direct interaction with the PostgreSQL database, returning JSON responses to frontend components via fetch calls.

For all database interactions, I deliberately avoided using Object-Relational Mappers (ORMs), opting instead for hand-crafted raw SQL queries. This decision was driven by several considerations.

First, raw SQL provides low-level access to query structure, allowing for precise optimization in a performance-critical context. Complex operations such as joins across dynamically generated schemas, aggregate statistics, and time window filtering are implemented more efficiently and transparently with direct SQL. ORMs often introduce overhead due to abstraction layers and cannot express certain advanced operations, such as cross-schema joins or query-time schema introspection, required by our legacy pipeline database structure.

Second, the transparency of raw SQL simplifies debugging and optimization. During development, a pipeline bug caused previous runs to be silently deleted. Because the SQL in IHW was not abstracted, it was immediately possible to verify that the application was not issuing any delete statements. This allowed me to rule out IHW as the source of the error and refocus attention on changes that had been made to the pipeline itself, even though those changes had not yet been committed to version control.

Third, the structure of the TURBO pipeline database necessitates a flexible and dynamic approach to querying. Each new pipeline run creates a unique PostgreSQL schema with timestamped image records. Queries must enumerate and join across these schemas while performing aggregations and filtering over specified time intervals. These operations are often difficult or impossible to express using standard ORM methods.

The IHW user interface includes three principal components. A date picker allows the user to select a time range of interest, over which all subsequent statistics and visualizations are computed. The first histogram displays the number of images processed during the selected interval, binned by user-selected time units (seconds, minutes, hours, days, months, or years). Each bin is divided into successful and failed processing outcomes, and the interface displays both the total count and the overall success percentage. Users can toggle between viewing all results, only successful runs, or only failures.

The second histogram displays the number of processing failures as a function of pipeline step. The horizontal axis corresponds to specific steps in the image processing pipeline, such as calibration, registration, subtraction, and candidate extraction, while the vertical axis shows the number of runs that failed at each stage. This view is particularly useful for identifying systematic points of failure.

Clicking on a column in the first histogram loads a detailed table corresponding to a specific pipeline run. This table shows metadata for each processed image, including the path to the raw image data, total run time, and verbose logs produced by the pipeline. For each image, the table also links to three image files: the raw image, the reference image used in subtraction, and the difference image. These assets are hosted on an internal Apache server and are served over the local network to enable fast retrieval during diagnostic workflows.

To ensure the long-term reliability and adaptability of the Image Health Website, particular attention was given to minimizing assumptions about the structure of upstream data sources. For example, rather than hard-coding pipeline step names into the frontend, IHW dynamically queries and retrieves them from the database at runtime. This approach prevents failures when new processing stages are introduced or old ones are renamed or removed, increasing resilience to changes in the pipeline software. CSR was also selected to reduce coupling between the frontend and backend environments and to simplify deployment. CSR allows the frontend to function independently of the application server's runtime state, improving robustness and maintainability.

The IHW plays a critical role in ensuring that the TURBO pipeline operates reliably under the demanding conditions of real-time transient astronomy. By combining a responsive web interface with high-performance SQL querying and direct integration with the TURBO infrastructure, the IHW provides both scientists and engineers with the tools needed to maintain and debug the system as it operates in production.

IV. CONCLUSION

The advent of multi-messenger astronomy has transformed our understanding of compact object mergers, enabling the simultaneous study of gravitational waves, electromagnetic radiation, and nuclear astrophysics. Binary neutron star mergers, in particular, offer a unique opportunity to probe the dense matter equation of state, test general relativity in the strong-field regime, and observe the synthesis of heavy elements via rapid neutron capture. These discoveries, catalyzed by the landmark detection of GW170817, have emphasized the need for fast, flexible, and high-throughput optical follow-up systems capable of observing the transient sky on the shortest timescales.

The Total-Coverage Ultrafast Response to Binary-Mergers Observatory (TURBO) is designed to meet this challenge. With dual arrays of robotic telescopes located at the Magdalena Ridge Observatory and Skinakas Observatory, TURBO will be capable of responding to gravitational-wave, neutrino, and gamma-ray burst triggers in under two seconds. Its high-cadence, wide-field imaging system enables both rapid transient discovery and continuous monitoring of nearby galaxies, opening new avenues in the study of core-collapse supernovae, kilonovae, and other fast-evolving transients.

In support of this effort, I developed the Image Health Website (IHW), a custom web application designed to diagnose, visualize, and verify the performance of TURBO's real-time image processing pipeline. Built using Next.js and TypeScript, and powered by a PostgreSQL database, the IHW provides detailed run-level diagnostics through histograms and metadata tables. It enables users to evaluate pipeline throughput, isolate processing failures, and examine detailed image artifacts, all through an intuitive browser interface. By favoring raw SQL over ORM abstractions, the system achieves high performance and remains fully transparent, facilitating fast debugging and enabling fine-grained control over complex database queries.

The combination of its hardware infrastructure, low-latency pipeline, and diagnostic web interface represents a significant step forward in real-time observational astrophysics. As gravitational-wave detectors increase in sensitivity and event rates, tools like IHW will be critical for managing the growing volume of transient data, ensuring pipeline stability, and accelerating the pace of discovery in this new era of time-domain astronomy.

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